iCORE ALBERTA INFORMATICS CIRCLE OF RESEARCH EXCELLENCE

Research Report

APRIL 2006 - MARCH 2007 VOLUME 6

WIRELESS COMMUNICATIONS LABORATORY • INTELLIGENT RF RADIO TECHNOLOGY • WIRELESS SCIENCE AND TECHNOLOGY • ADVANCED TECHNOLOGY INFORMATION PROCESSING SYSTEMS • WIRELESS LOCATION RESEARCH • HIGH CAPACITY DIGITAL COMMUNICATIONS • ALGORITHMIC NUMBER THEORY AND CRYPTOGRAPHY • BROADBAND WIRELESS NETWORKS, PROTOCOLS, APPLICATIONS AND PERFORMANCE • WIRELESS TRAFFIC MODELING • NANOENGINEERED ICT DEVICES • THIN FILM ENGINEERING • INFORMATION SECURITY • NANOSCALE ENGINEERING PHYSICS • QUANTUM INFORMATION SCIENCE • QUANTUM CRYPTOGRAPHY AND COMMUNICATION • NANOSCALE INFORMATION AND COMMUNICATIONS TECHNOLOGY • MULTIMEDIA • COLLABORATIVE VIRTUAL ENVIRONMENTS • INTERACTIVE TECHNOLOGIES • BIOCOMPLEXITY AND INFORMATICS • SOFTWARE ENGINEERING DECISION SUPPORT • HIGH PERFORMANCE ARTIFICIAL INTELLIGENCE • APPLIED BIOINFORMATICS • COMPUTER PROCESS CONTROL • REINFORCEMENT LEARNING & ARTIFICIAL INTELLIGENCE • INTELLIGENT SENSING SYSTEMS •

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iCORE

Message from the President

THERE IS NO LONGER ANY SUCH THING AS A LOCAL JURISDICTION BUT ONLY A WIDE RANGE OF LOOSELY OR TIGHTLY INTEGRATED GLOBAL COMMUNITIES.

Modern communications and transportation has shrunk the planet into a smaller social space than every before; in fact it seems to take more effort to remain in isolation, than to participate in the global community. And within this era, information is the currency.

This currency, in one form or another, is almost always managed by modern digital computers. The digital need and exchange of information is so deeply entwined within our society that shutting down computer systems is tantamount to shutting down the planet.

In our little part of the world, the iCORE academy now consists of 28 Professors, Chairs, and Industry Chairs. These Chairs and their teams are working across a broad diversity of information processing problems, which span a range of applications that affect the entire planet. For example, there are investigations at the physical scale where the smallest measurable amount of energy can be controlled to create switched memory, all the way to machine learning algorithms creating control functions that can control vehicles, and even continent-wide power systems.

The interesting thing is that from a beginning with four academic departments, the iCORE Academy now spans nine departments, across six faculties, and two universities. In fact iCORE is an agent of change, providing the research threads that are stitching together new multi-disciplinary research, and dissolving old discipline boundaries.

What's the point?

In this world that is becoming increasingly compact and complex, most problems are so grand and challenging that there are no solitary discipline-based solutions: human disease, global warming, ecologically sound resource management are all examples of problems that no single discipline can address.

So goes the evolution of iCORE. More diversity across more disciplines with a single focusing theme: the creation, manipulation, and deployment of information by teams focused on excellence in Alberta.

Randy Goebel

President and CEO

iCORE

About iCORE

The role of the Alberta Informatics Circle of Research Excellence

iCORE was established in October 1999 by the Government of Alberta to foster an expanding community of exceptional researchers who support and grow the ICT sector. This investment stems from a belief that strong fundamental research is at the core of a healthy economic sector, which in turn creates social, cultural and economic advantages for Albertans.

Mission

The mission of the Alberta Informatics Circle of Research Excellence (iCORE) is to attract and grow a critical mass of exceptional researchers in the field of informatics, that is, areas of computer science, electrical and computer engineering, physics, mathematics and other disciplines related to information and communications technology (ICT).

Target areas

As part of the Government of Alberta's strategy to create a globally competitive knowledge-based economic sector, iCORE is directing its support to areas in which Alberta has a chance to develop internationally recognized research teams. It is also focusing on areas in which Alberta companies are active, so that intellectual property and valuable knowledge workers resulting from iCORE's investment will have compelling reasons to stay in Alberta.

Focus on people

iCORE invests in people – the highest caliber research scientists who work on fundamental and applied problems in informatics. Around these leaders, world-class research teams are developed.

The iCORE principle is simple: exceptional people produce exceptional results.

Flagship Grant Programs

Chair and Professor Establishment (CPE) Grants

iCORE Chairs are awarded to exceptional researchers with outstanding research records that place them in the top five percent of their fields. iCORE Professors are mid-career researchers with outstanding potential whose record may not yet justify a Chair position.

Funding research teams may vary in size from a single Chair or Professor working alone to teams with ten or more members. iCORE funds can be used to cover the salaries of chairs, professors, research associates, postdoctoral fellows and graduate students, as well as some research operating and equipment costs. The research itself may range from fundamental to applied.

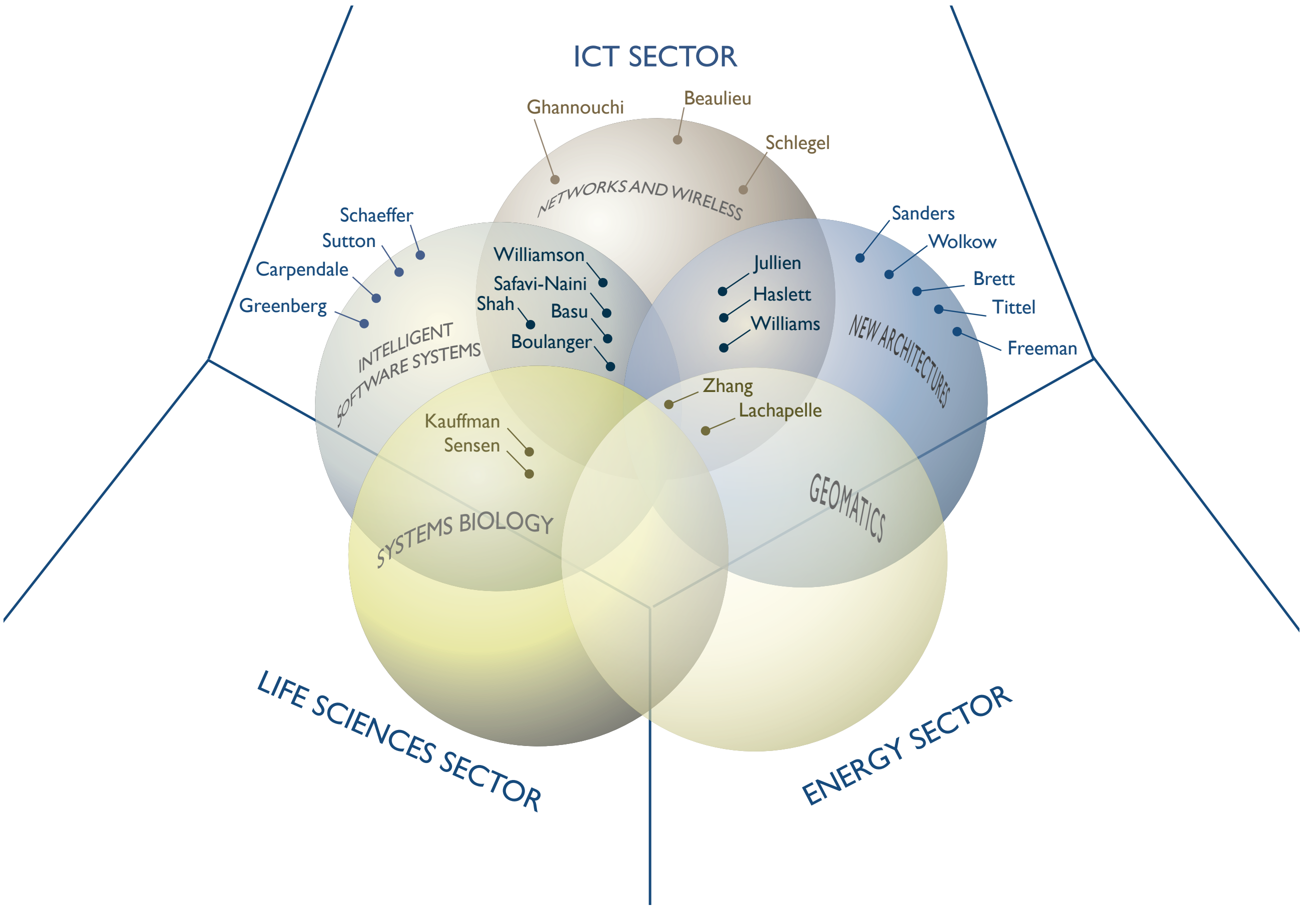
CPE grants are normally awarded for five years, represent one-half or less of the total budget, and are renewable on a competitive basis.

Industry Chair Establishment (ICE) Grants

iCORE Industrial Chairs are awarded to researchers undertaking high-caliber, internationally competitive research. Industrial Chairs are always developed in conjunction with a sponsor company(s) that has demonstrated a willingness and ability to collaborate closely with the research team, and to exploit proposed research in Alberta. The program is also typically matched with NSERC awards.

Funded research teams may vary in size from one to ten or more members, and may include a Chair, professors, research associates, postdoctoral researchers, graduate students and research staff. The funds may also cover operating and equipment costs.

ICE grants are normally awarded for five years, represent one-third or less of the total budget, and are renewable on a competitive basis.



Support programs

Graduate Student Scholarships (GSS)

- Designed to recruit exceptional graduate students in computer science and electrical and computer engineering
- Operates in conjunction with NSERC

Visiting Professor (VP) Grants

- Designed to bring internationally recognized researchers to Alberta for six months to two years to develop partnerships and possibly recruit Chairs or Professors

ICT Strategy Planning and Recruiting (ISPR) Grants

- Designed to support the interaction with potential candidates for major iCORE award programs
- Supports ICT conferences and workshops in Alberta in areas where a Chair or Professor award may be made

Banff Informatics Summit

- An annual event that brings together iCORE researchers and their national and international colleagues

Emerging Clusters

NETWORKS AND WIRELESS COMMUNICATION		START DATE
Wireless Communications	Dr Norman C. Beaulieu	2000-01
Intelligent RF Radio Technology	Dr Fadhel Ghannouchi	2004-05
Wireless Science and Technology	Dr James W. Haslett	2002-03
Advanced Technology Information Processing Systems	Dr Graham Jullien	2000-01
Wireless Location	Dr Gérard Lachapelle	2000-01
High Capacity Digital Communications	Dr Christian Schlegel	2001-02
Algorithmic Number Theory and Cryptography	Dr Hugh Williams	2001-02
Information Security	Dr Rei Safavi-Naini	2006-07
Broadband Wireless Networks, Protocols, Applications, and Performance	Dr Carey Williamson	2001-02
Wireless Traffic Modelling and Simulation	Dr Carey Williamson	2002-03
NEW ARCHITECTURES		
Nanoengineering ICT Devices	Dr Michael Brett	2000-01
Thin Film Engineering	Dr Michael Brett	2003-04
Nanoscale Physics and Nanomaterials	Dr Mark Freeman	2003-04
Quantum Information Science	Dr Barry Sanders	2003-04
Quantum Cryptography and Communication	Dr Wolfgang Tittel	2005-06
Nanoscale ICT	Dr Robert Wolkow	2002-03
INTELLIGENT SOFTWARE SYSTEMS		
Advanced Digital Media for Education	Dr Anup Basu	2005-06
Collaborative Virtual Environments	Dr Pierre Boulanger	2004-05
Interactive Technologies	Dr Sheelagh Carpendale and Dr Saul Greenberg	2006-07
Biocomplexity and Informatics	Dr Stuart Kauffman	2004-05
Software Engineering Decision Support	Dr Guenther Ruhe	2001-02
High Performance Artificial Intelligence	Dr Jonathan Schaeffer	2000-01
Applied Bioinformatics	Dr Christoph Sensen	2004-05
Computer Process Control	Dr Sirish Shah	2005-06
Reinforcement Learning and Artificial Intelligence	Dr Rich Sutton	2003-04
Intelligent Sensing Systems	Dr Hong Zhang	2003-04

Wireless Communications Laboratory

The overall goal of the iCORE Wireless Communications Laboratory (iWCL) research program is to create new engineering science and technologies that will lead to high capacities in broadband wireless communication systems at lower cost.

Ultra-wide bandwith wireless, or UWB, is a hot topic in wireless research. Called "bluetooth on steroids", UWB is an overlay technology that will replace cables and wires by enabling users to send data at hundreds of megabytes per second. The picture shows a personal computer, PDA, telephone, laptop computer, home entertainment system, and printer all connected to the internet (without wires or cables) through an UWB link.

Current topics under investigation include ultra-wide bandwidth (UWB) systems, orthogonal frequency division multiplexing (OFDM) systems, multi-user detection, space-time coding, multiple input multiple output (MIMO) systems, and cooperative wireless networks.

Successful collaborations have resulted in journal papers, conference papers, patent applications, and technology licensing. Six patents were applied for in the reporting period on technologies for UWB, MIMO, and OFDM. The reporting period also saw the first patent granted to the iCORE Wireless Communications Laboratory, "Methods, Systems and Devices for Generating Pulse Shapes," on November 28, 2006.

The Chair published an unprecedented number of 27 refereed journal papers in the reporting period, all in leading international journals. A further 28 refereed journal papers are in press or were accepted in the reporting period, again all in leading international journals. In addition, 39 conference papers were presented by the iCORE Chair and his research trainees. In this reporting year, Professor Beaulieu and his postdoctoral fellow, Bo Hu, won an IEEE Prize Paper Award at the 2006 International Conference on Ultra-Wideband (ICUWB) for their work on novel UWB receiver designs. Dr Beaulieu was appointed an IEEE Distinguished Lecturer and was listed in MARQUIS Who's Who in Science and Engineering, MARQUIS Who's Who in American Education, and MARQUIS Who's Who in America.

Outreach activities include authoring an encyclopedia article for eight to ten-year-olds and giving seminars on intellectual property to new Faculty Members.

In consequence of the achievements, awards, recognition and growth of the first eighty-one months, the iCORE Wireless Communications Laboratory is now renowned in the international communications research community and is increasing international and national awareness of Alberta, iCORE, and the University of Alberta.

Research Overview

Wireless communications research has been given great impetus by the advent of cellular telephony, mobile satellite, and portable personal communication services. The exponentially growing user demand for services, together with the increasing demands for higher speed transmission of large amounts of data, as well as customer requests for multimedia services, create the need for new technologies.

The overall goal of the proposed research is higher capacity in broadband wireless communication systems at lower cost. The iWCL wants to offer more wireless services with higher quality to more users. This is a significant challenge, scientifically and technologically, because the wireless spectrum (bandwidth) is a fixed resource. The primary thrust of this research is investigation into fundamental properties, limitations, and improvements in broadband wireless systems. Without new discoveries in engineering science, the available spectrum will become overloaded and unable to provide wireless services to the anticipated number of future users. A secondary thrust is the application of the research results to present and future systems. New engineering science must be put into action in the development of new technologies for real world systems. This two-pronged approach is consistent with Dr Beaulieu's belief that strong fundamental research is vital to the understanding and improvement of technically challenging systems, while application of the fundamental research results is an important step in creating economic advantages for the supporting community.

Future wireless networks will allow people on the move to communicate with anyone, anywhere, and at any time using a range of multimedia services. Wireless communication will also enable a new class of intelligent home electronics that can interact with each other and with the Internet. Wireless video will support applications such as distance learning and remote medicine, and self-configuring wireless networks will provide the baseline technology for widespread sensor networks and automated information highways. These advances will require innovation at every stage from theory to implementation. Future wireless systems will require higher data rates with better coverage for a large number of users operating with a large variety of different systems. There are many technical challenges that must be overcome in order to make this vision a reality. Wireless communication theory has a critical role in not only establishing a language and framework for thinking about solutions, but also in establishing fundamental limits of wireless communication systems.

A small number of "hot" topics under investigation in the iWCL are briefly described here to give an idea of the nature, relevancy and impact of the work.

Ultra-Wide Bandwidth Communications Systems

UWB refers to new systems and technologies that are envisioned to provide short range, high data rate services to multiple users in an unlicensed transmission format. UWB systems are a hot research topic, attracting great scientific and industrial interest. These systems are unconventional in that they spread the information signal over an extremely wide bandwidth, occupying many gigaHertz of spectrum. Correspondingly, the signals have an extremely small power spectral density and appear as noise to existing users. As an emerging technology, UWB offers great potential as an area wherein one can make fundamental theoretical contributions and at the same time develop technology that can lead to socio-economic benefits for the supporting community.

Cooperative Diversity

Recently, researchers have considered utilizing the multiple protocol layers that exist in mobile wireless networks to solve some of the problems related to the physical implementation of multiple-element antenna arrays. In particular, a cross-layer network algorithm that has recently garnered considerable attention is cooperative diversity. Essentially, the idea of cooperative diversity is that multiple wireless devices benefit by relaying messages jointly as opposed to independently. Through cooperation, the broadcast nature of competing wireless signals, traditionally treated as interference, are used in a beneficial way. In fact, in certain wireless channels, cooperative diversity has been shown to provide full spatial diversity; that is, as if each individual transmitter had as many transmitter antennas as the entire set of cooperating transmitters. The iWCL group is pursuing several projects related to cooperative diversity to develop rigorous mathematical models that accurately model practical cooperative networks and that can be used to predict outage, coverage and error rate performance. These models will be invaluable for cooperative network design and optimization. The challenges in defining and solving realistic analytical models for cooperative networks are significant. In particular, the decentralization of the diversity operations and combining makes mathematical treatment complex.

Orthogonal Frequency Division Multiplexing Systems

Orthogonal frequency division multiplexing (OFDM) technology belongs to the class of multi-carrier modulations where data are transmitted by modulating several parallel sub-channels simultaneously. The benefits of OFDM make it popular in today's broadband wireless communications industry by maximizing data transmission capacity through effectively converting a frequency-selective fading channel into several nearly flat-fading sub-channels, reducing intersymbol interference. New OFDM technologies are expected to be leading candidates for fourth generation wireless (4G) systems. For example, by utilizing OFDM in the physical layer, IEEE 802.11a is specified to achieve data rates up to 54 Mbps in the 5.2 GHz radio spectrum. This technology is also used in many systems proposed by the European Telecommunications Standard Institute (ETSI), such as digital audio broadcasting (DAB), digital video broadcasting over terrestrial (DVB-T) and the HIPERLAN/2 standard. There is very strong and growing interest in using OFDM for the next generation of land mobile communication systems orthogonal frequency division multiple access (OFDMA), which implements multiple access by assigning distinct users to distinct subcarriers. Recently, OFDMA technology was adopted as a physical layer specification for 2 - 11 GHz broadband wireless access systems for metropolitan area networks in IEEE 802.16a.

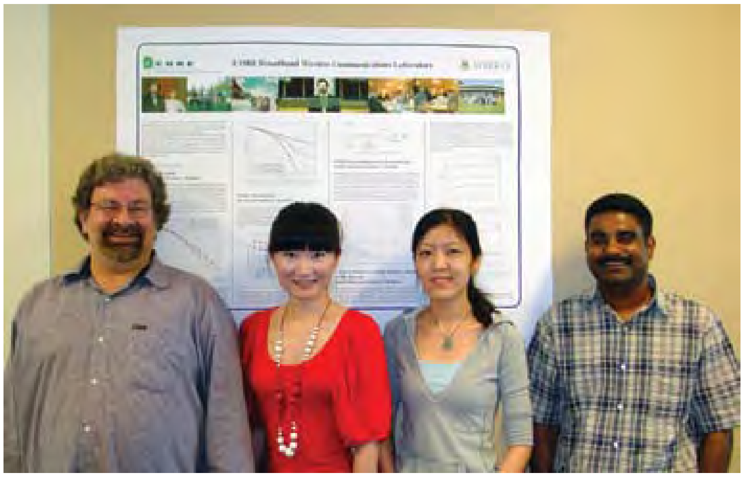
Research Projects

Many scientifically important and industrially relevant results are being achieved in the research projects.

Ultra-Wide Bandwidth Wireless Systems

UWB wireless is a very hot topic in university and industrial research and has great commercial potentials. The iWCL's research into UWB wireless systems has resulted in the following achievements;

UWB Channel Estimation: In published work the iWCL team has established theoretical limits on the performance of channel estimators for UWB systems.



iCORE researchers, (left to right) Norman Beaulieu, Bo Hu, Hua Shao and Somasundaram Niranjayan have published papers in international journals and conferences and filed patents on novel technologies for UWB as a result of their research in UWB.

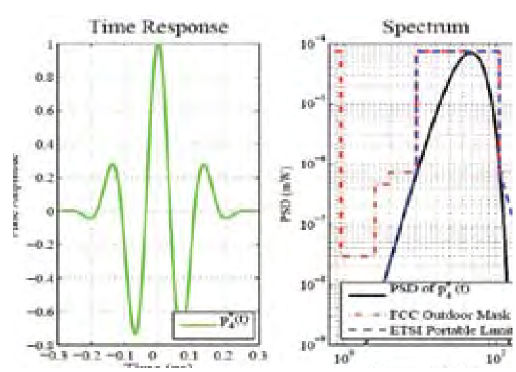
On the practical side, the team has discovered a novel UWB multipath component attenuation estimator that operates with one-fifth of the error of previous attenuation estimators. The team has also designed a UWB multipath component delay estimator that is better than previous delay estimators. These estimators will find application in Rake multipath diversity UWB receivers. The estimators have the advantage that they do not require pilot or overhead symbols for their operation. The estimators are the subject of a University of Alberta (U of A) patent application. In addition, PhD graduate Yunfei Chen was awarded an NSERC Innovation Challenge Honourable Mention Award for this work.

UWB Receiver Designs for Multiuser Interference Environments: Conventional UWB receivers use the matched filter or correlator receiver structure. However, this structure is not optimal for multi-user interference environments that exist when more than one UWB device is operating in geographical proximity. The iWCL team has discovered four new UWB receivers, each of which has superior performance to conventional UWB receivers. Patents are being filed by the U of A on all four of these novel designs. The first novel receiver design was reported in a paper titled, "An Adaptive Threshold Soft-Limiting UWB Receiver with Improved Performance in Multiuser Interference."

Improved Rake Receivers for Impulse Radio: State-of-the-art receivers for UWB employ a Rake structure to "comb" the wireless transmission medium for multiple transmitted signal rays. The iWCL has proposed new Rake receiver structures that outperform conventional Rake receivers. In future work, the team will design new, improved Rake UWB receivers by deriving a new combining strategy for the outputs of the fingers based on the statistics of the multiple access interference.

Symbol Synchronization in UWB Systems: All UWB systems transmit information using extremely short pulses, which are very difficult to track in wireless channels. Poor synchronization will seriously deteriorate the receiver performance. The iWCL will conduct rigorous theoretical investigations into the principles of synchronization for UWB transmission systems, and search for practical synchronization schemes for UWB receivers. Two different approaches to be pursued are maximum likelihood estimation and feature-extraction-based timing recovery.

Efficient Simulation Models for UWB Systems: Direct simulation of the widely used IEEE UWB channel model is very time consuming, particularly for oversampled (more than one sample per bit) system studies. The iWCL team proposes to find more efficient simulation techniques for UWB systems by combining some semi-analytical models with the



Unique electrical UWB pulses invented in the iWCL.

IEEE UWB channel model. In particular, the IEEE UWB model incorporates a number of sums of fading random variables. Recently published work reports simple and highly accurate analytical approximations to sums of lognormal, Rayleigh and Ricean random variables. The team will use these results to construct more efficient semi-analytical simulation models for UWB systems.

Space-Time Coding and Multiple Input Multiple Output Systems

MIMO antenna systems can, in some cases, increase the capacity of a wireless network by a factor of ten. Space-time coding is a MIMO technique that spreads the transmitted signal across multiple transmitter antennas, using space (multiple transmitter antennas) as another dimension, in addition to time, to achieve huge capacity gains. iWCL space time codes have been licensed to an American WiMAX company, and adopted in the IEEE 802.16e industry standard, the WiMax Standard. This intellectual property is assigned to the university and generates revenue.

In other MIMO research, the iWCL has developed a novel scheme for decision-feedback detection of block differential space-time modulations. Differential space-time modulation is of great value for applications on time-varying channels as it does not require channel estimation. The cost savings in receiver complexity is significant because a coherent space-time system receiver (one requiring channel estimation) must estimate the fading gains for each pair of transmitter/receiver antennas. However, differential space-time modulation suffers from an error rate floor (minimum achievable error rate) on fast fading channels, and the rate of channel variation limits the number of transmitter antennas that can be efficiently deployed in MIMO systems, vitiating the huge theoretical gains promised by MIMO systems for larger numbers of transmitter antennas. The combination of decision feedback differential detection with block differential space-time modulation eliminates these problems. A patent on this novel technology has been filed by the U of A.

Cooperative Wireless Networks

The use of multiple antennas can be an effective solution to combat the signal fading and shadowing that causes performance degradation in wireless systems. However, in many applications there may not be adequate room to accommodate multiple antennas spaced far enough apart to experience independent fading. This problem is further highlighted by the decreasing size of wireless communications devices. In cooperative wireless networks, users cooperate by receiving and retransmitting (relaying) the signals of other users. In this way, the cooperating users create a multiple antenna array. These innovative wireless networks aim to increase the channel capacity and reliability of wireless communications.

The iWCL has derived new mathematical solutions that can be used to predict in advance how often a cooperative wireless network will be in outage (that is when the signal or call is dropped). These solutions for outage probability are expressed in terms of the wireless network parameters. Hence, they can be used in the design phase to construct cooperative wireless networks having minimal outages.

In other work, the iWCL has proposed and studied a new relaying protocol for cooperative wireless networks. Based on the elimination of orthogonal noise, this new protocol reduces power consumption at the relay nodes and decreases the outage of the users.

Orthogonal Frequency Division Multiplexing Systems

Receiver Windowing for Intercarrier Interference (ICI) Reduction: While OFDM is effective in reducing or eliminating intersymbol interference (ISI) caused by frequency-selective fading, it suffers from ICI due to carrier frequency offset. Work done by the iWCL has demonstrated that receiver windowing can be effective in reducing ICI in OFDM systems. Further, different window function shapes have been assessed with a view to determining the best window shape that will result in the minimum bit error rate in the transmitted OFDM signal. In particular, a novel window shape discovered by Dr Beaulieu (patented by the U of A) has been shown to improve the performance of practical OFDM systems more than four other popular windowing functions.

Improved OFDM System Designs: Practical OFDM systems require a modest amount of channel equalization in order to yield the best performance. While the conventional OFDM structure employs a cyclic prefix and equalizer, recent work by American researchers showed that a structure employing a zero-padding scheme and equalizer can outperform conventional OFDM employing a cyclic prefix and equalizer. The iWCL team discovered that the new zero-padded OFDM system will have better performance if a discrete cosine transform (DCT) is employed rather than a FFT, and analysis shows substantial improvement in the presence of ICI. This OFDM system structure is the subject of a U of A patent application.

Engineering Science Results: Results from analytical tools developed by iWCL researchers have shown the benefits that can be achieved by receiver windowing in OFDM systems that are affected by carrier frequency offset. In other theoretical work, the iWCL has published the first accurate, and conceptually correct, analysis of the error rate performance of OFDM on frequency-selective Nakagami-m fading channels.

Objectives for Next Year

The iWCL has established itself as an internationally leading wireless research centre, creating recognition and awareness of iCORE, the U of A, and Alberta in the engineering science and industrial communities. In the first years of the iCORE Chair, efforts were focused on building a critical mass of wireless researchers in Edmonton at the U of A. A nucleus of Professors, Graduate Students and Research Associates is now in place. Presence and credibility in the academic world was targeted and achieved through prolific publication of scholarly research, winning awards and honours, training of highly skilled personnel, and professional activities such as editorial board service, conference organization, and service on funding panels, national and international. Having achieved the immediate preliminary goals, the planning for the future evolution of the research program and the development of the laboratory aims at three objectives.

The first objective is to maintain or increase the present levels of scholarly research and training of highly skilled personnel. That is, to preserve the world-class standing of the wireless research centre in Edmonton. The general areas of the proposed work are broadband wireless and wireless networks, which conducts scholarly research on relevant and timely topics that have real-world applications. The primary thrust of the research is investigation into fundamental properties, limitations, and improvements in broadband wireless communication systems. A secondary thrust is the application of the research results to present and future systems. The overall goal of the research is higher capacity in broadband wireless systems at lower cost. This goal will always be relevant and, in fact, will increase in relevancy with time since spectrum is a finite resource whereas demands for service are growing exponentially. New and better solutions evolve, but the fundamental problem remains the same. The "hot" new solutions being investigated now were not under investigation just six and one-half years ago when Dr Beaulieu was appointed iCORE Chair.

The second objective is the recruitment of exceptionally qualified graduate students. In the past, the iWCL has recruited exceptional "top of the class" foreign and Canadian graduate students from national and international leading universities. There are, however, a number of circumstances that will result in it becoming increasingly difficult to recruit top graduate students to the Electrical and Computer Engineering Department at the U of A. The recently relaxed policies for granting student visas to foreign graduate students in the United States (USA) and an upturn in the job prospects for highly qualified personnel in the Information Technology sector in the USA are causing more outstanding graduate student applicants to choose American universities over Canadian universities. Meanwhile, the quality of the output of the research program is strongly dependent on the quality of the graduate students in training. Hence, graduate student recruitment will become more proactive in the future, with the goal of maintaining the present and past exceptional level of quality trainees. This may include moving some resources into proactive graduate student recruitment, for example, recruitment trips to national and international universities and sponsored recruitment visits to the U of A.

The third objective is the development of an intellectual property portfolio. Dr Beaulieu has a plan for instituting a policy and direction for the development of an intellectual property portfolio in the future. This plan is built on the basic premise of creating benefit for the U of A and the province of Alberta. While maintaining or increasing the stature of the group as an international centre of excellence in wireless through research, scholarly publication and the training of highly skilled personnel, all research results will be carefully reviewed with a view to potential value in intellectual property. This process will be selective and will involve consultation with industrial collaborators. Results that are assessed as having true potential for wealth creation will be submitted to the Technology, Entrepreneur & Company Development agency of the U of A (TEC Edmonton Ltd.) for patent prosecution and commercialization. All inventions will be assigned to the U of A; there will be no commercialization independent of the university. In cases where inventions arise in collaborative research with researchers based outside the U of A, fair interest in intellectual property will be retained for the university. Consistent with this objective of building an intellectual property portfolio, Dr Beaulieu has filed six patents on wireless inventions in the reporting year.

Outreach

The Chair presented a talk on intellectual property at the TEC Edmonton Orientation Workshop for new Faculty Members on August 18, 2006 and on January 24, 2007.

Dr Beaulieu also served as a Member of the Student Paper Award Selection Committee, IEEE/URSI/IEICE International Conference on Ultra-Wideband (ICUWB) 2006, Waltham, MA, September 2006.

The Chair has contributed an article on Wireless Communications to the World Book Encyclopedia. This article is intended for an 8-10 year old reader audience.

Research Team Members and Contributions

Team Leader
Professor Norman C. Beaulieu
*i*CORE Research Chair in Broadband Wireless Communications
Canada Research Chair in Broadband Wireless Communications
Recipient J Gordin Kaplan Award for Excellence in Research 2006
Recipient 2005 Royal Society of Canada Thomas W. Eadie Medal
Recipient Médaille K.Y. Lo Medal (2004)
Fellow of the Royal Society of Canada
NSERC E.W.R. Steacie Memorial Fellow
Fellow of the Canadian Academy of Engineering
Fellow of the Institute of Electrical and Electronics Engineers (IEEE)
Fellow of the Engineering Institute of Canada (EIC)
Editor-in-Chief of the *IEEE Transactions on Communications* (2000-2003)
President of the Canadian Society for Information Theory
Listed in *MARQUIS Who's Who in America*
IEEE Distinguished Lecturer
Listed in *MARQUIS Who's Who in American Education*
Listed in *MARQUIS Who's Who in Science and Engineering*
IEEE Prize Paper Award, *2006 International Conference on Ultra-Wideband ICUW*

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Dr Chintha Tellambura	Professor	Registered as P.Eng. with APEGGA
Dr Masoud Ardakani	Assistant Professor	
Dr Abraham Fapojuwo	Associate Professor	

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PostDoctoral Fellows

Name	Awards/Special Info
Dr Yunfei Chen	NSERC Innovation Challenge Award (Honourable Mention Prize)
Dr Bo Hu	IEEE Prize Paper Award, 2006 International Conference on Ultra-Wideband ICUWB
Dr Young Gil Kim	
Dr Xiaodi Zhang	2007 NSERC PDF Recipient

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PhD Candidates	
Name	**Awards/Special Info**
Yunfei Chen	Alberta Ingenuity Fund Full-Time Student Scholarship iCORE Graduate Student Scholarship
Ethan Davis	
Payam Dehghani Rahimzadeh	
Golnaz Farhadi	Alberta Ingenuity Fund Full-Time Student Scholarship iCORE Graduate Student Scholarship J Gordin Kaplan Graduate Student Award Invited to Chair Session WA-18 at ICC'06
Sasan Haghani	Alberta Ingenuity Fund Full-Time Student Scholarship iCORE Graduate Student Scholarship
Farhad Hossain	
Bo Hu	Alberta Ingenuity Fund Full-Time Student Scholarship iCORE Graduate Student Scholarship
Jeremiah Hu	Alberta Ingenuity Fund Full-Time Student Scholarship iCORE Graduate Student Scholarship NSERC CGS AB Scholarship Program Ralph Steinhauer Award of Distinction
Pavel Loskot	Alberta Ingenuity Fund Full-Time Student Scholarship iCORE Graduate Student Scholarship
Reza Nikjah	Alberta Ingenuity Fund Full-Time Student Scholarship iCORE Graduate Student Scholarship
Somasundaram Niranjayan	Alberta Ingenuity Fund Full-Time Student Scholarship iCORE Graduate Student Scholarship
Amirmasoud Rabiei	Alberta Ingenuity Fund Full-Time Student Scholarship iCORE Graduate Student Scholarship
Hua Shao	
Peng Tan	Alberta Ingenuity Fund Full-Time Student Scholarship iCORE Graduate Student Scholarship
David Young	
Xiaodi Zhang	Alberta Ingenuity Fund Full-Time Student Scholarship iCORE Graduate Student Scholarship
Changqin Huo	Co-supervised with Dr Sesay

Beaulieu

MSc Candidates	
Name	**Awards/Special Info**
Robert Carruthers	NSERC PGSM Award iCORE Graduate Student Scholarship Alberta Graduate Student Scholarship
Shuo Liu	
Ali Sharifkhani	
Hua Shao	
Xin Wang	

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Undergraduate Students		
Name	**Role/Topic**	**Awards/Special Info**
Xiaoqian Liu	Undergraduate	Dean's Research Award, Faculty Of Engineering, U Of A
Xin Wang	Undergraduate	Dean's Research Award, Faculty of Engineering, U OF A GE Fanuc Software Undergraduate Scholarship

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Other Team Members		
Name	**Role/Topic**	**Awards/Special Info**
Sandra Abello	Administrative Assistant	
Martha Benitez	System Administrator	
Robert Carruthers	Research Engineer	
Wenyu Li	Research Assistant	
Amanda Ross	Administrative Assistant	
Sharon Walker	Administrative Assistant	
Xin Wang	Research Assistant	

Tellambura

PostDoctoral Fellows		
Name	**Role/Topic**	**Awards/Special Info**
Dr Zhongshan Zhang		
PhD Candidates		
Name	**Role/Topic**	**Awards/Special Info**
Yu Fu		Co-supervised with Dr Krzymien
Alireza Ghaderipour		
Luqing Wang		
Yue Wu		
MSc Candidates		
Name	**Role/Topic**	**Awards/Special Info**
Xinwei Deng		FGSR Travel Award
Mahdi Hajiaghayi		
Khoa Tran Phan		
Metaz Sharmin		
Wei Zhang		FGSR Travel Award

Ardakani

PostDoctoral Fellows		
Name	**Role/Topic**	**Awards/Special Info**
Dr Mohammad Rahman		
MSc Candidates		
Name	**Role/Topic**	**Awards/Special Info**
Ali Sanaei		
Moslem Noori		
Mahdi Ramezani		
Raman Yazdani		FGSR Travel Award

Fapojuwo

PhD Candidates		
Name	**Role/Topic**	**Awards/Special Info**
Abdul Hasib		
Helen Lampow-Maundy		
Ian Lee		
Xiao Liu		TRLabs Scholarship NSERC Graduate Scholarship iCORE Scholarship
Azfar Moid		TRLabs Scholarship

MSc Candidates		
Name	**Role/Topic**	**Awards/Special Info**
Liqi Shi		
Ahmed Zaki		
Alejandra Cano-Tinoco		
Kejin Huang		
Sidhesh Basavaraj		

Other Team Members		
Name	**Role/Topic**	**Awards/Special Info**
Joshua Ang	NSERC Summer Student	
Sangheon Kim	NSERC Summer Student	

GRADUATES

Beaulieu

Name	*Research Topic*	*Current Position*
PhD Graduates		
Peng Tan	"Orthogonal Frequency Division Multiplexing Data Transmission System Designs for Intercarrier Interference Mitigation"	Subsequently employed by TELUS, Edmonton, AB
Xiaodi Zhang	"Effects of Correlation on Multiple Antenna Systems"	Subsequently employed by NORTEL, Ottawa, ON
MSc Graduates		
Robert Carruthers	"Improved Markov Chain Modeling of the Rayleigh Fading Channel"	Subsequently employed by *i*CORE Wireless Communications Laboratory
Hua Shao	"A Novel Zonal UWB Receiver with Superior Performance"	Subsequently enrolled in the PhD program at the U of A

Tellambura

Name	*Research Topic*	*Current Position*
PhD Graduates		
Dung Ngoc Dao	"Design of low complexity space-time block codes for wireless communication systems"	Subsequently employed as a Post Doctoral Fellow at McGill University, Montreal
MSc Graduates		
Saeed Kaviani	"Closed-loop transmit diversity for multiple antenna systems"	Subsequently enrolled in the PhD program at the U of A

Fapojuwo

Name	*Research Topic*	*Current Position*
PostDoctoral Graduates		
Mohammad Rahman	"Research on Security Protocols for MANETs"	Subsequently employed as an Assistant Professor, Pakistan
MSc Graduates		
Kejin Huang	"A Technology Framework of Dynamic Software Upgrading"	Subsequently employed by Nortel Networks, Calgary, AB
M Eng. Graduates		
Shidan Ashraf	"Reliability of Telecommunication Networks in Power Utility Transmission Networks"	Subsequently employed by SNC-LAVALIN, Calgary, AB

COLLABORATIONS

Beaulieu

Participants	*Nature of Collaboration*
Provincial Collaborations	
Faculty of Engineering, MINT Program	Funding Assistance
TEC Edmonton	Financial Assistance
ECE Dept., U of A	Financial Assistance and IT Assistance
M. Ardakani, U of A	One International conference paper Funding Assistance
C. Tellambura, U of A	Funding Assistance
Fapojuwo, U of C	Funding Assistance
D.P. Wiens, U of A	One Published journal paper
ECE Graduate Students	Graduate Students' Seminar Series (20 seminar presentations)
Dr A. Basu, U of A, Computer Science	Meeting to discuss collaborative research
Dr J. Liu, University of Alberta, Medicine	Meeting to discuss collaborative research
National Collaborations	
Dr J. Cheng, UBC Okanagan	Two Accepted journal papers One International conference paper
Dr M.O. Damen, University of Waterloo	One Published journal paper
Dr K.E. Baddour, Communications Research Centre (CRC), Ottawa	One Accepted journal paper One International conference paper
Dept. of Mathematics & Statistics, Queen's University, Queen's Communications Group	Dr N.C. Beaulieu, Adjunct Professor
Canadian Society of Information Theory (CSIT) Workshop (CWIT 2007), Edmonton AB, June 6 - 8, 2007	General Chair (one of two)
Canadian Society of Information Theory	President
Dr S. Boumaiza, U of C	Meeting to discuss collaborative research
International Collaborations	
Dr S.J. Lee, Electronics & Telecommunications Research Institute (ETRI), Korea	One Accepted journal paper One Published journal paper One International conference paper
Dr Z. Du, Huawei Technologies, a leading telecommunications equipment manufacturer	Two Accepted journal papers One Published journal paper One International conference paper

Participants	*Nature of Collaboration*
International Collaborations Cont'd	
Dr H. El Gamal, Ohio State University	One Published journal paper
Dr M.Z. Win, MIT	One Published journal paper Invited Distinguished Seminar Series Speaker
Dr J. Silverstein, North Carolina State University	Invited Tutorial presenter
Dr G. Karagiannidis, Aristotle University of Thessaloniki, Greece	Invited External Examiner and Seminar Series Speaker
W. Li, ALTERA Corp., California	One Accepted journal paper Two International conference papers
Dr K. Sivanesan, SAMSUNG, Korea	One Accepted journal paper One Published journal paper
Dr C. Xiao, University of Missouri, Columbia	One Published journal paper
Dr Y.R. Zheng, University of Missouri-Rolla, Rolla	One Published journal paper
Industrial Collaborations	
Strategic Wireless Solutions, Inc., Plant City, Florida	Consulting Agreement on Space-Time Codes

Tellambura

Participants	*Nature of Collaboration*
Provincial Collaborations	
Dr S. Vorobyov	Graduate student, Joint supervision

Dr Ardakani

Participants	*Nature of Collaboration*
National Collaborations	
B. Smith, Dr W. Yu, Dr F. R. Kschischang (U of T)	Joint research on complexity optimization of LDPC codes
International Collaborations	
Dr P. Zarrinkhat, Airvana Inc., Boston, USA	Research on robust decoding algorithms and authoring joint papers

Dr Fapojuwo

Participants	*Nature of Collaboration*
National Collaborations	
Cape Breton University, Sydney, Petroleum Applications of Wireless Systems Research Group	Wireless Sensor Network Architecture and Protocol Design for Petroleum Plants
International Collaborations	
General Dynamics Canada	Networking and Capacity Solutions for Tactical Mobile Ad hoc Networks

INTELLECTUAL PROPERTY

Patents	*Title/Name*	*Status*
N.C. Beaulieu and H. Shao	"A Zonal UWB Receiver and Method"	US and Canadian Provisional Patent Application, filed March 9, 2007
N.C. Beaulieu and Y. Chen	"Non-Data-Aided Channel Estimators for Multipath and Multiple Antenna Wireless Systems"	US and International Patents Application, filed March 7, 2007
N.C. Beaulieu and Z. Du	"Decision-Feedback Detection for Block Differential Space-Time Modulation"	US and Canadian Provisional Patent Application, filed August 31, 2006
N.C. Beaulieu	"System and Method for Receiving Time-Hopping UWB Signals"	US and Canadian Provisional Patent Application, filed August 23, 2006
N.C. Beaulieu and W. Li	"Antenna Selection Methods for Alamouti Multiple Input Multiple Output (MIMO) Systems"	US and International Patents Application, filed July 31, 2006

Patents	*Title/Name*	*Status*
N.C. Beaulieu and P. Tan	"MMSE Equalizer and Method for One-Dimensional Modulation OFDM Systems"	US Patent Application, filed May 15, 2006
N.C. Beaulieu	"Methods, Systems and Devices for Generating Pulse Shapes"	United States Patent, US 7,142,613 B2, November 28, 2006
N.C. Beaulieu	Threaded Algebraic Space-Time Constellations and Threaded Algebraic Space-Time Code Construction Methodology	Licenced to an American corporation TEC Edmonton receives royalties for usage based on the number of units using the technology. There is a minimum royalty per year to be paid regardless of the number of unit installations. The legal agreement provides for profit sharing with TEC Edmonton if the licencee licences the technology to other companies.

FUNDING

Dr Norman Beaulieu has a five-year iCORE Chair award ($4.2M). This year he and his team received funding from NSERC ($446K), Alberta Ingenuity ($100K), CFI ($20K) and industry ($38K). They have also received funds from CRC for a Tier 1 Canada Research Chair ($200K).

PUBLICATIONS

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P. Tan and N.C. Beaulieu, “Effect of Channel Estimation Error on Bit Error Probability in OFDM Systems Over Rayleigh and Ricean Fading Channels,” accepted pending revisions for publication as a full paper in *IEEE Transactions on Communications*.

P. Tan and N.C. Beaulieu, “Precise BER Analysis of π/4-DQPSK OFDM With Carrier Frequency Offset Over Frequency Selective Fast Fading Channels,” accepted pending revisions for publication as a full paper in *IEEE Transactions on Wireless Communications*.

Y. Chen and N.C. Beaulieu, “Optimum Pilot Symbol Assisted Modulation,” to appear as a full paper in *IEEE Transactions on Communications*.

E. Davis and N.C. Beaulieu, “Asymptotic Results in PSK Modulation Classification,” accepted pending revisions for publication as a full paper in *IEEE Transactions on Communications*.

X. Zhang and N.C. Beaulieu, “Explicit Analytical Expressions for Outage and Error Rate of Diversity Cellular Systems in the Presence of Multiple Interferers and Correlated Rayleigh Fading,” accepted pending revisions for publication as a full paper in *IEEE Transactions on Communications*.

N.C. Beaulieu, “Switching Rates of Dual Selection Diversity and Dual Switch-and-Stay Diversity,” accepted pending revisions for publication in *IEEE Transactions on Communications.*

J. Hu and N.C. Beaulieu, “Accurate Closed-Form Approximations for the Performances of Equal Gain Combining Diversity Systems in Nakagami Fading Channels,” accepted for publication as a full paper in *IET Communications*.

J. Hu and N.C. Beaulieu, “Performance Analysis of Decode-and-Forward Relaying With Selection Combining,” to appear in *IEEE Communications Letters*.

P. Loskot and N.C. Beaulieu, “On Monotonicity of the Hypersphere Volume and Area,” accepted for publication in *The Journal of Geometry*.

X. Zhang and N.C. Beaulieu, “A Closed-Form BER Expression for BPSK Using MRC in Correlated CCI and Rayleigh Fading,” to appear in *IEEE Transactions on Communications*.

Y. Chen and N.C. Beaulieu, “SNR Estimation Methods for UWB Systems,” to appear in *IEEE Transactions on Wireless Communications*.

N.C. Beaulieu and X. Zhang, “On the Maximum Number of Receiver Diversity Antennas That can be Usefully Deployed in a Cochannel Interference Dominated Environment,” to appear as a full paper in *IEEE Transactions on Signal Processing*.”

B. Hu and N.C. Beaulieu, “Precise Performance Analysis of DS-UWB Systems on AWGN Channels in the Presence of Multiuser Interference,” accepted pending revisions for publication as a full paper in *IET Communications*.

S. Haghani and N.C. Beaulieu, “Performance of S+N Selection Diversity Receivers in Correlated Rician and Rayleigh Fading,” to appear as a full paper in *IEEE Transactions on Wireless Communications*.

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S.J. Lee and N.C. Beaulieu, “Performance Improvement of Non-Data-Aided Feedforward Symbol Timing Estimation Using the ‘Better Than’ Raised-Cosine Pulse,” to appear in *IEEE Transactions on Communications*.

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S. Haghani and N.C. Beaulieu, "Performance of two Dual-Branch Postdetection Switch-and-Stay Combining Schemes in Correlated Rayleigh and Rician Fading," to appear in *IEEE Transactions on Communications*.

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P. Loskot and N.C. Beaulieu, "The Input-Output Weight Enumerator of Binary Hamming Codes," *European Transactions on Telecommunications*, vol. 17, pp. 483-488, Jul./Aug. 2006.

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M. Hajiaghayi and C. Tellambura, "Unitary Signal Constellations for Differential Space-Time Modulation," *IEEE Communications Letters*, vol. 11, no. 1, pp. 25-27, Jan. 2007.

Y. Fu, C. Tellambura and W. Krzymień, "Transmitter Precoding for ICI Reduction in Closed-Loop MIMO OFDM Systems," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 1, pp. 115-125, Jan. 2007.

D.N. Dao and C. Tellambura, "A General Combinatorial Sphere Decoder and its Application," *IEEE Communications Letters*, vol. 10, no. 12, pp. 810-812, Dec. 2006.

A. Annamalai, G. Deora and C. Tellambura, "Analysis of Generalized Selection Diversity Systems in Wireless Channels," *IEEE Transactions on Vehicular Technology*, vol. 55, no. 6, pp. 1765-1775, Nov. 2006.

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T. Cui and C. Tellambura, "Analysis and Optimization of Pilot Symbol-Assisted RAKE Receivers for DS-CDMA Systems," *IEEE Transactions on Vehicular Technology,* vol. 55, no. 4, pp. 1159-1170, Jul. 2006.

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M. Shehata, A. Eberlein and A.O. Fapojuwo, "Using Semi-Formal Methods for Detecting Interactions Among Smart Homes Policies," *International Journal of Science of Computer Programming* (in press).

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P. Loskot and N.C. Beaulieu, "A Family of Low Complexity Adaptive Binary Linear Block Codes," *IEEE GLOBECOM*, San Francisco, California, Nov. 27-Dec. 1, 2006.

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S. Niranjayan and N.C. Beaulieu, "On the Integrated Cross-Noise Component in Correlation Receivers," *IEEE GLOBECOM*, San Francisco, California, Nov. 27-Dec. 1, 2006.

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N.C. Beaulieu and B. Hu, "A Soft-Limiting Receiver Structure for Time-Hopping UWB in Multiple Access Interference," *9th International Symposium on Spread Spectrum Techniques and Applications ISSSTA 2006*, Manaus, Brazil, pp. 417-421, Aug. 28-31, 2006. Invited Paper.

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R. Nikjah and N.C. Beaulieu, "Antijamming Capacity and Performance Analysis of Multiple Access Spread Spectrum Systems in AWGN and Fading Environments," *IEEE International Conference on Communications ICC 2006*, Istanbul, Turkey, pp. 5153-5159, Jun. 11-15, 2006.

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SPECIAL/INVITED PRESENTATIONS

N.C. Beaulieu, "On the Maximum Number of Receiver Diversity Antennas That can be Usefully Deployed in a Cochannel Interference Environment," Distinguished Speaker Seminar presented at the University of Calgary, Electrical and Computer Engineering Department, February 9, 2007.

N.C. Beaulieu, "Technology Commercialization From the Researcher's Perspective," presented at TEC Edmonton Event, Tech Commercialization Workshop for U of A Researchers in Engineering, January 24, 2007.

N.C. Beaulieu, "On the Maximum Number of Receiver Diversity Antennas That can be Usefully Deployed in a Cochannel Interference Environment," presented at NTT DoCoMo Communications Laboratories USA, Inc. Network Lan (NWL) Silicon Valley, California, December 1, 2006.

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N.C. Beaulieu, "Reflections of a Serial Inventor," presented at TEC Edmonton, New Faculty Orientation, Aug. 18, 2006.

N.C. Beaulieu, "Research in the *i*CORE Wireless Communications Laboratory," presented at the *i*CORE Summit 2006, May 23-25, 2006.

Awards

DR BEAULIEU

Listed in *MARQUIS Who's Who in America*

IEEE Distinguished Lecturer

Listed in *MARQUIS Who's Who in American Education*

IEEE Prize Paper Award, *2006 International Conference on Ultra-Wideband ICUWB*

Listed in *MARQUIS Who's Who in Science and Engineering*

DR ARDAKANI

Alberta Ingenuity New Faculty Award

DR FAPOJUWO

Nominated for a teaching excellence award in ENEL573

Theses

DR BEAULIEU

Xiaodi Zhang, "Effects of Correlation on Multiple Antenna Systems," PhD Thesis, Jan. 2007; subsequently employed as WiMax System Engineer by NORTEL, WiMax Research & Development Group, Ottawa, ON.

Hua Shao, "A Novel Zonal UWB Receiver With Superior Performance," MSc Thesis, Dec. 2006; subsequently enrolled in the PhD program at the UNIVERSITY OF ALBERTA.

Robert Carruthers, "Improved Markov Chain Modeling of the Rayleigh Fading Channel," MSc Thesis, Dec. 2006; subsequently employed by *i*CORE WIRELESS COMMUNICATIONS LABORATORY.

Peng Tan, "Orthogonal Frequency Division Multiplexing Data Transmission System Designs for Intercarrier Interference Mitigation," PhD Thesis, Aug. 2006; subsequently employed as Engineer, Technology Strategy, by TELUS, Edmonton, AB.

DR FAPOJUWO

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Intelligent RF Radio Technology

The Intelligent RF Radio Laboratory (iRadio Lab) mission is to develop new knowledge and innovative enabling technologies pertinent to intelligent radio systems and related applications that are valuable to partners and sponsors, and to train highly qualified personnel in radio frequency (RF) and wireless communications science and technology.

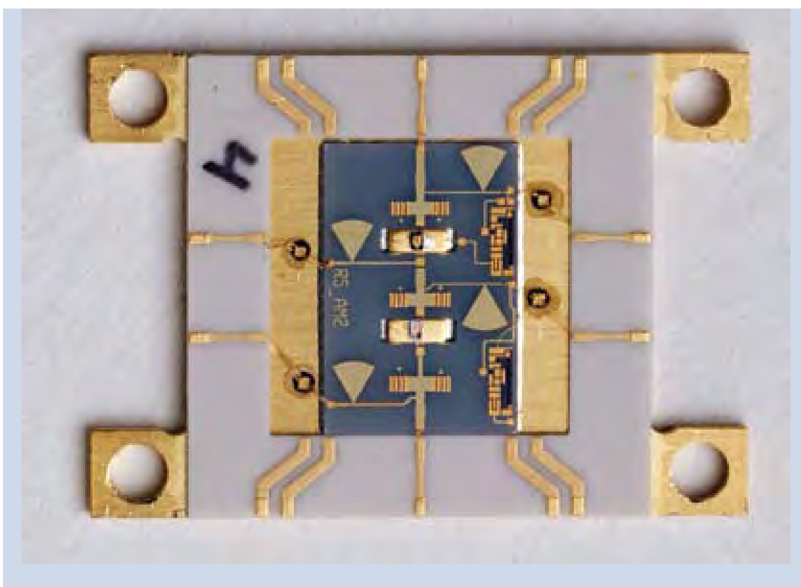


***Figure 1** Amplifier Prototype*

This laboratory is devoted to advanced research and development activities in intelligent RF radio technology applicable to broadband wireless communication systems. The research program is concerned with RF and microwave devices, circuits and systems; adaptive digital signal processing (DSP); modeling of devices, systems and channels; linearization and equalization concepts; and multiple-input multiple-output (MIMO) systems; software-hardware implementation and integration issues; and, other related applications.

The iRadio Lab was formally launched on November 28th, 2005 and is already staffed with more than fifteen graduate students and talented researchers, recruited worldwide. The main space dedicated to the iRadio Lab in the University of Calgary's ICT building has been completed, and an auxiliary space in the Engineering building, allocated for printed circuit board fabrication and circuit prototyping, is under renovation. The iRadio Lab facilities are supported by a number of CAD based software tools, test benches and rapid prototyping setups.

This laboratory is positioned at the crossroads of several fields relevant to highly promising broadband wireless communication systems; it is in a position to provide a unique platform for pre-competitive research and for industrial and technological development.

Leading-edge research, development, testing, validation, and evaluation of new concepts and architectures relevant to software-defined and software-enabled RF radio activities are being conducted in collaboration with the RF and wireless communications industries and government research and development (R&D) agencies. Despite its recent creation, the iRadio Lab has succeeded in the initiation of close formal collaborations with several national and international academic institutions, industry partners and government agencies. Several non-disclosure agreements to access proprietary information and/or technologies have been signed to support these collaborations. Furthermore, the iRadio Lab was formally accepted in February 2007 as an Associate Member of a European Center of Excellence (TARGET – Top Amplifier Research Groups in a European Team).

The innovative and applications-oriented R&D activities being carried out at the iRadio Lab have led to more than forty refereed journal and conference papers, a United States (US) patent and a provisional patent application. Four distinguished speakers have given talks to students and researchers at the University of Calgary (U of C) and a two-day course related to switching mode amplifiers was organized by the iRadio Lab which attracted engineers and researchers from the university and the local industry.

Research Program Overview

The Research Team

The people affiliated with the iRadio Lab encompass faculty members, research staff, students, support staff and associated members. The iRadio Lab personnel connected directly with the U of C include two faculty members, one technical support staff and one administrative support staff, a lab manager, three postdoctoral fellows, and twenty graduate students.

Research Partners

This laboratory is mainly funded by joint sponsorship from iCORE, Canada Research Council (CRC), Canada Foundation for Innovation (CFI) and the National Sciences and Engineering Research Council of Canada (NSERC). Formal academic collaborations are maintained with Canadian and international universities in the area of power amplifiers, and transmitters design and optimization. In addition, close collaborations have been made with major national and international leading companies, in the following areas: (i) semi-conductor technology (Freescale, Nitronex, RFHIC); (ii) wireless and satellite communications infrastructure (Nortel Networks, Nanowave Technologies, Canadian Space Agency, Powerwave Technologies, Rockwell Collins); and, (iii) digital electronics, DSP and computer aided design software (Analog Devices, Altera, and Agilent Technologies).

Major Research Directions

The scope of this iCORE Professorship/CRC chair research program is related to the development of intelligent RF radio systems for emerging wireless and satellite communications. The main goal is the development of software-defined high-performance transceivers. This multidisciplinary research program calls for

broad knowledge in the fields of DSP and mixed signal technology, RF and microwave technology, and communications systems, including the implementation and manufacturing processes in these respective fields.

The ongoing research activities span over the following research directions:

Device, system, and channel modeling:

The development of device, circuit and system models is essential for the design and optimization of the RF front-end. Behaviour/channel modeling is a key element for system level analysis of radio systems as well as in pre-distortion and pre-equalization applications.

Design of power-efficient power amplifier modules:

The power amplifier (PA) is the most critical and expensive subsystem in all wireless systems, as its performance dictates the overall performance of the transmitter in terms of linearity and power efficiency. Accordingly, the development of power-efficient PA modules used in advanced transceiver architecture is essential for any high-performance transceiver design in hybrid and/or integrated technologies.

Signal processing techniques for wireless radio systems:

The advances in transceiver architectures call for the RF/DSP co-design approach, in order to ensure the desired functionality and optimal system level performance. This includes impairment pre-compensation, architecture dependant signal processing and conditioning.

Multi-band, multi-mode and multi-antenna software-defined radio based transmitters:

The design of such multi-band, multi-mode transmitters is an important element for the development of truly software-defined radio (SDR) based transmitters for the infrastructure of ubiquitous networks. The use of multi-antenna radio architectures will further improve system performance, mainly in terms of capacity, coverage, and service availability.

Adaptive multi-band reconfigurable receivers:

This is the counterpart of the multi-band transmitter required for software-defined high-performance transceivers. New architectures that support multi-frequency, multi-standard applications will be investigated.

These projects all serve the intention of the original research proposal, which was aimed at the development and advancement of knowledge and know-how related to the design of intelligent and reconfigurable RF front-ends for multi-standard broadband communications systems.

Research Projects

The research program is being conducted along five major research tracks.

Microwave and Radio Frequency Devices, Circuits and Systems Characterization and Modeling

The main goals of this research project are related to the development of realistic characterization techniques and accurate device and behavioural models of active RF devices/circuits and systems.

During the last year, study and investigation of scientific and technical problems related to the characterization and modeling of amplifiers and transmitters have been carried out. This work led to the development of innovative and original characterization and modeling approaches, which are required to successfully design spectrum-efficient and/or power-efficient transmitters for third generation (3G) and beyond wireless applications. An integrated software tool, the Nonlinear Behaviour Modeling System (NBMS), was developed to be able to perform the modeling task seamlessly and efficiently in an academic or industrial environment. The NBMS allows for accurate modeling and correction of any impairments due to the hardware components. This software resulted in an invention disclosure to the university and is being considered for further improvement and possible commercialization.

At the device level, an accurate extraction technique for hetero-junction bipolar transistors (GaAs HBT) that takes into account the current crowding and self-heating effects has been developed. Furthermore, a gallium nitride (GaN) based high electron mobility transistor (HEMT) nonlinear model was developed and used in designing switching mode class D power amplifiers for wireless applications.

Advanced Power Amplification Systems for 3G and Beyond Applications

This research project targets the design of advanced multi-branch power amplification architectures that will achieve high-power efficiency. This encompasses the development of innovative linearization techniques and the use of emerging semi-conductor technologies.

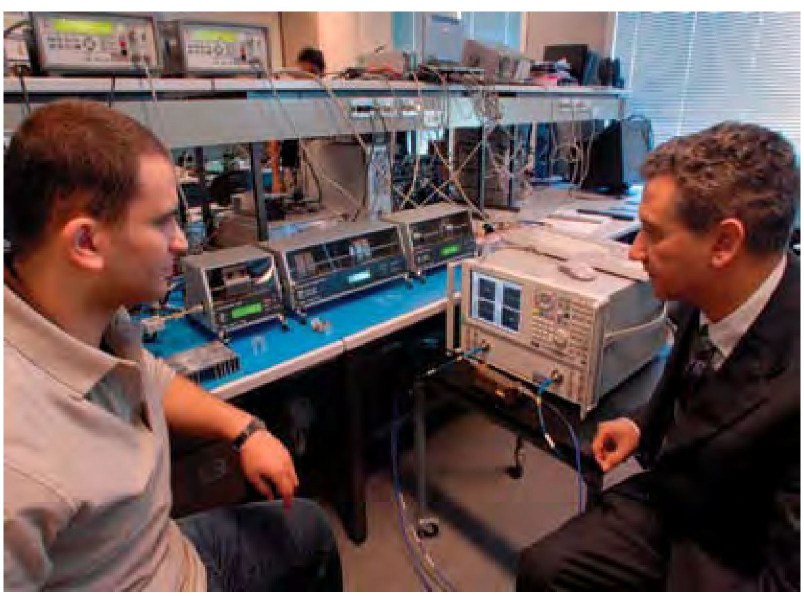
In the last year, the iRadio team successfully developed a radio frequency switched-mode amplifier prototype, using a GaN transistor, which showed excellent power efficiency (about 80%). Furthermore, the team has proposed a new mode multiplexing linear amplification with nonlinear components (MM-LINC) that shows outstanding linearity and efficiency enhancement (better than 300%), when compared to a traditional linear amplification system with nonlinear components (LINC) amplification scheme. The iRadio team has also begun the development of a potential all-digital radio transmitter, suitable for future communications infrastructure, which will integrate the switched-mode amplifier prototype and a sigma-delta modulator.

Handheld and mobile terminal performance sensitivity, in terms of signal integrity and power efficiency, as a result of power amplifier/transmitters (PA/Tx) load-mismatch effects, was extensively studied in the previous reporting period. Attributed to the antenna vicinity and temperature changes, the load mismatch was found to be critical; an adequate compensation scheme was proposed to avoid significant deterioration of the transmitter performance.

Advanced Adaptive Digital Signal Processing Algorithms for Wireless Transceivers

The objectives of this research project are to develop an advanced DSP algorithm at the transmitter and receiver sides. This will further improve the performance of the designed transceivers by providing the required and optimized driving signals synthesized in the DSP module of the anticipated innovative multi-branch transmitter architectures.

The advancement of digital base band pre-distortion was an important research theme for the group last year. In particular, excellent power leakage in the adjacent channels and superior error vector magnitude performance were successfully obtained as a result of the linearization of wideband and nonlinear radio frequency transmitters. Critical issues, related to the use of digital base band pre-distortion techniques to linearize highly nonlinear power amplifiers, were studied, and advanced pre-distortion techniques have been proposed and the optimization of the digital pre-distortion implementation in a hybrid DSP/FPGA platform was addressed. The application of recursive and iterative adaptive filtering techniques for the synthesis of the digital base band pre-distortion function allowed for substantial computation complexity reduction. Furthermore, an advanced blind signal peak-to-average power ratio reduction method has been applied to OFDM signals to further improve the power efficiency of the transmitter.



Doctor S. Bensmida (left) and Professor F. Ghannouchi (right)

The direct conversion technique, which is found to be the most adequate for the software-enabled radios, suffers substantially from its relatively limited performance as a result of its inherent and unavoidable implementation imperfections (gain and phase imbalance, DC offset). In the reported period, the iRadio team successfully developed an adaptive algorithm that is able to detect and compensate for the impairments of direct conversion based WiMax transceivers.

Multi-band, Multi-mode and Multi-antenna SDR-based Transmitters

This research project focuses on the development of SDR-based transmitters that will efficiently handle multi-standards. In addition, these transmitters have to be designed to offer concurrent operation with minimum hardware overhead. In order to achieve higher data throughput, multi-antenna architectures are being considered as a valuable solution.

The first phase of this research theme was aimed at the development of multi-band filters and power combiners using planar circuits. The iRadio team successfully built a dual-band band-pass filter to be used in dual mode WiMax/WCDMA transceivers. Furthermore, compact and high-performance multi-band power combiners were successfully built and will be used in the future in the development of a multi-band WiMax/WCDMA transceiver. Preliminary results relevant to the design of multi-band power amplifiers have been achieved.

In addition, multiple-input multiple-output (MIMO) based radio systems require multiplication of the number of RF front-ends used, in order to improve system performance. This comes at the price of higher hardware cost and complexity, as well as supplementary signal processing computation. A new adaptive antenna selection algorithm was developed as an efficient way to reduce the cost and complexity of these systems without compromising much of the performance of the radio link.

Adaptive and Tunable Receivers

The main objective of this research project is to design and prototype adaptive multi-band receivers to be used with the multi-band transmitters reported in the previous section.

In the last year, advanced multi-standard receiver architecture that can support UMTS, GSM, and IEEE 802.11 standards concurrently was developed using the RF sub-sampling technique. This original SDR-based receiver architecture was implemented in advanced design system (ADS) software. Further validation, using a rapid system level prototyping system, is planned for the near future.

Objectives for Next Year

Modeling

At the system level, the iRadio team plans to continue to work in the behaviour modeling area with more emphasis on developing new models that can be easily identified and implemented in commercial and widely available DSP and FPGA modules. Further improvement of the first release of the nonlinear behaviour model software will be carried out, in order to develop a trial version for marketing purpose and potential commercial use. Attempts to use a vector quantization approach to develop a table based robust behaviour model will be initiated this year. In addition, this approach has to provide the reverse model that can be used to compensate for linear and nonlinear impairments in the power amplifier or transmitters.

At the device level, efforts will be deployed to develop a nonlinear model for GaN HEMT that can be used in designing RF power amplifiers for wireless and satellite communication applications. The team is also planning to study GaN devices that will be provided to us by Nitronex Corporation, Cree Incorporated and RFHIC.

Power Amplifiers

Major suppliers of power amplifier/transmitter (PA/Tx) modules have recently pointed out the load-mismatch effects on mobile terminals performance, in terms of signal integrity and power efficiency. Experimental validation of this phenomenon is planned for the next year and is anticipated to lead to a compensation scheme that can be implemented at the system level in order to avoid significant transmitters' performance deterioration under load-mismatch conditions.

To increase the power-added efficiency of RF PAs substantially recent industry directions suggest the move from continuously driven PAs to switched-mode PAs. Therefore, the team is planning to continue the work related to the design and prototyping of switching mode (class D, class E) and harmonically controlled (class F) PAs. Targeted applications of interest to industrial sponsors are UMTS, WiMax, satellite, and avionics. These power amplifiers will be used within delta-sigma and Doherty based transmitters.

LINC-based amplifiers perform badly, in terms of power-added efficiency, when driven with highly varying envelope signals, such as CDMA and OFDM. MM-LINC architecture has been proposed to improve the overall power efficiency of the amplification system. The goal for next year is to further investigate the manner in which MM-LINC amplifiers' efficiency can be improved in the context of multi-carrier signals while assuring standard compliant signal quality. An integrated engineering prototype will be designed and fabricated to carry out the validation of the anticipated scheme/architecture for WiMax access point applications.

SDR Transmitters

Multi-band SDR-based transmitters have to maintain the performance of the RF chain for all the frequencies/channels considered. This implies the access and use of multi-standard and multi-frequency high-power amplification stages, as well as multi-band power combiners and matching circuits. During the next year, the team will continue to study and investigation of possible techniques that can be used to achieve the design of these multi-frequency RF front-end key components. Efforts will be spent on designing multi-band multi-harmonic matching circuits for switching mode or/and harmonically controlled PAs.

The study and investigation of the transmitter architecture that allows for the communication signal to be kept in a digital binary format as close as possible to the antenna will also be carried out. Delta-sigma modulator based transmitters have been proposed in the past for relatively low frequency applications. The intention is to push the frequency limit of these transmitters further so that they can be used at RF frequencies.

Digital Signal Processing for Wireless Communications

As a continuation of efforts in the digital pre-distortion area, the iRadio team is pursuing the development of a robust and accurate digital RF pre-distortion technique that does not require the pre-knowledge/access to the base band signal. This technology can be used on RF amplifiers and repeaters driven by RF signals. The synthesis of the digital RF pre-distortion function necessitates more advanced and recursive adaptive algorithms for identification purposes of the pre-distortion function.

Crest factor reduction techniques have been proposed and used to "cut" the peaks in the signals without greatly affecting quality, in terms of spectral re-growth and error vector magnitude metrics. Effort will be dedicated to experimental validation of the already developed blind crest factor reduction approach for WiMAX applications.

Outreach

Community outreach activities:

- iRadio lab is an associate member of TARGET consortium.
- Dr Ghannouchi is a member of the strategy committee of the TARGET consortium.
- Dr Ghannouchi gave a series of talks in China in December 2006.
- In March 2007, Dr Ghannouchi made a technical presentation to the executive officers and senior technical staff of Nanowave Technologies about advanced radio systems technologies for satellite and avionics applications.

Antenna selection techniques can be used to optimize the number of RF frond-ends in MIMO systems and minimize the overall cost of MIMO based communication systems. Efforts will be spent next year on the development of robust and computational bearable algorithms that can be implemented in commercial DSP/FPGA.

Adaptive and Tunable Receivers

For the same reasons mentioned in the previous section, SDR-based receivers require frequency agility and/or multi-band operation capability. The study and investigation of multi-band RF filters and matching circuits will be carried out next year for the purpose of designing a multi-band RF receiver head for dual applications.

In addition, further co-simulation and analysis of the developed tri-band (GSM, UMTS and WiFi) RF sub-sampling receiver architecture will be performed to evaluate its suitability in a real traffic environment, where the three communications signals can co-exist simultaneously. An experimental validation of this new multi-band receiver will be conducted using a quick prototype platform that uses both FPGA and DSP modules, as well as suitable analog-to-digital converters (ADCs) and accessory circuits.

Research Team Members and Contributions

Team Leader
Professor Fadhel Ghannouchi
Team Leader, Director of iRadio Laboratory, and (Tier 1) Canada Research Chair
Research interests are in the areas of microwave instrumentation, modeling of microwave devices and communications systems, design and linearization of RF amplifiers, and SDR and multi-band radio systems
Member of College of Reviewers of Canada Research Chairs
Session chair and workshop organizer in IEEE sponsored conferences
Subcommittee / Track chair in IEEE sponsored conference (ICECS'2006, IMS'2007, RWS'2007, MWCAS/NEWCAS'2007, ISSSE'2007)
Member of Technical Coordinating Committee IEEE-MTT-5, "Microwave High Power Techniques"
Member of Speaker's Bureau of IEEE-MTT- 5
IEEE Fellow (2007) for his contribution to advanced microwave amplification circuits and sub-systems
Awarded the title of Guest Professor of Ningbo University, China

Research Associates

Name	Role/Topic	Awards/Special Info
Dr Anton Seregin	Narrow Band Interference Cancellation in Spread Spectrum Based Receivers	

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Dr Slim Boumaiza	Assistant Professor and iCORE Research Associate Research interests include multi-band and reconfigurable transmitters/ receivers; advanced digital signal processing; design, characterization, modeling and linearization of high-power RF amplifiers	Academic staff member IEEE Senior Member Officer of the IEEE Southern Alberta msection (secretary) IEEE COMMTTAP chapter chair Technical program chair of IEEE SIPS2006 conference

PostDoctoral Fellows

Name	Role/Topic	Awards/Special Info
Dr Souheil Bensmida	Characterization of Microwave Circuits and Systems	Recruited from École Nationale Supérieure des Télécommunications, Paris, France in October 2006
Dr Taijun Liu	Channel Behaviour Modeling and Nonlinearity Pre-compensation of Wireless Transmitters	Awarded a postdoctoral fellowship from Le Fonds Québécois de la recherche sur la nature et les technologies (FQRNT) for 2006 - 2008 Co-supervised by Dr A. Sesay
Dr Renato Negra	Power-efficient Linear Amplification Systems for Modern Wireless Transmitters	Recruited from the Swiss Federal Institute of Technology Zurich in January 2006

PhD Candidates

Name	Role/Topic	Awards/Special Info
Pouya Aflaki	RF Digital Predistortion Techniques	Received the Dean's entrance scholarship
Rim Barrak	Multi-standard Receivers Using RF Sub-sampling Technique	Associate, SupCom, Université Tunis Carthage, Tunisia Co-supervised by Dr A. Ghazel
Seyed Aidin Bassam	MIMO Transceivers for 4G Wireless Communication Systems	Received the Dean's entrance scholarship Co-supervised by Dr S. Boumaiza

PhD Candidates Cont'd

Name	Role/Topic	Awards/Special Info
Sonia Bouajina	Behavioural Modeling of RF Power Amplifiers with Memory Effects	Associate, ENIT, Université Tunis El Manar; Tunisia Co-supervised by Dr M. Jaidane.
Louay Degachi	Nonlinear Large Signal Modeling of HBT Transistors	Associate, École Polytechnique Montreal
Walid Saber El-Deeb	Design of 4G Integrated Transceivers	Currently holding an international graduate scholarship from the Egyptian Government Co-supervised by Dr S. Boumaiza.
Bogdan Georgescu	Q Enhancement of RFIC Inductances	NSERC post graduate scholarship (PGS-D), iCORE scholarship, TRLabs scholarship Co-supervised by Dr I. Finvers
Oualid Hammi	Software Defined Multi-branch Transmitters for Wireless and Satellite Communication Systems	Currently holding the NSERC Canada graduate scholarship (CGS-D), and iCORE scholarship
Safar Hatami	Delta-sigma Modulator Based RF I/Q Transceiver for Software-Defined Radio	
Mohamed Helaoui	Modified LINC Transmitters for OFDM Radios	Received the iCORE international student award (September 2006 to August 2008) Co-supervised by Dr S. Boumaiza.
Mohamed Mostageer	OFDM/LINC Transmitters Design	Associate, École Polytechnique Montréal Currently holding an International Graduate Scholarship from the Egyptian Government

MSc Candidates

Name	Role/Topic	Awards/Special Info
Han Gil Bae	Linear and Highly Efficient Transmitters for WiMAX Base Stations	Joined the iRadio Lab after 4 years experience in RFIC design with Samsung Electronics, Korea Co-supervised by Dr S. Boumaiza
Marie-Claude Fares	Effects of Nonlinear Distortions on Communication Systems	Supervised by Dr S. Boumaiza
Andrew Kwan	Implementation of Baseband Digital Predistortion Techniques	Co-supervised by Dr M. Smith

MSc Candidates Cont'd

Name	Role/Topic	Awards/Special Info
Nizar Messaoudi	RF Power Amplifiers' Efficiency Enhancement Using Load Modulation Techniques	Supervised by Dr S. Boumaiza
Demirel Nejda	Visiting international student from Université de Bordeaux, France Sigma-delta Based Transmitters	Co-supervised by Dr E. Kerhervé
Tony Pellerin	Design of Integrated HBT Based Doherty Amplifier for Satellite Applications	Associate, École Polytechnique Montréal Co-supervised by G. Brassard, Canadian Space Agency
Vijayachandran Ramchandran	Linearization of RF Power Amplifiers using Digital RF Predistortion Technique	Co-supervised by Dr S. Boumaiza
Alexander Sadeve	Visiting international student from Université de Bordeaux, France Design of Multi-band Power Amplifiers	Co-supervised by Prof E. Kerhervé
Farzane Taringoo	Behavioural Modeling of a Dynamic Nonlinear System	Associate, École Polytechnique Montréal Co-supervised by Dr R. Malhame

Other Team Members

Name	Role/Topic	Awards/Special Info
Andrea Berbic	Administrative support to Dr Ghannouchi and the iRadio Lab Team	
Oualid Hammi	Lab Manager	
Andrew Kwan	Undergraduate summer project	Undergraduate NSERC research scholarship from May 1, 2006 to August 31, 2006
Nizar Messaoudi	Undergraduate summer project	Undergraduate NSERC research scholarship from May 1, 2006 to August 31, 2006
Christopher Simon	Technical support PCB fabrication and instrumentation	

Visiting Speakers and Professors

Name	Role/Topic	Awards/Special Info
Dr Aly Fathy	Visiting Speaker, Reconfigurable Antennas for Multi-band Wireless Services	Seminar, July 5, 2006 Professor, University of Tennessee, Knoxville, USA
Mr. Nathan Sokal	Visiting Speaker, RF Power Amplifiers, Class A through S – How they operate, and when to use each	Two-day course, November 6 and 7, 2006 CEO and founder of Design Automation Inc., USA
Dr Ke Wu	Visiting Speaker, Unified and Accurate CAD Model for RF, Microwave and Millimiterwave Integrated Circuits and Antennas	Seminar, July 6, 2006 Professor, École Polytechnique, Montréal, Canada
Dr Toshiyuki Yakabe	Visiting Speaker, An Alternative Vector Network Analyzer Based on Six-port Technology	Seminar, June 9, 2006 University of Electro-Telecommunications, Tokyo
Dr Nadir Zia	Visiting Professor, Polar Transmitters Design	Invited Professor from Sultan Qaboos University, Oman

GRADUATES

Name	Research Topic	Current Position
PostDoctoral Graduates		
Dr Taijun Liu	Channel Behaviour Modeling and Nonlinearity Pre-compensation of Wireless Transmitters	Assistant Professor at the Ningbo University of China, China
PhD Graduates		
Rim Barrak	Multi-standard Receivers Using RF Sub-sampling Technique	Associate Professor, University of Tunis, Tunisia
MSc Graduates		
Demirel Nejda	Sigma-delta Based Transmitters	PhD candidate, Université de Bordeaux, France
Tony Pellerin	Design of a Doherty Tx for Micro-Satellite in HBT	Digital Communication Engineer, Canadian Space Agency
Research Associate		
Dr Anton Seregin	Narrow band interference cancellation in spread spectrum based receivers	

COLLABORATIONS

Participants	Nature of Collaboration
National Collaborations	
École Polytechnique Montréal Dr M. Sawan Dr R. Malhame	Collaboration with Dr M. Sawan on digital implementation of the pre-distortion technique recently led to the approval of an US patent on the developed technology
École Polytechnique Montréal Dr K. Wu	The collaboration with Poly-Grames Research Center (Dr K. Wu) concerns the access to advanced PCB fabrication facilities by the iRadio Lab team. Three graduate students from École Polytechnique Montréal are currently supervised by Dr Ghannouchi (Lead contact person: Dr Ghannouchi)
Université de Québec Dr A. Kouki	The ongoing theme of collaboration is related to LINC-based amplifiers. One joint paper has been co-authored with Dr Kouki's group (Lead contact person: Dr Ghannouchi)

Participants	*Nature of Collaboration*
International Collaborations	
Pohang University of Science and Technology (POSTECH), Korea Dr B. Kim	Related to the performance improvement of a Doherty power amplifier designed by the POSTECH team using the linearization techniques developed at the iRadio Lab (Lead contact person: Dr Ghannouchi)
Université de Tunis, Tunisia Dr A. Ghazel Dr M. Jaidane	The ongoing themes are related to behaviour modeling of nonlinear systems, implementation of DPD technology using DSP/FPGA modules, and the design of multi-standard receivers using RF sub-sampling techniques. Several joint papers have been published that report the results obtained so far. Dr Ghannouchi is co-supervising the work of two PhD candidates (Lead contact person: Dr Ghannouchi)
Université de Bordeaux, France Dr E. Kerhervé	Initiated last year with IXL laboratory of the Université de Bordeaux to study, analyze, and assess the suitability sigma-delta based modulators in designing RF digital amplifiers. Two graduate students from the Université de Bordeaux spent two terms at the iRadio lab (Lead contact person: Dr Ghannouchi)
Industrial Collaborations	
TRLabs, Canada Dr R. Davis	Concerns the development of an antenna selection algorithm for MIMO systems and RF front-end design for MIMO radio systems (Lead contact person: Dr Ghannouchi)
Canadian Space Agency, Canada Mr. G. Brassard	In the frame of a NSERC Collaborative Research and Development Grant (CRD) (2007-2009), this collaboration aims at the development of GaN based innovative Doherty power amplifiers intended for CSA's quicksat program. The ongoing collaboration covered the co-supervision of a master thesis of a CSA engineer (Lead contact person: Dr Ghannouchi)
Focus Microwaves, Canada Dr C. Tsironis	Focus Microwaves is sponsoring the ongoing NSERC Collaborative Research and Development Grant (CRD) (2007-2009), and providing privileged technical support for activities related to the load-pull characterization of active devices (Lead contact person: Dr Ghannouchi)
Nanowave Technolgies, Canada Dr A. Rahal	Collaborating with Nanowave Technologies since 2006 within a NSERC CRD project, the ongoing collaboration involves an NSERC strategic research project related to the development of GaN based switching mode amplifiers for satellite and avionic applications. (Lead contact person: Dr Ghannouchi)
Nortel Networks, Canada T. Dashin	Initiated this year, Nortel's technical staff assisted with the two-day course organized by the iRadio Lab. Recently, Nortel Networks supported an NSERC strategic grant application (Lead contact person: Dr Ghannouchi)
Agilent Technologies, USA A. Amini	This work concerns the co-simulation and optimization of WiMAX transmitters within Agilent's Advanced Design System (ADS) software. For this purpose, privileged access to Agilent's ADS WiMAx library was granted to the iRadio Lab (Lead contact person: Dr Boumaiza)

Participants	*Nature of Collaboration*
Industrial Collaborations Con't	
Rockwell Collins, Government Systems, USA Dr G. Hegazi	A nine-month contract was awarded to the iRadio Lab. (Due to the confidential nature of the work, details of this project are not reported). Non-confidential parts of this work related to GaN devices modeling were reported in joint publications (Lead contact person: Dr Ghannouchi)
Powerwave Technologies, USA B. Vassilakis	Initiated this year, this collaboration is aimed at the modeling and linearization of Powerwave's commercial power amplifiers, as well as amplifier prototypes to be used in their future base stations infrastructure (Lead contact person: Dr Ghannouchi)
Freescale, USA J. Wood	Freescale is providing LDMOS based devices and evaluation boards of their products to be used as devices under test for the ongoing research topic related to the design of high-efficiency power amplifiers (Lead contact person: Dr Boumaiza)
Nitronex Corporation, USA P. Rajagopal	Initiated this year, this collaboration covers the support of a NSERC strategic grant application, as well as privileged access to Nitronex's GaN device technology (Lead contact person: Dr Ghannouchi)
RFHIC Corporation, Korea	RFHIC, Korea, provides the iRadio Lab with privileged access to their GaN transistor products for characterization, modeling and application to the design of wideband RF power amplifiers (Lead contact person: Dr Boumaiza)
Altera, USA	This collaboration provides the iRadio Lab with FPGA boards within their university program (Lead contact person: Dr Boumaiza)
Analog Devices, USA	This collaboration provides the iRadio Lab with DSP boards and circuits within their university program (Lead contact person: Dr Ghannouchi)

INTELLECTUAL PROPERTY

Patents	*Title/Name*	*Status*
Applied for through UTI	LBG Behaviour Model	Applied for this year
US patent # 7,035,345, April 2006.	"Adaptive Predistortion Device and Method Using Digital Receiver"	Granted this year

FUNDING

Dr Fadhel Ghannouchi has a five year iCORE Professor award ($1.5M). This year he received grants from CFI and NSERC ($443K). He also holds a Tier 1 Canada Research Chair ($200K). Other yearly funding comes from cash and contributions from industry ($517K) and from the University of Calgary ($694K).

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

R. Negra, F. M. Ghannouchi, and W. Bächtold, "Study and design optimisation of multi-harmonic transmission-line load networks for class-E and class-F K-band MMIC power amplifiers", *IEEE Trans. Microwave Theory and Tech.*, in press.

O. Hammi, S. Boumaiza and F. M. Ghannouchi, "On the Robustness of Digital Predistortion Function Synthesis and Average Power Tracking for Highly Nonlinear Power Amplifiers", *IEEE Trans. Microwave Theory and Tech.*, in press..

M. Abd Elaal and F. M. Ghannouchi, "Modified LINC Architecture for OFDM-Based Communication Transceivers", *International Journal of Microwave and Optical Technology*, in press.

M. Helaoui, S. Boumaiza, F. M. Ghannouchi, A. B. Kouki and A. Ghazel, "A New Mode-Multiplexing LINC Architecture to Boost the Efficiency of WiMAX Up-Link Transmitters", *IEEE Trans. Microwave Theory and Tech.*, Vol. 55, Issue: 2, Feb. 2007, pp. 248-253.

S. Bousnina, L. Degachi and F. M. Ghannouchi, "Systematic Extraction Method for the Determination of HBT Temperature-Dependant DC Model Parameters", *International Journal of Microwave and Optical Technology*, Vol. 2, Issue: 1, January 2007, pp. 28-34.

L. Degachi and F. M. Ghannouchi, "Simple Technique for a Quick Evaluation of HBT Temperature-Dependant DC Model Parameters in Forward Active Regime", *International Journal of Microwave and Optical Technology*, Vol. 2, Issue: 1, January 2007, pp. 14-17.

T. Liu, S. Boumaiza, A. B. Sesay and F. M. Ghannouchi, "Quantitative Measurements of Memory Effects in Wideband RF Power Amplifiers Driven by Modulated Signals", *IEEE Microwave and Wireless Components Letters*, Vol. 17, Issue: 1, January 2007, pp. 79-81.

B. Georgescu, I. Finvers and F. Ghannouchi, "2 GHz Q-Enhanced Active Filter with Low Passband Distortion and High Dynamic Range", *IEEE Journal of Solid-State Circuits*, Vol. 41, Issue: 9, September 2006, pp. 2029-2039.

O. Hammi, J. Sirois, S. Boumaiza, and F. M. Ghannouchi, "Design and Performance Analysis of Mismatched Doherty Amplifiers Using Accurate Load-Pull-Based Model", *IEEE Trans. Microwave Theory and Tech.*, Vol. 54, Issue: 8, August 2006, pp. 3246-3254.

A. Issaoun, A. B. Kouki and F. M. Ghannouchi, "A Simple Large Signal Model for III-V HBT Devices Exceeding VBIC Model Performances", *International Journal of Electronics and Communications*, Vol. 60, Issue: 5, May 2006, pp. 367-375.

M. Helaoui, S. Boumaiza, A. Ghazel and F. M. Ghannouchi, "Power and Efficiency Enhancement of 3G Multi-carrier Amplifiers Using Digital Signal Processing with Experimental Validation", *IEEE Trans. Microwave Theory and Tech.*, Vol. 54, Issue: 4, April 2006, pp. 1396-1404.

T. Liu, S. Boumaiza and F. M. Ghannouchi, "Augmented Hammerstein Predistorter for Linearization of Broadband Wireless Transmitters", *IEEE Trans. Microwave Theory and Tech.*, Vol. 54, Issue: 4, April 2006, pp. 1340-1349.

REFEREED CONFERENCE PROCEEDINGS

T. Liu, Y. Ye, S. Boumaiza, and F. M. Ghannouchi, "Dynamic Behavioral Models for Wideband Wireless Transmitters Stimulated by Complex Signals Using Neural Networks," *Fourth International Symposium on Neural Networks (ISSN 2007)*, Nanjing, China, June 2007. (accepted)

R. Negra, T. D. Chu, M. Helaoui, S. Boumaiza, G. M. Hegazi, and F. M. Ghannouchi, "Switch-based GaN HEMT model suitable for highly-efficient RF power amplifier design", *IEEE MTT-S International Microwave Symposium (IMS'2007)*, Honolulu, Hawaii, June 2007. (accepted)

A. Harguem, N. Boulejfen, and F. M. Ghannouchi, "Prediction of Spectral Regrowth in Nonlinear Multicarrier Wireless Communiation Systems", *International Conference on Fourth Generation Mobile Communications*, San Fransisco, CA, May 2007. (accepted)

S. A. Bassam, M. Kalantari, S. Boumaiza, R. Davies, and F. M. Ghannouchi, "Adaptive Antenna Selection Algorithm for Spatial Multiplexing MIMO Systems", *IEEE Canadian Conference on Electrical and Computer Engineering*, Vancouver, BC, Canada, April 2007, on CDROM.

N. Messaoudi, O. Hammi, J., Sirois, S. Boumaiza and F. M. Ghannouchi, "A Comparative Study of Power Amplifiers' Sensitivity to Load Mismatch: Single Branch vs. Doherty Architectures", *IEEE Canadian Conference on Electrical and Computer Engineering*, Vancouver, BC, Canada, April 2007, on CDROM.

O. Hammi, S. Boumaiza and F. M. Ghannouchi, "Multi-Branch Polynomial Model with Embedded Average Power Dependency for 3G RF Power Amplifiers", *IEEE Canadian Conference on Electrical and Computer Engineering*, Vancouver, BC, Canada, April 2007, on CDROM.

M. Helaoui, N. Demirel, R. Negra, S. Boumaiza, E. Kerhervé, A. Ghazel, and F. M. Ghannouchi, "Digitally Optimized Delta-Sigma Modulator for WiMAX Transmitter Design," *IEEE Radio Wireless Symposium (RWS 2007)*, Long Beach, CA, January 2007, pp. 419-422.

O. Hammi, S. Boumaiza, and F. M. Ghannouchi, "Study of the Output Load Mismatch Effects on the Load Modulation of Doherty Power Amplifiers," *IEEE Radio Wireless Symposium (RWS 2007)*, Long Beach, CA, January 2007, pp. 393-396.

N. Boulejfen, A. Harguem, and F. M. Ghannouchi, "Prediction of Spectral Regrowth of Quasi-Memoryless Fifth-order RF Power Amplifiers Under Multitone Excitation", *IEEE International Conference on Microelectronics (ICM'2006)*, Dhahran, Saudi Arabia, December 2006.

R. Negra, F. M. Ghannouchi and W. Bächtold, "Compact Device Level Linearization Technique Using a Reduced Complexity Derivative Superposition Approach," *2006 Asia Pacific Microwave Conference (APMC'2006)*, Yokohama, Japan, pp. 1739-1742.

T. Liu, S. Boumaiza, A. B. Sesay and F. M. Ghannouchi, "Dynamic Nonlinear Behavior Characterization for Wideband RF Transmitters Using Augmented Hammerstein Models," *2006 Asia Pacific Microwave Conference (APMC'2006)*, Yokohama, Japan, pp. 967-970.

M. Helaoui, S. Boumaiza, A. Ghazel and F. M. Ghannouchi, "Short Term Memory Effects Study for Optimal Predistortion-based Linearization of Base-Stations Wireless Transmitters", *2006 Asia Pacific Microwave Conference (APMC'2006)*, Yokohama, Japan, pp. 1047-1050.

N. Demirel, R. Negra, E. Kerhervé, and F. M. Ghannouchi, "A Study of High-Frequency Bandpass Delta-Sigma Transmitter Architectures", *IEEE International Conference on Electronics, Circuits and Systems (ICECS'2006)*, Nice, France, December 2006, pp. 1117-1120.

A. Benchahed, A. Ghazel, M. Mabrouk, C. Rebai, and F. Ghannouchi, "RF Digital Predistorter for Power Amplifiers of 3G Base Stations", *IEEE International Conference on Electronics, Circuits and Systems (ICECS'2006)*, Nice, France, December 2006, pp. 999-1002.

R. Barrak, A. Ghazel, and F. M. Ghannouchi, "Design of Sampling-Based Downconversion Stage for Multistandard RF Subsampling Receiver;" *IEEE International Conference on Electronics, Circuits and Systems (ICECS'2006)*, Nice, France, December 2006, pp. 577-580.

C. Rebai, H. Ayari, A. Ghazel, S. Boumaiza, and F. Ghannouchi, "Optimized Design of a Digital IQ Demodulator Suitable for Adaptive Predistortion of 3rd Generation Base Station PAs", *IEEE International Conference on Electronics, Circuits and Systems (ICECS'2006)*, Nice, France, December 2006, pp. 573-576.

M. Abd El-Aal and F. M. Ghannouchi, "ACPR Performance Study for Modified LINC Amplifier", *IEEE International Conference on Electronics, Circuits and Systems (ICECS'2006)*, Nice, France, December 2006, pp. 435-438.

A. Kwan, M. Smith, F. Ghannouchi, and S. Boumaiza, "Automating the Verification of SDR Base band Signal Processing Algorithms Developed on DSP/FPGA Platform", *IEEE Workshop on Signal Processing Systems (SIPS 2006)*, Banff, Canada, October 2006.

R. Barrak, A. Ghazel, and F. M. Ghannouchi, "Design and Optimization of RF filters for Multistandard RF Sub-sampling Receiver", *IEEE Design and Test of Integrated Systems Conference,* Tunis, Tunisia, September 2006, pp. 105-109.

M. Abd El-Aal, and F. M. Ghannouchi, "A Modified LINC Amplification System for Wireless Transceivers," *IEEE Vehicular Technology Conference 2006 Fall (VTC'2006 Fall)*, Montreal, QC, Canada, September 2006.

S. Boumaiza and F. M. Ghannouchi, “Study and minimization of the out-phasing amplifiers nonlinearity,” *36th IEEE European Microwave Conference (EuMC’2006)*, Manchester, UK, September 2006, pp. 188-191.

R. Negra, F. M. Ghannouchi and W. Bächtold, “On the design of MMIC multi-harmonic load terminations for class-F amplifiers,” *IEEE 36th European Microwave Conference (EuMC’2006)*, Manchester, UK, September 2006, pp. 180-183.

H. G. Bae, M. Helaoui, A. Seregin, S. Boumaiza and F. M. Ghannouchi, “Blind Peak-to-Average Power Ratio Reduction Technique for WiMAX RF Front-end,” *36th IEEE European Microwave Conference (EuMC’2006)*, Manchester, UK, September 2006, pp. 149-152.

O. Hammi, S. Boumaiza and F. M. Ghannouchi, “On the Robustness of the Predistortion Function Synthesis for Highly Nonlinear RF Power Amplifiers Linearization,” *36th IEEE European Microwave Conference (EuMC’2006)*, Manchester, UK, September 2006, pp. 145-148

M. Abd El-Aal and F. M. Ghannouchi, “The DSP Implementation of the LINC Amplifier to Improve ACPR and Imbalance Performance”, *International Symposium in Antenna technology and Applied Electromagnetics (ANTEM’2006)*, Montreal, QC, Canada, July 2006, pp. 133-136.

M. Helaoui, S. Boumaiza and F. M. Ghannouchi, “Reconfigurable Platform for Software/Hardware Co-Design of SDR Base Band Pre-Processing Module”, *International Symposium in Antenna technology and Applied Electromagnetics (ANTEM’2006)*, Montreal, QC, Canada, July 2006, pp. 465-468.

S. Boumaiza, T. Liu and F. M. Ghannouchi, “On the Wireless Transmitters Linear and Nonlinear Distortions Detection and Pre-Correction”, *IEEE Canadian Conference on Electrical and Computer Engineering*, Ottawa, ON, Canada, May 2006, pp. 1465 - 1468.

O. Hammi, S. Boumaiza, J. Kim, S. Hong, I. Kim, B. Kim and F. M. Ghannouchi, “RF Power Amplifiers for Emerging Wireless Communications: Single Branch vs. Multi-Branch architectures”, *IEEE Canadian Conference on Electrical and Computer Engineering*, Ottawa, ON, Canada, May 2006, pp. 1469 - 1472.

SPECIAL/INVITED PRESENTATIONS

F. M. Ghannouchi, “Advanced Transceivers Architecture for 3G and Beyond Communication systems”, *Presentation in University of Ningbo*, Ningbo, China, December 2006.

F. M. Ghannouchi, “iRadio Laboratory: An overview”, *Practical Real World Technologies for Communications and Embedded Platforms Conference*, Banff, Canada, May 2006.

F. M. Ghannouchi, “iRadio Laboratory: Status and Perspectives”, *Informatics Circle of Research Excellence Summit (iCORE Summit)*, Banff, Canada, May 2006.

NON REFEREED CONFERENCE PAPERS

H. G. Bae, M. Helaoui, S. Boumaiza, and F. M. Ghannouchi, “Peak-to-Average Power Ratio Reduction for SDR Transmitters,” *Practical Real World Technologies for Communications and Embedded Platforms Conference*, Banff, Canada, May 2006, pp. 33-34.

O. Hammi, and F. M. Ghannouchi, “Intelligent Radio Transmitters: An Enabling Technology for High Performances Wireless Communication System,” *Practical Real World Technologies for Communications and Embedded Platforms Conference*, Banff, Canada, May 2006, pp. 41-42.

M. Helaoui, S. Boumaiza, and F. M. Ghannouchi, “Reconfigurable Platform for SW/HW Co-Design of SDR Pre-Processing,” *Practical Real World Technologies for Communications and Embedded Platforms Conference*, Banff, Canada, May 2006, pp. 43-44.

O. Hammi, and F. M. Ghannouchi, “Design of High Efficiency Intelligent RF Transmitters for Satellite and Wireless Communications,” *3rd Annual Schulich School of Engineering Grad Students Conference*, Calgary, Canada, May 2006.

WORKSHOPS

R. Negra, F. M. Ghannouchi, and W. Bächtold, “Practical aspects in designing MMIC switching mode amplifiers”, Workshop on Switching Mode Amplifiers with Applications to Wireless Transmitters Design, in *2006 IEEE International Microwave Symposium (IMS2006)*, San Diego, USA, June 2006.

POSTERS

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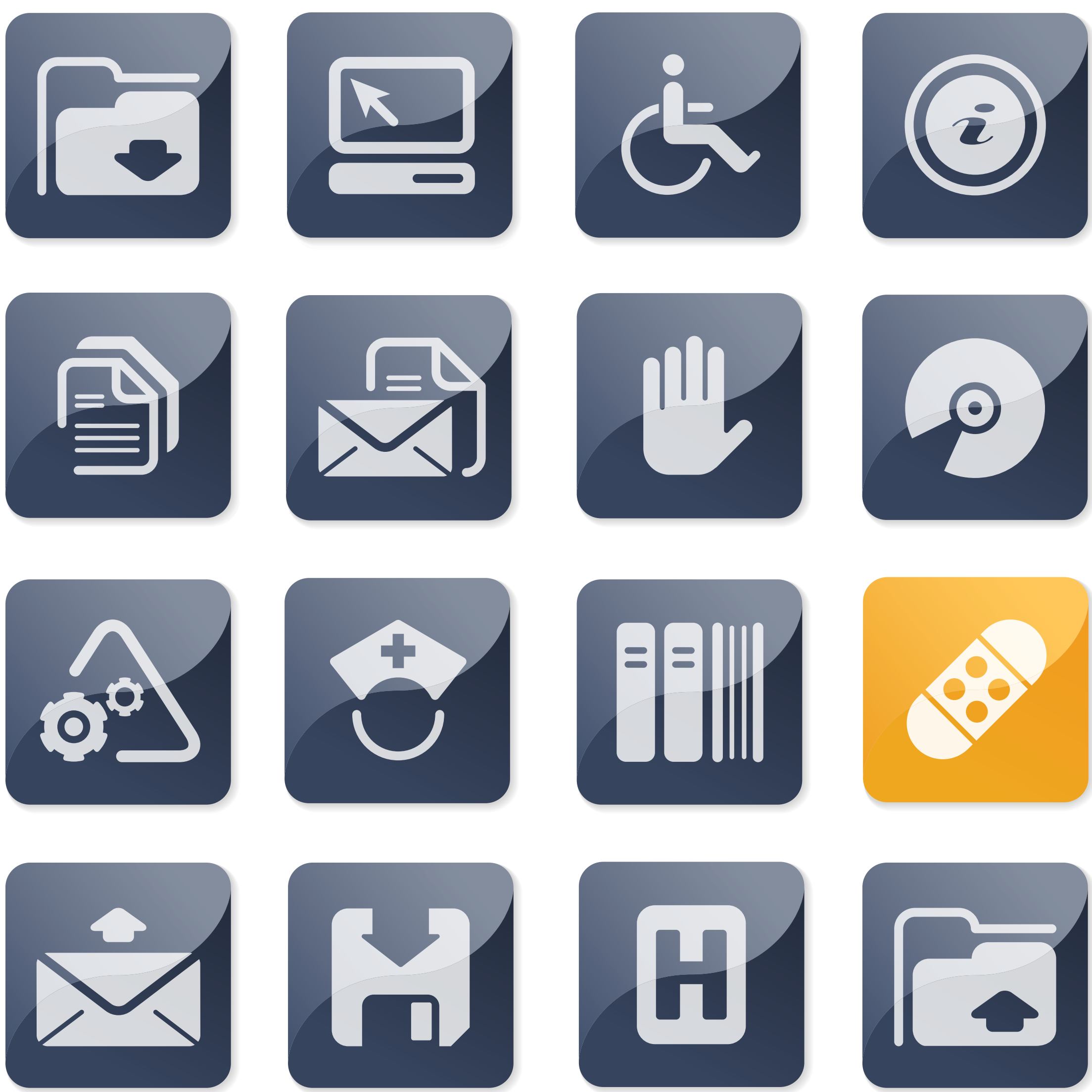
Wireless Science and Technology Initiative



The Radio Frequency Integrated Circuit (RFIC) research group utilizes a variety of technologies, including deep submicron monolithic integrated circuits, Micro-Electro-Mechanical Systems (MEMS), System-on-Chip (SoC), and advanced sensors to design new wireless communications devices and systems.

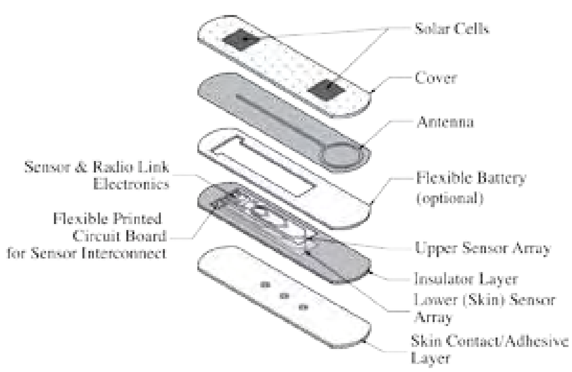


Figure 1 *Single Chip Prototype Vision; the standard elements of a Smart Band-aid*

The Radio Frequency Integrated Circuit (RFIC) Design Group at the University of Calgary (U of C) conducts research into the design of novel circuits to facilitate complete ultra low power "radio-on-a-chip" systems for a variety of new applications

including wireless ad hoc self organizing sensor networks, wireless medical applications, and a special application relating to a next generation radio telescope; the international square kilometer array.

The goal is to enable Albertan and Canadian industry to attain a competitive advantage in world markets such as health care and environmental monitoring. The research activities of the RFIC research chair is highly interdisciplinary, resulting in the training of highly qualified personnel with the expertise needed to design, develop, project manage, train, and implement these types of systems in industry.

In the fifth year of chair operation an outstanding team of academics, Post Doctoral Fellows (PDFs), research associates, and graduate students worked to achieve the goals of the RFIC Industrial Chair Program. The efforts of the team continue to support an exciting expansion of research directions and collaborations that include four major collaborative research projects:

- The wireless patient vital sign monitoring initiative with the Calgary Health Region, the Faculty of Medicine, U of C, and Associated Health Systems Inc., now progressing to trials at the Foothills Hospital in Calgary.
- An ultra low power wireless sensor platform for the medical vital signs project that builds on collaborative links between the U of C, McGill University, and Carleton University.
- The CMOS ultra low noise signal chain design initiative for the international Square Kilometer Array next generation radio telescope, with NRC's Dominion Radio Astrophysical Observatory in Penticton, British Columbia.
- The design of smart antenna communication systems for multi-user networks

In the past year, the RFIC research program resulted in 58 publications, including three book chapters, the filing of three new patents, seven journal papers, 23 conference proceedings papers, 12 workshop presentations, and four short courses to conferences. In addition, six journal and two conference papers are currently under review. Twelve integrated circuits were designed, submitted for fabrication and/or tested during the reporting period.

The team brought in over $2M in grants and contracts in addition to the iCORE funding. This included substantial infrastructure support from CMC Microsystems (formerly the Canadian Microelectronics Corporation), which contributed integrated circuit design software, subsidized chip fabrication, rapid prototyping FPGA platforms and other infrastructure in support of the microelectronics program in Electrical and Computer Engineering (ECE).

Research Program Overview

The Research Team

After five years of operation, a very strong research team has been assembled; well-trained in the art of sophisticated analog and digital RF integrated circuit design for wireless communication systems, including a number of highly skilled recruits from industry. The team, consisting of Dr Haslett, Dr Sebastian Magierowski, nine PhD and six MSc students, one Post Doctoral Fellow, two PhD Research Associates, and an MSc Research Assistant, has won several local, national, and international awards for research in the past year.

Research Partners

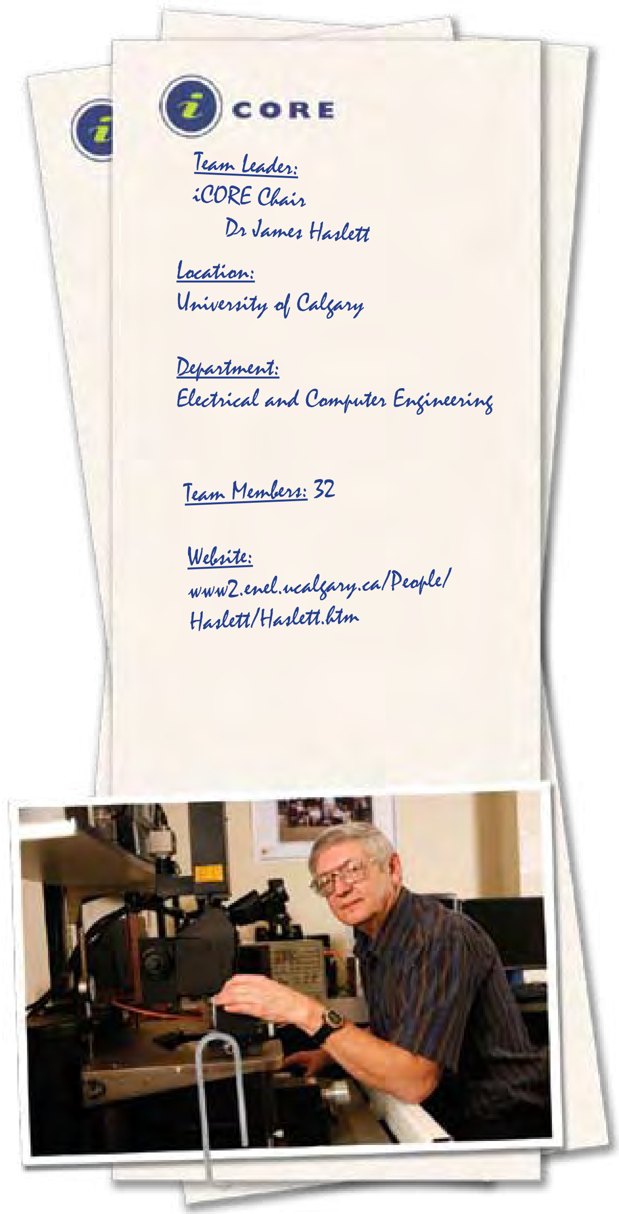
The chair program is supported by industry via the TRLabs industrial research consortium, by the provincial government through the iCORE program, by the federal government through the National Sciences and Engineering Research Council (NSERC) Industrial Research Chair Program, and via substantial support from the Dean of the Schulich School of Engineering and the U of C senior administration. The RFIC group also partners directly with other research chairs at the U of C, with local and national industrial firms, with the NRC Dominion Radio Astrophysical Observatory, with the Faculty of Medicine, with the Calgary Health Region, with two industrial partners, and with several other Canadian universities.

The RFIC research group, as part of the ATIPS Laboratory cluster, is a member of the CMC's System-on-Chip Research Network, headed by iCORE Chair Dr Graham Jullien.

Infrastructure

The new Radio Frequency (RF) test lab in the Calgary Centre for Innovative Technology now houses two sophisticated RF wafer probers, a triple wavelength laser cutter system, a wire bonder, a large RF shielded room, a state of the art Specific Absorption Ratio robotic measurement system, and a RF instrumentation suite. Also included is a complete ultra wide band measurement capability, along with a new "source pull load pull" system and an accurate noise measurement system.

The team continues to have access to state of the art software tools, and is designing in the latest fabrication technologies, including 180nm, 130nm, and 90nm CMOS. The team is currently signing agreements with



CMC Microsystems and CMP in France, to access the 65nm CMOS technologies provided through CMP and ST Microelectronics.

Research Projects

Building on the opportunities that have arisen in the past year, the 2007 research program will focus on the following key areas:

Medical Ward of the 21st Century and the Calgary Health Trust (Haslett)

The U of C and the Calgary Health Region (CHR) have emerged as organizations dedicated to addressing the challenges of safety and quality of medical care by undertaking an exciting and ambitious clinical infrastructure project – the development of a "Medical Ward of the 21st Century" (W21C). Launched in 2002, this initiative led to the opening of a state-of-the-art medical ward on Unit 36 of the Foothills Medical Centre in Calgary in May of 2004. Dr Haslett's research group has been working with the Medical Ward of the 21st Century to design a wireless patient vital sign monitoring "smart band-aid" for the past 2 years. These smart band-aids have been identified as a key tool in the medical arsenal by colleagues in the Faculty of Medicine and at the CHR, and will provide critical advanced warning and monitoring capabilities. Once refined, the platform can readily be adapted to perform other vital sign monitoring tasks. The unique

***Figure 2** Second Generation Smart Band-aid*

access to a front-line medical ward provided through the RFIC team's collaboration on the W21C project provides the team with an outstanding opportunity to design and test the platform in a working environment and to obtain direct feedback from those who will use and benefit from the technology.

A second generation device has been designed and 25 prototypes are to be manufactured in April 2007, with financial support from the Calgary Health Trust to facilitate initial testing. Patents have been filed on the sensor portion of the device this past year.

A longer term target is to produce a single chip device, to reduce cost and power consumption, with financial support from NSERC. An exploded view of the envisaged final prototype is shown at the left. To design the highly integrated device, several teams with expertise in different areas are designing the building blocks, which will then be integrated to produce the final prototype. These components include the wireless transceiver interface (U of C, Carleton, McGill), the antenna and impedance matching circuitry (U of C), sensor design (U of C), the power scavenging system (Carleton, McGill, U of C), and the integration of these to produce the final temperature measuring wireless device (U of C).

The Calgary Center for Engineered Care (CCEC) (Haslett, Jullien, Okoniewski)

This initiative, as part of the activities of the Center for Biomedical Engineering Research and Education, (CBRE), encompasses the Advanced Micronanosystems Integration Facility (AMIF), with a target to design, fabricate and test novel new devices for a variety of biomedical applications, including hospital and home care monitoring and drug delivery devices.

These initiatives are supported by new infrastructure as follows:

Expansion of the Advanced Micronanosystems Integration Facility (AMIF)

The AMIF is a major new micronanosystems design, integration, characterization, and packaging facility that will support and enable much of the research planned for the coming year and beyond. Construction of the Class 100 clean room was completed in 2005 and is now fully operational and in regular use for photolithography, flip-chip bonding, and chemical etching. Construction of a Class 1000 facility adjacent to the Class 100 area that houses additional equipment for film deposition, bonding, etching, characterization and packaging was completed in the late Fall of 2006 and is also fully operational. The new Class 1000 space also houses a unique femtosecond laser micromachining facility.

Microsystems represent an assembly of two or more nano-micro structure devices that have been individually fabricated in separate, often disparate, processes. Devices generated by such leading edge integration techniques will form the backbone of the future disruptive technology of ubiquitous sensing, processing, and wireless networking micro devices. This technology will revolutionize many application areas including: health sciences; environmental monitoring; industrial and manufacturing processes; personal communications; military technology; security systems; entertainment; automotive, etc. The technology will also provide opportunities to enhance, in a disruptive fashion, many research areas including those of interest to the U of C such as: neuroscience; bio-materials; bio-sensors; oil and gas exploration; and advanced communication technologies.

An important target of the new facility is to build the capability to design packaging for the new micro-nano devices that are fabricated and integrated in the facility, and to provide manufacturable prototyping that will then assist the proposed Edmonton ACAMP facility to produce industry quantities of those devices.

The International Square Kilometer Array Initiative (SKA) (Haslett)

Ultra Low Noise Signal Chains for Radio Telescopes

The international astronomy community is embarking on a project to construct the largest centimeter wave radio telescope array ever built. At one million square meters in size, the project is known as the Square Kilometer Array (SKA). The International SKA studies will have a transformative impact on cosmology and other areas. Through the National Research Council's Hertzberg Institute of Astrophysics, and with key involvement of Dr Russ Taylor, Head of Physics and Astronomy at the U of C, Canada is a leader in the SKA initiative. Dr Haslett's research group is designing the ultra low noise front end circuits for the multi-antenna element signal chains, attempting to achieve less than 0.2 dB noise figures in CMOS amplifiers at ambient temperature in the GHz frequency range, to dramatically lower cost and power consumption in the new design. Over the past year, LNAs targeting the required specifications and have been designed, fabricated and successfully tested in 180nm and 90nm CMOS. Recently, the team has achieved a measured sub 0.2 dB noise figure from 800MHz to 1.4GHz. This is a world record by a substantial margin, for the overall performance of a broadband, impedance matched, high gain LNA in CMOS at ambient temperature. The team is now investigating ways of achieving further noise reduction by beginning to work in 65nm CMOS with CMP in France.

Building Blocks for Next Generation Wireless Transceiver Systems (Haslett)

Realizing Fully Monolithic RF Wireless Transceivers in CMOS Fabrication Technology

The goal in this area is the design of on-chip circuitry that will enhance the performance of on-chip passive elements, such as inductors and capacitors, which are key components of wireless transceivers and the poor performance of which characteristics prevent the achievement of fully integrated systems at this time. During the past year, the team successfully demonstrated the realization of high quality on-chip high frequency filters. In particular, the RFIC research group has recently realized a high order tunable 2.4 GHz bandpass filter, with real time hardware automatic tuning to provide programmability as well as tuning to overcome fabrication process variations.

Designing Ultra Low Power Wireless Transceivers for Ad Hoc Sensor Networks

Goals in this project include designing a series of transistor level building blocks to address a major future industry thrust – the achievement of ultra low power or self powered miniature single chip radios. These will then be employed in a wide variety of applications, from smart clothing to medical monitoring to environmental sensing. During the past year, the team been working with Dr Okoniewski's CRC Research Chair group to marry their high quality MEMS inductors and capacitors to oscillator circuits designed by the RFIC group, using the AMIF. Collaborations with Dr Calvin Plett's research group at Carleton University on new transceiver architectures, the deposition of supercapacitors as energy storage elements, and MEMS energy scavenging circuits designed by Dr Mourad El-Gamal's research group at McGill University will move this research forward in the coming year.

Outreach

- Dr Jim Haslett and Dr Sebastian Magierowski represented the U of C at the opening of the CMC Microsystems Advanced RF Systems Lab, part of the CMC National Microelectronics and Photonics Testing Collaboratory, in Winnipeg, Manitoba. Dr Haslett is a member of the CMC Standing Committee on Test that oversees the establishment of the four test collaboratory facilities across Canada.

- Dr Haslett was interviewed by Innovation Alberta to discuss the wireless research activities of the group.

- Dr Haslett and PhD student Leonid Belostotski were featured in articles on the SKA radio telescope research.

Cosmic Giant

By Alana Mikkelsen
Photos by George Webber

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U of C guides plans for world's largest telescope

Dr. Russ Taylor, engineering student Leonid Belostotski and engineering professor Jim Haslett examine a ultra-sensitive miniaturized radio amplifier being developed at U of C for the SKA radio telescope.

Sept. 28, 2006

International experts have narrowed their choice of locations for the largest telescope ever to be built, and a University of Calgary scientist is playing a key role in plans to study the universe in the greatest detail ever.

The Square Kilometre Array (SKA) will be a revolutionary radio telescope: 50 times more sensitive than any imaging radio telescope array ever built; able to survey the sky 10,000 times faster, observe farther back in time, and over a larger volume of space. It will be able to penetrate clouds of dust deep at the centre of our galaxy and peer far into the cosmos to pick up signs of the first star and galaxy formation. It will also provide a new approach for researching Dark Energy, the mysterious force that is continually driving the universe apart. And it will allow scientists to conduct new tests of the theory of general relativity involving pulsars and black holes.

Two countries – Australia and South Africa – have been short-listed to host the Square Kilometre Array, a grid of radio telescopes with a reflective surface of one square kilometer. The grid will be distributed over an area the size of Canada. The massive project is being spearheaded by research consortia in 17 countries including Canada who are working out the details of technology and construction, predicted to begin in 2014. Radio telescopes, which look like satellite dishes, pick up faint, low-frequency cosmic radio waves, which reveal the dark part of the universe that lies between stars. Radio waves also can probe the so-called "dark ages" of the universe, before light existed and stars formed – an era invisible to optical telescopes like the Hubble Space Telescope.

Computer model of the Square Kilometre Array. Produced by Xilostudios in Italy under contract from the International SKA Project Office.

"Radio astronomy has produced some of the greatest discoveries of the 20th century, including three Nobel Prizes in Physics," said radio astronomer Russ Taylor, head of the physics and astronomy department at the University of Calgary, a member of the international committee that selected the two sites, and chair of the board of directors overseeing the Canadian component of the project.

The Canadian team is providing scientific oversight for the project as well as developing key technologies for the telescope, including ultra-sensitive miniaturized radio amplifiers being developed in U of C's Department of Electrical and Computer Engineering. At the U of C's Radio Astronomy Laboratory, researchers including Taylor are developing systems that will help guide the SKA's technical design. Research on the Canadian portion of the project is partially funded by the National Research Council.

Designing Building Blocks for Fully Programmable Digital Radios

Radio receivers that perform analog to digital conversion closer to the antenna and do most of the signal processing in the digital domain are known as digital receivers. Digital receivers are re-configured for multi-standard operation, can facilitate performance improvements by using digital filters for signal processing, and can potentially realize savings in chip area, power consumption and cost.

The goal of this project is to design a very small footprint, low power analog to digital converter, first for use at intermediate frequencies, and eventually at RF frequencies, to achieve A/D conversion as close to the antenna as possible. Last year the RFIC team achieved a 4.8 ENOB (Effective Number of Bits) 1.2 GS/s A/D converter in 130nm CMOS that consumes 700uW of dc power, in a footprint less than 300um by 300um. This design has been improved over the past few months, and a new chip was submitted for fabrication in 90nm CMOS on April 11, 2007.

RF Front-Ends for Multi-Input Multi-Output (MIMO) Communicators

This project is investigating the design of low-power, fully integrated RF transmitter and receiver chains intended for MIMO wireless systems. MIMO systems improve the quality of the wireless link, but require more hardware (i.e. more radios) to do so.

This increased complexity is addressed with microsystems technology, which allows the extra hardware to be fabricated over a very small area. The exact dimensions vary with application, but can generally range from MIMO communicators consisting of dozens of input/outputs (I/Os) spread over a few centimeters to several I/Os spread over a few millimeters. The significant problem of coupling the electronics to each antenna I/O is significantly eased by microsystems technology therefore allowing large arrays to be constructed. A difficult hurdle is the need to electrically isolate the various elements from one another such that each element acts as a unique input. This work is benefiting greatly from the on-site availability of the AMIF.

Smart Antenna Communication Systems (Magierowski)

CDMA/SDMA Indoor Wireless Base Station Back-end

The goal of this project is to design the key back-end building blocks of a digital CDMA/SDMA demodulator in a production CMOS technology. The motivation for designing such a system is its potential to serve as a backbone for high-speed multi-user wireless local area networks (WLANs).

Over the past year the system employed a bi-directional space-time filter distributed among the basestation and user terminals. It is designed to guarantee 128-Mbps to 32 users over a 20-MHz bandwidth in a flat fading channel. An extensive set of experimental wireless channel measurements emulating a multi-user network while using a compact, custom-designed circular antenna array were compared with current spatial channel models and the results showed spectral efficiency doubled. Investigations into the analog front-end for this system are ongoing.

Millimeter Wave Parametric Integrated Circuits

The goals of this project are to design and fabricate millimeter wave amplifier and frequency converter circuits for ultra-low-noise signaling applications and initial studies have targeted a parametric circuit design approach. Rather than using transistors, parametric circuits rely on reactive elements to achieve amplification. The main benefit of the parametric approach is the ability to amplify very high-speed signals without adding very much noise. The concept of parametric circuits is well known within the microwave engineering community but has yet to be widely adopted by integrated circuit designers. The RFIC team's work on adapting this approach to IC design has been successful in developing customized MOS components for parametric applications, along with techniques for optimizing their performance.

Objectives for Next Year

Major Research Directions in 2007-2008

Over the next year the team will continue to apply the knowledge gained over the past five years to the biomedical and radio astronomy fields, and continue to address difficult issues in next generation wireless communications product design. The RFIC research group will work with partners to design entirely new devices based on the integration of disparate technologies in the AMIF, particularly for applications in health care. In the process, the RFIC group expects to design new wireless communications systems that will find application in a host of other areas, from environmental sensing to home technologies.

A substantial part of the Chair's research program will continue to focus on developing the necessary microelectronics hardware for smart antenna communicators. A descendent of war-time radar research, this technology is of keen interest to network designers. By allowing transceivers to focus wireless signals in any necessary direction this technology offers significant advantages to wireless networks, including:

i. simplified multiple-access-control processing,

ii. reduced interference between users,

iii. lower-power signaling requirements; and

iv. improved wireless security.

Although the theory behind modern smart antenna systems is maturing, realistic hardware implementations for mobile applications are still extremely rare. The immediate goals in the field is to build high-speed wireless microsystems with high spatial resolution, and to do so using custom integrated electronic and electromagnetic components.

New Initiatives in 2007-2008

Initial research on high-speed low-power analog to digital conversion for digital RF receivers, using time-to-digital techniques, has been very successful. This work will be refined in the coming year. A spin-off activity relates to the use of the circuits for Serializer-deserializer (SerDes) techniques in large digital systems. SerDes chips facilitate the transmission of parallel data between two points over serial streams, reducing the number of data paths and thus the number of connecting wires required. A patent has been filed to protect the new technique, and discussions are under way with major industry companies to use the new technology.

Research on Smart Antenna Communication Systems is well under way, including the design of new wireless base station back end circuitry, smart antenna front end circuitry, antenna arrays, and millimeter wave parametric amplifier design.

Research Team Members and Contributions

Team Leader
Professor James W. Haslett
Research interests include analog and digital integrated circuit design in a variety of fabrication technologies for applications in wireless communication systems, biomedical devices, and instrumentation
A Fellow of the IEEE and the Canadian Academy of Engineering and the Engineering Institute of Canada
Won 16 teaching and research awards during his career
Awarded a 2006 Research Excellence Award for Electrical and Computer Engineering, from the Schulich School of Engineering

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Dr Ivars Finvers	iCORE Associate, researching precision high performance analog CMOS integrated circuit design and wireless vital sign monitoring as part of the Medical Ward of the 21st Century Technology	Ten years of industrial experience at Nortel, Novatel and SiWorks Seventeen teaching and research awards during his career
Dr Sebastian Magierowski	Academic Staff Member, hired as part of the NSERC Industrial Research Chair program	Research interests include theoretical and practical behavior of RF wireless transceiver building blocks, and smart antenna communication systems

Research Associates

Name	Role/Topic	Awards/Special Info
Pranavi Anand	Research Assistant from U of A Ultra Low Power Transceiver Design for ad hoc networks and biomedical devices	
Dr John McRory	Adjunct Professor	Company scientist, Extreme Systems, Calgary RF designer with extensive industry experience and particular expertise in RF Power Amplifier Design
Dr Abdel Yousif	High performance digital signal processing systems and architectures for digital radio	Seven year design history at Intel, working on the design of the Pentium P4 processor

PostDoctoral Fellows

Name	Role/Topic	Awards/Special Info
Dr Ahmad Chamseddine	High frequency circuit design, in the 50 GHz range Self-tuning impedance matching networks for antennas, and passive millimeter wave systems for object detection with applications such as automotive anti-collision systems	PhD from France, joined in 2004, left in September 2006 to join Canadian Industry

PhD Candidates

Name	Role/Topic	Awards/Special Info
Leonid Belostotski	Ultra low noise amplifier design, working with researchers from the NRC Dominion Radio Astrophysical Observatory in Penticton, as part of the Canadian contribution to the Square Kilometre Array initiative for a next generation Radio Telescope	NSERC Canada Graduate Scholarship (CGS) iCORE Scholarship U of C Silver Anniversary Scholarship in Fall 2006 Dean's Research Excellence Award TRLabs Scholarship supplement, 2006-2007 2006 Runner Up Best Poster Award (CAD/Componentware category) at the annual CMC Microsystems TEXPO in Ottawa, October 23-24, 2006
Jean-Francois Bousquet	CDMA/SDMA smart antenna transceiver.	(Supervised by Dr Magierowski) Work has resulted in the design of a low-power multi-user distributed space-time detector.
Josh Nakaska	RF monolithic filter design, and automatic self-tuning circuits for on-chip filters	NSERC PGSB and iCORE Scholarships Dean's Research Excellence Award. TRLabs Scholarship supplement, 2006-2007 Awarded a 2006 Analog Devices Inc. Outstanding Student Designer Award, presented at ISSCC 2006, San Francisco, February 2006 Selected as a finalist in the student paper competition at the IEEE International Microwave Symposium, Hawaii, June 2007.
Mahesh Pai	Multi-standard RF receiver front ends for next generation radi	Joined from the U of A in January 2006 and holds a TRLabs Scholarship Third place in the iCORE Summit student poster competition in Banff, May 23-25, 2006, with Mostafa Rashdan.

PhD Candidates Cont'd

Name	Role/Topic	Awards/Special Info
Holly Pekau	Sub sampling mixers and high-speed data conversion circuits for RF transceivers	Five years prior industrial IC design experience with Analog Devices and IBM NSERC PGSB and iCORE scholarships Dean's Research Excellence Award. Joined Smart Technologies in June 2006 Completing PhD part time
Rob Randall	Fully integrated high linearity CMOS Power Amplifier design	NSERC PGSB and iCORE scholarships Funded by a TRLabs scholarship and the IRC chair program in 2006-2007
Mostafa Abd ElHakeem Rashdan	Ultra Low Power transceiver design for ad hoc networks and medical applications	Co-supervised by Dr Muand Third place in the iCORE Summit student poster competition in Banff, May 23-25, 2006, with Mahesh Pai
Ken Townsend	Low power CMOS RF transceiver building blocks for applications in wireless sensor networks Involves the mating of tunable MEMS inductors and capacitors (developed by Dr Okoniewski's group) to standard CMOS circuitry, to achieve low power Part of a national research collaboration with researchers at Carleton, and McGill Universities, targeted at designing a low power wireless sensor network platform for medical applications	NSERC Canada Graduate Scholarship (CGS) and iCORE scholarships Dean's Research Excellence Award University Technologies International Fellowship, summer 2006 TRLabs scholarship supplement 2006 Analog Devices Inc Outstanding Student Designer Award One of 25 finalists worldwide in the student paper competition at the IEEE International Symposium on Circuits and Systems, (ISCAS 2007), New Orleans
Ahmed Youssef	Design of ultrawideband transceivers for wireless ad hoc networks	Graduated Ain Shams University, Egypt & funded by the IRC chair program Renewal of the Gordon Lewis Hedberg Doctoral Scholarship, June 2006, for 2006-2007 TRLabs Telecommunications Research Scholarship, 2006-2007

MSc Candidates

Name	Role/Topic	Awards/Special Info
Howard Chan	RF MOS parametric converter/ amplifier design, and mm-wave integrated conversion circuits	(Supervised by Dr Magierowski)
Michael Chen	Low phase noise RF CMOS VCO's, which has culminated in the design and implementation of a new semiconductor varactor that reduces the effects of external noise on the VCO	Completed MSc in February 2007, and joined local industry (Emscan Corp.) (Supervised by Dr Magierowski, J.W. Haslett co-supervisor)
Jim Kulyk	Transformer based Q-enhanced CMOS monolithic RF Filter Design	Recruited from current collaborator PMC Sierra and funded by a TRLabs Scholarship and the IRC chair program Received the U of C 40th Anniversary Senate Graduate Award for best MSc thesis Graduated 2006, now working at Nortel in Calgary
Andrew Macpherson	Ultra High Speed, low Power GS/s A/D Converters for Wireless Communications systems	NSERC Canada Graduate Scholarship (CGS) Alberta Ingenuity Fellowship iCORE Graduate Scholarship Dean's Research Excellence Award One of ten IEEE Microwave Theory and Techniques Scholarships worldwide
Robert Salmond	CDMA/SDMA smart antenna transceiver. Contribution will concentrate on low-power RF front-ends.	(Supervised by Dr Magierowski)
Steven Zhai	Low power medical sensors for the ad hoc wireless sensor network project with Foothills hospital Successfully interfaced a commercial blood oxygen/heart rate sensor to the wireless ad hoc sensor network, for patient vital sign monitoring.	Completed MSc in March 2007, and moved to industry in Alberta (Suncor Energy) (Supervised by Dr Magierowski, J.W. Haslett and E. Nowicki co-supervisors)

Undergraduate Students		
Name	**Role/Topic**	**Awards/Special Info**
Laina Hynes	Pulse Oximeter for wireless patient vital sign monitoring	Part of a fourth year project team
Jason Miller	Pulse Oximeter for wireless patient vital sign monitoring	Part of a fourth year project team
Diane Vaillancourt	Pulse Oximeter for wireless patient vital sign monitoring	Part of a fourth year project team
Nik Webber	Pulse Oximeter for wireless patient vital sign monitoring	Part of a fourth year project team

GRADUATES

Name	*Research Topic*	*Current Position*
PhD Candidacy Exams Completed		
Leo Belostotski	Low Noise LNA's for Radio Astronomy	U of C ECE October 2006
Ahmed Youssef	UltraWideband Communications Transceivers	U of C ECE September 2006
MSc Graduates		
Zhongbo Chen	RF low noise VCO's	Alberta Industry (EMSCAN) February 2007
Jim Kulyk	RF Monolithic Filter Design	Nortel, Calgary October 2006
James Quan	Baseband Variable Gain Amplifiers	Acceleware, Calgary June 2006
Steven Zhai	Wireless Heart Rate/Blood Oxygen Monitoring System	Suncore Energy, Fort McMurray March 2007

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
TRLabs	The industrial sponsor of the chair program, TRLabs provides a salary component to Dr Haslett and scholarships to several students. Staff scientists worked with the Chair and the research group on an ongoing basis
Dr Graham Jullien, Dr J. W. Haslett, Dr Michal Okoniewski, Dr Elise Fear, Dr Karan Kaler, Several staff from Mechanical Engineering, The Schulich School of Engineering and the U of C Senior Administration	Expansion of the CCIT AMIF – A Class 100 room and an adjoining Class 100 facility are now fully operational in the Calgary Centre for Innovative Technology A full time lab manager, who is a former Nortel employee from Ottawa, manages the facility
Faculty of Medicine (U of C) & Calgary Health Region Dr John Conly, Dr William Ghali, Dr Barry Baylis, Nancy Guebert, Sonja Morrison, *et al*	Wireless patient vital sign monitoring initiative Designed a third generation prototype wireless low-power band-aid and has filed full Canadian and US patent applications for this unique, non-invasive body-temperature measurement method and design Clinical trials of 25 prototypes began in May and June of 2007
Dr Graham Jullien Dr Naweed Syed – U of C	Centre for Advanced Nervous System Technologies (CANST) CFI application Work will heavily leverage and supplement AMIF's capabilities Investigating the stimulation of brain neurons by direct interface with silicon chips and allows the simultaneous recording of responses
Dr Michal Okoniewski	Self-configuring antenna systems and RF MEMS A self-tuning impedance matching system was designed and fabricated, working in the GHz range, that uses a genetic algorithm and a series of programmable, switched tuning stubs in a transmission line to achieve the impedance match automatically Mating MEMS high quality inductors designed by Dr Okoniewski's group with CMOS RF circuitry integrated by the research group, to achieve low-noise, low-power RF circuits

Participants	*Nature of Collaboration*
National Collaborations	
RFIC Group, U of C, Dr Calvin Plett, Carleton University, Dr Mourad El-Gamal, McGill University, Dr John Conly, Foothills Hospital and Faculty of Medicine, U of C, Carol Gray, Calgary Health Region, and Associated Health Services, Edmonton	The national collaborative research project involves the design of a wireless low power SOC platform for acquiring and transmitting sensor data for medical patient vital sign monitoring. An NSERC Strategic Projects grant was awarded to the team, with Dr Haslett as principal investigator, in November 2006 for a three-year period
Dr Peter Dewdney and Dr Bruce Veidt, NRC Dominion Radio Astrophysical Observatory, Penticton, BC	Designing the front-end ultra low noise amplifiers and signal chain components for a proposed next generation radio telescope, the International Square Kilometer Array (SKA) This research effort involves 17 countries, and researchers and industrial companies around the world. The LNA team at U of C, led by Jim Haslett and Leonid Belostotski, has achieved world record ultra-low-noise wideband LNA designs. NRC has awarded a five-and-a-half year contract to Dr Haslett, which began January 1, 2007
Dr Russ Taylor, Physics Dept, U of C, Dr Peter Dewdney, DRAO, Penticton, BC	Jim Haslett is a Principal Investigator on a national Research Network proposal for the Canadian Square Kilometer Array Consortium (CSKAC)
International Collaborations	
Associated Health Systems, Edmonton and Vancouver	Industrial partner on the NSERC Strategic Projects grant, 2006-2009

INTELLECTUAL PROPERTY

Patent/Author	*Title/Name*	*Status*
Abdel Yousif and J. W. Haslett	"Time to Digital Converter"	Full Canadian Patent filed September 18, 2006.
J.W. Haslett, Ivars Finvers and Graham Jullien,, Canadian Application # 2538940, 2007 US Application 11/681,628,	"Bandage with Sensors"	Filed March 2, 2007 in the United States Filed March 3, 2006, and second Canadian application March 2, 2007

FUNDING

Dr Jim Haslett has a five year Industrial Chair award ($1M). This year he received federal funding from NSERC, CFI & NRC ($464K) and funding from the University of Calgary ($664K), TRLabs ($200K), and Calgary Health Trust ($100K).

PUBLICATIONS

BOOK CHAPTERS IN PRESS

J. W. Haslett and Leonid Belostotski, "Low Noise Amplifiers", *Emerging Wireless Technologies: Circuits, Systems, and Devices,* editor K. Iniewski, CRC Press, to be published summer 2007.

S. Magierowski, H. Chan, K. Iniewski, T. Zourntos, "Parametric Converters: Integrated Devices, Circuits and Systems", *Emerging Wireless Technologies: Circuits, Systems, and Devices,* editor K. Iniewski, CRC Press, to be published summer 2007.

BOOK CHAPTERS ACCEPTED FOR PUBLICATION

J.W. Haslett and Abdel Yousif, "Ultra High Speed Analog to Digital Conversion", *Circuits for Emerging Technologies-CMOS and Beyond*, editor K. Iniewski, CRC Press, to be published in 2008.

REFEREED JOURNAL PUBLICATIONS

Abdel Yousif and James Haslett, "A Fine Resolution TDC Architecture for Next Generation PET Imaging", *IEEE Transactions on Nuclear Science*, accepted for publication April 25, 2007.

Tommy K. Tsang, Mourad N. El-Gamal, Krzysztof Iniewski, Kenneth A. Townsend, James W. Haslett, and Yanjie Wang, "Current Status of CMOS Low Voltage and Low Power Wireless IC Designs", *Analog Integrated Circuits and Signal Processing, (Springer),* in press.

H. Pekau, and J.W. Haslett, "Cascaded Noise Figure Calculations for Radio Receiver Circuits with Noise Aliasing Properties", *IEE Proceedings, Part G: Circuits Devices and Systems,* Volume 153, Issue 6, Dec. 2006, pp. 517 – 524.

L. Belostotski, and J. W. Haslett, "Noise Figure Optimization of Inductively-Degenerated CMOS LNA's with Integrated Gate Inductors", *IEEE Transactions on Circuits and Systems Part I: Regular Papers*, Volume 53, Issue 7, July 2006, Page(s):1409 – 1422.

A. Chamseddine, J. Haslett, M. Okoniewski, "CMOS Silicon-On-Sapphire RF Tunable Matching Networks", *EURASIP Journal on Wireless Communications and Networking*, Volume 2006 (2006), Article ID 86531.

B.Maundy, S. Gift, and S. Magierowski, "Constant Bandwidth Current Feedback Amplifier from Two Operational Amplifiers," *International Journal of Electronics*, in press.

H.Chan, Z. Chen, S. Magierowski, and K. Iniewski, "Parametric Conversion and Frequency Control using Custom MOS Varactors," *EURASIP Journal on Wireless Communications and Networking*, Volume 2006 (2006), Article ID 12945.

REFEREED CONFERENCE PROCEEDINGS

Ahmed Youssef, Jim Haslett, and Sebastian Magierowski, "Design Issues for Sensor Network RF Receivers", oral presentation at the *20th Canadian Conference on Electrical and Computer Engineering, (CCECE 2007)*,Vancouver, Canada, April 23-25, 2007.

P. Anand, L. Belostotski, K. Townsend, R. Randall and J. W. Haslett, "An Image-Reject Low Noise Amplifier with Passive Q-enhanced Notch Filters", oral presentation at the 20th Canadian Conference on Electrical and Computer Engineering, (CCECE 2007), Vancouver, Canada, April 23-25, 2007.

Mostafa Rashdan, Mahesh M. Pai, Pranavi Anand, James W. Haslett, and Brent J. Maundy, "An Ultra-low-power 2.4GHz Wireless Transceiver for Vital Patient Monitoring System", oral presentation at the 20th Canadian Conference on Electrical and Comp*uter Engineering, (CCECE 2007)*, Vancouver, Canada, April 23-25, 2007.

L. Belostotski, J. W. Haslett, "Wide band room temperature 0.35-dB noise figure LNA in 90-nm bulk CMOS", presented at the *IEEE Radio and Wireless Symposium*, Long Beach, CA, U.S.A., 9-11 January 2007, conference proceedings pages 221-224.

I. G. Finvers, J. W. Haslett, G. A. Jullien, "Wireless Temporal Artery Bandage Thermometer", presented at the *2006 IEEE Conference on Biomedical Circuits and Systems (BioCAS 2006)*, London, Nov. 29 – Dec. 1, 2006, conference proceedings pages 166-169.

R. L. Salmond, J. F. Bousquet, and S. Magierowski, "RF Hardware Modeling of a Direct Conversion Receiver using SDMA," in *Proceedings of the 2006 IEEE 64th Vehicular Technology Conference (VTC 2006-Fall)*, Montreal, September 2006.

J. F. Bousquet, R. L. Salmond, and S. Magierowski, "Development of the Forward Link Physical Layer in a Multiuser SDMA/CDMA Low-Power Transceiver," in Proceedings of the *2006 IEEE 2nd International Conference on Wireless Networking and Mobile Computing*, Wuhan City, China, September 2006.

J.W. Haslett and L. Belostotski, "CMOS Ultra Low Noise LNA Designs for Radio Astronomy", presented by J. W. Haslett at the *International Emerging Technologies Workshop*, Banff, Alberta, July 19-21, 2006.

R. H. Johnston, I. G. Finvers, J. W. Haslett, "Antenna Optimization for RF Mote Communications", *2006 IEEE International Symposium on Antennas and Propagation (part of AP-S / URSI / AMEREM),* Albuquerque, NM, 9-14 July 2006.

L. Belostotski, J.W. Haslett, "On Selection of Optimum Signal Source Impedance for Inductively-Degenerated CMOS LNSa", *IEEE Canadian Conference on Electrical and Computer Engineering, CCECE'06*, Ottawa, Canada, May 7-10, 2006 pp. 2435-1440.

H. Pekau, A. Yousif, J.W. Haslett, "A CMOS Integrated Linear Voltage-to-Pulse-Delay-Time Converter for Time Based Analog-to-Digital Converters", *IEEE Symposium on Circuits and Systems (ISCAS'06)*, Kos, Greece, May 21-24, 2006, pp. 2373-2376.

K. Townsend, J.W. Haslett, "Low Power Q-Enhancement for Parallel LC Tanks", *IEEE International Symposium on Circuits and Systems (ISCAS'06)*, Kos, Greece, May 21-24, 2006. pp. 3746-3749.

L. Belostotski, J.W. Haslett, "Wide-band CMOS Low Noise Amplifier for Applications in Radio Astronomy", *IEEE International Symposium on Circuits and Systems (ISCAS'06)*, Kos, Greece May 21-24, 2006, pp. 1347-1350.

K. Townsend, L. Belostotski, J.W. Haslett, J. Nielsen, "Ultra-Wideband Front-End with Tunable Notch Filter", *IEEE North-East Workshop on Circuits and Systems (NEWCAS '06)*, Gatineau, Quebec, June 18-21, 2006, pp. 177-180.

Youssef, J.W. Haslett, "Ultra WideBand Communication Systems", Wireless Technologies and Circuits Workshop, presented at the *IEEE Midwest Symposium on Circuits and Systems*, Puerto Rico, August 2006.

H. Pekau, J. Kulyk, L. Belostotski, J.W. Haslett, "Linearization Techniques for Cross-coupled Transconductor Circuits Used in Integrated Q-Enhanced LC Filters", *IEEE Canadian Conference on Electrical and Computer Engineering, (CCECE'06)*, Ottawa, Canada, May 7-10, 2006, pp. 1101-1106.

Youssef, J. W. Haslett, J. Nielsen, "4G OFDM Wireless Systems: Multi-Media over Wireless", presented by Ahmed Youssef at the *Wireless Technologies and Circuits Workshop*, European Microwave Week, Manchester, UK, September 2006.

CONFERENCE PAPERS ACCEPTED FOR PRESENTATION

J. Nakaska, and J.W. Haslett, "2 GHz Automatically Tuned Q-Enhanced CMOS Bandpass Filter", accepted for oral presentation at the *IEEE International Microwave Symposium*, Honolulu, Hawaii, June 2007.

Belostotski, L. and Haslett, J.W. "CMOS LNAs for Large Arrays" invited paper accepted for oral presentation at the *International Union of Radio Science (URSI) North American Radio Science Meeting*, July 22 to 26th, Ottawa Canada.

G.J. Hovey, B. Carlson, D. Chalmers, P.E. Dewdney, G. Lacy, B. Veidt, A. Chippendale, P. Hall, J. O'Sullivan, L. Belostotski, and J.W. Haslett "Technologies and their Impact on the Cost of a Square Kilometer Array," accepted for presentation at *International Union of Radio Science, North American Radio Science Meeting*, Ottawa, July 2007.

G.G. Messier, J.F. Bousquet, S. Magierowski, "IEEE 802.11b SDMA Performance in Realistic Environments", accepted for presentation at the *2007 IEEE Vehicular Technology Conference*, Dublin, April 2007.

H. Pekau and J. W. Haslett, "A 0.18um 2.1 GHz Sub-Sampling Receiver Front End with Fully Integrated Second and 4th Order Q-Enhanced Filters", accepted for oral presentation at the *IEEE International Symposium on Circuits and Systems (ISCAS 2007)*, New Orleans, May 27-30, 2007.

K.A. Townsend, J.W. Haslett, J. Nielsen, "A CMOS Integrated Power Detector for UWB", accepted for oral presentation at the *IEEE International Symposium on Circuits and Systems (ISCAS 2007)*, New Orleans, May 27-30, 2007.

POSTER PRESENTATIONS

L. Belostotski and J.W. Haslett "Ultra Low Noise Wide Band CMOS LNAs for Next Generation Radio Telescopes," poster presentation at *CMC Microsystems TEXPO*, Ottawa, Oct 23-24, 2006. Runner up Best Poster Award, CAD/Componentware category.

L. Belostotski, J.W. Haslett, B. Veidt, P.E. Dewdney "CMOS LNAs for SKA?" *SKA FPA Pathfinders Meeting*, Sydney, Australia, March 12-19, 2007.

K. Townsend, Imed Zine-ElAbidine, J.W. Haslett and John Nielsen, "UltraWideband Microsystem for Wireless Medical Sensor Monitoring", poster presentation at *CMC Microsystems TEXPO*, Ottawa, Oct 23-24, 2006.

Abdel Yousif, Holly Pekau and J.W. Haslett, "A 1GS/s, 5-Bit, and Low Power Time-Based ADC", poster presentation at *CMC Microsystems TEXPO*, Ottawa, Oct 23-24, 2006.

L. Belostotski, J. W. Haslett, "Wideband Room Temperature 0.35-dB Noise Figure LNA in 90-nm Bulk CMOS", *Square Kilometre Array (SKA) Engineering and Joint Workshop Group Meeting*, Paris, Sept. 4-8, 2006.

P. Anand, J. W. Haslett, "An Image-Reject Low-noise Amplifier", *iCORE Informatics Summit 2006*, Banff, Alberta, May 23-25, 2006.

A. Youssef, J. W. Haslett, "Communication System for Wireless Medical Networks", *iCORE Informatics Summit 2006*, Banff, Alberta, May 23-25, 2006.

Z. Chen, S. Magierowski, J. W. Haslett, "Differential Varactor and Its Applicaton In A 5-GHz VCO", *iCORE Informatics Summit 2006*, Banff, Alberta, May 23-25, 2006.

R. Salmond, S. Magierowski, "Hardware Modeling of a Direct Conversion Receiver", *iCORE Informatics Summit 2006*, Banff, Alberta, May 23-25, 2006.

M. M. Pai, M. A. Elhakeem, J. W. Haslett, "Ultra Low Power Transceiver For Wireless Patient Vital Signs Monitoring", *iCORE Informatics Summit 2006*, Banff, Alberta, May 23-25, 2006.

J. Nakaska, J. W. Haslett, "Tunable Q-Enhanced RF Bandpass Filters", *iCORE Informatics Summit 2006*, Banff, Alberta, May 23-25, 2006.

J-F. Bousquet, S. Magierowski, "A Multiple Antenna Transceiver for Multiuser Detection", *iCORE Informatics Summit 2006*, Banff, Alberta, May 23-25, 2006.

H. Chan, S. Magierowski, "Sub-Harmonic Pumping in Parametric Amplification", *iCORE Informatics Summit 2006*, Banff, Alberta, May 23-25, 2006.

PAPERS SUBMITTED FOR REVIEW DURING THE REPORTING PERIOD

S. Magierowski, H. Chan, and T. Zourntos, "Subharmonically Pumped RF CMOS Paramps," submitted to I*EEE Transactions on Electron Devices*, March 2007.

L. Belostotski and J.W. Haslett "Sub-0.2 dB Noise Figure Wide-Band Room-Temperature CMOS LNA with Non-50 Ω Signal-Source Impedance," submitted for review to *IEEE Journal of Solid-State Circuits*, April, 2007.

L. Belostotski and J.W. Haslett "A Technique for Differential Noise Figure Measurement of Differential LNAs," submitted for review to *IEEE Transactions on Instrumentation and Measurement*, April, 2007.

S. Magierowski, H. Chan, and T. Zourntos, "MOS-Based Dual-Mode Subharmonic Parametric Downconverter with DC Gain Control," submitted to the *IEEE Electronics Letters*, March 2007.

C.A. Marquart, T. Zourntos, S. Magierowski, N.J. Mathai, "Sliding-Mode Amplitude Control Techniques For Harmonic Oscillators", submitted with minor revisions to *IEEE Transactions on Circuits and Systems II: Express Briefs*, March 2007.

L. Belostotski and J.W.Haslett, "Two-Port Noise Figure Optimization of Source-Degenerated Cascode CMOS LNA's", *Springer Analog Integrated Circuits and Systems Journal*, December 2006, under review.

Belostotski, L. and Haslett, J.W. "Noise Figure Optimization of Wide-Band Inductively-Degenerated CMOS LNAs" submitted to the *IEEE Northeast Workshop on Circuits and Systems/Midwest Symposium on Circuits and Systems (NEWCAS/MWSCA '07)*, Montreal Quebec, August 2007.

Ahmed Youssef, Jim Haslett, "Low Power Interference-Robust UWB Low Noise Amplifier in 0.18-μm CMOS Technology", submitted to the *IEEE International Midwest Symposium on Circuits and Systems, MWSCAS 2007*, Montreal, August 2007.

CHIP DESIGNS

The following chip designs have been completed, fabricated, and/or tested during the year.

ICLCYK10, Abdel Yousif, Ken Townsend, Mostafa Salah and Andrew Macpherson, 90nm CMOS. A new interconnect architecture design and a high speed ADC are implemented on the chip.

ICFCYOFD, Ahmed Youssef, a wideband low noise amplifier for UWB OFDM applications, 180nm CMOS.

ICLCYLG4, Leo Belostotski- – LNAs with non-50 Ohm impedance, 90 nm CMOS.

CMPCYLG5 Leonid Belostotski –Design consists of two specially crafted large transistors to be used in a study of the noise parameters of 90nm RF CMOS and as part of an LNA design. CMP France.

ICFCYIR1, Pranavi Anand, –The chip is a narrow-band low noise amplifier with passive Q-Enhanced notch filters for attaining image rejection over a bandwidth.

ICFCYUL1, Pranavi Anand, Mahesh Pai, Mostafa Salah Abd Elhakeem Rashdan - A 0.18um CMOS low-power front end for the Wireless Patient Monitoring System. The design employs a VCO (voltage controlled oscillator) based on a ring-oscillator topology, a power amplifier, and a mixer and filter system, and makes use of passive gain in an impedance matching circuit for reduced power consumption.

ICFCYR04, Rob Randall - This design is a 2.4 GHz Doherty power amplifier in 180nm CMOS.

ICFCYESA, Mostafa Salah Abd Elhakeem Rashdan, Mahesh Pai, Pranavi Anand , - A 0.18um CMOS low-power front end for the Wireless Patient Monitoring System. The design employs a power amplifier, an active mixer and a LC tank VCO (voltage controlled oscillator) which feeds the mixer as well as the power amplifier.

ICFCYQF3, Josh Nakaska, A parallel resonant LC-tank utilized in a quality factor (Q) enhanced LNA (a form of integrated RF filter) for operation from 2.4 to 2.5GHz. The LC-tank in the LNA is tunable in Q and frequency. Measurements demonstrate LC-tank Q's beyond 80 (a bandwidth of approximately 30MHz at 2.45GHz) in the laboratory.

ICFCYHAC, Michael Chen and Howard Chan, 0.18-um 5.6-GHz VCOs with power supply rejection circuitry and complementary differential MOS varactors

ICGCYSKI, Sebastian Magierowski, 0.13-um MOS varactors with variable channel doping for millimeter-wave parametric circuit applications

ICFCYQF2, Josh Nakaska, A 2nd generation quality factor enhanced bandpass filter was fabricated and had superior measured performance. The filter was tunable in frequency and quality factor.

KEYNOTES & INVITED TALKS

Dr Ivars Finvers gave a presentation on the group's research efforts at the *iCORE Banff Informatics Summit* during the research exchange, with a focus on the biomedical systems research in collaboration with the Calgary Health Region.

Dr Haslett gave a guest lecture, *The Medical Ward of the 21st Century: New Opportunities for Collaborative Research with the Schulich School of Engineering*, to the biomedical engineering class during Block Week, January 5, 2007.

Drs Jullien, Haslett, Okoniewski, ONeill and Finvers prepared an invited presentation to the Schulich School of Engineering Industry Associates program breakfast meeting, *Micro/nanoSystems: A Multidisciplinary Approach to Engineered Care*. The presentation was amde by Dr Jullien to 61 attending Associates on January 20,2007, and included a live demonstration of the latest version of the wireless "smart bandaid".

S. Magierowski gave a technical presentation, *Parametric Converters: Transistorless Amplification*, to the joint sections of the IEEE Circuits and Systems/Solid-State Circuits Societies, Southern Alberta Chapter, University of Calgary, December 11, 2006.

SPECIAL WORKSHOPS & TUTORIALS

The RFIC group hosted Dr Juin Liou who presented a talk on "Recent Advances in MOS Devices for RF Applications" in Septmeber to the *Electrical Engineering department in the Schulich School of Engineering (U of C)*. Dr Liou is an IEEE distinguished lecturer from the School of Electrical Engineering and Computer Science at the University of Central Florida, Orlando.

PhD student Ahmed Youssef presented a short course on "Wireless Integrated Architectures for 4G Communication Systems" to the *49th IEEE International Midwest Symposium on Circuits and Systems (MWSCAS 2006)* in Puerto Rico in August where he also chaired a session on Wireless Communication.

PhD student Ahmed Youssef presented an invited short course on November 21, 2006, entitled "An Introduction to RF Wireless Integrated Systems", for the *4th IASTED International Conference on Circuits, Signals and Systems*, San Francisco, California, USA (3 hours).

PhD student Ahmed Youssef also presented an invited short course on December 4, 2006, entitled "RF Wireless Integrated Architectures for 4G Communication Systems", at the *IEEE Asia Pacific Conference on Circuits and Systems, APCCAS 2006*, Singapore, and chaired a technical session at the conference.

Research Associate Abdel Yousif made a presentation to *Intel corp*, Portland, Oregon, USA, March 2007, entitled "Interconnect architectures for sub-micron technologies".

Advanced Technology Information Processing Systems

The Advanced Technology Information Processing Systems Laboratory (ATIPS) at the University of Calgary (U of C) leverages highly advanced and emerging technologies to conduct research into the development and implementation of a variety of information processing systems.

These systems are used for high performance digital signal processing, machine-vision, information security, streaming video, bioengineering, arithmetic intensive processors, wireless networking, opto-electronic sensors and processors.

ATIPS' research effort is focused on the exploitation of microstructure techniques, including micro-electronics, System-on-Chip, micro-electro-mechanical systems, microfluidics, and sensors, to the benefit of Canadian industry, Canadian health, technology diversification in Alberta, and the training of highly qualified personnel.

The ATIPS Labs conducts research into advanced and emerging technologies for use in solving a variety information processing tasks. The team of 54 personnel now covers a range of major initiatives including biomedical microsystems, information security, multimedia processing, hardware/software co-design, and advanced imaging technologies. These complementary disciplines form the backbone of a concerted effort to develop new and exciting solutions to some of science's most challenging problems.

The sixth year of operation continues to nurture collaboration as a key mode of operation. This approach has been rewarded with three major successes:

1. A three-year National Sciences and Engineering Research Council (NSERC) Collaborative Research and Development grant (with the University of Windsor) to support the transfer of key technologies to Gennum Corporation for possible inclusion in their product portfolio.
2. A CIHR Regenerative Medicine and Nanomedicine grant (Primary Investigator Dr Douglas Zochodne – Department of Clinical Sciences, Faculty of Medicine) entitled "Dynamic manipulation of nerve regeneration: An electronic-axon interface".
3. The completion of the 1000ft2 Class 1000 extension to the Advanced Micro/nanosystems Integration Facility (AMIF). This work was supported by a donation from the U of C and helped strengthen AMIF's position as a key open-access facility within Alberta's growing micro and nano technology (MNT) community.

Research

The sixth year of operation has continued to build on the exciting successes of previous years as the group continues the second term of Dr Jullien's iCORE chair.

In biomedical technology, the ATIPS team is currently involved in designing microsystems platforms for two major initiatives: the Medical Ward of the 21st Century (W21C), a highly multi-disciplinary programs that include expert medical researchers, engineers, and front line medical staff; and neuron/silicon interface microsystems in conjunction with the Hotchkiss Brain Institute (HBI) and as part of a research contract with

Neurosilicon Inc. These exciting programs are developing technologies that could enable the repair of nervous system damage (HBI/Neurosilicon) and wireless monitoring devices for in-situ real-time vital sign measurements. Another significant program underway is a collaboration with the U of C Department of Chemistry where ATIPS researchers have completed development of a prototype micro-system containing signal conditioning and processing circuitry bonded to a novel glucose sensor. This project won a best paper award at both the International Solid-State Circuits Conference (ISSCC) and the Design Automation Conference (DAC) for 2007.

This year also saw new iCORE Industrial chair Dr Wolfgang Tittel take up his position with the U of C, enabling the ATIPS team to build upon existing connections with Dr Barry Sanders' Institute for Quantum Information Science (IQIS). This work is investigating the ICT and microsystems issues associated with the Quantum Key Distribution (QKD) problem. QKD offers the potential for information theoretically secure communications and this collaboration promises to bring new implementation ideas to the burgeoning field of quantum cryptography.

Team Players

The ATIPS team of more than 50 researchers and students has contributed 14 journal papers, 31 refereed conference papers, one book chapter, four contributions to international standards, and five new patent applications. Dr Wael Badawy co-edited three conference proceedings and the June 2006 publication of the IEEE Proceedings, a special issue devoted to System-on-Chip, was co-edited by Dr Jullien and Magdy Bayoumi of the University of Louisiana at Lafayette. ATIPS senior team members have also co-chaired and co-organized a number of major conferences and conference sessions.

In the past year, the ATIPS Lab has also welcomed eight new recruits to the team while graduating three PhD and six Master's candidates.

Finally, the ATIPS Lab represents the U of C's portal to the services of CMC Microsystems, with dozens of integrated circuit designs fabricated using tools running on the ATIPS server. ATIPS workstations and servers host over 100 U of C users, addressing all aspects of integrated circuit design.

Research Program Overview

Now well into the second term of Dr Jullien's iCORE chair, the ATIPS Labs continues its mission to "investigate the use of advanced and emerging fabrication technologies" and to "provide a knowledge link between these technologies and the chosen application areas" in the major new application areas of bio-technology and health sciences. The ATIPS team is also continuing programs in wireless networking, embedded systems and fault tolerant processors, and computing with nanotechnology.

Biomedical Technologies

Microconvergence continues to be an integral part of the ATIPS teams mode of operation and the joint initiatives with researchers in the Faculty of Medicine are addressing key challenges in fields such as nerve-regeneration, bio-cell ion-channel activation, and wireless patient monitoring. Collaborations continue to grow in scale and currently the ATIPS team is working with partners in the Calgary Health Region, the Foothills Hospital, the Faculty of Medicine (U of C) and Neurosilicon Inc. The ATIPS team is investigating other partners in exciting new technologies and anticipate that the biomedical application of ATIPS technology portfolio will contribute strongly to the growth and collaborative development of bio-medical technologies at the U of C.

In support of these and other programs, the ATIPS group, together with leadership from iCORE Chair Dr Jim Haslett's RFIC team, continues to develop both wireless and implantable medical sensor platforms that leverage low-power, wireless, and system-on-chip design expertise and will benefit strongly from integration and characterization capabilities now offered by AMIF. A key application of these technologies is a collaboration with Dr Viola Birss (Department of Chemistry, U of C) to develop an implantable glucose sensor for Type 1 diabetics. The ATIPS researchers have completed the development of a second generation device with integrated signal conditioning and processing circuitry and flip-chip bonded this system to a unique nano-particulate sensor. This sensor promises to implant a device without the common problems associated with low oxygen levels in the blood and the production of hydrogen peroxide.

The glucose sensor has showcased the capabilities offered by AMIF with a second flip-chip bonded microsystem following last year's success and won a highly prestigious award.

CIHR Grant

Dr Graham Jullien was a principal applicant on a successful CIHR Regenerative Medicine and Nanomedicine grant application, led by Douglas Zochodne (faculty of Medicine, U of C), for research into "Dynamic manipulation of nerve regeneration: An electronic-axon interface". The fundamental goal of the CIHR's Regenerative/Nano-medicine strategic initiative is the development of meaningful multi-disciplinary research approaches though the continued integration of health sciences, engineering, computational and chemical sciences.

Neuron-Silicon Work

ATIPS neuron-silicon interfacing work continues to grow with several advances in technology, intellectual property, and personnel. Dr Jullien was part of a team that visited Peter Fromherz to discuss the next generation chip design. Subsequent research has developed a 180nm test chip that is being used to evaluate surface preparation techniques that are able to be used after the commercial level processing of the die. Controlling the surface dielectric is essential for high fidelity recording of neuronal activation potentials and maintaining an environment conducive to long-term experiments with neuronal clusters. This and other devices were developed under the auspices of Neurosilicon Inc. and in collaboration with Dr Naweed Syed's lab and Dr Michael Colicos' lab at the U of C.

This year three patent applications, based on joint work between the ATIPS Laboratories, the Hotchkiss Brain Institute, and Neurosilicon Inc., have been submitted or published through the US Patent Office: Electrically Stimulating Nerve Regeneration; High Throughput Use Dependence Drug Screening Device and Assay; and Detecting Electrical Activity and Assessing Agents for the Ability to Influence Electrical Activity.

Advanced Micro/nanosystems Integration Facility

With support from the U of C, iCORE, and Alberta Innovation and Science, the completion of the 1000 ft^2 Advanced Micro/nanosystems Integration Facility (AMIF) Class 1000 extension provides the ATIPS team and partners with an expanded capacity and houses a greater range of high-precision integration and characterization equipment. This unique facility enables the assembly of new micro-nano devices from a mix of available fabrication technologies, and provides exceptional training and experience to researchers including a graduate course in Microsystems Technology.

ATIPS-Integrated Sensor Lab

Supported by Dalsa Corp., a CFI New Opportunities Grant, an I2I award, and iCORE, the ATIPS-Integrated Sensor Lab (ATIPS-ISL) is an advanced research facility for the design, development, and testing of specialized CMOS based sensors, equipped with industrial grade signal generation and data acquisition elements. The ATIPS-ISL represents the experimental toolbox needed to support the design, development, and testing of sensor chips: completed designs are sent out for fabrication at partner facilities and returned for testing and design verification. Dr Alex Fish has completed his first year as ISL Labx Manager and has been instrumental in pushing through the second generation chip designs and starting new projects. This year saw the fabrication of second generation chip designs from the ATIPS-ISL.

Technology Transfer

The ATIPS Labs, together with long-term partners at the RCIM (University of Windsor), have been successful in an application for an NSERC Collaborative Research and Development grant to transfer technology to Gennum Corporation. This work will address a range of processing technologies developed by the ATIPS team over the past few years that are of interest to Gennum for possible inclusion in their product line. ATIPS Labs has also successfully transferred out Tbps Digital Signal Processing chip to TRLabs for its wireless LAN development program.

Information Security

The ATIPS team continues to work closely with iCORE Chair Dr Hugh Williams' Centre for Information Security and Cryptography (CISaC) on the Novel Implementation of Cryptographic Algorithms on Custom Hardware Platforms Strategic Grant, now approaching the final year of its three year research program and focussing on microsystems implementations. This work is now leading to further collaborative proposals with fellow iCORE Chairs Dr Barry Sanders and Dr Wolfgang Tittel. Dr Tittel is conducting research in the exciting field of quantum communications, a field that will benefit greatly from ATIPS' photonics, electro-optics, and system-on-chip expertise. This latter collaboration started in earnest in June of 2006.

As the first phase of what is expected to be a significant collaboration, Dr Tittel is co-supervising ATIPS researcher Philip Chan with Dr Jullien. Chan will be spearheading the ATIPS teams involvement in the program investigating microsystems solutions to the challenges of QKD for cryptographic systems.

Research Projects

Wireless Networks

System-on-Chip for Secure Communications

The ATIPS team continues to investigate novel cryptographic implementations on custom hardware, research that began in collaboration with fellow iCORE chair Dr William's CISaC group as highlighted in the 2005-2006 annual report. The aim of this program is to develop faster implementations of commercially used cryptographic algorithms using novel arithmetic techniques and hardware architectures.

In addition, the ATIPS team has produced new results for accelerating the point multiplication problem common to Elliptic Curve Cryptography (ECC) systems (and many other applications) using the Double-Base Number System (DBNS). The point multiplication problem is a fundamental component of ECC and research conducted by a collaborative team from ATIPS, CISaC, and CNRS (France) has shown that judicious use of DBNS representations can lead to substantial improvements in the implementation of ECC protocols. These techniques have also demonstrated resistance to side-channel attacks thanks to side-channel atomicity.

Digital Signal Processors for Wireless Base-Stations

Using the fault tolerant Modulus Replication Residue Number System (MRRNS) the ATIPS labs produced an advanced DSP prototype which has been successfully tested on a board level system. The MRRNS arithmetic is carry-free and is performed over small dynamic ranges and thus carries a smaller area and power overhead when compared to classical methods. Typical fault tolerant designs add around 200% to the footprint of the chip: the new fault correction design adds only 87.2%.

Design verification and testing (DVT) of the processor test chip has been successfully conducted using a scan-based built-in self-test (BIST) design that was implemented in the parallel filter structure. This technology is now complete and available for transfer to TRLabs and any interested parties. This work is also the subject of an invited paper to the system-on-chip session of the Asilomar Conference on Signal, Systems and Computers, in November 2007.

Wireless Biomedical Monitoring Systems

This year ATIPS demonstrated a low power wireless device that provides transcutaneous power transfer and data communication using RF signals. The test vehicle for this work is an implantable blood glucose monitor that could be used as the front-end for an autonomic insulin delivery system for diabetics.

A related project, conducted jointly with Dr Haslett's RFIC group, is investigating in-situ, real-time, patient monitoring, initially focusing on temperature measurement and using a (patent applied for) sensing technique to determine a patient's core body temperature from measurements taken on their forehead. This work is now the subject of two clinical trials: the first will address ergonomic considerations and the second will assess the technology in operation on a critical care ward.

Embedded Systems/Fault Tolerant Systems

This section describes research into systems containing full custom, field programmable, or processor-based integrated circuits. Goals in this field are to develop new and custom algorithms and implementation techniques that reduce targeted cost functions such as power, area, and processing speed.

Machine Vision

This program has evolved from developing and transferring an industrial process inspection technology to developing new algorithms and implementation techniques for in-camera processing of moving images.

Work this year has focused on concluding the new FPGA-based Automated Incident Detection (AID) project for the City of Calgary. The AID system automatically identifies traffic related 'incidents' that could impact road safety. Having successfully demonstrated algorithms that suppress the false detections sometimes caused by shadows and/or glare in the image, this project has now moved to the next phase: technology commercialization. Leading this activity are commercial partners Citilog and Fortran Traffic, while the research team continues to further refine, test, and validate the designs.

Application-Optimized Arithmetic (AOA)

This field remains one of the ATIPS group's core strengths and has shown that 'redesigned' arithmetic operations can reduce computational complexity, increase accuracy, reduce design times, decrease silicon 'real-estate' requirements, or improve the fault-tolerance of many designs particularly for cryptography and multimedia/signal processing applications.

The discrete cosine transform (DCT) is commonly used in digital signal processing, image processing, cryptographic applications, and so on. Within the DCT itself, the implementation of constant integer multiplications is a significant bottleneck that largely defines the speed of the entire process and so must be implemented in as efficient a way as possible. The problem of optimizing multiplication by constant integers is that not all constants behave the same way, and thus the ATIPS team is interested in finding solutions that optimize multiplication with a significant number of constants over a specified range.

Novel work published this year addresses the problem of optimization of multiplier blocks as the size of constant integers grows and demonstrates that the novel DBNS algorithms introduced consistently outperform many traditional constant integer multiplication methods by exploiting simple yet unorthodox topologies. The ATIPS team showed results for a practical FPGA implementation that provides a 50% reduction in processing time on the smallest Koblitz curve K-163 by using short decompositions found by an extensive search. Future work will address detailed analysis of runtime and memory requirements and comparison with "best-in-class" algorithms.

Mike Jacobson, CLIAS member, and Laurent Imbert, an international ATIPS member, are conducting research that addresses the implementation of hyperelliptic curve (HEC) cryptography, particularly in the so-called real model of an HEC.

This international collaboration will use the ATIPS team's expertise in computational number theory, algorithm design, and hardware implementation to devise efficient, novel algorithms for HEC-based cryptographic protocols.

Advanced Video Processing

A significant number of this year's successes address video processing for tracking applications – applications including the tracking of highly maneuverable objects and biocells using a variety of novel techniques.

Related to this work have been initiatives in fully automated cell analysis, cluster classification, and video microscopy. Most cell counting is performed by eye and can be a tedious and error-prone process. Automatic cell counting typically uses image-based (not method-based) techniques with limited accuracy and high computational cost. ATIPS researchers, Brinda Prasad and Iris Choi also received an award at the 29th Conference of the Canadian Medical and Biological Engineering Society for their work on the automation of cell analysis

This year ATIPS researchers made an additional four contributions to the definition of these standards. In recognition of ATIPS' contributions, Dr Wael Badawy is now a member of the MPEG-4 editorial board.

Advanced Technologies and Computing with Nanotechnology

Advanced System-on-Chip Platforms

The ATIPS Lab is investigating the growth, control, and observation of the behaviour of live neurons on silicon as part of a team led by Dr Naweed Syed (Faculty of Medicine, U of C). The first neuron/silicon interface test-chip was fabricated in the TSMC 180nm CMOS technology, brokered by CMC Microsystems. A team jointly supported by the ATIPS team and Neurosilicon Inc. carried out the design and the test chip will be used to explore surface preparation techniques and to verify the signal conditioning circuit design. The chips will be tested in Dr Naweed Syed's laboratory in the Department of Cell Biology and Anatomy in the Faculty of Medicine using devices integrated in the AMIF.

The ATIPS Labs is developing large arrays of neuron stimulators and sensors along with information processing systems on single wafers on which neuronal networks may be grown.

Under the guidance of Dr Wael Badawy, ATIPS MPEG-4 / H.264 research continues to contribute to the definition of the international standards for multimedia hardware and hardware/software codesign platforms. Extending ATIPS' System on Chip collaborations, Dr Badawy continues to nurture a strong working relationship with Xilinx®, a major supplier of FPGA boards, that provides internships to ATIPS researchers.

Advanced Image Sensors

The ATIPS team's advanced image sensor work considers small sensor systems and addresses the particular problems that biomedical and other challenging environments can represent to image sensors.

This year the ATIPS group saw the development of second generation chips for both the low light direct contact biosensor and the watermarking sensor project. New members of the ATIPS-ISL team, Yonatan Shoshan, Marianna Beiderman, and Dr Alex Fish have been leading this project. Dr Fish has also taken over responsibility for the management of the ATIPS-ISL.

Microconvergence

Microconvergence refers to the integration of diverse microstructure technologies such as microelectronics, MEMS, micro-fluidics, RF-wireless, and opto-electronics into a single microscale device. ATIPS' principal objectives in this field lie in the integration of these and other technologies for biomedical/health sciences applications.

The integration of microstructure technologies requires precisely controlled conditions and a range of microsystems design and integration capabilities. To support ATIPS work, and in collaboration with other researchers in the Schulich School of Engineering at the U of C, the ATIPS Lab led the foundation the AMIF, a clean room environment with an array of high-technology integration and characterization tools to support the ATIPS team's design and research goals.

Once such system that has developed is the advanced implantable glucose-level monitor design. This system uses a nanoparticulate iridium/enzyme matrix developed in the Department of Chemistry deposited onto a microsensor designed by the ATIPS team which is flip-chip bonded onto signal conditioning and processing circuitry also designed in the ATIPS Lab. The nanoparticulate matrix that enables this sensor to be implanted does not require oxygen for its operation and thereby offers improved accuracy and longer-term stability. It is envisaged that the sensor will operate in a similar fashion to an radio-frequency identification (RFID) tag, and the backend electronics design incorporates ATIPS' wireless power and data transfer technology that was developed previously. The use of wireless power transfer that helps minimize the system volume and allows the ATIPS team to design for battery-free operation. For his excellent work on the implantable glucose sensor, Mohammad Ahmadi won this year's DAC/ISSCC Student Design Contest paper, submitted in the Operational category, SDC-PO494.

Nano/MEMS technologies

The ATIPS team's award winning implantable glucose monitoring system design uses a nano-particulate enzyme matrix that was developed by Dr Viola Birss' team in the Department of Chemistry (U of C).

Quantum-Dot Cellular Automata (QCA) is considered to be one of a handful of nano-computing technologies with the most promise for commercial fabrication. Because QCA can be used to represent the binary logic states used in modern circuit design, it promises a reasonably smooth transition from conventional digital circuit design techniques. The ATIPS team is interested in exploring the potential of this technology by defining a new research paradigm by developing a preemptive Computer Aided Design (CAD) tool, QCADesigner, providing researchers and designers with the ability to analyse a circuit design technology that cannot yet be manufactured, thus enabling them to identify the strengths and weaknesses of the technology, design trade-offs, promising implementation schemes, and 'best-practices' in advance, potentially saving significant levels of research, design investment, and time needed to move the technology from the research laboratory into the market place.

Finally, AMIF has produced a number of cutting-edge MEMS processes that are being considered as potential service offerings to other academic and industrial customers. MEMS development is being conducted under the leadership of Canada Research Chair Michael Okoniewski and showcases the collaborative nature of research and development at the Schulich School of Engineering and the range of technologies that AMIF can enable.

Objectives for Next Year

The ATIPS team's primary research goal is to study emerging nanotechnologies that have the most potential for a smooth transition from existing microelectronics design techniques. This has been extended to include significant MEMS technologies that are not described under other headings. Through collaborations, the ATIPS team's goal is to devise more effective and efficient solutions than either group would be able to develop on its own.

The research goals for System on Chip for secure communications are to develop more efficient and/or low-power technologies and platforms for secure communications protocols that will help protect private and confidential transmissions over a variety of media including wireless, fibre-optic, and conventional wired networks. The ATIPS lab objectives are to bring the advantages of System on Chip design to research projects that require advanced system-level implementation techniques and develop several basic chip architectures (or platforms) that can be custom modified to target, for example, low-power bio-platforms, or high-throughput signal processing platforms.

The goal of digital signal processors – a collaboration with TRLabs – was to produce single-chip high performance solutions for the very high throughput multirate signal processing required for next generation Gbps asymmetric wireless networks. With the push to integrate multiple complex systems on a single chip increasing the demand for high performance the challenge of achieving the very high data rates required of the signal processing chain has been compounded by the need for fault tolerance.

The ATIPS group also aims to develop advanced, wireless microsystem platforms for the monitoring and recording of biomedical parameters such as core temperature and blood glucose. This work supports a key pillar of the second term of the ATIPS Chair (biomedical systems) and there is great future potential for adapting this work to enable a range of implantable devices.

The goals and objectives of advanced video processing research are to increase the efficiency of implementation of internationally ratified image and video compression standards and to take part in the process of defining new standards. The goal with advanced imaging sensors is to develop custom and generic imagers with enhanced functionality, such as for very high-contrast or low-light scenes.

Outreach

Traffic Camera

The traffic camera project with the City of Calgary has now reached maturity with the completion of a series of successful trials. commercial partners Citilog (France) and Fortran Traffic (Toronto) are now pursuing investigating commercialization options for this technology that provides automatic incident detection for road traffic monitoring systems. This work has been very well received by the City and it is anticipated that it will be rolled out for use in Calgary's traffic monitoring systems where it can help alert police to potentially dangerous scenarios, stalled vehicles, and so on. This system should greatly reduce the amount of data that the emergency services must sift through and help to decrease response times.

Trade Visits

Dr Wael Badawy was a key delegate in the Trade mission for the Calgary-Phoenix sister city program visiting both the Translational Genomics Research Institute and the Flexible Display Screen Research Center at the Arizona State University Research Park to discuss opportunities for collaboration. Dr Badawy also visited Avrio Group Western Region, Mission Critical Electronic Systems Inc, Zetatec International, and VIACK Corp.

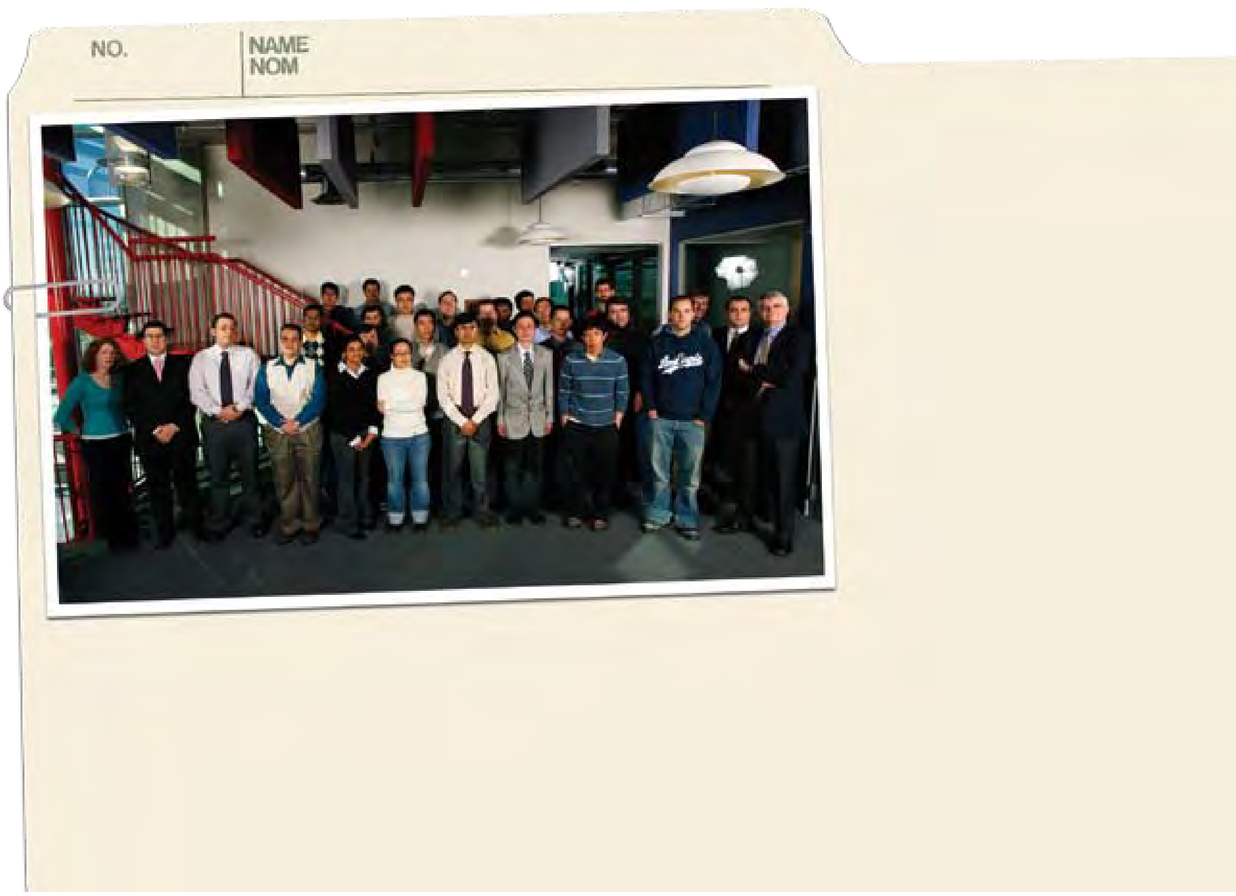
Undergraduate Training

Kambiz Tavassoli, a third year Electrical Engineering student, has been designing a prototype for parallel motion estimation architecture using Full-Search Block Matching Algorithm (FBMA) under the supervision of Dr Wael Badawy.

The 4th year undergraduate research team of David Hansen, Chad Erven, Scott Quiring, and Kurt Weppler have been designing a programmable platform for a portion of the H.264 Video Decoder and are beta testing the new Tensilica toolset. This work has been conducted under the supervision of Dr Graham Jullien, with assistance from Dr Chris O'Neill.

Research Team Members and Contributions

Team Leader
Professor Graham Jullien
Integrated Circuits, MEMS, System-on-Chip, QCA, Computer Arithmetic, Signal and Video Processing, Machine Vision, Neural Networks, Fault Tolerance
Fellow of the IEEE and the Engineering Institute of Canada
Board Member of CMC Microsystems, DALSA Inc.
Founding member of Neurosilicon
Member of eight national and international awards and review committees.



Research Associates		
Name	**Role/Topic**	**Awards/Special Info**
I. Finvers	Wireless (Vital Sign) Patient Monitoring, Nervous System Regeneration Technologies	Joint position with J. Haslett's RFIC group and Neurosilicon Inc.
Z. Huang	Integrated circuit designs for security applications	Part-funded from NSERC Strategic Grant Now with Motorola (China)

Faculty Team Members		
Name	**Role/Topic**	**Awards/Special Info**
W. Badawy	Research Associate. VLSI architectures & prototyping, System-on-Chip, Video Processing, Image Recognition, Low-power Design	IEEE award for notable service and contributions towards the advancement of IEEE and the engineering professions Founder Smart Camera Technologies Inc.
V.S. Dimitrov	Research Associate Number Representations, Cryptography, Digital Signal Processing, Large-scale Optimization, Parallel Algorithms	PI on NSERC Strategic Grant Senior Member of the Centre for Information Security and Cryptography (CISaC) Management Board
O. Yadid-Pecht	Research Associate CMOS Image sensors, Integrated Sensors, Smart Sensors, Image Processing algorithms & Hardware implementation, Micro-systems	Fellow of the IEEE IEEE International Conference on Electronics, Circuits & Systems General Conference Chair Deputy Editor-in-Chief of the IEEE Trans. on Circuits and Systems IEEE Circuits & Systems Society–Distinguished Lecturer & Achievement Award

PostDoctoral Fellows		
Name	**Role/Topic**	**Awards/Special Info**
A. Fish	CMOS image sensors, analog and digital on-chip image processing, algorithms for dynamic range expansion, neuromorphic processing and low-power design techniques for digital and analog circuits	Transferred from Ben Gurion University 2006 Engineering Faculty "Teaching Excellence" award from Ben Gurion University Young Innovator Award for Outstanding Achievements in the field of Information Theories and Applications – ITHEA 2005
Y. Ghallab	Neuron-Silicon Interfacing, Sensors for electric fields in micro-channels	Now full-time with Neurosilicon Inc. Alberta Ingenuity Industry Associate Award.
L. Imbert	Computer arithmetic, data security and cryptography, application optimised arithmetic, efficient implementation of cryptographic systems, high speed computing, fault-tolerant algorithms	International Member with Laboratoire d'Informatique Robotique et Microélectronique de Montpellier (LIRMM), France
K. Jarvinen	Efficient architectures and FPGA design for Elliptic Curve Cryptography	International Member with GETA, Finland
P. Mishra	Theoretical aspects of DBNS, Analysis using Graph Theory, Implementation of ECC protocols based on DBNS, DBNS resistance against side-channel attacks	Invited speaker at Cryptography for Small Devices Conference Co-supervised by Dr Dimitrov Part-funded by NSERC strategic grant
R. Potucek	Neuron-silicon interfacing Dr Potucek is the first joint PDF between the ATIPS group and the Faculty of Medicine	Joint initiative with Prof. Naweed Syed's Neuroscience Research Laboratory Now full-time with Neurosilicon. Alberta Ingenuity Industry Associate Award
M. Shehata	Shadow Detection in Video Sequences, Ambient conditions detection	Now employed at the ATIPS Spin-off SMART Camera Alberta Ingenuity Industry Associate Award
P. Zhang	Bio MEMS, Optical MEMS, MEMS Processes, Integration Facility procedures	Part of the biomedical MEMS/ microsystem team
W. Zhang	Design and implementation of MDLNS DCT circuits, Error Prediction and Correction and advanced number systems	Working on Gennum technology transfer project

PhD Candidates

Name	Role/Topic	Awards/Special Info
J. Adikari	Efficient hardware implementation of cryptographic algorithms and cryptography in (wireless) network security	Graduated MSc (Stockholm)
M. Ahmadi	Wireless Implantable Microsystem for Continuous Blood Glucose Monitoring	eMPOWR (NSERC) Scholarship. 2006 DAC/ISSCC Best Student Design award in the Operational category. Third place award in the 2006 Analog Devices Inc. annual Student Design Contest
I. Amer	Thesis – *Efficient Variable Block Size Selection for an H.264 Video Encoder*	Successfully defended PhD – November 2006 Working at German University – Cairo, Egypt
J. Cai	Thesis – *Detecting Environmental Conditions in Traffic Video Streams*	Successfully defended PhD – November 2006 Research Associate LIVS Group
M. Elsersy	Advanced Multimedia Encoding	Member of the LIVS group
R. Glabb	System on Chip design, rapid prototyping technologies, quantum memory	Accepted a position with Solarflare Communications Inc. of California
S. Hammouda	Analog IP migration	Group lead with Mentor Graphics (Cairo, Egypt)
M. Ibrahim	Micro-particle sensors for air pollution	Scholarship for Egyptian Ministry of Higher Education
H. Kamel	Thesis – *Fuzzy Logic Particle Filter for High-Performance Target Tracking in Track-While-Scan Radar*	Successfully defended PhD October 2006 Teaching at the Military Technical College – Cairo, Egypt
M. Mirhassani	Hybrid Architectures of Multiple-Valued Arithmetic Units with Continuous Valued Digits	Research Centre for Integrated Micro-systems (RCIM): University of Windsor. NSERC Scholarship Co-supervised by G. Jullien and M. Ahmadi (RCIM)
T. Mohamed	Streaming video compression standards and algorithms, Architecture for motion tracking	iCORE Scholarship AIF Studentship

PhD Candidates Cont'd		
Name	**Role/Topic**	**Awards/Special Info**
B. Prasad	Lab-on-a-Chip analysis platform, Cell tracking algorithms for bio-sensors	Third place award in the 29th Conference of the Canadian Medical and Biological Engineering Society
Y. Qiu	Hardware-Accelerated Codesign for MPEG-4	Took part in the Xilinx internship program Graduated MSc 2006
A. Rahman	Motion Estimation Architectures for H.264/ MPEG-4 Part 10 Advanced Video Coding.	iCORE International Scholarship
A. Razavi	Depth recovery imaging systems, hybrid CMOS Imagers	Co-supervised by Dr O. Yadid-Pecht
M. Sayed	High-bandwidth computational architectures for streaming video.	iCORE International Scholarship
K. A. Wahid	Thesis – *Error-free Algorithms and Architectures of Discrete Cosine Transforms*	Honorary Killam Memorial Scholarship U of C's Graduate Faculty Council Scholarship An Associate Professor at the University of Saskatchewan Defended his thesis May 4, 2007
K. Wooding	Cryptography and Network Security, Computational Number Theory, Computer Engineering	Co-supervised by V. Dimitrov and H. Williams NSERC PGS AIF Ingenuity iCORE Studentship
R. Zhang	Fluid flow in MEMS devices, microneedles, microfluidics, microsystems for bioanalysis	AIF Scholarship

MSc Candidates

Name	Role/Topic	Awards/Special Info
R. Ball	Non-standard optimization techniques	Part-funded by NSERC Strategic Grant
M. Beiderman	CMOS image sensors design for fluorescence applications, VLSI post processing	Graduate of Technion- Israel Institute of technology
A. Chan	FPGA implementations and ECC encryption protocols	Co-supervised by V. Dimitrov & M. Jacobson, part-funded by NSERC. Now working with Symantec
I. Chervensky	The use of wavelet transforms in biomedical imaging	Co-supervised by V. Dimitrov and M. Mintchev, part-funded by NSERC. Working for Honeywell
J-S. I. Choi	Thesis – *A High Throughput Cytometry Algorithm for Leukemia Cells*	Successfully defended MSc thesis December 2006
H. Gomaa	High performance architectures for data streaming	Recruited from University of Alexandria, Egypt
M. Ibrahim	Data hiding in video and imagery	Recruited from the Arab Academy for Science and Technology, Egypt
M. Mazur	Sputtering deposition techniques with applications in the fabrication of QCA devices	Co-supervised with Dr A. Budiman, now working in Singapore
V. Milirud	Thesis – *Wide Dynamic Range Wireless Image Sensor for Motion Detection*	Defended MSc in December 2007 Working with PMC-Sierra, Burnaby, BC
G. Nelson	Thesis – *A CMOS APS Image Sensor with Watermarking*	NSERC Postgraduate Scholarship Defended MSc in February 2007
G. Schulhof	Thesis – *QCADesigner: From Utility To Application*	Defended MSc in September 2006 Now working with Nokia in Finland.
P. Sheridan	Galois field arithmetic and efficient algorithms for matrix inversion over finite fields and ring	Co-supervised by V. Dimitrov and H. Williams, part-funded by NSERC
Y. Shoshan	On-chip (CMOS) image encoding and watermarking	Graduate of Ben Gurion University (Israel)
I. Steiner	MRRNS Complex Adaptive Equalizer, SoC and ASIC design, VLSI implementation of MRRNS, DSP architectures, Fault tolerant design	NSERC PGS M scholarship Working chip completed
T. Tam	Thesis – *A CMOS Active Pixel Sensor Contact Imager for Cell Detection in Biosensing Applications*	NSERC PGS M scholarship Defended MSc in February 2007
A. Zakaluzny	Thesis – *Double Base Number System in Constant Multiplication Alogrithms*	NSERC Postgraduate Scholarship Defended MSc in March 2007 Continuing as a PhD Student

Other Team Members		
Name	**Role/Topic**	**Awards/Special Info**
P. Chan	ATIPS Secure SoC Lab Technical Manager	Also MSc Candidate
C. Dalton	AMIF Lab Manager	PhD (University of Wales), Part time with Neurosilicon Inc.
J. Eskritt	ATIPS Lab Manager, Facilities Manager	PhD candidate, MSc (University of Windsor)
B. Isenor	AMIF Lab Manager (partial funding from ATIPS)	Facilities manager, previously with Nortel
J. Nakaska	ATIPS Lab Assistant, Webmaster	Also PhD Candidate
C. O'Neill	Strategic Research Manager	PhD (University of Glasgow), previously with BAE Systems

GRADUATES

Name	*Research Topic*	*Current Position*
PhD Graduates		
Ihab Amer	Efficient Variable Block Size Selection for an H.264 Video Encoder	
Jun Cai	Detecting Environmental Conditions in Traffic Video Streams	Research Associate LIVS Group, ATIPS Labs
Hazem Kamel	Fuzzy Logic Particle Filter for High-Performance Target Tracking in Track-While-Scan Radar	
MSc Graduates		
Jong-Sook Iris Choi	A High Throughput Cytometry Algorithm for Leukemia Cells	
Vadim Milirud	Wide Dynamic Range Wireless Image Sensor for Motion Detection	
Graham Nelson	A CMOS APS Image Sensor with Watermarking	
Gabriel Schulhof	QCADesigner: From Utility To Application	
Terence Tam	A CMOS Active Pixel Sensor Contact Imager for Cell Detection in Bio-sensing Applications	
Andrew Zakaluzny	Double Base Number System Algorithms in Constant Integer Multiplication	Continuing with ATIPS as a PhD student

COLLABORATIONS

Over the past year the ATIPS group has developed and maintained numerous important collaborations. Some represent current work and some represent an investment that will enable future research growth and technology transfer activities. Of the collaborations listed, some have provided financial support to the ATIPS group while the remaining will or have enabled access to otherwise confidential IP and knowledge.

Participants	*Nature of Collaboration*
Provincial Collaborations	
Hotchkiss Brain Institute and the Faculty of Medicine, U of C: N. Syed, D. Zochodne, G. Jullien, R. Midha, V. Verge (Saskatoon), T. Gordon (Edmonton), M. Chan (Edmonton)	Spinal Cord and Nerve Regeneration Focused on the discovery and development of new and improved ways to detect, prevent, and treat neurological and mental health conditions CIHR Regenerative Medicine and Nanomedicine grant Dynamic manipulation of nerve regeneration: An electronic-axon interface
Department of Chemistry, U of C: V. Birss, G. Jullien	The team is investigating instrumentation techniques for nano-biosensors and their integration with low-power SoC bio-platform. A key part of this collaboration is the work on implantable glucose monitors
Centre for Information Security and Cryptography (CISaC), Department of Mathematics, U of C: H. Williams, R. Scheidler, V. S. Dimitrov, G.A. Jullien, M. Jacobsen	The collaboration was established in 2003 to bring together a multidisciplinary group with a shared interest in cryptography and quantum computing. Drs. Dimitrov and Jullien are members of this centre and Dr Dimitrov also sits on the board of CISaC as the Engineering Representative. A joint project between CISaC and the ATIPS Lab was started in 2003
Calgary Laboratory for Information Assurance and Security: H. Williams, R. Scheidler, V. S. Dimitrov, G. A. Jullien, B. Sanders, W. Tittel	This collaboration supports the promotion of a major initiative in the field of Information Assurance and Security (IAS). Grew out of the ATIPS collaboration with iCORE chairs Drs Hugh Williams and Barry Sanders The ATIPS team continues dialogues with potential commercial partners

Participants	*Nature of Collaboration*
Provincial Collaborations Cont'd	
Calgary Health Region, Faculty of Medicine, Computer Science, RFIC Group, U of C: J. Conley, W. Ghali, B. Bayliss, J. W. Haslett, W. Badawy, S. Carpendale et al.	A highly multi-discplinary program that includes staff from Calgary Health Region and the Faculties of Medicine, Engineering, and Computer Science at the U of C. Part of the team investigating the development of wireless monitoring devices for in-situ real-time vital sign measurements The ATIPS team is also supporting W21C through the Advanced Micro/nanosystems Integration Facility.
City of Calgary: W. Badawy	Work on vision systems applied to the development of an Active Camera Tracking System for Traffic Analysis Industrial partners Citilog (France) and Fortran Traffic (Toronto) are now investigating commercialization of this technology.
Institute for Quantum Information Science, (IQIS) U of C: B. Sanders, G. Jullien, W. Tittel	Quantum Key Distribution (QKD) for cryptographic systems and discussions on addressing the quantum error correction problem The ATIPS team hopes to continue to exploit the overlap between research portfolios to develop new initiatives addressing the photonic and microsystems needs of quantum memory and quantum communications
National Collaborations	
RCIM Laboratory faculty, University of Windsor: G. Jullien V. Dimitrov M. Ahmadi R. Muscedere	PhD student at RCIM that continues to collaborate on implementations of application-optimized arithmetic schemes The Research Centre for Integrated Microsystems received an NSERC CRD grant sponsored by Gennum Corporation
CMC Microsystems: G. Jullien, J. Haslett, C. O'Neill, Other ATIPS Laboratory members and Faculty from the Schulich School of Engineering Other Canadian university participants in the SOCRN	Ongoing discussions regarding the proposed CMC West initiative would see CMC establish a base in Western Canada and expand its brokering of microsystems services and capabilities The IP block-authoring suite being developed by the Technical Advisory Committee. The ATIPS Secure SoC laboratory was set to support this work and to handle commercial IP blocks in the development of SoC platforms

Participants	*Nature of Collaboration*
National Collaborations Cont'd	
University of British Columbia: G. Jullien, K. Walus	QCA structures and the QCADesigner tool Former ATIPS researcher Konrad Walus is now an assistant professor at UBC and continues to collaborate with the ATIPS teams
Mount Allison University, New Brunswick: V. Dimitrov, F. Sica	Dr Franceso Sica is collaborating with Dr Dimitrov on advanced number theory problems including public-key cryptography, implementation and security of elliptic curve cryptosystems, and analytic number theory
International Collaborations	
CARLINK – Finnish Meteorological Institute, VTT, Vaisala, Taipale Telematics, Plenware, CRP Henri Tudor, DRQ, CETIC, Alcatel ETCA, Euskaltel, University of Málaga, ETRA I+Dm APIF MOVIQUITY. W. Badawy et. al	The team is working on project CARLINK, which is developing an intelligent wireless platform to be installed on cars, supported by roadside WLAN transceivers. The primary applications will be road safety and traffic management, such as the relay of real-time local weather data, congestion monitoring, and urban information broadcasting.
Laboratoire de l'Informatique du Parallelisme (LIP) Lyon J.-M. Muller, G. Jullien, J-L. Beauchat, A. Tisserand	A research exchange agreement was signed last year with LIP to promote collaboration in graduate training and research. Both parties are providing short term research internships for graduate and exchange students. Training consists of collaborative research projects between laboratories and supervisors at the two institutions.
Graduate School in Electronics, Telecommunication and Automation (GETA): Helsinki University of Technology: V. Dimitrov, G. Jullien, I. Hartimo	Dr V.S. Dimitrov has strong ties with GETA, and was a consultant there from 1997 – 2000 on digital signal processing, number theoretic techniques and cryptography. Dr Dimitrov has also taught short courses at GETA since 1998. Dr Jullien has participated in two of these courses. In 2004 the ATIPS team signed a student exchange agreement with GETA that continues to facilitate research collaborations with other Finnish universities associated with GETA.
Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier, France: G. Jullien, V. Dimitrov, L. Imbert, J-C. Bajard, V. Berthé, M. Robert, H. Williams	The focus is on computer arithmetic, cryptography, and fault tolerance This collaboration has resulted in the submission of five research papers in the past year and a signed research exchange agreement. Drs Imbert and Mike Jacobson (Computer Science – U of C), have applied to the French embassy in Canada for a travel grant to support international collaboration on hyper-elliptic curve cryptography.

Participants	*Nature of Collaboration*
International Collaborations Cont'd	
Ben-Gurion University: O. Yadid-Pecht, M. Katz	As the former head of the VLSI Systems Center at Ben-Gurion University (Israel), Dr Yadid-Pecht continues to collaborate on a number of research initiatives with Ben-Gurion researchers
CNRS (France), Macquarrie University (Australia): V. Dimitrov, L. Imbert, C. Doche	V. S. Dimitrov and international ATIPS member L. Imbert (CNRS) are collaborating with Dr C. Doche (Centre for Advanced Computing, University of Sydney) investigating the use of double-base chains in cryptographic applications, combining a number of ATIPS Labs' core mathematical technologies. This year Dr L. Imbert visited Dr Doche in Sydney to further this collaboration
Utah State University: K. Shenai, G.Jullien	Possible collaborative research projects in the area of intelligent sensor systems
University of Louisiana at Lafayette: G. Jullien, M. Bayoumi	Prof M. Bayoumi, Director of the Centre for Advanced Computer Studies and Head of the Computer Science Department at the University of Louisiana at Lafayette, has been a long-time collaborator with Dr G. Jullien
Academic Collaborations	
Johns Hopkins University Dr R. Etienne-Cummings	Neuromorphic Engineering, Smart Sensors
University of Texas, Austin Dr E. Swartzlander	Array processing and computer arithmetic
Notre Dame University, Indiana Dr Craig Lent	Quantum-dot Cellular Automata
Industrial Collaborations	
Gennum Corporation: G. Jullien, V.S. Dimitrov, D. Salvador, D. Lynch, D. Simmons, X. Liu	Gennum are the industrial sponsor on the Joint University of Calgary/University of Windsor NSERC Collaborative Research and Development grant providing cash and in-kind support and matched by NSERC Dr Jullien has been working with Gennum for over ten years. Collaborative projects have included broadcast quality video signal processing systems and completely in-canal hearing instrument processors. The ATIPS group is now investigating further advanced number systems implementations and video processing algorithms and architectures

Participants	*Nature of Collaboration*
Industrial Collaborations Cont'd	
DALSA Corp.: G. Jullien, O. Yadid-Pecht, J. Roberts, G. Ingram, C. Flood, M. Miethig	Dr Jullien has a long-term research interaction with DALSA Inc. and helped pioneer the concept of in-camera defect detection in 1990 with DALSA's Dr J. Roberts. This idea was patented in 1995. Micronet has supported related research with matching funds from DALSA DALSA is currently sponsoring ATIPS digital watermarking NSERC I2I, led by Dr O. Yadid-Pecht
Citilog: W. Badawy	Dr Badawy has been applying his novel work on vision systems to the development of an Active Camera Tracking System for Traffic Analysis. The industrial partners Citilog (France) and Fortran Traffic (Toronto) are now investigating licensing the technology for commercialization
Fortran Traffic: W. Badawy	Industrial collaborators, with Citilog, on the Active Camera Tracking System for Traffic Analysis
Neurosilicon Inc.: G. Jullien N. Syed	Developing technology and services to create, operate, and market neuron to silicon interfaces The ATIPS Lab has been working very closely with the growing company and a number of the researchers have taken positions helping to develop world-leading optical and electronic interfaces for stimulation and recording of brain neuron activity
Smart Camera Technology: W. Badawy	The ATIPS' spin-off Smart Camera, under the leadership of Dr Wael Badawy, is continuing to develop technologies in collaboration with the ATIPS Lab In addition to the City of Calgary project, Smart Camera has signed a sole manufacture agreement with Toronto Microelectronics Corporation
ACM Automation Inc.: G. Jullien	A leader in cost effective, high integrity, critical control and safety systems Following preliminary discussions earlier this year, Graham Jullien was appointed to the advisory board
PackagingOne: G.Jullien	Following initial discussions regarding packaging for microsystems, Graham Jullien has been appointed to the advisory board of Ontario-based PackagingOne Corporation

INTELLECTUAL PROPERTY

Patents/Author	Title/Name	Status
N. Sayed, G.A. Jullien	"Method and Apparatus for Guiding Growth of Neurons" U.S. Patent Application No. 20070092958	Application Published: April 26, 2007
A. Wissman, B. Mok, W. Badawy, K. Frandsen, I. Baykal	"Nematode Motility Assay" US Prov. Patent	Filed: June 2006
W. Badawy, M. Shehata, M. Shah Pervez, J. Cai, A. Radmanesh, T. Burr	"Detection of Environmental Conditions in a Sequence of Images" United States Patent Application 11/444,170	Filed: May 30, 2006
W. Badawy, M. Shehata, M. Shah Pervez, J. Cai, A. Radmanesh, T. Burr	"Detection of Environmental Conditions in a Sequence of Images" Canadian Patent Application No. TBA	Pending: May 30, 2006
G. Zamponi, N. Sayed, M. Colicos, G.A. Jullien	"High Throughput Use Dependence Drug Screening Device and Assay" US Patent Application	Submitted: May 5, 2006
O. Yadid-Pecht, G. R. Nelson, G.A. Jullien	"Digital Watermarking CMOS Sensor" United States Patent Application, No. 20070019090	Application Published: January 25, 2007
N.I. Syed, G.A. Jullien, G. Zamponi	"Detecting Electrical Activity and Assessing Agents for the Ability to Influence Electrical Activity" United States Patent Application, No. 20070017530	Application Published: January 25, 2007
N.I. Syed, G.A. Jullien	"Electrically Stimulating Nerve Regeneration" United States Patent Application, No. 20060287660	Application Published: December 21, 2006

FUNDING

Dr Graham Jullien has a five year iCORE Chair award ($3.1M). This year he and his team received funding from NSERC ($234K), CIHR ($525K), and from industry and other interests ($147K). Other funding for this year included a grant from the Alberta Science and Research Investments Program ($205K).

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

M. Sayed, W. Badawy, "An Affine Based Algorithm and SIMD Architecture for Video Compres-sion with Low Bit-rate Applications," IEEE Transactions on Circuits and Systems for Video Tech-nology, Vol. 16, Issue 4, pp. 457-471, April 2006.

M. Sayed, W. Badawy, "A Computational Memory Architecture for MPEG-4 Applications with Mobile Devices," Journal of VLSI Signal Processing, Special Issue on Digital and Computational video, Vol. 42, No. 1, pp. 35-42, January 2006 (not previously included).

Y. H. Ghallab, W. Badawy, "A New Topology for a Current-mode Wheatstone Bridge," IEEE Transactions on Circuits and Systems II, vol. 53, no.1, pp. 18-22, January 2006 (not previously in-cluded).

Y. H. Ghallab, W. Badawy, M. A. El-Ela, M. H. El-Said, "The Operational Floating Current Con-veyor and Its Applications," IEEE Journal of Circuits, Systems and Computers, Vol. 15, No. 3, June 2006. in print.

G.A. Jullien, M.A. Bayoumi, "Special Issue on System-on-Chip: Scanning the Issue", Proceedings of the IEEE - Special Issue on System-on-Chip: Design and Integration, Vol. 94, No. 6, June 2006, pp. 1045-1049.

K. Walus, G.A. Jullien, 2006, "Design Tools for an Emerging SoC Technology: Quantum-Dot Cel-lular Automata," Proceedings of the IEEE - Special Issue on System-on-Chip: Design and Integra-tion, Vol. 94, No. 6, June 2006, pp. 1225-1244.

J.-C. Bajard, L. Imbert, C. Nègre. "Arithmetic Operations in Finite Fields of Medium Prime Char-acteristic using the Lagrange Representation," IEEE Transactions on Computers. Vol. 55, No. 9, pp. 1167-1177.

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Wireless Location Research

The iCORE Chair for the Wireless Location Research and the Position, Location, and Navigation (PLAN) group, which began in January 2001, has been renewed until 2010.

This Chair focuses on research related to outdoor and indoor wireless location, high performance navigation and positioning using global navigation satellite systems (GNSS) and ground-based Radio Frequency (RF) techniques, integration with self-contained sensors for navigation, and the development of related innovative applications.

Collaboration with faculty members at the University of Calgary (UofC) and at other universities in Canada and abroad, in addition to collaborations with industry and government, have contributed to the progress achieved on eight major research projects. These ranged from the design of novel GNSS signal tracking algorithms to the development of novel applications. These research projects have resulted in high quality personnel training, publications, and technology transfer. Personnel training in the PLAN Group included the degree completion of five MSc, one MEng, two PhD students and the transfer of one senior research engineer to industry. Eleven papers were published and several more were accepted and/or submitted for publication in refereed journals, and some 15 were presented at conferences and published in conference proceedings. Dr Lachapelle made numerous invited oral presentations in Canada and abroad. Technology transfer consisted of one patent submission, the licensing of software and of other technology transfer through external contracts and grants. In recognition of their efforts, members of the research team and collaborators received 15 awards that have contributed to the sustained international recognition of the PLAN Group and the Alberta GNSS industry.

The objectives for the forthcoming 12-month period continue to be a mix of planned and opportunity-driven research and development. The latter is considered most important for the overall activities of the PLAN group to remain relevant, innovative, and to maximize high quality personnel training and economic development.

Research Program Overview

Specific research objectives for this reporting period:

i. Pursuing the design of innovative GNSS algorithms and methods to improve GPS and Galileo multiple-frequency signal acquisition and tracking, in order to benefit navigation and location performance both under line-of-sight and attenuated conditions such as indoors. The emergence of new GPS frequencies and the new Galileo system make this long-term objective of paramount relevance and timeliness

ii. Pursuing research into the fusion of GNSS signals and self-contained sensors with emphasis on inertial measurement units (IMUs) in the ultra-tight fusion mode whereby both GNSS RF and IMU measurements benefit from each other in a closed loop scheme

iii. Continuing the development and enhancement of the PLAN Group's software GNSS receiver to support mentioned objectives, test the new algorithms under field conditions, and design novel applications with industrial partners

iv. Designing, developing, and testing innovative GNSS-based pedestrian navigation methods to support location-based services in urban areas

v. Continuing research into the development of ground-based RF methods for location and positioning using cellular telephone networks

vi. Continuing to monitor, conceptualize and design innovative methods, algorithms, processes, and applications for evolving location and communication technologies, especially associated disruptive technologies, and emerging novel applications and markets

The PLAN group aimed to match these objectives with current personnel capabilities. The PLAN group also aimed to acquire new in-house expertise and/or develop new collaborations as required, forming strategic alliances to develop and test these objectives, maximize the creation of new intellectual property in the process, and create new industrial opportunities, while ensuring a strong high quality personnel training component.

These objectives were achieved partly as a result of effective collaboration and strategic alliances with outside partners and sponsors while maintaining a strong PLAN Group team and effective collaboration with other faculty members in the Schulich School of Engineering.

Research Projects

The following eight major projects were the focus of the PLAN Group during this last year. The first five projects are multi-year and considered central to the Chair's fundamental objectives. The last three projects are opportunity-driven, of a more limited duration, typically one to three years, and are in response to specific industrial needs. Most projects received additional funding from outside agencies.

Weak GPS Signal Analysis for Indoor Location

Empirical studies of indoor GPS positioning have focused primarily on the spatially-diverse nature of signal degradations. The nature and sources of multipath propagation indoors have been investigated by using multiple antennas oriented in different directions to capture signals. Analyses of the signals captured by each antenna have shown in what ways the signal degradations are correlated with angle of arrival. Results suggest that the pursuit of an omni-directional antenna design for indoor positioning (e.g. cellular positioning) may be less important than originally thought. Research in this area is ongoing, including attempts to use the observed spatial diversity to improve GPS sensitivity.

The fundamental sources of indoor positioning problems are also being investigated, along with methods to mitigate those problems. Oscillators, and their impacts on GPS performance, are a major area of focus. An observed failure mode in a set of commercial high-sensitivity GPS receivers was investigated, caused by of temperature variations on the receivers' local oscillator frequencies. The impact of oscillator errors is a well known hazard of receiver design that is not often quantified. Further research aimed at quantifying the impact of oscillator errors in GPS-INS systems is ongoing. A software test platform for implementing high-sensitivity GPS algorithms on an inertially-aided receiver has been developed and tested and is being used for testing various oscillators that will eventually form a part of a prototype GPS-INS software receiver front end. In the future, it will also be used for empirical studies of indoor multipath, with attempts to identify multipath based on Doppler changes.

Software GNSS Receiver and Ultra-Tight Integration with Inertial Navigation Systems

Software-based GNSS receiver development has remained a major research thrust for the group over the past year with emphasis given to improving overall efficiency and to extending functionality.

Previous research into the use of single-instruction, multiple-data (SIMD) instructions on Pentium and x86 compatible processors has continued and resulted in a real-time capable L1-only GPS receiver. Sampling rates as high as 10 MHz can be used with the receiver, an achievement particularly important for high accuracy applications requiring large bandwidths to mitigate multipath effects. Extensive work has gone into improving the overall efficiency of the software for post-mission use, both through the implementation of efficient new algorithms and careful code optimization. This work is particularly important for cooperation with Defence Research and Development Canada (DRDC) to develop a real-time multiple-frequency receiver.

The functionality of the GPS receiver has been improved considerably with the addition of a more robust yet highly flexible signal acquisition framework. This framework will also be the basis for acquisition of highly attenuated signals. Second, identification and correction of half-cycle lock errors within the receiver means the receiver-generated measurements can provide cm-level positioning accuracy when using real-time kinematic (RTK) processing strategies. Third, work has begun on implementing closed loop tracking of highly attenuated signals using data-bit wipe off techniques that approximate Assisted GPS (AGPS) performance.

Two new signal tracking methods have been added to the software receiver. A Kalman filter-based discriminator and tracking loop algorithm provides improved signal tracking, particularly for receivers in high dynamic situations. The filter-based approach does not suffer from digital approximations to continuous-time loop filters. A vector-based tracking approach has been developed and tested. Initial results illustrate improved carrier phase tracking of weak signals, and an overall smoother position estimate (i.e., less variability over time).

Building upon the group's experience with inertial processing, ultra-tight integration of GPS and INS has received more significant attention this year. A new integration method has been proposed that combines the benefits of both vector-processing and more traditional signal tracking algorithms. This work has shown a significant improvement in the ability to track the carrier phase of weak GPS signals. Also, experiments have been conducted to assess the impact of inertial sensor errors as a limiting factor in ultra-tight integration. A reduced order, lower cost inertial system, akin to what would be available in automobiles, is also being investigated as a means to improve GNSS signal tracking without the cost of full six degree of freedom IMU.

Assessment of GPS II/III and Galileo Signal Performance

The performances of the new GPS L2C, GPS L5, and Galileo signals have been investigated at both the measurement and position levels. The group's existing software GPS receiver has been enhanced to allow L5 signal tracking and positioning, and has been tested with simulated signals using a state-of-the-art hardware simulator. Fundamental research into the tracking loop modifications required to better handle this new high-bandwidth signal has also been undertaken, using the L5 software receiver as a test platform. The availability of several modernized GPS Block IIR-M satellites has driven research into more advanced acquisition and tracking of L2C signals. Algorithms developed in the past for acquisition of long P(Y) codes using a code folding technique have been modified for the new L2C signal and tested extensively, which has led to the development of a new algorithm for combined L1 C/A and L2C code acquisition and has the potential to improve both acquisition sensitivity and speed. Phase lock loop enhancements under adverse conditions such as ionospheric scintillation have also been developed.

Research related to future GNSS systems has accelerated in the past year, with work begun on development of a software-based simulator for Galileo signals. This simulator is intended as a test signal source for ongoing development of a Galileo software receiver. Signals from the Galileo in-orbit validation satellite, GIOVE-A, are also being captured and used to verify operation of both the software receiver and simulator. A set of new C/A codes has been added to the specification for GPS III.

Finally, the group has acquired several new combined GPS-GLONASS receivers in the past year, and has conducted various experiments to characterize the issues affecting dual-system positioning. Among these are the stability of inter-system biases, differences in ephemeris reference systems, and the accuracy of ionospheric delay estimates that can be obtained from combined GPS-GLONASS observations.

GPS Interference

During this year, GPS Interference research focused on L5 (1176.45 MHz) interference, a new signal that will become gradually available on GPS satellites during the next six years, and on novel signal detection schemes. GPS is inherently resilient to external radio frequency interference (RFI) as it employs spread spectrum transmission. Nevertheless, interference sources in the vicinity of a GPS receiver can potentially block weak GPS signals and all the transmitted GPS satellite signals share the same spectrum and are vulnerable to "near-far" interference, especially indoors. Judicious design of front-end filters, automatic gain control and analog-to-digital converters can alleviate the effect of RFI. Wideband interference is tackled using advanced beam steering arrays. Alternatively, post-correlation interference mitigation involves the use of external aiding (i.e. IMU) to improve tracking thresholds. Frequency excision techniques offer good interference suppression (IS) performance with moderate increase in system complexity levels.

Potential RF interference on L5 that was investigated includes cross-correlation and broadband random noise. A software receiver was used to study parameters such as average SNR, tracking jitter, and symbol estimation error rate, by varying specific parameters on the receiver. The investigation focused on the performance of the correlator and phase tracking loops. Numerical evaluations and their analyses were completed. Novel signal detection schemes to combat both narrowband and wideband interference during acquisition were also investigated. Taking advantage of the fundamental signal characteristics, a novel pre-filtering/multi-correlation differential detection (PF/MCDD) technique was developed. This technique utilizes the C/A code periodicity for coherent filtering and the shift-and-multiply property for performing differential detection. The proposed technique provides an efficient means to detect and mitigate various types of interference. Hardware simulated signals corrupted with strong continuous wave and narrow band interference were then utilized to evaluate performance. The research then further included the influence of interference mitigation schemes alongside the standard and the developed PF/MCDD scheme in terms of acquisition performance.

High precision GNSS carrier phase positioning

The use of GPS for high precision formation flying of nano-satellites was conducted in cooperation with the Canadian Advanced Nanospace eXperiment (CanX) Program of the Space Flight Laboratory at the University of Toronto's Institute for Aerospace Studies (UTIAS/SFL). Simulation results demonstrated that relative position and velocity could be determined with sufficiently high accuracy (2-3 cm for position and 2 mm/s for velocity) to allow for on-orbit control of the satellites. Hardware in the loop testing is ongoing to ensure that hardware requirements are also being met.

Research on relative (over-time) positioning was also continued as part of collaboration with U.S. Navy's anti-submarine warfare program. An algorithm developed by the group last year was used during system testing and was shown to be able to resolve the spectrum of the system's motion (which is of primary interest for system calibration) with an accuracy comparable to that of preferred techniques that are not otherwise usable in normal operating conditions.

As part of a collaboration with General Motors (GM), PLAN's FLYKIN+™ software, which normally computes cm-level positions relative to a know location, was modified for determining the relative position between vehicles. The concept is used to develop safer automobile information systems (e.g., to determine when another vehicle is in your blind spot). A related project was also undertaken to manage the communication of GPS data between several users (vehicles) using wireless data links. Cm-level positioning accuracy during periods of favourable satellite visibility was demonstrated in real-time using a communication system and the modified version of FLYKIN+™.

Investigations into the use of the traditional narrow-lane linear carrier phase combination showed that using the L1 and L2 carrier phase directly can provide more precise positioning information over short baselines. The group's GPS-based attitude determination software, HEADRT+™, was modified accordingly to yield improved attitude estimates.

The group also undertook the certification of a GPS/INS system used by the Department of National Defence Aerospace Engineering Test Establishment (AETE). The system is being used to verify the accuracy of a new Time, Space and Position Information (TSPI) system at the Primrose Lake Evaluation Range in Cold Lake, Alberta.

Finally, investigations into to use of carrier phase-based positioning for high accuracy performance sport training applications were initiated and tested on selected winter sports.

Vehicular and pedestrian location and navigation using GPS integrated with self-contained MEMS sensors

Research into the integration of GPS and inertial measurement units (IMU) of varying qualities for vehicular and pedestrian navigation applications was continued. The vehicle navigation system (VNS) was designed using GPS with IMU and on-board vehicle sensors such as lateral and longitudinal acceleration sensors (G-sensors), steering angle sensors, yaw-rate sensors and wheel speed sensors (WSS). Specific focus has been on the usage of a low-cost automotive-grade IMU, and the performance evaluation of the system in open area and pseudo-urban environments using four different integration strategies each involving different sensor components. The method developed for integrating GPS with other sensors uses a tightly coupled technique, which makes optimal use of available GPS measurements and enhances system reliability. The designed algorithms and integration strategies were implemented in the SAINT™ software, a real-time GPS/INS integration software developed by the PLAN group. The software was further enhanced to include the capability to integrate the on-board vehicle sensor data in real-time. The primary focus in terms of performance analysis was on achievable position/velocity accuracies (in the absence of GPS) as well as on the ability to reduce the time to resolve GPS carrier phase ambiguities. This work has resulted in a patent application.

The system designed for pedestrian navigation (PNS) uses an HSGPS receiver and a low cost MEMS IMU. Efforts have primarily focused on development of a GPS/INS based vehicular navigation system aided by a pedestrian navigation system that can be used seamlessly when traveling in a vehicle to walking in urban canyons. A shoulder/belt mounted PNS system and a foot mounted PNS system were designed. Two different algorithms were used to process the IMU measurements for integration with GPS. The first is the conventional INS algorithm whereby the output of an IMU is integrated to obtain the navigation solution. This algorithm performs well for the foot-mounted system because the dynamics of the foot facilitates resetting the inertial system during the stance phase of the user's gait. This helps significantly reduce INS error accumulation over time (in the absence of GPS), thus facilitating the usage of the system for seamless outdoor-to-indoor navigation. To make the system more autonomous, an algorithm to detect the stance phase of the user's gait cycle was also developed and implemented. The second method used for processing IMU measurements makes use of the fact that the user takes one step at a time, and thus propagates the step-length in the direction of motion (in a local level frame), known as pedestrian dead-reckoning (PDR). The algorithm involves three components, namely determination of the heading of the pedestrian from the gyro signal, detection of the step from the accelerometer signal, and the estimation of the step-length through updates from GPS (when available) or through the magnitude of accelerometer signal. This algorithm is seen to work well for the case when the sensor is placed on the shoulder and/or belt. Both INS and PDR were integrated with GPS using a tightly coupled integration strategy and their performance was evaluated under dense urban canyons, in forest areas, and indoors.

Work has focused on evaluating the foot-mounted system's applicability to general human gait analysis, specifically in the realms of foot pronation and supination. Traditionally foot and ankle kinematics are obtained using a three-dimensional camera/sensor system used in special gait laboratories, which limits its general unrestrained use, thereby limiting the clinical value of the data. This aspect of work involved the use of multiple IMUs mounted on the foot and ankle of the user. The performance evaluation involved using data collected with multiple subjects of different ages under a wide variety of operating conditions, ranging from hilly terrain to relatively flat terrain. Initial results showed a high degree of correlation with the results seen in literature, which were obtained using traditional optical methods. This research and associated findings constitute a significant and unforeseen spin-off of the above project and will be pursued.

Effect of Water, Ice and Snow on GNSS Signal Reception

The applicability of GPS receivers for avalanche rescue was investigated. Following a theoretical analysis, the tracking performance of various High Sensitivity Global Positioning System (HSGPS) receivers under avalanche deposited snow was tested. The miniature Global Navigation Asset Tracker (GNAT™) developed by the PLAN Group, which integrates the SiRFstar III HSGPS receivers with a microcontroller, onboard flash storage and a 2.4 GHz Zigbee radio modem, was used. The test systems were placed down a hole bored in avalanche deposited snow for several hours with data collected continuously. Sufficient GPS signals for positioning were received by the receivers buried in nearly three metres of avalanche deposited snow. Methods of improving the GPS position beneath the avalanche debris were investigated, resulting in horizontal position accuracies within a few metres at depths of up to nearly three metres.

A complementary study of the degradation experienced by a GPS signal when the antenna is covered by snow, ice, or liquid water was also performed. In order to grasp the importance of the problem at hand, an investigation of the different properties of the water molecule and the influence of an electromagnetic wave was first conducted. From that, a model was developed to represent the theoretical attenuation and reflection properties of RF signals at GPS frequencies. Several indoor tests were performed through the use of an RF GPS signal simulator. One of those tests investigated the affect of the polarization of the water molecules on the transmission of GPS signals by creating a strong electric field between metal plates using a high voltage generator. The results were studied through the observations of carrier-to-noise ratio (C/N_0) and relative standard deviations of the pseudorange observables. A 4 cm layer of ice was tested tested, resulting in a reduction of signal strength of about 2 dB and an increase in pseudorange standard deviation of approximately 17 cm. Snow was found to have an even smaller effect on the signal. A 14 cm layer of snow in the line of sight reduces the C/N0 by 2 dB and added 8 cm to the relative standard deviation. On the other hand, 1 mm of water was enough to stop the signal as a C/N0 reduction of 9 dB was observed. Finally, it was observed that polarizing the water using a very strong electric field, even if no gain was observed, permitted the signal to be tracked during the duration of the test.

Wireless location using ground based systems

Investigations into the use of cellular telephone networks to provide location was continued using IS-95 Code Division Multiple Access (CDMA) pilot signals transmitted in the Personal Communication Services (PCS) spectrum between 1.93 and 1.99 GHz. The research outcome of this project contributed to the Defense Research and Development Canada's (DRDC) Tactical Outdoor Positioning System (TOPS) project. The outcome from the previous phase was the development of a real-time receiver using a Field Programmable Gate Array (FPGA), which is capable of tracking multiple base stations simultaneously using dedicated correlator structures to enable Time of Arrival (TOA) and Angle of Arrival (AOA) measurements. During the reporting period the project focused on novel signal processing and navigation algorithm development, which uses the FPGA pre-processed data to estimate position precisely. The developed algorithms can be categorized into four areas, namely:

(i) basic positioning with TDOA/TOA,

(ii) AOA estimation with multi-antennas,

(iii) positioning with AOA-enhanced TOA/TDOA, and

(iv) single channel AOA estimation.

The algorithm development was conducted in conjunction with extensive testing to verify and validate effectiveness and performance. All the algorithms developed have been targeted for the Xilinx FPGA platform operating in conjunction with a PC interconnected with high speed USBee data communication devices. Preliminary testing of the receiver and algorithms demonstrates successful positioning using independent/combined TOA, TDOA and AOA measurements with optional augmentation of GPS for time synchronization and other sensors such as inertial measurement units under various signal strength conditions and geometries. Various antenna configurations, from a single to multi-antenna incorporating array processing have been initially tested as well.

Outreach

- Several government and industrial representatives from Canada, the United States, Europe and Asia visited the PLAN Group to discuss existing and new collaborations and resulted in several new collaborative efforts
- Meetings were held with other government and industrial representatives during specific trips to conferences in the United States and Europe
- The Chair made a graduate student recruitment trip to Europe where he visited two academic institutions and stated collaborative negotiations with a third one
- The Chair, Prof Cannon, Dr Petovello, and other PLAN Group researchers made presentations to numerous interest groups in Canada and gave GPS lectures to numerous industrial groups in North America and Europe, reaching some 150 professionals
- Dr Mark Petovello, senior engineer in the PLAN Group, now chairs the Institute of Navigation Student/Education Outreach Sub-Committee and gave a presentation in March 2007 to a Calgary Junior High School class
- The Chair and Prof Cannon gave invited research presentations to universities in Canada, the United States, Britain, Switzerland, and France and an estimated 300 people were reached.
- The Chair continued to chair the Alberta Section of the Institute of Navigation and organized five presentations throughout the year, with an attendance of 30 to 40 experts from the Calgary GNSS community at each meeting

Objectives For Next Year

The planned objectives for next year can be sub-divided into two groups, planned and opportunity-driven objectives The latter group is considered important for the overall activities of the PLAN Group to remain relevant, innovative and to maximize career opportunities for its graduates and overall economic developments.

Planned Research and Development

i. Pursue the design of innovative GNSS algorithms and methods to improve GPS, Galileo and GLONASS multiple-frequency signal acquisition and tracking in order to benefit navigation and location performance under both line-of-sight conditions and attenuated conditions, such as indoors. The emergence of new GPS frequencies (L1C, L2C and L5) and the new Galileo system and enhanced Russian GLONASS system make this long-term objective of paramount relevance and timeliness.

ii. Pursue research into the fusion of GNSS signals and self-contained sensors with emphasis on inertial measurement units (IMUs) in the ultra-tight fusion mode whereby both GNSS RF and IMU measurements benefit from each other in a closed loop scheme. Research in this area is needed to improve the accuracy, availability and reliability performance of GNSS-based navigation and location systems, especially indoors.

iii. Continue the development and enhancement of the PLAN Group's software GNSS receiver to support objectives (a) and (b), test the new algorithms under field conditions, and design novel applications in partnership with industrial partners.

iv. Design, develop and test innovative GNSS-based pedestrian navigation methods to support a variety of applications, including kinesiology and sport training.

v. Continue research into the development of ground-based hybrid RF methods for location and positioning using cellular telephone networks.

External industrial and government funding for the above activities is confirmed for next three years.

Opportunity-Driven Research and Development

i. Continue to monitor evolving location and communication technologies, especially associated disruptive technologies, and emerging novel applications and markets.

ii. Conceptualize and design innovative methods, algorithms, processes and applications, based on the outcome of the above planned activities.

iii. Match the above potential thrusts with current personnel capabilities and acquire new in-house expertise and/or develop new collaborations as required and form strategic alliances to develop and test the above, maximize the creation of new intellectual property in the process and create new industrial opportunities, while ensuring a strong high quality personnel training component.

Research Team Members and Contributions

Team Leader
Professor Gérard Lachapelle
Michael Richey Medal (with Ross Stirling and Ken Fyfe for joint contribution), Royal Institute of Navigation, 2006
Fellow, Royal Institute of Navigation, U.K., 2006
Schulich School of Engineering Graduate Education Award, 2005
Alberta Centennial Medal, 2005
Outstanding Leadership in Alberta Technology, Alberta Science and Technology (ASTech) Leadership Foundation, 2004
Faculty of Engineering Research Excellence Award, 1995, 1998 and 2004
Honorary Prof, Universita' Degli Studi Di Napoli Parthenope, Naples, Italy, 2003
Fellow, Canadian Academy of Engineering, 2003
Fellow, US Institute of Navigation, 2003
Fellow, Royal Society of Canada, 2002
Honorary Prof, University of Wuhan, China, 2002
Kuznetsov Medal, Kuznetsov Applied Mechanics Research Institute, Russia, 2000
APEGGA Frank Spragins Summit Award, 2000
Full Member, Russian Academy of Navigation and Motion Control, 1999
Honorary Prof, University of Electronic Science and Technology of China, 1999
Alouette Award, Canadian Aeronautics and Space Institute, 1998
Johannes Kepler Award, U.S. Institute of Navigation, 1997

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Professor M.E. Cannon	Satellite-based location, positioning and navigation, interference, integrated systems	Woman of Vision, Global Television, Calgary (2006)
Professor N. El-Sheimy	GPS/MEMS sensor integration	
Professor S. Skone	GPS meteorology and ionospheric scintillation effects on tracking loops	
Professor K. O'Keefe	Satellite-based precise positioning and indoor location	

Faculty Team Members		
Name	**Role/Topic**	**Awards/Special Info**
Professor R. Klukas	RF propagation, GPS indoor location, ground-based cellular telephone location systems	Adjunct Professor, U of C
Professor J. Nielsen	Design, prototyping and evaluation of CDMA equipment and algorithms for ground-based wireless location	

PostDoctoral Fellows and Research Engineers		
Name	**Role/Topic**	**Awards/Special Info**
Walid Abdel-Hamid	NavLab Manager Navigation equipment performance testing	
Saurabh Godha	Research Engineer GNSS-based system design and integration for pedestrian and vehicular navigation and location, and carrier phase positioning	Best session paper presentation, GNSS 2006 International Conference, Fort Worth, TX, September 2006
Cillian O'Driscoll	Senior Research Engineer GNSS signal processing	
Mark Petovello	Senior Research Engineer Design of advanced GPS/INS integration algorithms and carrier phase GNSS positioning	
John Schleppe	Senior Research Engineer Wireless location/ communication integration and system testing	
Robert Watson	Research Engineer GNSS indoor location and advanced RF signal processing methods	

PhD Candidates

Name	Role/Topic	Awards/Special Info
Zahidul Bhuiyan	GNSS signal enhancements	
Ali Broumandan	Ground-based RF system development	Co-supervised by Prof Nielsen
Jussi Collin	Integration of GPS and MEMS sensors for personal outdoor/ indoor navigation	Co-supervised with Prof Takala, Tampere Univ. of Technology
Jianchen Gao	Navigation sensor fusion for vehicular navigation	Supervised by Prof Cannon Best Student Paper award, GNSS06
Guojiang Gao	Development of GNSS software receiver aiding methods	
Lionel Garin	GNSS network-based distributed systems	
Cyrille Gernot	GNSS signal enhancements	Co-supervised by Prof O'Keefe
Jakob Jakobsen	GNSS RTK positoning	Co-supervised with Prof C. Tscherning, University of Copenhagen
Angelo Joseph	GNSS signal enhancements	
Dingchen Lu	Ground-based RF location method development	Co-supervised with Prof Nielsen in ENEL
Florence Macchi	Galileo signal simulation and software receiver development	Co-supervised by Dr Petovello
Upal Mahfuz	GNSS signal enhancements	Co-supervised by Prof Nielsen Best Student Paper GNSS06, iCORE Poster Award 2006
Cécile Mongrédien	GNSS signal acquisition and tracking methods	Supervised with Prof Cannon Best Session Paper, GNSS06
Kannan Muthuraman	GNSS signal enhancements	
Surendran Shanmugam	GNSS signal acquisition and tracking methods	Supervised with Prof Nielsen Best Student Sponsorship Award, GNSS 06 Conference
Debo Sun	Ultra-tight GNSS-INS integration	Co-supervised with Prof Cannon
Patrick Xu	GNSS signal evaluation methods	Co-supervised with Prof Cannon
Bo Zheng	Development of GPS L5 signal acquisition and tracking techniques	

MSc Candidates

Name	Role/Topic	Awards/Special Info
Saloomeh Abbasian Nik	GLONASS software receiver development and analysis	Co-supervised by Dr Petovello
J. Al-Azizi	Course-based MEng	
S. Charkandeh	Real-Time L1 GPS software receiver	iCORE Poster Paper Award 2006 Best Paper Presentation Award, U of C, 2006 Co-supervised by Prof Cannon
Alexander Ebner	GPS signal simulations	Co-supervision by Dr A. Wieser
Ashkan Izadpanah	GNSS signal enhancements	Co-supervised by Dr O'Driscoll
Pejman Kazemi	GNSS signal enhancements	
Q. Marji	GNSS kinematic positioning	Supervised by Prof Cannon
G. Mao	GPS/eLoran integration algorithm development	
Dina Megahed	GNSS signal enhancements	
A. Moghaddam	Ground-based location system component development and analysis	Co-supervised with Prof Nielsen
S. Phalke	GPS-Galileo network RTK positioning	Supervised by Prof Cannon
Jianning Qiu	GPS L2C signal interference	Co-supervised with Prof Klukas
N. Salimi	RF signal processing in FGPA	Co-Supervised with Prof Nielsen
S. Singh	Assisted-GPS performance analysis	Supervised by Profs Cannon and Klukas
D. Yao	GPS L2C signal interference	Co-Supervised with Prof Skone
W. Yu	Signal processing algorithm development	Best Student Sponsorship Award, GNSS 2006 Conference Co-Supervised with Prof Skone

Other Students		
Name	**Role/Topic**	**Awards/Special Info**
Jared Bancroft	GNSS kinematic positioning methods and testing	Internship student
Cyrille Gernot	Ground-based RF systems	Visiting student, March-August 2006
Sid Kwakkel	Application of INS technology to kinesiology	Summer student
Serge Lacoste	GNSS kinematic software enhancements and testing	Visiting student, March-July 2006
Tao Lin	Ground-based RF systems and GNSS signal processing	Internship student
Florence Macchi	Ground-based RF systems	Visiting student, March-August 2006
Richard Ong	GNSS kinematic positioning methods and testing	Internship student
Chidara Sunil Kumar	Navigation sensor estimation	Visiting student

GRADUATES

Name	*Research Topic*	*Current Position*
MEng Graduates		
J. Al-Azizi	GPS positioning in urban canyons	Geomatics industry, Dubai
PhD Graduates		
J. Collin	Investigations of Self-Contained Sensors for Personal Navigation	GNSS industry, Finland
G. Gao	INS-Assisted High Sensitivity GPS Receivers for Degraded Signal Navigation	GNSS industry, Calgary
MSc Graduates		
S. Charkandeh	86-Based Real Time L1 GPS Software Receiver	GNSS industry, USA
S. Phalke	GPS and Galileo Performance Evaluations for Multiple Reference Station Network Positioning	GNSS industry, Calgary
J. Qiu	RF Interference Impact on GPS L5 Reception Performance	GNSS industry, Calgary

Name	*Research Topic*	*Current Position*
MSc Graduates		
S. Singh	Comparison of Assisted GPS and High Sensitivity GPS in Weak Signal Conditions	GNSS industry, Calgary
W. Yu	Selected GPS Receiver Enhancements for Weak Signal Acquisition and Tracking	GNSS industry, USA
BSc Graduates		
S. Kwakkel	Foot and Ankle Kinematics During Gait Using Foot Mounted Inertial Sensor	Graduate studies, PLAN Group

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
U of C, Deptartment of Geomatics Engineering M. E. Cannon N. El-Sheimy Y. Gao K. O'Keefe S. Skone	GNSS research, associated graduate student supervision
U of C, Deptartment of Electrical and Computer Engineering Professor J. Nielsen,	Development of ground-based wireless location methods and GNSS signal processing methods, associated graduate student supervision
National Collaborations	
University of British Columbia Professor Richard Klukas	GNSS signal enhancements
Carleton University Prof Jim Wight	GNSS signal enhancements
Aerospace Engineering Test Establishment, DND	Navigation system performance analysis
Defence Research and Development Canada, DND	Ground-based RF navigation system development
Defence Research and Development Canada, DND	Software receiver development

Participants	*Nature of Collaboration*
International Collaborations	
École Nationale de l'Aviation Civile, France	Galileo signal acquisition and tracking techniques
Tampere University of Technology, Finland	Personal location and navigation
U.S. Navy - NAWC	Aircraft buffeting estimation
Technical University at Graz, Austria	GPS signal simulation
Industrial Collaborations	
General Motors	GPS vehicular navigation
Nokia, Europe	Wireless location of cellular telephones
GNSS company, USA	Assisted GPS receiver evaluation
Asian automobile manufacturer	Integrated vehicular navigation systems

INTELLECTUAL PROPERTY

Patents/Licences	*Title/Name*	*Status*
Satellite And Inertial Navigation Technology, 2002	SAINT™	Available for licensing
GPS software for the determination of a mobile platform's attitude parameters, 1994 plus enhancements	HEADRT+™	Available for licensing
Navigation Development Library, 2001 plus enhancements	NDL™	Available for licensing
Single point and differential GPS positioning – mature software, 1990 plus enhancements	C3NAVG2™	Available for licensing
New Unambiguous BOC (n,n) Signal Tracking Algorithm, O. Julien, C. Macabiau, M.E. Cannon and G. Lachapelle	Patent Application	Pending (Submitted to U.S. Bureau of Patents previously (2004)
Differential Signal Processing Schemes for Enhanced GPS Acquisition, S. K. Shanmugam, J. Nielsen, G. Lachapelle, and R. Watson	Patent Application	Pending (Submitted to U.S. Bureau of Patents previously (2005)
A new method of Doppler Removal and Correlation for software GNSS receivers, M. Petovello and G. Lachapelle	Patent Application	Pending (Submitted to U.S. Bureau of Patents previously (2006)
Vehicular navigation and positioning systems, J. Gao, M.E. Cannon, M. Petovello, K. Nagamiya, I. Maeda, K. Kagawa	Patent Application	Submitted to U.S. Bureau of Patents during reporting period

FUNDING

Dr Gerard Lachapelle has a five year iCORE Chair award ($2.5M). This year his federal funding is sourced from WED, NSERC, NCE and others ($605K). His team has received other funding for the year ($533K) from many areas including naval, aeronautical, automotive, and agricultural interests. Dr Lachapelle also holds a Tier 1 Canada Research Chair ($200K/year).

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

Godha, S, and M.E. Cannon. "GPS/MEMS INS Integrated System for Navigation in Urban Areas". *GPS Solutions*, http://dx.doi.org/10.1007/s10291-006-0050-8 (January 3, 2007).

O'Keefe, K., B. Lin, and G. Lachapelle "Network RTK performance analysis using RTCM 3.0 and the Southern Alberta Network". *Geomatica*, 61, 1, 267-274.

Schleppe, J. and G. Lachapelle (2007) "GPS Tracking Performance under Avalanche Deposited Snow". *GPS Solutions,* Springer, Published online, DOI 10.1007/s10291-007-0060-1

Hu, T., G. Lachapelle and R. Klukas (2007) "Controlled GPS Signal Simulation for the Indoors". *Journal of Navigation*, Royal Institute of Navigation, 60, 2, 265-280.

O'Keefe, K., M. Petovello, G. Lachapelle and M.E. Cannon (2006) "Assessing probability of correct ambiguity resolution in the presence of time-correlated errors". *Navigation*, U.S. Institute of Navigation, 53, 4, 269-282.

Yu, W., B. Zheng, R. Watson and G. Lachapelle (2006) "Differential Combining for Acquiring Weak GPS Signals". *EURASIP Journal of Signal Processing*, doi:10.1016/j.sigpro.2006.08.004

Ma, C., R. Klukas, and G. Lachapelle (2007) "A Non-Line-of-Sight Error Mitigation Method for TOA". Measurements. *IEEE Transactions on Vehicular Technology,* 56, 2 (March), 641-651.

Raimondi, M., and G. Lachapelle (2006) "Performance Analysis of a High Sensitivity GPS Receiver Under the Forestry Canopy". *Navigation*, Institut Français de Navigation, 54, 214, pp. 13-27.

Petovello, M.G. (2006) "Narrowlane - Is It Worth It?", *GPS Solutions*, John Wiley & Sons, Inc., Volume 10, Number 3, pp. 187-195.

Lachapelle, G. (2006) "Pedestrian Navigation With High Sensitivity GPS Receivers and MEMS". *Journal of Personal and Ubiquitous Computing*, Springer, published online, 10Oct06, http://dx.doi.org/10.1007/s00779-006-0094-3.

Watson, R., G. Lachapelle, R. Klukas, S. Turunen, S. Pietilä and I. Halivaara (2006) "Investigating GPS Signals Indoors with Extreme High-Sensitivity Detection Techniques". *Navigation*, Institute of Navigation, 52, 4, 199-213.

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Kwakkel, S., S. Gahda, and G. Lachapelle (2007) "Foot and Ankle Kinematics During Gait Using Foot Mounted Inertial Systems". *Proceedings of National Technical Meeting* (San Diego, 22-24 Jan), The Institute of Navigation, 9 pages.

Shanmugam, S.K., J. Nielsen, G. Lachapelle and R. Watson (2006) "Pre-Correlation Noise and Interference Suppression for Use in Direct-Sequence Spread Spectrum Systems With Periodic PRN Codes". *Proceedings of GNSS06* (Forth Worth, 26-29 Sep, Session C3), The Institute of Navigation, 12 pages.

Yu, Wei, G. Lachapelle and S. Skone (2006) "PLL Performance for Signals in the Presence of Thermal Noise, Phase Noise and Ionospheric Scintillation": *Proceedings of GNSS06* (Forth Worth, 26-29 Sep, Session D5), The Institute of Navigation, 17 pages.

Gao, Jianchen (2006) "GPS/INS/G Sensors/Yaw Rate Sensor/Wheel Speed Sensors Integrated Vehicular Positioning System". *Proceedings of GNSS06* (Forth Worth, 26-29 Sep, Session E3), The Institute of Navigation,13 pages.

Gao, Guojiang, and G. Lachapelle (2006) "INS-Assisted High Sensitivity GPS Receivers For Degraded Signal Navigation". *Proceedings of GNSS06* (Forth Worth, 26-29 Sep, Session D6), The Institute of Navigation, 13 pages.

C. Mongrédien, G. Lachapelle, M.E. Cannon, The University (2006) "Testing GPS L5 Acquisition and Tracking Algorithms Using a Hardware Simulator". *Proceedings of GNSS06* (Forth Worth, 26-29Sep, Session C6), The Institute of Navigation, 13 pages.

Schleppe, J., and G. Lachapelle (2006) "GPS Tracking Performance Under Avalanche Deposited Snow". *Proceedings of GNSS06* (Forth Worth, 26-29 Sep, Session F6), The Institute of Navigation, 12 pages.

Moghaddam, A.R.A., R. Watson, G. Lachapelle and J. Nielsen (2006) "Exploiting the Orthogonality of L2C Code Delays for a Fast Acquisition". *Proceedings of GNSS06* (Forth Worth, 26-29 Sep, Session C3), The Institute of Navigation, 10 pages.

Petovello, M.G., and G. Lachapelle (2006) "An Efficient New Method of Doppler Removal and Correlation with Application to Software-Based GNSS Receivers". *Proceedings of GNSS06* (Forth Worth, 26-29 Sep, Session C5), The Institute of Navigation, 11 pages.

Petovello, M., and G. Lachapelle (2006) "Comparison of Vector-Based Software Receiver Implementations With Application to Ultra-Tight GPS/INS Integration". *Proceedings of GNSS06* (Forth Worth, 26-29 Sep, Session C4), The Institute of Navigation, 10 pages.

Charkhandeh, S., M.G. Petovello and G. Lachapelle (2006) "Performance Testing of a Real-Time Software-Based GPS Receiver for x86 Processors". *Proceedings of GNSS06* (Forth Worth, 26-29 Sep, Session C5), The Institute of Navigation, 8 pages.

Godha, S., G. Lachapelle and M.E. Cannon (2006) "Integrated GPS/INS System for Pedestrian Navigation in a Signal Degraded Environment". *Proceedings of GNSS06* (Forth Worth, 26-29 Sep, Session A5), The Institute of Navigation, 14 pages.

Singh, S. (2006) Evaluation of Assisted GPS (AGPS) "Performance Using Simulator and Field Tests". *Proceedings of GNSS06* (Forth Worth, 26-29 Sep, Session D6), The Institute of Navigation, 11 pages.

Watson, R., G. Lachapelle and R. Klukas (2006) "Testing Oscillator Stability as a Limiting Factor in Extreme High-Sensitivity GPS Applications". *Proceeding of European Navigation Conference,* (Manchester, U.K., 8-10 May), Royal Institute of Navigation, 20 pages.

Lachapelle, G, S. Godha and M.E. Cannon (2006) "Performance of Integrated HSGPS-IMU Technology for Pedestrian Navigation Under Signal Masking". *Proceeding of European Navigation Conference*, (Manchester, U.K., 8-10 May), Royal Institute of Navigation, 24 pages.

SEMINARS, INVITED PRESENTATIONS AND LECTURES

Cannon, M. E. (2007) "Bringing Space Down to Earth with the Global Positioning System". Invited Seminar, McGill University, Montréal, March.

Lachapelle, G. (2007) "Indoor GPS". Invited Seminar, Ecole Nationale de l'Aviation Civile, Toulouse, France, March.

Cannon, M.E. (2007) "Positioning Geomatics in Alberta: Growing the Opportunities and Impacts", Alberta Geomatics Group (AGG),Calgary, March.

Lachapelle, G. (2007) "High Accuracy GPS Positioning Techniques & Applications". Two-Day Course for Automobile Industry, Detroit, March.

Lachapelle, G. (2007) "High Precision GPS Positioning Using Carrier Phase Measurements". Invited Seminar, Cornell University, USA, March.

Cannon, M. E. (2006) "Bringing Space Down to Earth with the Global Positioning System". Invited Seminar, Alberta Teacher's Association Science Council Conference, Kananaskis, November.

Lachapelle, G., and M. Petovello (2006) "Fundamentals of GPS and Carrier Phase Based Positioning". Five-Day Course for Calgary-based industry, November.

Lachapelle, G. (2007) "IP Licensing: Dealing with Expectations, Cultural Diversity and Much More". Invited Presentation, License Executive Society, Calgary, 14 February.

Lachapelle, G. (2006) "Finding and Interfacing with External Industrial Partners and Managing Expectations". Invited Presentation, Institute for Applied Scientific Research, Mount Royal College, 1 November.

Lachapelle, G., and M. Petovello (2006) "High Sensitivity GPS". Four-Day Course for Europe-based industry, October.

Lachapelle, G., and M. Petovello (2006) "High Sensitivity GPS". Two-Day Course for U.S.-based industry, November.

Lachapelle, G., and M. Petovello (2006) "High Sensitivity GPS". Two-Day Navtech Seminars Course for U.S.-based industry, Fort Worth, TX, September.

Watson, R., and G. Lachapelle (2006) "GNSS-Based Indoor Tracking: Approaches, Developments, and Test", WPI/CTC Technology Workshop, Worcester, Massachusetts, 7 August 06.

Lachapelle, G. (2006) "High Sensitivity GPS – Concepts and Computational Challenges". Keynote Address, Summer School on Highlights in Microtechnology, Neuchâtel, Switzerland, 12July 06.

Lachapelle, G. (2006) "High Sensitivity GNSS and Integration with Other Sensors". Invited Lecture, Summer School on Highlights in Microtechnology, Neuchâtel, Switzerland, 12July 06.

Mongrédien, C. (2006) "GNSS Modernization. Invited presentation", GEOIDE NCE Summer School, Calgary, 6 June.

Shanmugam, S. et al (2006) "A Novel Multi-Chip Differential Detection (MCDD) for Enhanced Synchronization in DS-UWB Systems". 2006 Canadian Summer School on Communications and Information Theory, Banff, Alta, 1-3 August.

Lachapelle, G., K. O'Keefe and M. Petovello (2006) "Principles and Applications of GNSS", Invited Lecture, GEOIDE Summer School, Calgary, 5-6 June 2006.

Lachapelle, G. (2006) "Communicating Science in Peer-Reviewed Journals". Presented at Panel Discussion, GEOIDE NCE Annual Conference, Banff, June 2.

Mongrédien, C. (2006) "Geomatics Enhancement with Dual Use of GPS II/III and Galileo". Oral Presentation, GEOIDE NCE Annual Conference, Banff, May 31-June 2.

Qiu, J. (2006) "GPS L5 Receive Acquisition Performance Under Broadband Noise and Self-Interference". Poster Paper, GEOIDE NCE Annual Conference, Banff, May 31-June 2.

Mongrédien, C. (2006) "Testing GPS L5 Acquisition Algorithms Using a Hardware Simulation". Poster Paper, GEOIDE NCE Annual Conference, Banff, May 31-June 2.

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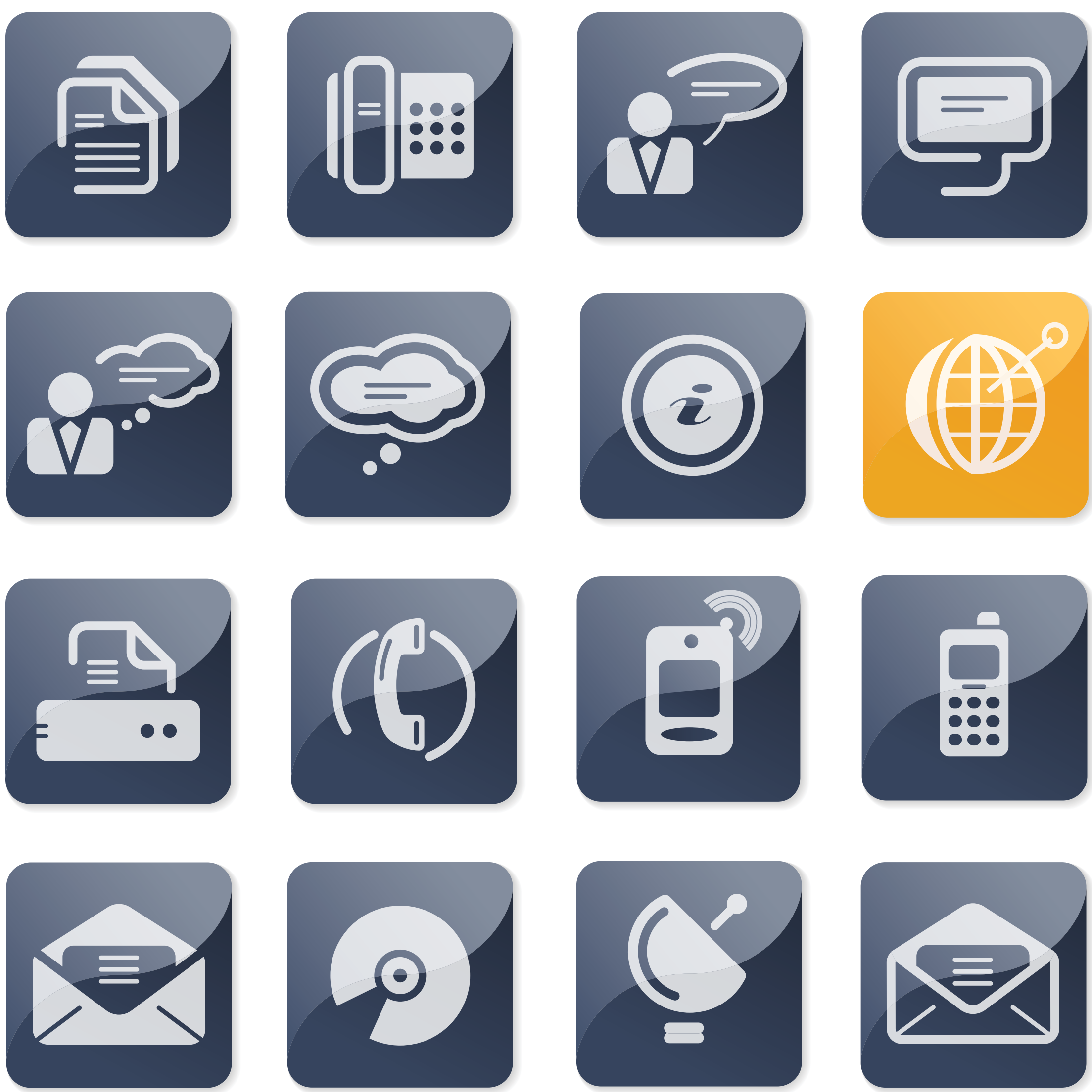
High-Capacity Digital Communications



The High-Capacity Digital Communications (HCDC) research group's mission is to provide leading-edge research in the area of digital information transmission theory and systems, information transfer and distribution, and data integrity and security.

These activities are core components of a strong future-oriented information technology thrust.

The technical expertise of the HCDC group spans mathematical modeling and theory, systems theory and practice, networking layer functionality and silicon-based implementation of circuits, and systems in custom application integrated circuits (ASIC) technology or field-programmable gate array (FPGA) structures. A recent re-orientation of the laboratory's focus in view of future activities has identified three core areas as the main pillars of the HCDC group: Systems Theory and Techniques, Microsystems Implementations, and Networking and Data Management. These pillars correspond to the different layers found in large-scale modern data communications infrastructures, viz., the physical device layer of the actual silicon circuits, the systems layer corresponding to the algorithmic components of modulation, error control coding, detection, synchronization and other relevant data link functionalities, the networking layer with its protocol, traffic management and optimization, and control objectives.

In the past year, the HCDC group has contacted researchers in the adjoining areas of very large scale integration (VLSI) and computing science with a vision of creating a large, comprehensive center of expertise and critical mass in covering all relevant aspects of modern information technology. The HCDC group is also heavily reaching out to industry partners and has established links with a variety of companies in this area, such as L3 Communications, Aquantia Corporation, PMC Sierra, Intel, Hewlett-Packard (HP), and IBM. The HCDC group is poised to form a concentration of know-how and cutting edge research activities in information technology, and establishing the University of Alberta (U of A) as one of the leading locations for information research.

In the past year, the HCDC group has fabricated and tested low-power digital error control decoders, analog data processors for ultra-low power applications, and sophisticated fast and resource-efficient channel emulation and noise generation cores in FGPA technology. The group has started the construction of novel virtual Network Emulator for Wireless Artificially Generated Environments (NEWAGE), for which the group has completed versatile, high-speed channel modules which can emulate virtually all varieties of wireless transmission channels. A large programmable network of such channel modules will form the core of NEWAGE. The HCDC group has also proposed novel signal processing algorithms that can efficiently handle concurrent wireless transmissions, a capability which will be indispensable in large-scale deployments of ad-hoc heterogeneous wireless networks. HCDC researchers have shown that these algorithms can theoretically achieve the local channel capacity and are implementable with a manageable complexity which scales linearly with the number of participating terminals. The group has proposed and studied protocols to make routing and relay traffic efficient in such networks using advanced receiver algorithms. These findings have been published in a series of journal and conference papers, and are currently being tailored for implementation by Microsystems colleagues and ultimate testing on NEWAGE.

Finally, apart from maintaining a strong leading presence in the research community, the HCDC group has strengthened its outreach activities. This summer the group will hold the second Western Canadian Summer School on Communications and Information Theory in Banff, Alberta, and will also hold the first Wireless Camp at the U of A this fall; an activity to introduce first-year students to the promise of wireless technology and services.

Research Program Overview

Information and Communications Technology (ICT) has reached a high level of maturity, with system capabilities growing rapidly over the past few decades. With a successful industry as a driving force, most of the research funding in Canada, and in North America, goes into traditional key areas such as health research and fossil fuel research, or into areas such as nanotechnology. The HCDC group firmly believes that ICT is ultimately going to be the key to solving many modern day issues important to society, and will enable other areas such as nanotechnology and medical/biomedical technologies. In the medical field, truly advanced communications will enable ambulatory monitoring and tracking of vital biological functions of patients or personnel in high-stress environments (soldiers, rescue workers, etc.), and even enable remote administration of drugs or biomedical stimuli to patients to act as immediate first aid. Advanced ad-hoc networking technologies are required to connect sensors, such as those created using nanotechnology, and transport the data to central or remote aggregation and control entities. Active radio frequency (RF) identification is yet another promising application with a staggering potential impact on the economy as it becomes possible to track goods and fleet material precisely and thus optimize supply chains, search efforts, and security and monitoring operations. ICT technology is fundamentally enabling other technological thrusts.

Fundamental components of ICT are telecommunications, i.e., reliable data transport, data integrity and authenticity, the organization of large networks of communicating devices, and the energy-efficient implementation of extremely complex algorithms which make all these functions possible. All of these aspects form the core of the HCDC Laboratory. High capacity refers to the capacity limits theoretically established by Claude Shannon in 1948, which give each communications channel a maximum rate at which reliable communication is possible. Achieving this rate has been the research and development focus of communications scientists and engineers over the past half century. Theoretical results from the turn of the last century, combined with Shannon's results on information processing, establish the completeness of digital information representation, that is, representing information in digital form is complete and entails no fundamental loss. The fundamental communications questions therefore are how to transport, store, and manipulate digital information optimally.

The goal of the HCDC laboratory is to expand into a true center of critical mass and know-how to cover all major aspects of ICT, and thus become Alberta's

leading ICT think tank, and one of a few elite leading centers world-wide. Over the past year the HCDC laboratory has actively forged collaborative projects with colleagues from computing science, the faculty of science (mathematics, cryptography), and medical/biomedical faculties. The vision is to draw the leading experts in these areas already resident in Alberta into a collaborative laboratory that maintains and sustains active research in all directly relevant ICT areas.

The HCDC group has focused on a host of associated activities targeted to involve industry, U of A students, and national and international visitors and collaborators. The HCDC group has held a number of laboratory presentations to exponents of the government, funding agencies, industry, and academic visitors.

Under the HCDC group's leadership, the first annual Western Canadian Summer School (WCSS), aimed at graduate students, was held in Banff, Alberta, August 1-3, 2006. WCSS focuses on recent advances in Information Theory and Communications. The goal is to provide a research exchange among students, and encourage students to present their work and get feedback from their peers and leading researchers in the field. Students also benefit from attending seminars presented by invited speakers and gain insight from a mathematical perspective that allows them to solve complex problems in modern Information Transmission. Motivated by the success of the first Western Canadian Summer School on Communication and Information Theory, WCSS is being held a second year August 20-22, 2007.

The HCDC laboratory is also hosting the U of A Wireless Camp, August 29-31, 2007. The Wireless Camp is a pioneer project with the goal of fostering the exchange of state-of-the art knowledge in wireless to undergraduate students in Alberta. The purpose of the camp is to introduce interested students to the dynamic world of wireless communications using short lectures, demonstration tours, and a "hands on" project to build a real wireless device, using soldering irons and basic testing equipment. The camp is designed to create interest for, and an appreciation of, wireless communications and its many applications in modern life in Alberta.

In the past year, the HCDC group has hosted a number of international visitors with whom the group maintains active research collaboration, foremost Dr Marat Burnashev, from the Russian Academy of Sciences, and Dr Tomohiro Takahashi from Tohoku University.

Research Projects

The HCDC laboratory has had a successful year, in particular in the area of error control coding, multiple access communications, and networking research.

Error Control Coding

In the HCDC group's core area, the laboratory has continued to make significant contribution to the implementation of low-power decoding of advanced error control codes, notably of low-density parity check (LDPC) codes. Code design and decoder architecture research have been reported in a number of publications. The HCDC group has designed algorithmic enhancements to deal with various implementation innovations and the low error floor problem of these codes. The power sensitive message design methodology has been invited to the International Workshop on Information Theory to be held in Tahoe later this year.

Multiple Access Interference Control

In the HCDC group's other core area of strength, AIF Fellow Dr Dmitry Truhachev and iCORE Professor Schlegel have made several fundamental contributions to joint detection and iterative interference cancellation systems, showing that simple cancellation methods, combined with appropriate error control coding, sophisticated randomized rate, and power allocation schemes can approach the physical capacity limit of a multiple access channel. This is achieved by a "modulation" method called partitioned signaling. Partitioned signaling, with iterative interference cancellation, is a possible competitive future extension of current detection methods. Verifying implement ability of such systems including prototype transmitter and receiver systems that will benefit from the laboratories expertise in FPGA test implementation techniques was jointly studied with PhD candidates Bagley and Krzymien, and a number of papers on the subject have been submitted to IEEE journals and conferences.

Low-Complexity VLSI Implementation

In this area, HCDC members Professors Vincent Gaudet and Bruce Cockburn have collaborated with iCORE Professor Schlegel to advance the state-of-the-art know-how on the implementation of high-speed large-scale digital error control decoders. A first test LDPC decoder of size 256 in custom ASIC has been measured and found to be fully functional. The HCDC group is planning the design of a follow-up ASIC decoder using the recent power-efficient messaging concepts as well as advanced low-power circuit implementation methods. Personnel and project management are currently being discussed.

Professors Schlegel (right) and Gaudet (left) in discussion with Swiss Ambassador to Canada, Mr. Baumberger (center), on the occasion of his visit to the HCDC group early in 2007.

Analog Signal Processing and Computing

In this area, the HCDC laboratory continues to be at the leading edge. Professor Gaudet served as the technical chair of the 6th International Analog Decoding Workshop, held in Montreal this past spring. Team Member Nima Sadeghi has completed the design of an analog discrete fourier transform processor to act as the analog demodulation front-end of a future all-analog receiver for multi-tone transmission systems. Extensive studies have been carried out on the viability of analog processing for digital data in advanced nano-meter technology.

Networking

PhD candidate Sumeeth Nagaraj and Dr Truhachev have investigated the maximum information carrying capacity of ad hoc networks which rely on message routing. The per node capacity in such networks decreases with the square root of the number of users, making large ad hoc networks very inefficient. The HCDC group has worked out information theoretic bounds on these limits under a variety of conditions and local cooperation strategies, and has shown that the use of joint detection receivers can improve the asymptotic capacity behavior of such networks. More importantly, however, on-going research indicates that the use of some form of joint detection is an absolute must unless less severe capacity degradations do occur.

FPGA Technology

The HCDC group's new postdoctoral associate, Dr Alimohammad, heads work in this area, The HCDC group has completed a versatile channel emulator to used in the NEWAGE project, as well as novel and extremely accurate noise generators, beta-versions of which have been given to several potential industrial collaborators. Team Member Fouladi Fard has developed an operating system and visual interface for the FPGA environments, which makes it much easier to use them for upcoming tests. A series of demonstration examples were also programmed and demonstrated to visitors in a number of laboratory demonstration tours this spring.

Packet Syncronization

In this area PhD candidates Sheehan Khan and Sumeeth Nagaraj have written a paper which examines the theory of efficient packet detection. The proposed method was analyzed with quadratic forms using the theory of Lagrange polynomials, and extensions to multi-path fading channels have been discussed and are under way. This methodology will be implemented as proof-of-concept cores on NEWAGE to verify robustness and the reliability.

Objectives For Next Year

The primary objective for the next year is the restructuring of the laboratory to encompass the full scope of ICT. To this end, the HCDC group's plan is to foster stronger relationships with computing science, the neighboring laboratory which focuses on VLSI circuits and systems, and the Faculty of Science at the University of Calgary (U of C) on data security and cryptography. Specifically, the major objectives for the next couple of years are highlighted by the following points:

The NEWAGE project

An ambitious large-scale network environment emulation system consisting of a multitude of specialized FPGA and compute blades interconnected in a server environment which allows the sample-signal-accurate emulation of transmission, channel, and receiver systems, which are controlled by realistic data traffic generated by compute servers. In this way, complex wireless networks can be emulated "in vitro" without the costly prototype deployments otherwise required. NEWAGE is an advanced concept to allow researchers and industrial partners alike to test specific networking, signaling, or communications methods, circuit cores, or algorithms, to be tested in accurately represented, but artificial transmission environments. To enable this, hundreds of complex transmission channels will need to be accurately emulated and coordinated. This requires a complex state-of-the art specialized compute environment. The different components of such a set-up are currently being investigated, and a small demonstration set-up is targeted to come on-line this fall.

Multiple Access Communications

In this area the HCDC group has identified a signaling strategy with the invention of partitioned signaling. Future research will concentrate on integrating this concept into efficient networking and relaying research. The HCDC team will also study various implementation aspects of partitioned signaling, the required auxillary functions of timing and phase synchronization in particular. The concepts of partitioned signaling need to be studied in view of efficient low-complexity implementations, which then need to be verified by simulation, and prototyping on NEWAGE. Professor Schlegel was appointed IEEE Distinguished Lecturer on this topic.

Networking research

This area will play an important role in the future extension phase of the HCDC group's research. As wireless packet networking becomes ever more important, the management and efficient routing of datagrams, or communications packets, becomes a central concern of the communications engineer. Primarily, the HCDC group plans to expand activities to include efficient routing at the higher network layers with cognizance of advanced signal processing capabilities of the physical layer. The HCDC team plans on integrating advanced joint detection methodologies, primarily and initially proposed random-packet CDMA into higher networking studies. Ad hoc networking research is also a new direction where the HCDC group is expanding, primarily in the study and applicability of advanced signal processing methods such as joint detection, cooperative distributed antenna arrays, adequate synchronization methods and detection methods, as well as the impact of traffic and traffic coordination on network capacity.

Error Control Coding

The HCDC group's work in error control coding and low-power circuits will enter a new phase with an emphasis on power-efficient processing. This requires the judicious combination of both theoretical tools and ideas, such as low-power message formats and density evolution analysis for LDPC codes, as well as the design of ultra-low power circuits to execute the required functions of the team's algorithms. Power will play a key role in all future digital signal processing, from communications systems to computational devices (microprocessors). The team's efforts will combine algorithmic and circuit design research to deliver the lowest power solutions to a given communications problem.

Analog Decoding

Projects on analog decoding will refocus on energy efficiency. The question is where and how analog processing should and are able to replace traditional digital computation to provide more power-efficient solutions. There is ample demonstration that analog decoding can provide energy efficient error control decoding solutions using mainstream CMOS process technology at 180nm and 130nm. Beyond this, the scaling of analog technology remains an active research area. Analog processing has also been recognized for its power-efficiency potential in standard filtering applications, where analog circuit solutions provide significantly superior solutions. The HCDC group continues to research this topic, primarily scaling issues and the question on how to combine conventional analog processing with the analog information processing methodology pioneered by the group in order to build advanced iterative receiver systems with minimal processing power requirements.

Research Team Members and Contributions

Team Leader
Professor Christian Schlegel
Part of the HCDC core team
Editor, IEEE Transactions of Communications, Proceedings of the IEEE IEEE Distinguished Lecturer (2007)
iCORE Professorship (2001, 2006)
Canada Research Chair (CRC) (2001, 2006)
NSF Career Award (1997)

Faculty Team Members

Name	Awards/Special Info
Prof Bruce Cockburn	NSERC Grant Holder CFI Grant Holder CMC Grant Holder
Prof Vincent Gaudet	NSERC Grant Holder NSERC Scholarships and Awards Committee 176: Member 2005-2007, Chair 2007 CFI Grant Holder CMC Grant Holder
Prof Iaonis Nikolaidis	

Research Associates

Name	Awards/Special Info
Dr Zachary Bagley	Part of the HCDC extended team
Professor Stephen Bates	CEO, SDS Corporation, Canmore Part of the HCDC core team
Professor Aiden Bruen	Part of the HCDC extended team
Dr Sheryl Howard	Part of the HCDC extended team
Dr Zhenning Shi	Part of the HCDC extended team
Dr Christopher Winstead	Part of the HCDC extended team

PostDoctoral Fellows	
Name	**Awards/Special Info**
Dr Amirhossein Alimohammad	Part of the HCDC core team
Dr Rafal Dlugosz	Alberta Ingenuity Fund (AIF) Postdoctoral Fellowship (2004-2006) Part of the HCDC core team
Dr Tomohiro Takahashi	Part of the HCDC extended team
Dr Dmitri Truhachev	Part of the HCDC extended team

PhD Candidates	
Name	**Awards/Special Info**
Saeed Fouladi Fard	AIF Studentship, iCORE Scholarship Part of the HCDC extended team
Sheehan Khan	NSERC PGS-D2 2007-2009 iCORE Scholarship Part of the HCDC extended team
Lukasz Krzymien	Part of the HCDC extended team
Hessam Moussavinik	Part of the HCDC extended team
Sumeeth Nagaraj	Part of the HCDC extended team
Amer Samarah	NSERC CGS-D3: Canada Graduate Scholarship – Doctoral Award (2007-2010) Part of the HCDC extended team
Marcel Jar Silva	Part of the HCDC extended team
Yanjie Wang	Part of the HCDC extended team

MSc Candidates	
Name	**Awards/Special Info**
Brendan Crowley	Part of the HCDC extended team
Russell Dodd	Part of the HCDC extended team
Ernest Wade Harrison	Part of the HCDC extended team
Rezwana Huq	Part of the HCDC extended team
Phil Marshall	Part of the HCDC extended team
Nima Sadeghi	Part of the HCDC extended team
Swaran Raj Singh	Part of the HCDC extended team
Meysam Zargham	Part of the HCDC extended team

Other Team Members		
Name	**Role/Topic**	**Awards/Special Info**
Prof Marat Burnashev	iCORE Visiting Prof; NSERC Visiting Professor	Part of the HCDC extended team
Prof Lance Perez	Academic Visitor	NSF Career Award Part of the HCDC extended team

GRADUATES

Name	*Research Topic*	*Current Position*
PostDoctoral Graduates		
Dr Amirhossein Alimohammad	Wireless Systems Modeling and Hardware Implementation	U of A Post Doctoral Fellow, HCDC Lab
Dr Zack Bagley	Layer MIMO Communications Systems	U of Utah Principal Research Engineer, L3 Corporation
Dr Rafal Dlugosz	Design of Analog Integrated Circuits	Post Doctoral Fellow, 2006-2007 HCDC Lab
Saeed Fouladi Fard	Ad hoc Networks, FPGA Implementation, MIMO Systems	U of A, Degree in Progress Research Assistant, HCDC Lab
Dr Sheryl Howard	Low SNR Iterative Phase Estimation	U of A Assistant Professor, NAU
Sheehan Khan	Detection/Acquisition/ Synchronization for Ad hoc Networks	U of A, Degree in Progress Research Assistant, HCDC Lab
Lukasz Krzymien	Multiple Antenna/Multiple Terminal Communications Systems	U of A, Degree in Progress Research Assistant, HCDC Lab
Boon Lim	Multiple Antenna Communications Systems	U of A, Degree in Progress Research Assistant, HCDC Lab
Hessam Moussavinik	Product Codes	U of A, Degree in Progress Research Assistant, HCDC Lab

Name	*Research Topic*	*Current Position*
PostDoctoral Graduates Cont'd		
Sumeeth Nagaraj	Advanced Packet Networks	U of A, Degree in Progress Research Assistant, HCDC Lab
Jorge Perez	Analog Decoding	France, Degree in Progress Visiting Student, Summer 2007 Ecole Nationale Superieure des Telecommunications de Bretagne
Amer Samarah	Power Estimation in LDPC Decoders	U of A, Degree in Progress Research Assistant, HCDC Lab
Dr Zhenning Shi	Iterative Joint Detection of CDMA	U of Utah Research Associate, Australia National University
Marcel Jar Silva	Error Control Coding Equalization	U of A, Degree in Progress Research Assistant, HCDC Lab
Dr Tomohiro Takahashi	Asynchronous Circuits	Tohoku University Post Doctoral Fellow Visitor, February 2007 HCDC Lab
Dr Dmitri Truhachev	Turbo and LDPC Codes	Lund University Post Doctoral Fellow, HCDC Lab
Yanjie Wang	Wireless Interface for Integrated Circuit Testing	U of A, Degree in Progress Research Assistant, HCDC Lab
Dr Chris Winstead	Analog Decoding	U of A Assistant Prof, Utah State University
MSc Graduates		
Huiqing Bai	Implementation of a Fuzzy Controller	Scanimetrics Inc, Edmonton
Keith Boyle	Analog CMOS Realization of an FFT Chip	U of A Industry, Idaho, USA
Brendan Crowley	VLSI Design, Bioinformatics, Hardware Acceleration	U of A, Degree in Progress Research Assistant, HCDC Lab
Russell Dodd	ECC and Multilevel Analog Memory Systems	U of A, Degree in Progress Research Assistant, HCDC Lab

Name	*Research Topic*	*Current Position*
MSc Graduates Cont'd		
Edmund Fung	Design of Digital LDPC Decoders	U of A Industry, California, USA
Soraya Kasnavi	Content Addressable Memories	U of A PMC-Sierra, Vancouver
Tobias Kiefer	MIMO	U of Offenburg Porsche, Germany
Jung Ko	Radio Software	U of A Altera Corp., California, USA
Ivan Kocev	MIMO	U of Offenburg Industry, Germany
David Li	CMOS Imaging	U of A Industry, Hong Kong
Phil Marshall	Bit-Serial LDPC Decoding	U of A, Degree in Progress Research Assistant, HCDC Lab
Aaron Milner	FPGA Implementation of Stochastic Decoder	U of A Industry
David Nguyen	Low Voltage Analog Decoding	U of A Aquantia Corp., Milpitas, CA
Michael Phan	FPGA Implementation of Fuzzy Logic Controller	U of A Industry, Saskatoon
Anthony Rapley	Stochastic Iterative Decoding on Factor Graphs	U of A PMC Sierra, Saskatoon
Nima Sadeghi	Interfaces for Analog Decoders	U of A Research Assistant, HCDC Lab
Swaran Raj Singh	High Resolution Digital-to-Analog Conversion	U of A, Degree in Progress Research Assistant, HCDC Lab
Mimi Yiu	BIST for Analog Decoders	U of A Industry, Hong Kong
Meysam Zargham	Analog Decoders/RF Electronics	U of A, Degree in Progress Research Assistant, HCDC Lab
Lei Zhu	VLSI Architecture for Decoding of Serial Concatenated Codes	Industry

Name	*Research Topic*	*Current Position*
MSEE Graduates		
Lovisa Bjorklund	EXIT Analysis of Convolutional codes	Sweden
Wing-Yee Chan	Testing of an LDPC Decoder ASIC	U of A Industry
Annika Engblom	Measurements with a Hardware MIMO Testbed	Sweden
Preeti Kota	A Novel Wireless Packet System	United States PhD Student, Berkeley
Sean Kozicki	LDPC Codes	U of A Emerson Project Management, Calgary
Shayne Messerly	Implementation of an Iterative Matrix Inverter	United States L3 Corporation, Utah
Lavanya Sridharan	An Iterative Viterbi Detector	USA
BSc Graduates		
Sheng Choi	VLSI Testing of an LDPC Chip	U of A, Degree in Progress Undergraduate Co-op Student,HCDC Laboratory
Ernest Wade Harrison		U of A, Degree in Progress
Patrick Mercier	Layout of Building Blocks for an Analog FFT Chip	U of A MIT
Ryan Smetaniuk	Testing an Analog Decoding FFT Chip	U of A, Degree in Progress Undergraduate Co-op Student, HCDC Laboratory
Ryan Wollenberg	FPGA Matrix Inversion	U of A, Degree in Progress Undergraduate Co-op Student, HCDC Laboratory

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
HCDC Lab; SiWorks Inc (Calgary)	Application submitted to NSERC for an NSERC I2I grant
HCDC Lab; Ghaith Saab (U of A)	Ghaith Saab (Co-op Engineering student) has been working on a faster USB interface to the MIMO testbed
National Collaborations	
HCDC Lab; University of Toronto team	NSERC SRO application
International Collaborations	
HCDC Lab; Claude Berrou (ENST-Bretagne, France); Dr Emmanuel Boutillon (Universite de Bretagne Sud, France); Texas A&M University, (United States)	Application submitted for an NSERC SRO grant Collaboration is active between participants
HCDC Lab; Tobias Kiefer and Ivan Kocev (University of Applied Sciences, Offenburg, Germany)	Tobias Kiefer and Ivan Kocev (Masters students) have been taking measurements using the HCDC MIMO testbed. HCDC will use these measurements to build a database on the HCDC website.
Industrial Collaborations	
HCDC Lab; Semi-Conductor Research Corporation; Agere	Investigating the design and implementation of transceiver architectures for wire line systems This project is backed by Agere Inc. and designs high speed decoders and encoders for applications such as communications and hard-disk read heads.
L3 Communications, Salt Lake City, Utah Dr Schlegel Mr Zachary Bagley Mr Shayne Messerly	Currently supporting hardware oriented research efforts. VLSI systems for the transmission and reception stages of hardware testbed have been developed. This collaboration is expected to implement an iterative layering processor in FPGA to be used to separate the data streams in MIMO systems testbed. L3 communications widened its relationship with the HCDC team by signing a research service agreement
North Carolina State University (NCSU) Dr Brian Hughes Dr Gianlucca Lazzi	The topic of this joint research work is efficient space-time coding systems. The funding currently supports students at NCSU and Utah
University of Utah Dr Schlegel Dr Behrouz Farhang	The design of efficient and rapid equalization methods for multiple antenna systems

Participants	*Nature of Collaboration*
Industrial Collaborations Cont'd	
SiWorks Inc. Calgary	A number of talks and meetings have been held with this Calgary-based wireless company about expertise and IP transfer from the HCDC group to SiWorks Provided assistance in an HCDC Ideas-to-Innovation application to NSERC
HCDC Lab; Dr Ayyoob Abbaszadeh, Senior Engineer, L3 Communications (United States)	The HCDC Lab members are establishing themselves as the 'coding experts' for the LDPC coding projects lead by Dr Abbaszadeh at L3 Communications. The HCDC group is currently negotiating a Service Contract with L-3 Communications in Salt Lake City, Utah that will have the HCDC Lab performing a feasibility study of low-density parity check (LDPC) codes
HCDC Lab; Zachary Bagley, Principal Research Engineer, L-3 Communications (United States)	The HCDC group demonstrated the MIMO testbed at L-3 Communications in Salt Lake City, Utah. This demonstration attracted industrial and academic interest in the HCDC MIMO testbed. Future projects in this area are currently being examined
HCDC Lab; Dr Behrouz Farhang, Associate Professor, University of Utah (United States)	The HCDC Lab has provided Dr Farhang with the MIMO Testbed design to enable the team at the University of Utah to start MIMO channel measurements. Dr Farhang's team collected indoor and outdoor measurements and performed stress tests on the MIMO design

INTELLECTUAL PROPERTY

Applicants	*Title/Name*	*Status*
L3 Communications	No official title yet Topic: Low-voltage implementation of analog processing nodes	Filed with the University patent office and is currently under consideration for patent application
HCDC Laboratory filed with the US patent office and Trade Office (UPSTO) Dr Amirhossein Alimohammad, Mr Saeed Fouladi Fard, Dr Bruce F. Cockburn, Dr Christian B. Schlegel	"Signal Filtering And Filter Design Techniques" Serial number 60/888,630. Assigned reference number: 2006045 (US Prov)	Filed February 7, 2007 The provisional patent is filed and a full patent is being prepared to be filed before February 7, 2008

Applicants	Title/Name	Status
HCDC Laboratory filed with UPSTO Dr Christian B. Schlegel, Dr Vincent Gaudet, Dr Bruce Cockburn, Dr Stephen Bates, Mr Paul Goud, Mr Robert Hang, Dr Sheryl Howard	The patent application is entitled: “Bit-Serial Method and Apparatus for Decoding Low Density Parity Check Codes”	Filed May 14, 2005
HCDC Laboratory filed with UPSTO Dr Christian B. Schlegel, Dr Christopher Winstead	“Low-Voltage CMOS Circuits for Analog Decoders” Reference no: 2002047 US PROV Serial No: unassigned	Filed March 23, 2004

FUNDING

Dr Christian Schlegel has a five year iCORE Professor grant ($1.5M). This year he received funding from NSERC ($190K), CFI ($97K), ASRA ($64K) and Micronet ($22K).

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S. Nagaraj, S. Khan, C. Schlegel and M. Burnashev, "On Preamble Detection in Packet-based Wireless Networks", *International Symposium on Spread Spectrum Techniques and Applications*, Aug. 29 - Sep 01, 2006, Brazil.

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Saeed Fouladi Fard, Amirhossein Alimohammad, Mazia Khorasani, Bruce F. Cockburn and Christian Schlegel, "A Compact and Accurate FPGA based Nonisotropic Fading Channel Simulator", *2007 IEEE Canadian Conference on Electrical and Computer Engineering* (CCECE'07), Apr. 22-25, 2007, Vancouver, BC, Canada, paper 69.2.

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L. Krzymien, D. Truhachev and C. Schlegel, "Coded Random CDMA with Partitioned Spreading", *44th Allerton Conference on Communication, Computing and Control*, Monticello, IL, USA , Sep. 2006.

K. Boyle, S. Kilambi, R. Dlugosz, K. Iniewski, and V. Gaudet, "An Examination of the Effect of Feature Size Scaling on Effective Power Consumption in Analog to Digital Converters", *IEEE Workshop on Signal Processing Systems* (SIPS), Banff, AB, pp. 194-199, Oct. 2006.

B. C. Lim, W. A. Krzymień, C. Schlegel, "Impact of Receive Antenna Selection on Scheduling for Orthogonal Space Division Multiplexing", *in Proc. WPMC'06*, San Diego, USA, Sep. 2006, pp. 840-844.

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K. S. Zigangirov, A. Jimenez, M. Lentmaier, and D. Truhachev, ``Encoders and Decoders for Braided Block Codes", *IEEE International Symposium on Information Theory 2006*, Seattle, USA, July 2006.

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N. Sadeghi, H. Nik, C. Schlegel, V. Gaudet and K. Iniewski, "Analog FFT Interface for Ultra-Low Power Analog Receiver Architectures", *5th Analog Decoding Workshop*, Turin, Italy, 5-6 June, 2006.

S. Bates and R. Swamy, "Parallel Encoders for Low-Density Parity-Check Convolutional Codes", *IEEE Intl. Sym. Circuits and Systems* (ISCAS) 2006, Kos, Greece, May 21-24, 2006.

N. Sadeghi, S. Howard, S. Kasnavi, K. Iniewski, C. Schlegel and V. Gaudet, "Analysis of Error Control Code Use in Ultra-Low-Power Wireless Sensor Networks", *IEEE Int. Sym. Circuits and Systems* (ISCAS) 2006, Kos, Greece, May 21-24, 2006.

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B. Cockburn and K. Boyle, "Design and Performance of a Digital Delay Locked Loop Synthesized from Standard Cells", *2006 Canadian Conference on Electrical and Computer Engineering*, Ottawa, ON, Canada, May 4-7, 2006.

C. Schlegel, D. Truhachev and L. Krzymien, "Iterative Multiuser Detection of Random CDMA Using Partitioned Spreading", *4th International Symposium on Turbo Codes and Related Topics*, 3-7 April, 2006; Munich, Germany.

S. Nagaraj, C. Schlegel and D. Truhachev, "On Upper Bounds on Communication Rates in Ad-hoc Networks with non-Uniform Traffic Pattern", *IEEE Wireless Communications and Networking Conference* (WCNC), 3-6 April, 2006; Las Vegas, USA.

Algorithmic Number Theory and Cryptography

The iCORE Chair in Algorithmic Number Theory and Cryptography (ICANTC), is focused on research and training excellence in cryptology and computer security.

Originally mandated to conduct research in fundamental algorithmic number theory and mathematical cryptography, ICANTC's scope now includes applied research into information assurance and security. The ICANTC group, through the Centre for Information Security and Cryptography (CISaC), maintains a strong membership cluster that includes academics in disciplines such as mathematics, physics, computer science, engineering, political science and law, as well as professionals from the public and private sectors. The ICANTC's vision is to be distinguished internationally for its fundamental cryptography research, exceptional trainees, and ability to transform knowledge into information assurance and security applications.

Over the past year, the ICANTC group has continued to expand, building on increasing public recognition of the need for better information security technologies and policies. Part of this growth includes the development of information security initiatives that can diversify Alberta's economy and create intellectual capital, commercialization and career opportunities within the province. The ICANTC's success will be strengthened with the arrival of Dr Rei Safavi-Naini, the new iCORE Chair in Information Security, and is further complemented by the recently appointed iCORE/General Dynamics Canada Industrial Research Chair in Quantum Cryptography and Communication, Dr Wolfgang Tittel. This added expertise represent a significant augmentation to the University of Calgary (U of C) and CISaC's strength in information security.

The ICANTC research team published or submitted for publication over 25 research articles and gave over 35 presentations in Calgary and around the world.

In the coming year, the ICANTC group will continue to conduct both planned and opportunity-driven research, remaining relevant, innovative and committed to training highly qualified individuals with the skills to protect the privacy and information security of Albertans and Canadians.

Research Program Overview

This year the ICANTC group continued to broaden its scope beyond theoretical cryptography into the highly publicized area of applied information security. CISaC operating under the ICANTC umbrella, is the vehicle by which the iCORE Chair conducts these expanded activities in the area of information security, effecting academic and industrial collaborations and training in addition to research.

CISaC-Related Activities

CISaC is a multidisciplinary research institute that operates as a collaborative faculty-based centre supported and administered by the Faculty of Science at the U of C. CISaC brings together researchers, students and professionals with a wide variety of expertise to work in partnership on projects involving information security. The iCORE Chair is CISaC's main funder, although the goal is for the centre to have a life of its own beyond that of the ICANTC.

One of the key initiatives begun this year is the restructuring of CISaC. This restructuring was prompted by the arrival of the Dr Rei Safavi-Naini to the Department of Computer Science at the U of C. Dr Safavi-Naini will assume the position of deputy director on the CISaC Management Board. Her involvement means that information security will be a very significant and noticeable component within CISaC.

Also poised for change is the Calgary Laboratory for Information Assurance and Security (CLIAS). Dr Safavi-Naini and Dr Wolfgang Tittel have both agreed to include their respective research groups as components of CLIAS and their involvement has raised the number of members to 30. The CLIAS business plan is being revised to reflect the contributions of these important new members whose active participation means that CLIAS can now offer a full spectrum of services related to the area of information security and should increase the potential to attract funding from traditional research, industry, and government sources.

One of CISaC's main goals is to train highly qualified personnel to meet the security demands of today's information-based society. The team continues to recruit students at all levels (undergraduate, Masters, PhD, and post-doctorate) with a strong interest in mathematical research. The program was strengthened when the U of C approved undergraduate courses for students wanting to establish an area of concentration in information security within the Computer Science program and went online in the fall of 2006.

iCORE

Team Leader:
iCORE Chair
Dr Hugh C. Williams

Location:
University of Calgary

Department:
Mathematics and Statistics

Team Members: 53

Website:
http://cisac.math.ucalgary.ca/

Other ICANTC Group Initiatives

Another significant initiative this last year was *Solving the Pell Equation*, a book Hugh Williams and Michael Jacobson, Jr. began writing. The subject is the history and theory of the Pell equation, which is central to any work that involves the arithmetic of quadratic fields. As there are several cryptographic systems that make use of the properties of these fields the timing seems right for a comprehensive volume discussing the past and, more importantly, the most recent developments of the theory of this equation. Springer has agreed to publish *Solving the Pell Equation* and a contract has been signed. The manuscript's deadline is in two years with nearly half of the projected 17 chapters already written.

Research Projects

The research the ICANTC group conducts centres around computational and algorithmic number theory as well as theoretical and applied cryptography. These research projects reflect the depth and breadth of research carried out in the group, and build on work done in the past five years. The research is fundamental to developing new and better applications to the growing field of information and network security.

Fast arithmetic in real quadratic fields

Quadratic fields represent an active area of number theoretic research and provide a suitable setting for cryptography. This is an ongoing project devoted to accelerating the speed of performing primitive operations in quadratic fields and implementing these in larger scale projects. This work is important in developing fast algorithms for invariant computation and various cryptographic protocols, and the ICANTC team has obtained new results that increase the speed of exponentiation of ideals.

Primality proving

The ICANTC team has discovered how to extend the use of pseudosquares in primality testing to pseudocubes. As pseudocubes grow much more rapidly than pseudosquares, this could be of great importance in improving the speed with which 100 to 128 bit numbers can be proved prime. This could be the case with a new definition of a pseudocube as an element of the Eisenstein ring instead of the rational integers or with a more effective method of using the pseudosquares.

Special recurrence functions

The ICANTC team has found a solution to an old problem of Edouard Lucas' concerning the generalization of his functions to number fields of degree three. These can be used for primality proving RSA and Diffie-Hellman cryptographic protocols.

Efficient arithmetic on hyperelliptic curves

The ICANTC team has investigated the use of the real model of a hyperelliptic curve for cryptography and shown that the resulting cryptographic protocols may be faster than those using the more common imaginary model. The team continues to investigate potential improvements to algorithms for solving the hyperelliptic curve discrete logarithm problem in both real and imaginary models.

Fast point multiplication on Koblitz curves

Jointly with researchers of the ATIPS group led by iCORE Chair Dr Graham Jullien, members of the ICANTC team are investigating the use of the double-Frobenius expansion to speed point multiplication on Koblitz curves. The resulting algorithm is a clear improvement over other algorithms where no precomputation using the base point is allowed. The team is investigating further improvements, including ways to improve the algorithm assuming the base point is known.

Solving the discrete logarithm problem and computing invariants in global quadratic fields

Members of the ICANTC team are investigating improvements to the subexponential algorithm for solving the discrete logarithm problem in imaginary quadratic fields. This algorithm should be faster than any other and will be used to determine parameter recommendations for secure cryptography in imaginary quadratic fields. The team is also working on a generic implementation of this algorithm and that for computing invariants (class group and regulator) for all quadratic number and function fields.

Class group tabulation in quadratic fields and function fields

Team members are working on tabulating class groups and regulators for all real quadratic fields with discriminants less than 2 x 1011 by generalizing the methods used for a recent tabulation for imaginary quadratic fields, especially the algorithm for unconditionally verifying the correctness of the class numbers.

Splitting of primes in cubic function fields

This is the continuation of a project that was begun at the RMMC Summer School on Computational Number Theory and Applications to Cryptography, held in summer 2006 at the University of Wyoming. Research focuses on determining an explicit way to describe how prime ideals split in purely cubic function fields.

Cubic function fields from quadratic infrastructure

Up until now the connection between quadratic and cubic fields has been largely theoretical. ICANTC members are using this connection for algorithmic purposes, developing a very efficient way to generate all isomorphic triples of cubic function fields of a given discriminant from the quadratic function field of that same discriminant.

Strong anonymity with Buses

The ICANTC team is investigating the use of a novel protocol called Buses to provide strong connection anonymity to Internet applications. A novel modification of this protocol, called Taxis, has been shown to provide as strong anonymity as any other existing protocol with linear scalability – the first of its kind. The team continues to work toward even better scalability without sacrificing anonymity.

Objectives for Next Year

While key research activities and outreach will carry on in the coming year, the addition of new graduate and undergraduate students and collaborators to the ICANTC team will continue to broaden the scope of the research program. The principal objective of the ICANTC team is to ensure the sustainability of the organization beyond the term of iCORE funding, which ends in 2011. Several initiatives that support the ICANTC team's increased involvement in the highly pertinent area of information security will be key to achieving this goal.

The focus this upcoming year is to restructure CISaC to reflect the growing significance of information and the increasingly important role it is playing in the ICANTC group's work. As part of this effort, CISaC is initiating steps to elevate its status from a faculty centre to a university centre. Successfully gaining university centre status would raise CISaC's profile and increase its ability to collaborate more successfully with local industry and government.

Another objective related to long-term sustainability is the expansion of the CLIAS business plan to reflect a broader mandate. With support from the new iCORE Industrial Chair in Quantum Cryptography and Communication and the iCORE Chair in Information Security, CLIAS will now be able to offer a full spectrum of services pertaining to the increasingly important area of information security.

The group will also focus on revising and running the third year of the Distinguished Lecture Series in collaboration with the new iCORE Chair in Information Security, and is planning a new privacy meeting in collaboration with the Calgary Security Professionals Information Exchange (SPIE).

Focus will continue to be the design, analysis, testing, implementation, and benchmarking of cryptographic schemes that apply to privacy and ultimately information and network security.

Research Team Members and Contributions

Team Leader
Professor Hugh Williams
Professor, Department of Mathematics & Statistics
iCORE Chair in Algorithmic Number Theory & Cryptography
CISaC Director
NSERC Discovery Grant, 2005-2009
Alberta iCORE Award (2006-2011)
Co-Investigator, NSERC Strategic Projects Research Grant (2004-2007)
MITACS award (held jointly with Alfred Menezes of the University of Waterloo) for 2006-2007
Professeur Invité for May 2006 at LIRMM and the University of Montpellier II, France

Outreach

Over the past year, the ICANTC group has built on its already substantial outreach activities. The growing popular interest in cryptography and information security was evidenced in Galadriel Watson's book *That's Science*. The ICANTC group continues to expand information security outreach and build profile through activities such as public lectures, special workshops, conferences and summer schools.

The *MITACS Discrete Mathematics Seminar*, which resumes in autumn 2007, will continue to bring top researchers from around the world to the U of C. One of the key objectives for next year is to expand the scope of the seminars in collaboration with the new iCORE Chair in Information Security. CISaC continued to partner with the Centre for Military and Strategic Studies to offer for the third time the *Distinguished Lecture Series,* a series of seven invited lectures open to students, industry professionals, and the public. Both events continue to attract a growing audience and raise awareness of the work the ICANTC group is doing.

Another successful outreach activity is the ICANTC's annual privacy conference. The third conference *Preventing and Handling a Privacy Breach* took place November 14, 2006 at the TELUS Convention Centre in Calgary. The one-day conference featured plenary sessions with a number of subject matter experts and an interactive workshop conducted one of Canada's leading privacy law authorities. A fourth meeting is being planned for 2007 in collaboration with Security Professionals Information Exchange (SPIE).

In addition, Dr. Williams chaired the organizing committee for the Fields Institute's *Thematic Program on Cryptography*, held August 15 - December 15, 2006. The aim was to engage the cryptographic and mathematical communities in Canada and abroad to increase awareness of recent developments and to initiate more collaboration to attack important problems. Close to 300 academics, private sector participants, graduate students, and postdoctoral fellows were involved in the event, which should stimulate new thinking and joint research.

ICANTC team members also served on a number of committees and participated in several activities that help raise the ICANTC's profile within the global academic committee:

- Renate Scheidler was appointed editor for the journal *Advances in Mathematics of Communications*, guest editor for a special issue on Algorithmic Number Theory and Its Applications to appear in the *Japan Journal of Industrial and Applied Mathematics*, and served on the faculty hiring committee for the U of C Department of Mathematics & Statistics.
- Adrian Tang was an organizer of *Calgary Math Circles*, an outreach program of enriched mathematics for gifted elementary and high school students, and is Deputy Leader for Canada in the upcoming 47th International Mathematical Olympiad, to be held in Hanoi, Vietnam in July 2007.
- Hugh Williams remains editor-in-chief of *Contributions to Discrete Mathematics*, is an active member, NSERC GSC 331 (Computing and Information Science – B) 2006-2007, a main organizer of the CAIMS Theme Symposium (Cryptography on Small Devices), and was a member of the Program Committee for the *7th Algorithmic Number Theory Symposium*, Technische Universität, Berlin, July 23 - 28, 2006.

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Dr Mark Bauer	Assistant Professor, Department of Mathematics & Statistics	NSERC Discovery Grant, 2004-2007
Dr Vassil Dimitrov	Associate Professor, Department of Electrical & Computer Engineering Member, CISaC Management Board	Principal Investigator, NSERC Strategic Grant Novel Implementation of Cryptographic Algorithms on Custom Hardware Platforms, 2004-2007 NSERC Discovery Grant, 2005-2010
Dr Michael J. Jacobson, Jr.	Assistant Professor, Department of Computer Science Member, CISaC Management Board	CFI Infrastructure Operating Fund. NSERC Discovery Grant, 2006-2011
Dr Graham Jullien	Professor, Department of Electrical & Computer Engineering	Principal Investigator, NSERC Discovery Grant, 2002-2007
Dr Richard Mollin	Professor, Department of Mathematics & Statistics	NSERC Discovery Grant, 2005-2010
Dr Renate Scheidler	Associate Professor, Department of Mathematics & Statistics and the Department of Computer Science iCORE Research Associate Member, CISaC Management Board	Co-Investigator, NSERC Strategic Projects Research Grant; total award (2004-2007) NSERC Discovery Grant, 2006-2011

PostDoctoral Fellows

Name	Role/Topic	Awards/Special Info
Dr Reinier Bröker	Postdoctoral Fellow	Postdoctoral research fellowship, U of C, 2006
Dr Lassina Dembélé	Postdoctoral Fellow	PIMS Postdoctoral Fellowship, 2005-07
Dr Shaoquan Jiang	Postdoctoral Fellow	Postdoctoral research fellowship, U of C, 2006
Dr Pradeep Mishra	Postdoctoral Fellow	Postdoctoral research fellowship, U of C, 2004-2007

PhD Candidates		
Name	**Role/Topic**	**Awards/Special Info**
Andreas Hirt	PhD, Computer Science	Alberta Ingenuity Studentship, May 2005 – April 2010
Eric Landquist	PhD, Mathematics, University of Illinois at Urbana-Champaign (USA)	
William Lorimer	PhD, Computer Science	Began full-time employment as an IT security consultant with AEPOS Technologies Corporation of Gatineau, Quebec on January 17, 2007 Remains a full-time PhD student with CISaC while working toward his candidacy exam and thesis proposal in August 2007
Matthew Musson	PhD, Mathematics	Dean's Entrance Scholarship, U of C, 2006
Eric Roettger	PhD, Mathematics	
Pieter Rozenhart	PhD, Mathematics	Eric Milner Graduate Scholarship Award (2006) Henrietta Weyland Graduate Scholarship in Mathematics (2006)
Reg Sawilla	PhD, Computer Science	NSERC PGS-D award was changed to an NSERC CGS-D. (September 2004-August 2006) Graduate Student Scholarship (2004-2006) Alberta Ingenuity Incentive Award (2004-2006)
Alan Silvester	PhD, Mathematics	MSc awarded 2006
Adrian Tang	PhD, Mathematics	
Jonathon Webster	PhD, Mathematics	
Kjell Wooding	PhD, Mathematics and Electrical & Computer Engineering	NSERC PGS Doctoral award 2005-2006. Alberta Ingenuity, 2002-2007 iCORE Graduate Student Top Up, 2005-2006
Qingquan Wu	PhD, Mathematics, University of Illinois at Urbana-Champaign (USA)	Dissertation Completion Fellowship, University of Illinois at Urbana-Champaign, August 2006-August 2007

MSc Candidates

Name	Role/Topic	Awards/Special Info
Karel Bergmann	MSc, Computer Science	Department of Computer Science Research Award, January 2006, Queen Elizabeth II Graduate Scholarship, June 2006
Andy Chan	MSc, Computer Science and Electrical & Computing Engineering	
Sarah Chisholm	MSc, Mathematics	NSERC Post Graduate Scholarship 2007-2009
James Chou	MSc Mathematics	MSc awarded 2006
Rennie de Graaf	MSc, Computer Science	
Jonathon Hammell	MSc, Computer Science	U of C, Department of Computer Science Research Award, 2006
Taysa Krivoruchko	MSc, Computer Science	iCORE International Scholarship for two years, 2005-2007
Ahmed Obied	MSc Computer Science	
Manisha Parmar	MSc, Computer Science (part-time)	
Nick Sullivan	MSc Mathematics and Computer Science	MSc awarded 2006
Mark Velichka	MSc, Computer Science	NSERC (PGSM) September 2005 to August 2006 iCORE; September 2005 to August 2006
Ryan Vogt	MSc, Computer Science	NSERC (PGSM), September 2005 to August 2006 iCORE, September 2005 to August 2006 Dean's Research Excellence Award

Other Team Members

Name	Role/Topic	Awards/Special Info
Robert Carls	Research Associate, University of Sydney (Australia)	Visitor, February 2007
Andreas Enge	Professor, École Polytechnique, Paris (France)	Visitor, November 2006
Henri Faure	Professor, Institut de Mathématiques de Luminy, France	Visitor, May 2006
Florian Hess	Assistant Professor, Technical University of Berlin (Germany)	Visitor, February 2007
Stéphane Lemieux	Assistant Professor, Acadia University, Nova Scotia	Visitor, February 2007
Mridul Nandi	Postdoctoral Fellow, University of Waterloo	Visitor, March 2007
Roger Oyono	Postdoctoral Fellow, University of Waterloo	Visitor, March 2007
Alexis Roper	Administrative Support	
Francesco Sica	Associate Professor, Mount St. Allison University, Nova Scotia	Visitor, April 2006
Betty Teare	Manager, Budgets & Administration	
Marc Wrubleski	Technical Support	

GRADUATES

Name	*Research Topic*	*Current Position*
PostDoctoral Graduates		
Dr Stéphane Lemieux	Applications of Groups to Cryptography	Assistant Professor, Acadia University, Wolfville, NS effective August 2006
Dr Bodo Möller	Cryptography and information security	Assistant at the University of Bochum Communication Security Group
Dr Roger Patterson	Continued Fractions	Not Reported

Name	*Research Topic*	*Current Position*
MSc Graduates		
James Chou	A Survey of Point Counting Algorithms for Rational Points on Elliptic Curves	PhD student in Mathematics at Queen's University
Shantha Ramachandran	Numerical Results on Class Groups of Imaginary Quartic Fields	Employee at General Dynamics Canada, Calgary
Alan Silvester	Fast and Unconditional Principal Ideal Testing	PhD, Mathematics student; U of C
Nick Sullivan	Fast Algorithms for Arithmetic on Elliptic Curves over Prime Fields	Employee at Symantec, Calgary

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
ATIPS; U of C	A strategic joint Information and Communications Technology (ICT) initiative to perform research into demonstration-standard implementations of the AES cryptographic protocols for SONET/SDH add-drop multiplexer (ADM) equipment continues to develop with OnSite Systems Inc.
CLIAS Initiative	An initiative that has expanded to include the new iCORE Industrial Chair in Quantum Cryptography and Communication and the new iCORE Chair in Information Security
Cybersecurity Protectorate	Preliminary talks for an initiative focused on launching an institution devoted to developing and implementing technologies and practices designed to protect individuals and institutions in Alberta from unlawful intrusions from the Internet
National Collaborations	
Fields Institute	A six-month program devoted to cryptography including a series of lectures, graduate courses, and distinguished lecturers from July 1 - December 31, 2007
International Collaborations	
Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier (LIRMM), France	LIRMM is a part of the CNRS and is affiliated with the University of Montpellier II. This collaboration will permit easy exchange of students and researchers between the two institutions. A memorandum of understanding has been signed.

INTELLECTUAL PROPERTY

The ICANTC team has developed an intellectual property policy, which has been detailed in previous reports. This policy will be put into effect when appropriate opportunities arise. As most of the team's work is theoretical, such opportunities will occur in conjunction with other groups such as ATIPS, IQIS, or the new information security group (ICIS) in the Department of Computer Science at the U of C.

FUNDING

Dr Hugh Williams has a five year iCORE Chair award ($2.3M) and receives yearly federal research funding from NSERC, CFI, and other federal agencies ($529K).

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

J. Aycock, R. deGraaf, and M.J. Jacobson, Jr., "Anti-disassembly Using Cryptographic Hash Functions," *Journal in Computer Virology* **2** (2006), 79-85.

M. Bauer, M.J. Jacobson, Jr., Y. Lee & R. Scheidler, "Construction of Hyperelliptic Function Fields of High 3-rank," to appear in *Mathematics of Computation 2006.*

M. Bauer and Bennett, M. "On a Question of Erdos and Graham," to appear in *l'Enseignement Mathématique.*

R. de Haan, M.J. Jacobson, Jr., and H.C. Williams, "A Fast, Rigorous Technique for Computing the Regulator of a Real Quadratic Field," to appear in *Math. Comp.* 2007.

M. J. Jacobson, Jr., R. Scheidler and A. Stein, "Fast Arithmetic on Hyperelliptic Curves Via Continued Fraction Expansions," to appear in *Advances in Coding Theory and Cryptology, Series on Coding Theory and Cryptology* **2,** World Scientific Publishing Co. Pte. Ltd., Hackensack, New Jersey, 2007.

M.J. Jacobson, Jr., R. Scheidler, and A. Stein, "Cryptographic Protocols on Real and Imaginary Hyperelliptic Curves," conditionally accepted to *Advances in Mathematics of Communications*, 2007.

R. Mollin, "Cryptography and Zero Knowledge," to appear in *International Journal of Pure and Applied Mathematics.*

R. Mollin, "On a Generalized Kaplansky Conjecture," to appear in *International Journal of Contemporary Math. Sci.*

R. Patterson, A.J. van der Poorten and H.C. Williams, "Characterization of a Generalized Shanks Sequence," *Pacific Journal of Mathematics* **230** (2007), 185-216.

R. Scheidler and A. Stein, "Class Number Algorithms in Cubic Function Fields," to appear in *Journal of Number Theory.*

Q. Wu and R. Scheidler, "An Explicit Treatment of Biquadratic Function Fields", *Contributions to Discrete Mathematics* **2** (2007), 43-60.

REFEREED CONFERENCE PROCEEDINGS

J. Aycock, R. deGraaf, and M.J. Jacobson, Jr., "Anti-disassembly Using Cryptographic Hash Functions," proceedings of the *15th Annual EICAR Conference*, 2006, 38-47.

V.S. Dimitrov, K. Järvinen, M.J. Jacobson, Jr., W.F. Chan and Z. Huang, "FPGA Implementation of Point Multiplication on Koblitz Curves Using Kleinian Integers," *CHES* 2006 (Yokohama, Japan), LNCS **4249**, Springer 2006, 445-459.

S. Erickson, M.J. Jacobson, Jr., N. Shang, S. Shen, and A. Stein, "Explicit Formulas for Real Hyperelliptic Curves of Genus 2 in Affine Representation," to appear in *WAIFI* 2007.

C. Jacob, S. Steil and K. Bergmann, "The Swarming Body: Simulating the Decentralized Defenses of Immunity," in *Proc. International Conference on Artificial Immune Systems (ICARIS)*, 2006, 52-65.

M.J. Jacobson, Jr., S. Ramachandran, H.C. Williams, "Numerical Results on Class Groups of Imaginary Quadratic Fields," *Algorithmic Number Theory – ANTS-VII* (Berlin, Germany), LNCS **4076**, Springer, Berlin 2006, 87-101.

S. Jiang, "Efficient Primitives from Exponentiation in Zp," *Information Security and Privacy: 11th Australasian Conference*, ACISP'06, L. Batten and R. Safavi-Naini (Eds.), LNCS **4058**, Springer-Verlag, Melbourne, Australia, July 3-5, 2006, 259-270.

S. Jiang and G. Gong, "A Round and Communication Efficient Secure Ranking Protocol," *Topics in Cryptology - CT-RSA* 2006, The Cryptographers' Track at the RSA Conference 2006, David Pointcheval (Ed.), LNCS **3860**, Springer, Berlin 2006, 350-364.

T. Krivoruchko, J. Diamond and J. Hooper, "Storing RSA Private Keys in Your Head," to appear in the proceedings of the 12th Pacific Rim International Symposium on Dependable Computing.

R. Vogt, I. Nikolaidis and P. Gburzynski, "Divalia: A Practical Framework for Anonymous Peer-to-Peer File Exchange in Wireless Ad-hoc Networks," proceedings of the 4th Annual Conference on Communication Networks and Services Research (CNSR 2006), Moncton, Canada, May 24-25, 2006, 149-156.

R. Vogt, J. Aycock, and M. Jacobson, Jr. "Army of Botnets," to appear in *Proceedings of the 2007 Network and Distributed System Security Symposium (NDSS 2007)*, San Diego, CA, February 28 – March 2, 2007.

K. Wooding and H.C. Williams, "Doubly-focused Enumeration of Pseudosquares and Pseudocubes," *Algorithmic Number Theory – ANTS-VII (Berlin, Germany)*, LNCS **4076**, Springer, Berlin 2006, 208-221.

OTHER PUBLICATIONS

S. Jiang, "Deniable Authentication on the Internet," *IACR eprint 2007/082*. Available at http://eprint.iacr.org.

S. Lemieux and A. Tang, A. "Low-Cost RFID, Private Key Authentication, Abstractions of Integer Arithmetic". Preprint.

R. Vogt and J. Aycock, "Attack of the 50 Foot Botnet," *Technical Report 2006-840-33*, Department of Computer Science, University of Calgary, 2006.

PAPERS UNDER REVIEW

R. Bröker "A p-adic Algorithm to Compute the Hilbert Class Polynomials," submitted to *Mathematics of Computation*.

R. Bröker and P. Stevenhagen, "Constructing Elliptic Curves of Prime Order," submitted for the *Proceedings of the AMS Special Session on Computational Arithmetic Geometry*.

M.J. Jacobson, Jr., R. Scheidler and A. Stein, "Faster Cryptographic Key Exchange on Hyperelliptic Curves," submitted to *Advances in Mathematics of Communications*; also University of Calgary Yellow Series **847**.

BOOKS AND CHAPTERS

R. Mollin, *An Introduction to Cryptography* (Second Edition), September 2006.

SPECIAL/INVITED PRESENTATIONS

M. Bauer, *Relating the ECDLP to Other Curves*, Computational Challenges Arising in Algorithmic Number Theory and Cryptography, Fields Institute, Toronto, Ontario, November 2, 2006.

R. Bröker, *Constructing Elliptic Curves for Cryptography,* Fields Institute, Toronto, Ontario, September 2006.

R. Bröker, *p-adic Class Invariants*, workshop on Algebraic Varieties, Fields Institute, Toronto, Ontario, October 2006.

R. Bröker, *p-adic Class Invariants*, Calabi-Yau Seminar, Queen's University, Kingston, Ontario, November 2006.

R. Bröker, *Constructing Elliptic Curves for Cryptography*, Cryptography Seminar, University of Maryland, College Park (US), December 2006.

R. Bröker, *p-adic Class Invariants*, Number Theory Seminar, University of Maryland, College Park (US), December 2006.

R. Bröker, *p-adic Class Invariants*, Quebec-Vermont Number Theory Seminar, Montreal, PQ, February 2007.

M. Jacobson, Jr., I*mproved Point Multiplication on Koblitz Curves*, AMS Central Sectional Meeting – Special Session on Number Theory, Notre Dame University, South Bend, Indiana (US), April 2006.

M.J. Jacobson, Jr., *Computing Class Groups of Quadratic Fields*, Computational Challenges Arising in Algorithmic Number Theory and Cryptography, Fields Institute, Toronto, Ontario, November 2006.

W. Lorimer, *Authentication Using a Biometric Value*, Alberta Security Forum, Edmonton, Alberta, October 17, 2006.

W. Lorimer, *CISaC: Providing Benefits and Support to the Alberta Business Community,* CISaC Third Annual Privacy Conference, Calgary, Alberta, November 14, 2006.

R. Mollin, *Cryptographic Applications of Number Theory*, University of Iraklion, Crete, Greece, July 24-August 7, 2006.

R. Scheidler, *Real Hyperelliptic Curves Part I: Theory and Algorithms*, American Mathematics Society (AMS) Sectional Meeting 1016, Notre Dame University, Southbend, Indiana (US), April 8, 2006.

R. Scheidler, *Cryptography – The Art of Secret Writing – from Old to New*, Math Awareness Week, University of Delaware, Newark, Delaware (US), April 21, 2006.

R. Scheidler, *Units in Cubic Function Fields*, Canadian Mathematical Society (CMS) Summer Meeting, University of Calgary, Alberta, June 3, 2006.

R. Scheidler, *Cryptography – the Art of Secret Writing – from Old to New*, public lecture, Rocky Mountain Mathematics Consortium (RRMC) Graduate Summer School on Computational Number Theory and Applications to Cryptography, University of Wyoming, Laramie, Wyoming (US), June 29, 2006.

R. Scheidler, *Biquadratic Function Fields*, Joint Mathematical Meetings, New Orleans, Louisiana (US).

R. Scheidler, *Cantor versus NUCOMP on Hyperelliptic Curves*, Joint Mathematics Meetings, New Orleans, Louisiana (US), January 8, 2007.

A. Tang, *Steganography: The Art and Science of Hiding Messages In Ancient and Modern Wars*, Society of Military and Strategic Studies 8th Annual Student Conference, February 11, 2006.

A. Tang, *Continued Fractions and Arithmetic in Real Quadratic Function Fields*, Third Annual Alberta Young Researcher's Conference, April 1, 2006.

A. Tang, *Bounded-Visibility Cops and Robber*, Acadia University, November 24, 2006.

H. Williams, *Cryptography, Pseudosquares and Number Sieves*, Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier (LIRMM), France, May 24, 2006.

H. Williams, *How to Determine Whether an Ideal is Principal*, Mathematics Seminar, Department of Mathematics, University of Montpellier II (France), May 29, 2006.

H. Williams, *Private Parts: Man's Fruitless Quest, Throughout History, for a Means of Protecting Privacy*, Fields Institute Annual General Meeting, University of Toronto, Ontario, June 15, 2006.

H. Williams, *Computing the Regulator of a Real Quadratic Field, Counting by the Numbers: Algorithms, Precision, and Complexity*, Workshop in honour of the 60th birthday of Richard Brent, Berlin, July 21, 2006.

H. Williams, *Cryptography, Pseudosquares and Number Sieves*, Mathematics Department Colloquium, Queen's University, Kingston, Ontario, October 20, 2006.

H.C. Williams, *How to Determine Whether a Given Ideal is Principal I*, Tutte Seminar, University of Waterloo, Waterloo, Ontario, October 27, 2006.

H.C. Williams, *My reminiscences of Emma Lehmer, Workshop on Computational Challenges Arising in Algorithmic Number Theory and Cryptography*, Fields Institute, Toronto, Ontario, October 30, 2006.

H.C. Williams, *How to Determine Whether a Given Ideal is Principal II*, Québec-Vermont Number Theory Seminar 2006-2007, McGill University, Montreal, Quebec, November 9, 2006.

H.C. Williams, *Cryptography, Pseudosquares and Number Sieves*, Mathematics Department Colloquium, University of Colorado, Boulder, Colorado (US), December 4, 2006.

H.C. Williams, *Private Parts: Man's Fruitless Quest, throughout History, for a Means of Protecting Privacy*, University of Calgary Women's Club, January 27, 2007.

CONTRIBUTED TALKS

R. Bröker, *Modular Curves as Moduli Spaces*, Fields Institute, Toronto, Ontario, Number Theory Seminar, October 2006.

R. Bröker, *Constructing Elliptic Curves in Polynomial Time*, Midwest Number Theory Seminar, Urbana-Champaign (US), October 2006.

R. Bröker, *p-adic Class Invariants*, Number Theory and Cryptography Research Seminar, Fields Institute, Toronto, Ontario, November 2006.

M.J. Jacobson, Jr., *Sublinear Point Multiplication on Koblitz Curves Based on Kleinian Integers*, Discrete Mathematics Seminar, University of Calgary, Calgary, Alberta, November 2006.

M.J. Jacobson, Jr. *FPGA Implementation of Point Multiplication on Koblitz Curves Using Kleinian Integers*, CHES 2006, Yokohama, Japan, October 2006.

S. Jiang, *Password Based Key Exchange with Mutual Authentication*, ICT 516, University of Calgary, Alberta, September 2006.

S. Jiang, *Basic Cryptographic Techniques for Secure Communication*, TRLabs, Calgary, March 28, 2007.

S. Ramachandran, *Numerical Results on Class Groups of Imaginary Quadratic Fields*, Algorithmic Number Theory Symposium 7, Berlin (Germany), July 2007.

P. Rozenhart, *Binary Quadratic Forms: Integral Coefficients and Generalizations*, Third Annual Alberta Conference for Young Researchers in Mathematics, University of Alberta, Edmonton, Alberta, April 2006.

P. Rozenhart, *Splitting Primes in Cubic Function Fields: Introduction*, University of Wyoming Summer School on Computational Number Theory and Applications to Cryptography, University of Wyoming, July 2006.

A. Silvester, *Counting Cyclic Cubic Fields*, Third Annual Young Researchers Conference for Mathematical and Statistical Sciences, University of Alberta, Edmonton, Alberta, April 1 to 2, 2006.

A. Silvester, *TeX for Anyone Parts I and II*, Pure Mathematics Research Seminar, University of Calgary, Calgary, Alberta, April 2006.

A. Tang, *Low-Cost RFID, Private Key Authentication, Abstractions of Integer Arithmetic*, Number Theory Seminar, Fields Institute, December 6, 2006.

A. Tang, *Zero-Visibility Cops and Robber,* MITACS Discrete Math Seminar, University of Calgary, March 16, 2006.

K. Wooding, *Doubly-Focused Enumeration of Pseudosquares and Pseudocubes*, Algorithmic Number Theory Symposium 7, Berlin (Germany), July 2007.

Q. Wu, *Computing the Unit Group in Global Bicyclic Biquadratic Function Fields*, Number Theory Seminar, University of Illinois at Urbana-Champaign, October 26, 2007.

Q. Wu, *Computing the Unit Group in Global Bicyclic Biquadratic Function Fields*, Midwest Number Theory Conference for Graduate Students IV, October 28, 2007.

SPECIAL WORKSHOPS AND PANELS

Numerous students and faculty members co-organized, attended, or participated in the following:

- iCORE Banff Informatics Summit, The Banff Centre, May 23-25, 2006.
- CMS Summer Meeting, University of Calgary/Westin Hotel, June 3-5, 2006.
- Rocky Mountain Mathematics Consortium Summer School on *Computational Number Theory and Applications to Cryptography*, University of Wyoming, June 19-July 7, 2006.
- *Elliptic Curve Cryptography*, Fields Institute, Toronto, September 18-20, 2006.
- *Computational Challenges Arising in Algorithmic Number Theory and Cryptography*, Fields Institute, Toronto, October 30-November 3, 2006.
- *Thematic Program in Cryptography*, Fields Institute, Toronto, Fall 2006.

THESES

- Alan Silvester, *Fast and Unconditional Principal Ideal Testing*, M.Sc., December 2006.
- Nick Sullivan, *Fast Algorithms for Arithmetic on Elliptic Curves over Prime Fields*, M.Sc., December 2006.
- Shantha Ramachandran, *Numerical Results on Class Groups of Imaginary Quartic Fields*, M.Sc., September 2006.
- James Chou, *A Survey of Point Counting Algorithms for Rational Points on Elliptic Curves*, M.Sc., June 2006.

Information Security

The iCORE Chair in Information Security (iCIS) is expectd to substantially grow over the following years through recruitment of new staff members attracting researchers, post doctoral fellows and research students with interest in information security.

Dr Safavi-Naini took up the position of iCORE Chair in Information Security (iCIS) at the University of Calgary (U of C) in January 2007. The vision of the iCIS Lab is to be a leading research center for conducting first class research on all aspects of information security. The iCIS Lab promotes pure and applied research, and values industry collaboration and engagement with local industries.

The iCIS Lab is part of the Center for Information Security and Crypgraphy (CISaC) and complements and enhances research strengths of other CISaC groups including the iCORE Chair in Algorithmic Number Theory and Cryptography (ICANTC) and Institute for Quantum Information Science. Integration of iCIS within CISaC resulted in an overhaul of CISaC structure to better reflect the broad spectrum of research activities in the iCIS. This report provides a glimpse at some of the achievements of iCIS Lab's core members in recent months and sets objectives for next year. These objectives will evolve with new recruitments and expansion of the lab planned for the coming years.

Research contributions of other associated members including Dr Jacobson and Dr Scheidler will be included in future reports.

Achievement Highlights

Dr Safavi-Naini is a new iCORE Chair this year. During the academic year, she served as program co-Chair of Australian Conference on Information Security and Privacy (ACISP 06) and ACM Workshop on Digital Rights Management (ACM DRM 06). She was a plenary speaker at the opening of Taiwan Information Security Center (TWISC) at National Cheng Kung University and National Taiwan University of Science and Techology. Dr Safavi-Naini served on the steering committees of International Conference on Information Theoretic Security and Asiacrypt and on the program committees of major conferences on information security, including ACM Conference on Computer and Communication Security (CCS 060, Asiacrypt 2006, ACM Symposium on Information, Computer and Communications Security (ASIACCS 07), Crypto 2007 and Recent Advances in Intrusion detection (RAID 07).

Research team member, Dr Aycock, authored the book "Computer Viruses and Malware, Advances in Information Security", which was published by Springer-Verlag. The book has found wide interest amongst professionals and educators. Dr Aycock also delivered a number of invited talks including at the the High Technology Crime Investigation Association (Western Canadian Chapter) and at XIV Semana Informática, Lisbon, Portugal.

Research Program Overview

The iCIS research program focuses on information security. The main focuses of the program are outlined on the next page.

These directions will be developed over time, taking into account the interests and strengths of researchers as well as collaborative opportunities.

RESEARCH PROJECTS

Information Theoretic Security

Information theoretic security was founded by the seminal work of Claude Shannon in 1949, and has become increasingly important because of progress in quantum computing and the development of efficient quantum algorithms that can break major public key cryptosystems. In information theoretically secure systems, the adversary has unlimited resources and security is due to lack of sufficient information and not the limit on his resources, which is the main assumption in computationally secure systems.

Research in this area explores and derives fundamental bounds on security of systems and provides construction for the `best' systems that achieve the bounds with equality.

Applied Cryptography

Applied cryptography models security properties of real life applications, such as anonymity in an electronic voting system, and uses cryptographic techniques to design security systems that can provably guarantees that property. This area covers a wide array of applications, with probability of security being central in all cases. Provable security models the system by describing the system's participants and their interaction, the resources of the adversary and then states the security goal of the system. Security proof is by reducing the problem of `breaking' the system in this setting to solving a mathematical problem that is known to be `hard'. This `reduction' method has been the centerpiece of security proofs in recent years.

One of the focus areas for applied cryptographic systems will be cryptographic primitives that enhance users' privacy.

System and Software Security

System and software security takes a holistic view of the system, considers attacks on large complex systems, and proposes solutions that prevent or detect such attacks. The research covers a wide range of attacks due to malicious software like computer viruses, worms, spyware, and botnets, as well as spam and phishing attacks, and explores approaches to protecting the system against these attacks.

Wireless and Sensor Security

In recent years network attacks have become more sophisticated; automated tools have been developed to launch coordinated attacks from victim hosts distributed all around the world. iCIS is continuing to look at the possibility of Internet attacks on a massive scale.

The team will investigate sensor networks because they add new dimensions to security: because of their small physical size, they can be stolen or corrupted, and only lightweight security mechanisms can be used.

Objectives For Next Year

Broad objectives in relation to the vision of becoming a 'leading research group in information security' are:

- To conduct first-class research in information security and establish national and international reputation in this area
- Attract excellent staff, researchers, postdoctoral fellows, and graduate students
- Establish collaborative linkages with security research groups nationally and internationally
- To enhance course offerings in the Information Security concentration in the Department of Computer Science
- To attract funding to strengthen research capacity of iCIS Lab

Research Objectives

Information Theoretic Security

The focus of the work will be on modeling and analyzing authentication systems under the strongest adversary model and providing secure construction under this model. This work assumes that there is a trusted center that distributes the required key to system users. The team will consider other models that relax this assumption and explore security levels achieved in this case.

An important direction will be to explore synergy between this work and research in Quantum Information Science at the University of Calgary to build systems that can deliver this security.

Applied Cryptography

The focus of this work will be the development of cryptographic systems that can be used to enhance users' privacy in their electronic interactions.

There are a range of mechanisms that can be used for this purpose. Examples are credential schemes that allow users to authenticate themselves to services and access them without having to reveal their identity. Credentials can also be used by users to mutually authenticate each other based on their attributes.

System and Software Security

One goal of this research is the design and implementation of robust and secure content management systems. Important security properties to be considered are the protection of intellectual property rights of content owner, the privacy of access to database and efficient and robust back-up and recovery systems. A second goal of this research is to employ the above framework to design systems for protection of privacy rights, allowing end users to specify their preferences in the way their submitted data will be handled by organizations that have collected their data.

Wireless and Sensor Security

The iCIS team is continuing to look at the possibility of Internet attacks on a massive scale. By using compromised computers, adversaries have access to unprecedented amounts of data, computing power, and network connectivity. An ongoing project is to identify what new attacks are within the reach of adversaries as a result, and devise means to stop those attacks.

The iCIS team will provide abstract security models for the required properties and design systems that satisfy the requirements. The team will investigate methods of detecting intrusions in sensor networks.

The researchers are developing a lightweight Internet simulator that is tailored for use with spamming techniques. Initially this will be used as a training tool, but iCIS envisions extending it as a research platform in the future, and for it to handle network-based malicious software.

Outreach

The iCIS Lab organizes a successful seminar series called the iCIS Security Seminar Series. The series includes talks by invited speakers, research students, and staff on all aspects of information, computer, and communication security.

Professor Safavi-Naini and members of her team that attended iCORE's 2007 Banff Summit conference.

Research Team Members and Contributions

The membership listed below is envisaged to grow substantially over the next two years through recruitment of new staff members, attracting other researchers with interest in information security, and recruitment of postdoctoral fellows and research students.

Team Leader
Professor Rei Safavi-Naini
Co-Chair of ACM DRM Workshop, November 2006
Plenary speaker at the opening of Taiwan Information Security Center (TWISC) at National Cheng Kung University
Publicity Chair of RAID 2007, Recent Advances in Intrusion Detection
On the steering committees of International Conference on Information Theoretic Security and Asiacrypt
Served on the program committees of CCS 2006, ACM Conference on Computer and Communication Security, Asiacrypt 2006, Annual International Conference on the Theory and Application of Cryptology & Information Security, ASIACCS 2007, ACM Symposium on Information, Computer and Communications Security, Crypto 2007, the 27th Annual International Cryptology Conference and RAID 2007

Faculty Team Members	
Name	**Role/Topic**
John Aycock	Faculty Team Member
Ken Barker	Associate Team Member
Marina Gavrilova	Associate Team Member
Mike Jacobson	Associate Team Member
Renate Shielder	Associate Team Member

PostDoctoral Fellows		
Name	**Role/Topic**	**Awards/Special Info**
Jeffrey Horton	Associate Team Member	Australian research fund
Farzad Salim	Associate Team Member	Australian research fund
Nicholas Sheppard	Associate Team Member	Australian research fund
Shuhong Wang	Associate Team Member	Australian research fund

PhD Candidates		
Name	**Role/Topic**	**Awards/Special Info**
Liang Lu	Network security	Australian Scholarship
Angela Piper	Scalable watermarking	Australian Scholarship
Mohammed-Reza Reyhanitabar	Cryptgraphis hashing and authentication	Australian Scholarship
Siamak Fayyaz Shahandashti	Credential systems	Australian Scholarship

Other Team Members		
Name	**Role/Topic**	**Awards/Special Info**
Ton Kalker	Visited March 15-March 18	Based at HP Labs, Palo Alto
Atefeh Mashatan	Visited April 19-April 21	Based at University of Waterloo
Alfred Menezes	Visited May 2-May 6	Based at University of Waterloo

COLLABORATIONS

Dr Safavi-Naini is a Visiting Professorial Fellow at the University of Wollongong, Australia. She has been leading research projects in the areas of Digital Rights Management, Privacy Rights Management, Information theoretically secure signature schemes and next-generation firewalls, funded by the Australian Research Council, Smart Internet Technology Cooperative Research Center and Australian Defense Signal Directorate. She is supervising five PhD students in these areas. These projects were mostly finalized in July 2007.

Dr Safavi-Naini has had long-term collaboration with Dr Wild and Dr Desmedt on information theoretically secure authentication systems. Recently she has been collaborating with Dr Burmester and Dr di Crecenzo. Dr Burmester is Harris Professor in the Department of Computer Science at Florida State University. He will be visiting the iCIS Lab for a period of three months starting September 2007.

Dr Aycock has been collaborating with Alana Maurushat, a staff member and Ph.D. candidate in the Faculty of Law at the University of New South Wales, Australia. They have several projects underway exploring issues related to malicious software, ethics, and law.

Participants	*Nature of Collaboration*
International Collaborations	
Royal Holloway University of London, UK Peter Wild	Academic collaboration on joint research in Information Theoretic Security
University of Wollongong, Australia Nicholas Sheppard Farzad Salim Jeffrey Horton Shuhong Wang Markus Hagenbuchner	Academic collaboration on joint research in RightsManagement (Digital/Privacy), Information theoretic security, and Network security
University College London, UK Yvo Desmedt	Academic collaboration on joint research in Information Theoretic Security
University of New South Wales, Australia Alana Maurushat	Academic collaboration on joint research in malicious software, ethics, and law.
Telcordia Giovanni Di Crecenzo	Academic collaboration on joint research in Virus localisation
Florida State University Mike Burmester	Academic collaboration on joint research in Sensor network security

FUNDING

Dr Savfavi-Naini is a new awardee this year and received a five year iCORE Chair award ($3.9M).

PUBLICATIONS

BOOKS

J. Aycock, "Computer Viruses and Malware". *Advances in Information Security*, vol. 22, Springer-Verlag, 2006.

REFEREED CONFERENCE PROCEEDINGS

R. Vogt, J. Aycock, and M. Jacobson, Jr., "Army of Botnets ," in *14th Annual Network and Distributed System Security Symposium, 2007*, pp. 111-123. (15% acceptance rate.)

R. Wiangsripanawan, W. Susilo and R. Safavi-Naini, "Design Principles for Low Latency Anonymous Network Systems," *Australasian Information Security Workshop 2007* (Privacy Enhancing Technologies) AISW-PET2007, 2007 (to appear).

L. Lu, J. Horton, R. Safavi-Naini and W. Susilo, "Transport Layer Identification of Skype Traffic", *The International Conference on Information Networking* (ICOIN 2007), Lecture Notes in Computer Science, Springer-Verlag, 2007.

W. Lu, W. Li, R. Safavi-Naini, P. Ogunbona, "A Maximum Likelihood Watermark Decoding Scheme", *2007 International Conference on Multimedia and Expo* (ICME'07) - Multimedia Assurance Track, Bejing.

S. Shahandashti, R. Safavi-Naini, and J. Baek, "Concurrently-Secure Credential Ownership Proofs", *Proceedings of the 2nd ACM Symposium on Information, Computer and Communication Security* (ASIACCS), pp, 161 – 172.

R. Safavi-Naini, S. Wang and Y. Desmedt, "Unconditionally Secure Ring Authentication", *Proceedings of the 2nd ACM Symposium on Information, Computer and Communication Security* (ASIACCS), pp. 173 – 181.

D. Tonien, R. Safavi-Naini, and P. Wild, "Combinatorial Characterizations of Authentication Codes in Verification Oracle Model", *Proceedings of the 2nd ACM Symposium on Information, Computer and Communication Security* (ASIACCS), pp. 183 – 193.

L. Lu, J. Horton, R. Safavi-Naini and W. Susilo, "An Adversary Aware and Intrusion Detection Aware Attack Model Ranking Scheme", *Applied Cryptography and Network Security* (ACNS'07), 5~8 June, 2007.

M. R. Reyhanitabar, S. Wang, R. Safavi-Naini, "Non-interactive Manual Channel Message Authentication Based on eTCR Hash Functions", Accepted for *Australasian Conference on Security and Privacy* (ACISP 2007), July 2007, Darwin, Australia.

G. Taban and R. Safavi-Naini, "Key Establishment in Heterogeneous Self-Organized Networks", *Fourth European Workshop on Security and Privacy in Ad hoc and Sensor Networks* (ESAS 2007), June 2007, Cambridge, UK.

F. Salim, N. P. Sheppard and R. Safavi-Naini, "Enforcing P3P Policies Using a Digital Rights Management System Management System", *Privacy Enhancing Technologies* (PET 2007), Ottawa, Canada.

L. Lu, R. Safavi-Naini, J. Horton, M. Hagenbuchner, S.L. Yong, A.C. Tsoi, "Ranking Attack Graphs with Graph Neural Network", *Knowledge-Based and Intelligent Information & Engineering Systems* (KES 2007), invited session "IS43: Pattern Recognition in Graphical Domains".

Broadband Wireless Networks, Protocols, Applications & Performance

Wireless Traffic Modeling

Dr Williamson is now an iCORE Chair in Broadband Wireless Networks, Protocols, Applications and Performance and finishing year three of five of the NSERC/iCORE/TELUS Mobility Industrial Research Chair (IRC) in Wireless Internet Traffic Modeling.

This reports the 2006-2007 accomplishments of Dr Carey Williamson, iCORE Chair in Broadband Wireless Networks, Protocols, Applications, and Performance, in the Department of Computer Science at the University of Calgary (U of C). Combined, a research team of 23 people with interests in wireless networks, Internet technologies, and network performance is lead by Dr Williamson. Much of the research has an experimental flavour, with an applied focus on industrially relevant network and protocol performance issues.

The highlights of this last year include:

- Leading an active research team involving three faculty members, seven research staff, and ten students (five PhD, five MSc)
- Managing a team that collectively produced 22 research publications, with 11 more papers accepted for publication, and 12 more papers currently submitted and under review
- Supervising two graduate students to successful completion of their MSc programs
- Extensive service contributions at department, university, national, and international levels

Research Program Overview

Wireless LAN technologies are widely deployed and have become a vibrant part of our networked information infrastructure. Users appreciate the freedom of tetherless computing, and the ubiquity of wireless Internet access. WiFi hotspots are available in many airports, hotels, restaurants, bookstores, and coffee shops around the world. University administrators have also embraced wireless technologies as a convenient and economical means to provide ubiquitous Internet access to a large and tech-savvy generation of students.

Despite the prevalent deployment and use of WLAN technologies, wireless networks are not without performance problems. Many examples, primarily in the context of IEEE 802.11b, have been identified and studied by the Chair's iCORE research team in the last five years: the anomalies that arise with the Transmission Control Protocol (TCP) on wireless networks; the unfairness properties that emerge in infrastructure-based WLANs; and the "bad apple" phenomenon that can degrade WLAN performance for media streaming users. These problems arise because of multilayer interactions between Internet protocols, and from the unique characteristics of wireless network environments (e.g., mobility, transient connectivity, time-varying channel conditions).

Many of these protocol performance issues will pervade emerging wireless technologies as well. Wireless is inherently a broadcast technology, and many of the fairness, scalability, and security problems arise from this broadcast property. Furthermore, many of the IEEE WLAN standards require backwards compatibility with previous standards, which means that many of the same performance vulnerabilities remain.

The general objectives of the proposed research program are to:

- identify protocol performance problems in broadband wireless networks
- propose and evaluate innovative solutions to these performance problems

These objectives will guide the research exploration across a broad range of wireless technologies, including WiFi, WiMax, ad hoc, sensor, wireless mesh, and hybrid wireless/cellular network technologies.

The research will use a combination of experimental, simulation, and analytical approaches. Empirical measurement and experimental evaluation will be a mainstay in the research, using the state-of-the-art facilities provided by the CFI-funded Experimental Laboratory for Internet Systems and Applications (ELISA) lab, as well as the Wireless Internet Performance Laboratory at the U of C.

Strong partnerships and industrial collaboration are anticipated throughout the duration of the research program. Interactions with TELUS Mobility will continue via the NSERC/iCORE/TELUS Mobility Industrial Research Chair in Wireless Internet Traffic Modeling. In particular, the IRC research program focuses on “Wireless Internet”. It assumes an underlying telco cellular data network, as exemplified by CDMA2000 EV-DO networks. The data rates in these networks are inherently low: typically 10-100 kbps. User applications are highly constrained by the limited wireless network bandwidth, and the limited capability of the end user devices. The evolution of these networks to support integration with IEEE 802 WLAN technologies is also being considered.

Research Projects

This section describes selected projects underway in 2006-2007. The number of projects discussed is small; the chosen projects demonstrate the variety of network performance research carried out in the group, and complement the larger set of projects discussed in the reports from previous years.

WLAN Traffic Measurement

An initiative completed this year was the collection and analysis of Internet traffic from the U of C campus wireless network.

The research team used specialized wireless network monitoring devices called RFGrabbers to collect wireless traffic concurrently from nine selected locations on the campus WLAN for six weeks. The aggregate trace contains almost 1 billion wireless frames, representing the WLAN activity generated by 6,775 users and 97 access points over a period of 38 days. This is the longest duration study to date of a campus WLAN using wireless-side measurement techniques.

Analysis of the data sets identifies similarities and differences in the user behaviors across the observed WLAN locations, as well as emerging trends in WLAN usage regarding application usage and session mobility. The study complements and extends existing WLAN measurement studies in the networking literature.

Internet Traffic Classification

The demand for bandwidth management tools that optimize network performance and provide quality-of-service guarantees has increased substantially in recent years, in part, due to the phenomenal growth of bandwidth-hungry Peer-to-Peer (P2P) applications. Recent measurement studies in the literature suggest that P2P now accounts for 50 - 70% of Internet traffic. Many network operators are interested in prioritizing traffic on their networks. The ability to accurately (and in realtime) identify and categorize packet traffic by the network application responsible for the flow is critical.

MSc student Jeffrey Erman proposes a methodology that classifies network flows by application using only flow-level statistics. The methodology is based on machine learning principles, and consists of two key components: a learner and a classifier. The goal of the learner is to discern a mapping between flows and applications from a given training data set. Subsequently, this learned mapping is used to obtain a classifier. Erman developed a technique that handles both known and unknown application types by learning and classifying using both labeled and unlabeled training flows.

The results from Erman's classification work are impressive, showing flow accuracy up to 98%, and byte accuracy up to 93%. Six publications have appeared describing different aspects of the work, with several of these in high-profile venues.

Cellular Network Provisioning

Research team member Yujing Wu has been working on cellular data network provisioning, as part of the research team's IRC with TELUS Mobility. Yujing's work has focused on performance modeling of cellular data networks, and the service disciplines used in such systems, such as Proportional Fairness (PF) scheduling.

To develop simple traffic engineering rules for the downlink of a cellular system using PF scheduling, the team studies the "strict" and "approximate" insensitivity of a Processor Sharing (PS) system, specifically for the Egalitarian (EPS) and Discriminatory (DPS) variants of PS. In the EPS queue, all concurrent flows are allocated an equal share of transmission slots regardless of flow types and locations. The team proves the performance insensitivity of EPS in a relevant new case that has not been studied in the literature. In the DPS queue, each traffic type is divided into subclasses with different assigned weights. Asymmetric weights among the subclasses are used to model the unequal channel sharing that occurs with PF scheduling in heterogeneous channel conditions.

The team's results show that the first-order performance is largely insensitive to the input traffic characteristics, as long as the weights among subclasses are not highly skewed. The findings, confirmed by the simulation of a cellular system, imply reduced complexity for traffic provisioning procedures. However, the study also shows that the first-order performance is sensitive to the traffic details when there is discrimination among different traffic types. This observation implies that the introduction of differentiated services may pose a great challenge to network provisioning in future cellular systems.

Objectives for Next Year

This last year has been a banner year of publications for the Broadband Wireless Networks, Protocols, Applications, and Performance group. The group's work is being disseminated in high-quality and high-visibility places, including IEEE INFOCOM, ACM Multimedia, WWW, ACM SIGMETRICS, and IFIP Performance.

The objectives for the next year fall into two main categories: research and renewal.

On the research front, Dr Williamson will begin a six-month sabbatical July 2007 with the primary objective to complete a long-overdue research monograph on Network Performance. This book will provide a capstone to Dr Williamson's past 15 years of research

Outreach

On the media front, Dr Williamson was interviewed by Cheryl Croucher from Innovation Alberta about the Broadband Wireless Networks, Protocols, Applications, and Performance and Wireless Internet Traffic Modeling iCORE Chair, which aired January 2007. She also interviewed Dr Williamson about the WWW2007 conference, which aired February 2007.

on network performance issues, and become a reference resource for ongoing graduate-level teaching on this topic. Another objective is to broaden the team's research directions into WiMax, wireless mesh networks, sensor networks, and network security.

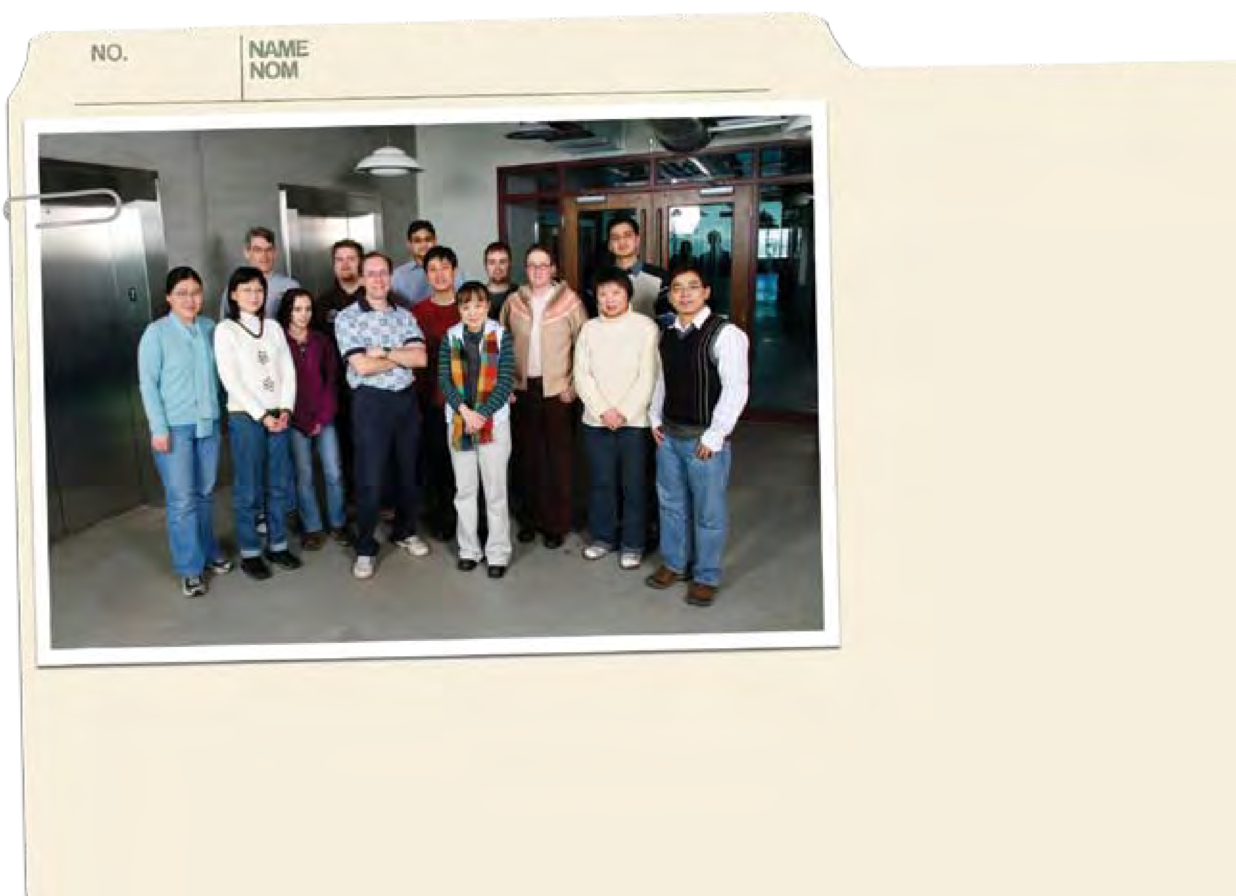
On the renewal front, the group has several holes to fill on the research team. The highest priority is finding a new junior colleague at the Assistant Professor level. Subsequent priorities are research staff, lab technical support, and research administrative support.

Research Team Members and Contributions

Team Leader
Professor Carey Williamson
NSERC/iCORE/Telus Mobility IRC

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Zongpeng Li	Network Coding, Optimization	Assistant Professor
Anirban Mahanti	Multimedia Systems	Assistant Professor



PhD Candidates		
Name	**Role/Topic**	**Awards/Special Info**
Jean Cao	Wireless Media Streaming	Candidacy December 2005
Mingwei Gong	Wireless Channel Scheduling	Candidacy January 2005
Ajay Gopinathan	Network Optimization	Supervised by Li
Emir Halepovic	Wireless Internet Performance	NSERC CGS and AB Ingenuity
Andreas Hirt	Anonymous Communication	NSERC CGS and AB Ingenuity Passed candidacy December 2005 Co-supervised
Nadim Parvez	TCP Modeling	Candidacy April 2007 Co-supervised

MSc Candidates		
Name	**Role/Topic**	**Awards/Special Info**
Naimul Basher	Network Measurement	iCORE Scholarship Supervised by Mahanti
Sean Boyden	TCP Vegas Video Streaming	Finished October 2006 Co-supervised
Jeffrey Erman	P2P Traffic Analysis	Queen Elizabeth Scholarship Supervised by Mahanti
Aniket Mahanti	Campus WLAN Measurement	Finished September 2006
Ahmed Obred	Network Security	Co-supervised with Jacobson
Partha Ramanujam	Game Theory	Supervised by Li and Higham
Phillipa Sessini	Media Streaming	NSERC USRA and CGS M Supervised by Li and Mahanti

Other Team Members		
Name	**Role/Topic**	**Awards/Special Info**
Martin Arlitt	Network Traffic Measurement	HPLabs, Grid Research Centre
Gwen Houtzager	Research/Admin Support	Transitioned March 2006
Jingxiang Luo	Wireless Network Traffic Modeling	TELUS Mobility project
Hongxia Sun	CDMA, Cellular, Stochastics	TELUS Mobility project
Nathan Wormsbecker	Network/System Admin	
Qian Wu	Network Simulation	Multi-channel MAC
Yujing Wu	Wireless, CDMA, EVDO	TELUS Mobility project

GRADUATES

Name	*Research Topic*	*Current Position/Awards*
Sean Boyden	"Streaming Media Performance with TCP Vegas"	Employed at General Dynamics
Emir Halepovic		Alberta Ingenuity award iCORE topup Killam fellowship
Aniket Mahanti	"Characterizing Usage of the AirUC WLAN"	Working as a Research Associate prior to starting his PhD at Georgia Tech
Nadim Parvez		Queen Elizabeth doctoral scholarship
Phillipa Sessini		(co-supervised by Anirban Mahanti and Zongpeng Li) NSERC CGS M

COLLABORATIONS

Participants	*Nature of Collaboration*
Institutional Collaborations	
CISaC	Member Organized by iCORE Chair Hugh Williams
Provincial Collaborations	
WestGrid	Member Long-term plans for file storage with WestGrid are being explored

Participants	*Nature of Collaboration*
National Collaborations	
NSERC	GSC-330 Member and Chair The committee received 170 Discovery Grant applications this year
ISSNet	Co-applicant A full proposal was submitted in Spring 2007 for a possible Strategic Network in the area of "Advanced Communication and Management of Information"
U of C, U of S, CFI	ELISA Lab Part of the TeleSim group Received a CFI IOF award to provide operating funds for lab support
International Collaborations	
SPECTS 2006	Local Arrangements Chair
WWW 2007	General Co-Chair Attended two IW3C2 committee meetings at WWW2006 in Edinburgh, Scotland Attended a meeting of the International World Wide Web Conference Committee (IW3C2) in Beijing to conduct a site visit of the facilities for the 17th International World Wide Web Conference (WWW2008)
IIT Delhi	New research collaboration was started with Professor S. Dharmaraja, who is currently collaborating with Hongxia Sun, Jingxiang Luo, and Dr Williamson on mathematical modeling for wireless networks
Industrial Collaborations	
TELUS Mobility	Part of the NSERC/TELUS/iCORE Industrial Research Chair in Wireless Internet Traffic Modeling Work with Hongxia Sun, Yujing Wu, and Dr Williamson continues on the 2006 Packet Data Modeling project for TELUS Mobility. A major emphasis is modeling Voice-over-IP (VoIP) and Quality of Service (QoS) mechanisms in EV-DO networks
TRLabs	Adjunct Scientists

FUNDING

Dr Carey Williamson has a five year iCORE Chair award ($2.1M) and a five year iCORE Industrial Chair award ($500K). This year he received funding from NSERC ($100K) and from his industry partners Telus Mobility and TRLabs ($100K).

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

M. Gong and C. Williamson, "Revisiting Unfairness in Web Server Scheduling", *Computer Networks,* Vol. 50, pp. 2183-2203, 2006.

G. Bai, K. Oladosu, and C. Williamson, "Performance Benchmarking of Wireless Web Servers", *Ad Hoc Networks*, Vol. 5, pp. 392-412, 2006.

Z. Li and B. Li, "Improving Throughput in Multi-hop Wireless Networks", *IEEE Transactions on Vehicular Technology*, Vol. 55, No. 3, May 2006.

Z. Li, B. Li, and L. Lau, "On Achieving Optimal Multicast Throughput in Undirected Networks", *IEEE Transactions on Information Theory*, Vol. 52, No. 6, June 2006.

J. Yuan, Z. Li, W. Yu, and B. Li, "A Cross-Layer Optimization Framework for Multihop Multicast in Wireless Mesh Networks", *IEEE Journal on Selected Areas in Communications*, Vol. 24, No. 11, November 2006.

M. Arlitt and C. Williamson, "The Extensive Challenges of Internet Application Measurement", to appear, *IEEE Network*, May/June 2007.

REFEREED CONFERENCE PROCEEDINGS

M. Gong, Q. Wu, and C. Williamson, "Queue Management Strategies to Improve TCP Fairness in IEEE 802.11 Wireless LANs", Proceedings of *2nd Workshop on Resource Allocation in Wireless Networks* (RAWNET), Boston, MA, April 2006. (Accept rate: unknown)

X. Cao, Y. Wu, and C. Williamson, "A Station-Based Adaptation Algorithm to Improve Robustness of IEEE 802.11", Proceedings of *7th IEEE International Symposium on a World of Wireless, Mobile, and Multimedia Networks* (WoWMoM), Buffalo, NY, pp. 410-418, June 2006. (Accept rate: 48/144 = 33%)

I. Wormsbecker and C. Williamson, "On Channel Selection Strategies for Multi-Channel MAC Protocols in Wireless Ad Hoc Networks", Proceedings of *2nd IEEE International Conference on Wireless and Mobile Computing, Networking, and Communications* (WiMob), Montreal, QC, pp. 212-220, June 2006. (Accept rate: 41/120 = 33%)

G. Houtzager, C. Jacob, and C. Williamson, "An Evolutionary Approach to Optimal Web Proxy Cache Placement", Proceedings of *IEEE Congress on Evolutionary Computation* (CEC), Vancouver, BC, July 2006. (Accept rate: approximately 30%)

H. Sun and C. Williamson, "On Pricing Strategies for Stochastic Capacity Networks", Proceedings of *IASTED CSA 2006*, Banff, AB, July 2006. (Accept rate: unknown)

H. Sun and C. Williamson, "On Effective Capacity in Time-Varying Wireless Networks", Proceedings of *SCS SPECTS 2006*, Calgary, AB, pp. 111-120, August 2006. (Accept rate: 71/116 = 61%)

P. Sessini and A. Mahanti, "Observations on Round-Trip Times of TCP Connections", Proceedings of *SCS SPECTS 2006*, Calgary, AB, pp. 347-353, August 2006. (Accept rate: 61%)

N. Basher and A. Mahanti, "A Simulation Study of Proxy Caching Algorithms and Strategies for Interactive Streaming Media", Proceedings of *SCS SPECTS 2006*, Calgary, AB, pp. 605-612, Calgary, AB, August 2006. (Accept rate: 61%)

Z. Li and A. Mahanti, "A Progressive Flow Auction Approach for Low-Cost On-Demand P2P Media Streaming", Proceedings of *QShine*, Waterloo, ON, August 2006. (Accept rate: unknown)

N. Parvez, A. Mahanti, and C. Williamson, "TCP NewReno: Slow-but-Steady or Impatient?", Proceedings of *IEEE International Communications Conference* (ICC), Istanbul, Turkey, August 2006. (Accept rate: 9822517 = 39%)

X. Cao and C. Williamson, "Towards Stadium-Scale Wireless Media Streaming", Proceedings of *IEEE/ACM MASCOTS*, Monterey, CA, pp. 33-42, September 2006. (Accept rate: 45/125 = 36%)

A. Madhukar and C. Williamson, "A Longitudinal Study of P2P Traffic Classification", Proceedings of *IEEE/ACM MASCOTS*, Monterey, CA, pp. 179-188, September 2006. (Accept rate: 36%)

J. Erman, A. Mahanti, and M. Arlitt, "Traffic Classification Using Clustering Algorithms", Proceedings of *ACM SIGCOMM Workshop on Mining Network Data* (MineNet), Pisa, Italy, September 2006. (Accept rate: 47%)

J. Erman, A. Mahanti, and M. Arlitt, "Internet Traffic Identification Using Machine Learning", Proceedings of *IEEE GLOBECOM*, San Francisco, California, November 2006. (Accept rate: 40%)

L. Shi, P. Sessini, A. Mahanti, Z. Li, and D. Eager, "Scalable Streaming for Heterogeneous Clients", Proceedings of *ACM Multimedia*, Santa Barbara, CA, November 2006. (Accept rate: 16%)

H. Sun, Q. Wu, and C. Williamson, "Impact of Stochastic Traffic Characteristics on Effective Capacity in CDMA Networks", Proceedings of the *2nd IEEE Workshop on Performance and Management of Wireless and Mobile Networks* (P2MNet), Tampa, FL, pp. 793-800, November 2006. (Accept rate: 16/42 = 38%)

P. Sessini, M. Leventer, and A. Mahanti, "Video to Go: The Effects of Mobility on Streaming Media in a CDMA2000 1xEV-DO Network", Proceedings of *ACM/SPIE Multimedia Computing and Networking Conference* (MCNC 2006), January 2007. (Accept rate: 30%)

S. Boyden, A. Mahanti, and C. Williamson, "TCP Vegas Performance with Streaming Media", to appear, Proceedings of *26th IEEE International Performance Computing and Communications Conference* (IPCCC), New Orleans, USA, April 2007. (Accept rate: 37%)

Z. Li, "Min-Cost Multicast of Selfish Information Flows", to appear, Proceedings of *IEEE INFOCOM*, Anchorage, Alaska, May 2007. (Accept rate: 18%)

J. Erman, A. Mahanti, M. Arlitt, and C. Williamson, "Identifying and Discriminating Between Web and Peer-to-Peer Traffic in the Network Core", to appear, Proceedings of *16th International World Wide Web Conference* (WWW2007), Banff, AB, pp. 883-892, May 2007. (Accept rate: 111/755 = 15%)

J. Erman, A. Mahanti, M. Arlitt, and C. Williamson, "Semi-Supervised Network Traffc Classification", to appear, *Proceedings of ACM SIGMETRICS Conference,* San Diego, California, June 2007. Poster paper. (Accept rate: 17% for full papers, 28% for poster papers)

J. Erman, A. Mahanti, and M. Arlitt, "Byte Me: A Case for Byte Accuracy in Traffic Classification", Proceedings of *ACM SIGCOMM Workshop on Mining Network Data* (MineNet), San Diego, California, June 2007. (Accept rate: unknown)

A. Mahanti and C. Williamson, "Assessing the Completeness of Wireless-side Tracing Mechanisms", to appear, Proceedings of *IEEE WoWMoM*, Helsinki, Finland, June 2007. (Accept rate: 47/148 = 32%)

Z. Li, B. Li, and M. Wang, "Optimization Models for Streaming in Multihop Wireless Networks", to appear, Proceedings of the 16th IEEE International Conference on Computer Communications and Networks (ICCCN), Honolulu, Hawaii, August 2007. (Accept rate: 29%)

A. Mahanti and C. Williamson, "Remote Analysis of a Distributed WLAN Using Passive Wireless-side Measurement", to appear, Proceedings of *IFIP Performance 2007*, Cologne, Germany, October 2007. (Accept rate: 24/103 = 23%).

Y. Wu and C. Williamson, "On Processor Sharing and Its Applications to Cellular Data Network Provisioning", to appear, Proceedings of *IFIP Performance 2007*, Cologne, Germany, October 2007. (Accept rate: 23%).

J. Erman, A. Mahanti, M. Arlitt, and C. Williamson, "Online/Realtime Network Track Classification Using Semi-Supervised Learning", to appear, Proceedings of *IFIP Performance 2007*, Cologne, Germany, October 2007. (Accept rate: 23%).

SPECIAL/INVITED PRESENTATIONS

"Wireless-Aware Protocol Stacks", *SPECTS 2006 Keynote*, August 1, 2006

"Performance Modeling of Stochastic Capacity Networks", *CanQueue 2006 Keynote*, September 15, 2006.

"Wireless Internet: The Good, The Bad, and The Ugly", *CISAC Seminar*, October 17, 2006.

THESES

Aniket Mahanti, Characterizing Usage of the AirUC WLAN, MSc, September 5, 2006.

Sean Boyden, Streaming Media Performance with TCP Vegas, MSc, October 24, 2006.

PAPERS UNDER REVIEW

N. Parvez, A. Mahanti, and C. Williamson, "An Analytic Throughput Model for TCP NewReno", submitted for publication, 2006.

A. Hirt, M. Jacobson, and C. Williamson, "Towards a Practical Buses Protocol for Anonymous Network Communication", submitted for publication, 2006.

Q. Wu and C. Williamson, "A DiffServ Framework for Context-Aware TCP/IP", submitted for publication, 2006.

Q. Wu, M. Gong, and C. Williamson, "Fairness Issues in IEEE 802.11 Wireless LANs", submitted for publication, 2006.

H. Sun, S. Dharmaraja, and C. Williamson, "On the Study of Stochastic Capacity Wireless Networks", submitted for publication, 2007.

J. Luo and C. Williamson, "Performance Implications of Fluctuating Server Capacity", submitted for publication, 2007.

A. Mahanti, C. Williamson, M. Arlitt, and A. Mahanti, "Characterization of a Campus WLAN: Challenges and Lessons Learned", submitted for publication, 2007.

P. Sessini, M. Arlitt, Z. Li, and A. Mahanti. "YouTube Traffic Characterization: A View from the Edge", submitted for publication, 2007.

N. Carlsson, D. Eager, Z. Li, and A. Mahanti. "Optimized Periodic Broadcast of Non-Linear Media", submitted for publication, 2007.

Z. Li, B. Li, and L.C. Lau, "A Finite Bound on Throughput Improvement of Network Coding in Undirected Networks", submitted for publication, 2007.

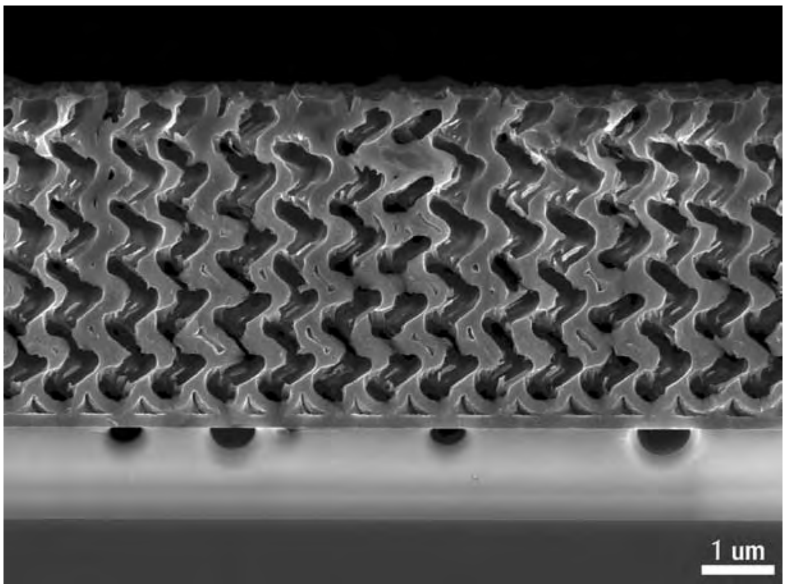
Z. Li, B. Li, D. Xu, and X. Chu, "Bandwidth-Efficient Information Access in Mobile Ad Hoc Networks", submitted for publication, 2007.

P. Sessini, L. Shi, A. Mahanti, Z. Li, and D. Eager, "Scalable On-demand Media Streaming for Heterogenous Clients", submitted for publication, 2007.

Nanoengineered ICT Devices

Thin Film Engineering

The Industrial Chair held by iCORE Professor Michael Brett continues to play an instrumental role in the growth of nanotechnology and nanofabrication research and training in Alberta.



An image of the inverse architecttures in silicon of the team's photonic crystals is to be included in an upcoming issue of the magazine Physics Today.

Key leadership initiatives have included the establishment of the University of Alberta (U of A) Micromachining and Nanofabrication Facility (NanoFab), cross appointment as Group Leader in Engineered Materials for Energy at the NRC National Institute of Nanotechnology (NINT) in Edmonton, and development of a new undergraduate program – the Nanoengineering Option of Engineering Physics.

The Laboratory for Nanoengineered ICT Devices has been involved in the development of nanostructured thin film materials and study of their device applications in the fields of sensors, photonics, energy, and nanobiotechnology. Industrial sponsorship by Micralyne and international collaboration with Philips Research (Netherlands) has provided a strong commercial perspective. A team of significant size and excellence has been assembled, comprising four professors, seven research associates, and 15 graduate students at its core, with 13 of the students recognized by major scholarships from Alberta Ingenuity or NSERC. Several of the research trainees have taken or will take their skills to the growing local Alberta nanotechnology industry. Initiatives such as the new Nanoengineering Option will help ensure a steady supply of highly qualified personnel for this field.

Dr Brett has continued his leadership in establishment of nanofabrication expertise and facilities, and has overseen the NanoFab in its growth to a user base of over 750 researchers. This facility is seen as the best of its kind in Canada, and defines Alberta as the focal point for nanotechnology processing by attracting users from six provinces. Recently Dr Brett has been the principal investigator for a successful application to the Alberta Science and Research Investments Program, which will provide funding for enhanced patterning processes to better fabricate micro- and nano-devices. Matching contributions from NINT will further improve the laboratory's etching and lithography capabilities.

Dr Brett's cross-appointment to NINT has provided new research opportunities through collaborations and access to a significant arsenal of equipment. A biosensor project has been initiated with Dr Mark McDermott, and application of porous nanostructured coatings to microfluidics devices is under exploration with Dr Jed Harrison. A significant new research thrust in collaboration with Dr Jillian Buriak is just underway in development of nanostructured photovoltaics, for application as low cost solar cells.

The nanofabrication facilities and collegial environment of NINT and the U of A, in conjunction with iCORE funding and top personnel, provide an ideal breeding ground for innovation in the development of new devices.

Research Program Overview

2006 marked end of the first year of the iCORE Professorship in the iCORE Laboratory for Nanoengineered ICT Devices and past the mid-point of the Micralyne/NSERC/iCORE Industrial Chair. The research of the Brett team within the iCORE Professorship and Industrial Chair programs is founded upon fabrication of nanostructured materials and application of those materials within devices for photonics, sensing, energy, medical, and display applications. Much of the research makes use of the Glancing Angle Deposition (GLAD) technology invented in the Laboratory for Nanoengineered ICT Devices, which is capable of creating nanostructures with unusual architectures in metal, semiconductor, insulator, polymer, and organic layers. This technology is leveraged by state-of-the-art nanofabrication capabilities at the U of A NanoFab, enabling fabrication of more complex materials and devices built upon the foundation of GLAD coatings. For the Micralyne/NSERC/iCORE Industrial Chair program it is particularly important to keep a focus on development of devices with commercial potential.

Dr Brett was cross appointed as a Senior Research Officer at NINT in summer, 2006, coinciding with the opening of the new NINT building on the U of A campus. This position has enabled access to a suite of specialized characterization tools at NINT, and catalyzed new collaborations with NINT researchers Dr Jed Harrison and Dr Mark McDermott, in the fields of microchromatograph devices on-chip and bio-sensor devices, respectively.

Research achievements of the past year have been made in a variety of application fields. The Laboratory for Nanoengineered ICT Devices has continued to be a leader in fabrication of square spiral photonic crystals for potential integrated optics applications, and has submitted two patent applications for new optical devices based on organic and inorganic materials. In collaboration with Dr Andriy Kovalenko of NINT, the laboratory has developed strong optical modeling capabilities to complement experimental work. Continuing collaborations include nanostructure fabrication, DNA assisted self-assembly, nanoelectromechanical devices, and liquid crystal devices described in the next section. Continuing external collaborations with Dr Tom Smy of Carleton University and Dr Dick Broer of Philips address modeling of nanostructure fabrication and materials for polymer microdevices. New external collaborations with Dr Lorne Whitehead of the University of British Columbia (UBC) and Dr Jim Tunney of the NRC ICPET laboratory (Ottawa) are catalyzing efforts in reflective displays and sensing. Also, in collaboration with Micralyne, projects have been initiated with a number of international firms in order to develop new product applications of the GLAD process.

Leadership in nanotechnology has been provided through establishment of the NanoFab at the U of A, the top single-location open-access facility in Canada. NanoFab has attracted over 750 users from 12 universities and six provinces, and is essential to new hires and also to established researchers currently comprising some 13 Canada Research Chairs. In early 2007, Dr Brett (as principal investigator) with co-applicants from four provinces (Alberta, BC, Saskatchewan, Manitoba) was awarded the Alberta Science and Research Investments Program for critical additions to the NanoFab, including high-capability electron beam lithography for precision nanoscale designs and a stepper for patterning complex structures.

Researchers are using the NanoFab equipment. Training for users in lithography and other fabrication processes has been provided by Stephanie Bozic, an iCORE-funded technician. Through the advanced training provided by Ms Bozic, iCORE has made a significant impact on facilitating the programs of 132 nanotechnology research and development teams. With a number of funding initiatives, Dr Brett and NanoFab Director Dr Ken Westra have been seeking to establish a new facility complementary to the NanoFab which would be dedicated specifically to training of new users, and enable increased undergraduate and graduate student training, including specific courses for external and industry researchers.

Generating and maintaining a strong supply of highly qualified personnel is necessary for a focused nanotechnology effort. To that end, as Director of Engineering Physics, Dr Brett led the formation of a new undergraduate BSc program: the Nanoengineering Option of Engineering Physics. This program admitted its first cohort of 17 engineering students into second year in fall, 2006, and will provide these engineers with specialty training in nanotechnology, nanobioengineering, and microfabrication. At the graduate level, Dr Brett has maintained outstanding recruitment: in a team of 15 graduate students, 13 hold scholarships at the NSERC level or higher.

Past graduates of the iCORE Professorship and ICE programs are playing key roles in Alberta nanotechnology development, including nanostructured materials for health applications, microdevice processing, and micro and nanodevices.

Research Projects

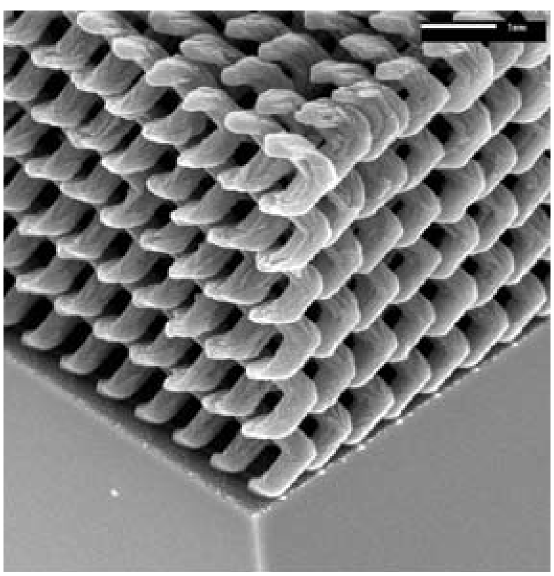
Traditionally, much of the research focus within Dr Brett's team involved complex structures that are engineered in thin film coatings on the nanoscale utilizing the GLAD process developed and patented at the U of A. These novel materials provide opportunities for team researchers to explore device applications where the nanoengineered architectures and large surface area provide advantages over conventional materials. In the past year new collaborations have led to a set of promising research projects involving biosensors and actuated devices, in addition to the areas of proposed activity identified in the 2005 annual report such as photonic devices, sensors, nanocomposite films, microfluidics, and aerosol studies.

A strong effort has been maintained in the photonics field, following closely the objectives outlined in last year's annual report, including achievements in photonic crystal fabrication, chiral luminescence, and optical filters. The first inverse square spiral photonic crystal structures (with theoretically improved optical characteristics) have been fabricated by team members Mark Summers and Jason Sorge. These structures consist of square spiral perforations in a silicon matrix, and are formed by inverting a regular square spiral using filling and etching processes. In collaboration with chemist Dr Jillian Buriak and PhD student Steven Chai, block co-polymer nanostructures have been developed and are under examination for their utility in photonic crystal fabrication.

In further photonics work, collaboration with Theory and Modelling Group Leader Andriy Kovalenko of NINT, Post Doctorate Fellow Kyrylo Tabunshchyk, and graduate student Viktor Leontyev has led to the development of simulators to predict optical behaviour of chiral nanostructures. These models have been used to optimize narrow bandpass optical filter devices, which were fabricated by PhD student Matthew Hawkeye. PhD student James Gospodyn has mastered methods for characterizing optical properties of nanostructured coatings with spectroscopic ellipsometry in order to provide necessary comparisons between theory and experiment. The team has also continued to develop its expertise in organic optical devices. The Laboratory for Nanoengineered ICT Devices has characterized the unusually strong chiral optical properties and preferential circular polarized luminescence in Alq3 films, created by the precise architecture of a self-organized array of helices. The architectural perfection of the organic structures is exceptional and unusual, and a US Patent has been submitted to cover this intellectual property, as there are potential applications to flat panel displays.

The Laboratory for Nanoengineered ICT Devices continues to develop its fast response humidity sensor devices, and has demonstrated both optical and capacitive sensing mechanisms. The laboratory has demonstrated how to tune the response by surface chemical functionalization. This development opens the door to the creation of sensors with chemical specificity. New applications to sensing other gases are under development, as sensing is a technology of strong interest to industrial sponsor Micralyne. The laboratory has initiated a biosensing project using GLAD structures in surface plasmon resonance devices to detect immunoglobulin. In a different approach to sensing by the Evoy group, small cantilevers (dynamic tunneling resonant devices) have been fabricated utilizing low-stress nanocomposite films that enable extremely sensitive resonant detection of self-assembled layers on the surface of the cantilever.

The microfabrication of polymer and liquid crystalline polymer structures are known to function as "artificial muscles" in response to various stimuli, and hold promise for actuation in plastic micromachined devices. The impregnation of porous nanostructures with dyes and liquid crystals has been studied. New



Another image of the architectures in silicon of the team's photonic crystals to be included in an upcoming issue of Physics Today.

methods for nanoscale patterning, utilizing programmed self-assembly of DNA has also been studied, and initial work has involved nanowire fabrication.

Some new projects have been initiated in the past year. Electrical actuation of nanospring devices has been demonstrated, with the initial results published in Applied Physics. The critical breakthrough necessary to achieve this result was the development of structuring of soft organic materials to form the springs. With improvement in performance, these devices may have application in electrically tuned mirrors in microdevices. Application of porous GLAD coatings in microfluidic or microchromatograph devices was tested; the GLAD coatings may offer advantages due to the range of structures and materials available.

Former team members have gone on to establish a collaboration dealing with new technologies for high contrast, low power reflective displays with Dr Lorne Whitehead.

Dr Brett and Dr Warren Finlay of Mechanical Engineering have continued efforts to utilize the GLAD process as a means to fabricate particles of precise geometry to be used in medical aerosol inhalation experiments. This work is sponsored in part by the 2006 award of an NSERC Special Research Opportunities. The capability of the GLAD process to precisely engineer nanostructural shapes provides a method to fabricate and evaluate the fluidic transport of aerosol particles dependent on particle geometry.

Objectives for Next Year

Projects for the coming year will emphasize further research in the key areas of photonic devices and materials, biosensors and gas sensors, microchromatograph devices. Projects will also emphasize collaborative efforts in optical modeling, hybrid liquid crystal optical devices, aerosols, and technologies for reflective displays.

Emphasis on development of nanostructured materials for photonic devices will continue. Optimization of photonic crystals is ongoing, with emphasis to be placed on improving the architecture of square spirals through the use of ion bombardment processes during deposition. Characterization of inverse square spiral photonic crystals will be performed, and the exacting process steps necessary to create these materials will be improved. The new optical modeling capability is enabling improved prediction of ideal structures, and will shorten the fabrication/test/redesign cycle. Optical modeling will also be used to explore new geometries for narrow bandpass rugate optical filters, with the ultimate goal of producing a device with optical behaviour that can be electrically switched. In another (related) modeling effort, collaboration has been re-established with Dr Tom Smy of Carleton University, with whom Dr Brett collaborated for over a decade in development of thin film growth simulators. Dr Smy will provide software models that are key to understanding how GLAD nanostructures grow, hopefully enabling optimization of our fabrication process. Development of reflective display technologies in collaboration with the Whitehead group at UBC will be continued.

The Laboratory for Nanoengineered ICT Devices will focus on collaborations to test conductive response of the team's sensors to various gases, and look at remote optical sensing of gases using optical fibre techniques and spectrophotometry. Continuing efforts will be made to understand the mechanisms for fast and/or specific response of the devices.

A stronger focus will be placed on research studying the use of GLAD porous coatings in microfluidic devices. Standard flat chromatograph plates will be developed, in order to better understand the transport behaviour through the structures. The next phase is construction and demonstration of microchromatography, wherein the challenge is to develop a fabrication process that will fill standard channels with specific GLAD nanostructures.

Five new core researchers have or will join the team, and some of these researchers (with the addition of a Masters student) will form the core of a new effort in renewable energy in collaboration with the Buriak team of Chemistry/NINT. One of the projects the laboratory will explore is the application of GLAD to produce low-cost, large area solar cells.

A strong connection with sponsor Micralyne will be maintained, particularly through Chief Scientist Glen Fitzpatrick and VP Marketing Bruce Alton. A number of exploratory (proprietary) projects are underway and some will be completed in the coming year. The valuable collaboration (in its second decade) with polymer and liquid crystal experts at Philips Research will be continued.

Outreach

Rick Mercer Report, January 16, 2007: Michael Brett and Stephanie Bozic appeared in the NanoFab with Rick Mercer for his nationally broadcast CBC comedy show.

Research Team Members and Contributions

Team Leader
Professor Michael Brett
Nanostructure Engineering

Research Associates	
Name	**Role/Topic**
Dr Jim Broughton	Supercapacitors
Tao Kong	Visiting researcher
Ms Shufen Tsoi	Surface Modification
Dr Doug Vick	Nanostructured Growth
Zhenxing Wang	Visiting researcher

Faculty Team Members	
Name	**Role/Topic**
Dr Stephane Evoy	Nanoelectromechanical Systems
Dr Jie Chen	DNA Templating
Dr Jeremy Sit	Nanostructured Devices

PostDoctoral Fellows		
Name	**Role/Topic**	**Awards/Special Info**
Dr Michael Fleischauer	Nanostructured polymers	NSERC, Killam, Ingenuity PDFs
Dr Nathan Gerein		
Dr Kryrlo Tabunshchyk	Optical modeling of nanostructures	
Dr Michael Taschuk		NSERC PDF

PhD Candidates

Name	Role/Topic	Awards/Special Info
Steven Chai	Block co-polymers	NSERC PGSD, Ingenuity
Graeme Dice		NSERC CGSD, Ingenuity, iCORE
Anastasia Elias	Replica nanostructures	NSERC CGSD, Ingenuity, iCORE
Doug Gish	Nanofibre devices	NSERC PGSD, Ingenuity, iCORE
James Gospodyn		
Matthew Hawkeye	Photonic filters	NSERC PGSD, Ingenuity, iCORE
Peter Hrudey		NSERC PGSD, iCORE
Katie Krause		NSERC CGSD, Ingenuity, iCORE, QEII
Viktor Leontyev		
Andy Van Popta	Chiral photonic devices	NSERC CGSD, iCORE, SPIE, Dissertation, Andrew Stewart
Jason Sorge	Potonic Crystal Wave guides	NSERC PGSD, iCORE, QEII
John Steele	Sensor devices	NSERC PGSD, iCORE
Mark Summers	Photonic Crystal Materials	NSERC PGSD, Ingenuity, iCORE, Killam

MSc Candidates

Name	Role/Topic	Awards/Special Info
Louis Bezuidenhout		NSERC CGSM, Ingenuity, iCORE
Sumudu Fernando		NSERC CGSM, Ingenuity, iCORE
Nathan Nelson-Fitzpatrick	Nanomechanical Resonators	Queen Elizabeth II
Bryan Szeto	Organiz Nanostructures	Kaplan
Nick Wakefield		Graduated 2005 as the top graduate in the Faculty of Engineering at U of A NSERC CGSD, iCORE, Ingenuity Ralph Steinhauer

Other Team Members

Name	Role/Topic	Awards/Special Info
Ben Bathgate	Technician	
Stephenie Bozic	Nanofabrication Technician	
Rebecca Hansen	Summer student researcher	
Karin Hayward	Administrative Assistant	
Robert Joseph	Summer student researcher	NSERC USRA

GRADUATES

Name	*Research Topic*	*Current Position*
PhD Graduates		
Anastasia Elias	Polymer nanostructures	NSERC PDF award
Peter Hrudey	Organic optical materials	NSERC PDF at UBC
RA Graduates		
James Broughton	Supercapacitor materials	Consulting
Doug Vick	Thin film growth	NINT research officer

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
U of A Mech Eng Dr W. Finlay	Fabrication of nanoengineered aerosol particles
U of A Elect. Comp. Eng Dr R. Fedosejevs Dr Y. Tsui	Optical characterization of nanostructures
U of A Elect. Comp. Eng Dr K. Westra	Nanostructured inorganic materials
U of A Chemistry/NINT Dr M. McDermott	SPR devices for sensing
U of A Chemistry/NINT Dr D.J. Harrison	Microfluidic devices
U of A Chemistry/NINT Dr J. Buriak	Polymer nanostructures, solar cells
U of A Chemistry Dr J. Veinot	Sensor devices and organic materials
NINT Dr A. Kovalenko	Optical theory and modelling

Participants	*Nature of Collaboration*
National Collaborations	
UBC Physics Dr L. Whitehead	Reflective display devices
NRC - ICPET Dr J. Tunney	Sensor devices
Carleton University Dr T Smy	Nanostructure growth modelling
International Collaborations	
Philips Research Corp., Netherlands Dr D Broer	Study of nanostructured liquid crystal devices
Tech. Univ.of Eindhoven, Netherlands Dr K. Bastiaansen	Polymer nanostructures and devices
Quantachrome, USA Matthias Thommes	Porous material characterization

INTELLECTUAL PROPERTY

Patents	*Title/Name*	*Status*
DE 69808653, EP1007754B(UK), EP1007754B(FR)	Glancing Angle Deposition of Thin Films	Granted prior to this year
US 5,866,204	Method of Depositing Shadow Sculpted Thin Films	Granted prior to this year
US 6,206,065	Glancing Angle Deposition with Controlled Porosity	Granted prior to this year
US 6,248,422	Shadow Sculpted Thin Films	Granted prior to this year
US 6,549,253	Optical Device	Granted prior to this year
WO9803695	Capped Porous Thin Films	Granted prior to this year
WO9906608	Glancing Angle Deposition of Thin Films	Granted prior to this year
CA 2,182,452	Shadow Sculpted Thin Films	Under review
CA 2,237,732	Glancing Angle Deposition of Thin Films	Under review
JP 2001502013	Capped Porous Thin Films	Under review
JP 2002509188	Glancing Angle Deposition of Thin Films	Under review

Patents	Title/Name	Status
US Provisional 60/719,905	Transparent Conductive Film with a Large Birefringence	Filed September 23, 2005
US application based on above	Transparent Conductive Film with a Large Birefringence	Filed September 22, 2005
US Provisional 60/740,901	Organic Luminescent Chiral Device	Filed November 30, 2005
US application based on above	Organic Luminescent Chiral Device	Filed November 29, 2005

SPIN-OFF COMPANIES

Name	Topic	Statsus
Chiral TF Devices Inc.		In a holding mode

FUNDING

Dr Michael Brett has a five year iCORE Professor award ($1.5M) and a five year iCORE Industrial Chair award ($500K). This year he received federal funds from NSERC ($548K) and CFI ($185K). He shares an NSERC facilities grant with Dr Mark Freeman ($245K). Other funding includes a Tier 1 Canada Research Chair ($200K) and cash and in-kind industry contributions ($139K).

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S. Tsoi, B. Szeto, M.D. Fleischauer, J.G.C. Veinot, and M.J. Brett, "Control of Alq3 Wetting Layer Thickness via Substrate Surface Functionalization," *Langmuir*, Apr. 21, 2007.

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SPECIAL/INVITED PRESENTATIONS

M.J. Brett, "Nanoengineered Thin Film Research and Nanofabrication Facilities," Invited seminar at *IEEE Ottawa (CAS/EDS/SSC Chapters) and Dept. Electronics* (Carleton U.), Ottawa, Mar. 19, 2007.

M.J. Brett, "Fabrication and Applications of Porous, Nanostructured Thin Films," Invited talk at *2006 Symposium of the Pacific Northwest Chapter of the AVS*, Forest Grove, Oregon, Sept. 21, 2006.

M.J. Brett, "Nanofabrication Facilities and Nanoengineered Thin Film Research," Invited seminar at the *Canadian Light Source*, Saskatoon, May 5, 2006.

M.J. Brett, "Nanoengineered Thin Film Research," Seminar at *NINT Sensors and Devices Group*, Edmonton, May 29, 2006.

Nanoscale Physics and Nanomaterials

The iCORE Centre for Nanoscale Physics and Nanomaterials Research (CoreNano) aims to be an integral component of the local nanoscale science and technology community and a source of exceptionally trained personnel for the Alberta nanotechnology research cluster.

Dr Freeman (right) and one of his team members (left) working in the lab.

The mission of CoreNano is to build upon strengths in nanoscale engineering physics to develop world-class expertise in selected areas of nanoscience. CoreNano is interested in the fundamental properties of the building blocks of future information technologies. These include nanomagnets and photonic devices.

Physics as a core discipline, and Condensed Matter Physics in particular, is an essential underpinning of nanotechnology. CoreNano aims to train students with the ability and interest to investigate fundamental questions at the foundations of applications. The earlier incarnation of CoreNano as part of the iCORE Nanoscale Engineering Physics Initiative (led by Drs Michael Brett and Mark Freeman) helped to develop the foundations for the critical mass of local nanotech activity now conducted through NanoFab and within the National Institute for Nanotechnology (NINT).

CoreNano continues to stress fundamental aspects of physics at the nanoscale level in efforts both to exploit and to accelerate the feedback between nanoscience and nanotechnology. CoreNano's primary focus is on nonequilibrium physical properties of nanosystems relevant to future ICT. Nonequilibrium properties ultimately underlie the operation of all active devices, and also pose some of the most interesting questions for current study.

CoreNano funds are used to support personnel at all stages of development, from undergraduates through postdoctoral fellows, in the acquisition of skills critical to international competitiveness in the high-tech sector. The activities of many of the personnel receive complementary support from other sources, particularly scholarships and fellowships. Twenty-five graduate students, five postdoctoral fellows, and three undergraduate students have been supported in part by CoreNano during this last year. Eight trainees from the past six years are now employed in the local Alberta nanotech industry. In addition, six undergraduates who worked with CoreNano went on to graduate studies in Alberta (either at the University of Alberta or University of Calgary).

A significant milestone for 2006-2007 was the funding of the "Ultrafast Nanotools Laboratory" proposal headed by Frank Hegmann, by the Canada Foundation for Innovation (CFI) and the Alberta Science and Research Investments Program (ASRIP). It is fair to say that this success would not have occurred without iCORE support. This instrumentation will start to arrive in Phase 1 of the Centennial Centre for Interdisciplinary Science in 2007-2008. The new lasers and microscopes will greatly extend the team's abilities to investigate the properties of nanosystems away from equilibrium, and can be applied to a broad range of problems encompassing one or more optical, electronic, magnetic, or mechanical properties.

applications including ultrahigh frequency nanomechanical devices.

During the first half of this reporting year, the CoreNano's laboratories from the (now demolished) Avadh Bhatia Physics Laboratory were relocated to Phase 1 of the new Centennial Centre for Interdisciplinary Science (CCIS). CCIS allows the team to expand the attempted scope of its efforts by removing an immediate limitation of space. A regeneratively-amplified Ti:sapphire laser system, acquired through the CFI and ASRIP funding, will fill an important void at the geometric centre of the tradeoff-space of pulse energy versus repetition rate currently limited to bookends

Research Program Overview

CoreNano is interested in the fundamental properties of the building blocks of future information technologies; nanomagnets and photonic devices. Conventional magnetic information storage methods have already evolved quite far into the "nano" regime, and the potential for new technologies such as spin electronics and nanomagnetic logic is significant.

The performance of all active devices used in information and communications technology is determined by the response of these systems to the addition of energy from an external source (usually by electrical, optical, or magnetic means). The underlying physics can be elucidated by pumping in extra energy "instantaneously" (much faster than the system can respond), and then tracking the evolution as a function of time. This approach becomes progressively more challenging as the systems of greatest interest decrease in size. Fortunately, CoreNano are now in the middle of great advances in the study of nanoscale dynamics through ultrafast microscopy. Ultrafast laser technology, partnered with continually improving microscopes (optical and scanned probe in this case), creates remarkable opportunities to extend the boundaries of stroboscopic imaging to shorter length and time scales. CoreNano has been studying magnetization dynamics in microstructures and nanosystems through time-resolved magneto-optical microscopy; ultrafast electron dynamics in molecules through time-domain terahertz spectroscopy; and electronic and photonic properties of inorganic nanostructures. CoreNano has begun to extend these approaches to other fascinating

where the average beam power remains roughly constant. The much higher (about 300x) pulse energy than non-amplified Ti:sapphire oscillators will enable new types of excitation for nonequilibrium studies, and broadband spectroscopy through nonlinear optical techniques. Meanwhile, the much higher repetition rate (about 300x) is much better suited to stroboscopic microscopy than that of existing amplifiers. The new Ultrafast Nanotools Laboratory in CCIS will also house an ultrahigh vacuum scanning tunneling microscope interfaced to the laser and to other high speed electronics, plus a combination confocal/near-field scanning microscope for high spatial resolution optical work.

In the annals of CoreNano alumni, highlights include former PhD student Kristen Buchanan joining the regular staff of the Center for Nanoscale Science and Technology at Argonne National Laboratory, where she was formerly a student. CoreNano continues to work with Mirwais Aktary at his company Applied Nanotools on new resist materials for electron beam lithography. Norcada Inc. in Edmonton and CoreNano are working together on nanomechanical devices. CoreNano's collaboration with Wayne Hiebert at the National Institute for Nanotechnology now includes the PhD projects of two students, Kar Mun Cheng and Joe Losby.

Research Projects

Technological applications are still far from having reached the limiting performance of magnetic devices. These remain primarily in the area of data storage with an additional growing emphasis on logic and computation. Team member Zhigang Liu's work on the determination of damping in ferromagnetic thin films using time-resolved magneto-optical Kerr effect microscopy was completed and recently published in Physical Review Letters. Damping in conducting ferromagnets is becoming necessary to engineer these intrinsic materials property through alloy composition in order to continue to enhance device performance. In addition, from the perspective of fundamental interest, it is only now becoming feasible to calculate the theoretically expected damping, although the framework for the calculations has been in existence for several decades. Continuing from this work, CoreNano has studied the magnetization dynamics in individual ferromagnetic nanostructures using the resonance frequency spectrum as a fingerprint of the magnetic configuration. The transitions between vortex states and quasi-single domain states in nanodisks have been examined in this manner, and the three-dimensional shape of the disks significantly influences the applied magnetic field strengths that switch between different states. This work sets the stage for many of CoreNano's plans involving nanomagnets.

In related magnetism work, many visits from CoreNano collaborators Bartek Kardasz and Alexandre Mosendz have culminated in an understanding of how to observe spin pumping between magnetic multilayers using ultrafast optical techniques.

CoreNano continued to investigate the routes to nanoscale control of silicon surface passivation in scanning tunneling microscopy experiments. The team's work on STM-induced dissociative reactions of physisorbed molecular hydrogen on silicon at cryogenic temperatures expanded to include exploration of an isotope effect on the reaction mechanism.

Collaborations organized through participation in NINT are proceeding on a number of fronts. NINT greatly expands the range of materials, devices, and techniques which CoreNano can variously exploit and elucidate through our research. Team member Robert Bryce, working closely with Dr Mirwais Aktary of Applied Nanotools, has developed a new electron beam resist of utility for patterning sub-micrometer stuctures in microfluidic. Bryce's PhD thesis work centers on novel applications of polymers in microfluidics, and in particular on the goal of using dilute polymer additions to promote mixing in electroosmotic-driven flow through the mechanism of elastic turbulence. Also on the "soft matter" front, the team's collaborators at the University of Manitoba have completed extensive simulations of the performance of the microwave capacitance probe, yielding very good agreement with results obtained on individual latex spheres and yeast cells.

Team member Al Meldrum and his group continue work on silicon nanocrystal-based optoelectronics, this year tracing out the complete formation route of silicon nanocrystals as they grow from amorphous clusters into larger, crystalline nanoparticles. The group has demonstrated the luminescent properties of both crystalline and amorphous Si nanoclusters and have built trial electroluminescent devices from Si nanocluster films. At the same time, the cluster-cluster interaction mechanisms have been elucidated via a nanocluster simulator newly developed by the group. The group's first erbium-doped silicon nanocluster waveguide devices have also been built and been used to identify the dominant loss mechanisms in these films. In concert with the nanocluster simulations, this work is revealing the directions that must be followed to develop waveguide amplifiers or silicon-based LEDs.

On theoretical fronts, team member Frank Marsiglio's group has studied magnetization reversal in small ferromagnetic spin chains, using an entirely quantum mechanical formulation. Spin torque is provided by a spin current, which is modelled with real-time wave packets. The breakdown of the semi-classical Landau-Lifshitz-Gilbert (LLG) formulation in certain parameter regimes is currently being explored, a scenario eagerly awaited after 70 years and counting of LLG successes. Magnetic properties of semiconductors are also of intense present interest, and the Marsiglio group have studied the various effects of strong spin-orbit scattering in low density semiconductors. One possibility is the Spin Hall Effect, where the additional effects of weak to moderate electron-phonon coupling lead to deviations from universal behaviour in the a.c. spin conductivity, albeit by a simple renormalization. Another possibility in semiconductors is enhanced superconductivity at low electron densities due to the effective dimensional reduction caused by the spin-orbit scattering.

In optical conductivity sum rule analysis of metallic/superconducting materials the optical spectral weight is expected to tell us about the behaviour of the electronic kinetic energy. Anomalous behaviour was first discovered by a group in Geneva in the high temperature superconductors about four or five years ago. Professor Marsilgio spent his sabbatical year as a Visiting Professor at the University of Geneva, and performed a number of calculations pertinent to the cuprate materials and to further measurements by this group. Most significant was an explanation of the anomalous increase in the spectral weight below Tc, due to a collapse of the quasiparticle scattering rate.

Over the past twelve months, Massimo Boninsegni and his extended research groups (including scientists at University of Massachusetts, City University of New York and ETH Zurich) have focused on the quantitative, microscopic theoretical understanding of supersolidity in helium and superfluidity in hydrogen droplets. Significant results have been obtained, and are now the leading theoretical groups in both subjects. Specifically, how a superfluid signal can arise in a quantum solid at a grain boundary was demonstrated, and one of the most accredited scenarios of supersolidity was ruled out. Also, the intriguing phenomenon of "quantum melting" has been observed by simulations of para-hydrogen droplets.

Outreach

Nanotechnology-inspired experiments are being developed for the second year undergraduate physics laboratories at the University of Alberta. The American Association of Physics Teachers will hold its annual summer meeting in Edmonton in 2008, and the CoreNano physics team is supporting this initiative.

Objectives for Next Year

CoreNano's research programs will continue to focus on experimental studies of the properties of nanomagnetic, nanomechanical, and other building blocks of ICT; development and application of advanced characterization techniques based upon low temperature ultrahigh vacuum scanning tunneling microscopy and ultrafast optical spectroscopy, development and application of theoretical methods to elucidate the properties of quantum matter at the nanoscale.

The team will work towards two different means of engineering the damping of magnetization oscillations in nanomagnetic materials. Too little or too much damping negatively affects device performance, but the damping strength is an intrinsic property of a given material and not normally an adjustable parameter. CoreNano will study damping of thin films grown in ultrahigh vacuum, through in-vacuum measurements of the decay of ferromagnetic resonance oscillations. Sub-monolayer surface coverages of rare-earth adsorbates will be applied in order to gauge the effectiveness of increasing damping through spin-orbit scattering at interfaces. In a second scheme, the team will build ferromagnetic nanomechanical resonators as a step towards observing the transfer of energy between magnetic and mechanical modes and creating artificial materials in which the damping could be strongly tuned through external applied fields.

In-vacuum and other specially controlled sample environments will be maintained during the movement of samples between different growth and characterization stations. The focus will be to extend this capability beyond the confines of the new lab, additionally to allow interfacing with existing, complementary apparatus.

Researchers are already benefiting from the spin-offs of the establishment of a critical mass of nanotech-related activity in the region, in addition to contributing to the ongoing development. A second generation of high frequency bridge and cantilever resonators is now being designed and will be tested in the coming year.

CoreNano's Manitoba collaborators have used numerical and analytical modeling to refine the detailed design of the microwave capacitance probe interfaced to a microfluidic channel. A second generation of chips will be fabricated through the Canadian Microelectronics Corporation and tested as an all-electrical, in-vitro probe of the mechanical properties of individual mammalian cells. This will evaluate the potential of the technique to address questions of biological interest.

In nanophotonics research, Professor Meldrum's group is accelerating the design of new materials with their new simulator, for which the next task is to incorporate nanocluster-erbium interactions. Properly accounting for the electron-phonon couplings involved in the transfer mechanisms is a difficult but necessary task. The simulations suggest that ultrafast optical measurements will shed light on the mechanism responsible for the luminescent properties of crystalline and amorphous Si nanoclusters, and these will be pursued in collaboration with Professor Hegmann. In order to gauge the potential for real applications, the group will strive for electroluminescence at telecommunications wavelengths, and work towards increasing the efficiency of optical sources and interconnects by reducing non-radiative channels and known loss mechanisms in silicon-nanocluster-based devices and waveguides.

In a new thrust expected to start in September 2007 with new recruit Dr Pablo Bianucci, CoreNano plans to couple Si nanocluster luminescence into high-Q microcavity resonators (single spheres and fibers), which are showing great promise for photonics applications.

Theoretical work in the coming year will include examination of the Spin-Hall effect in the limit where the Fermi energy is low, and comparable to other energy scales in the problem. This will allow understanding of experimental results from systems with very low electron density. Professor Marsiglio's group will also extend work concerning time-dependent relaxation to electron systems coupled to ions. This will allow them to study the process of polaron formation, a mechanism central to many of the dynamical problems studied experimentally by the Hegmann group. Ultimately this work may give insight on the formation of a Cooper pair, the central actor at the heart of the conventional mechanism of superconductivity. Exploring superfluidity in quantum crystals will continue with specific emphasis on other extended defects beyond the grain boundaries elucidated this year, such as dislocations, and will also investigate the effect of isotopic impurities on the superfluid properties of quantum droplets.

Research Team Members and Contributions

Team Leader
Professor Mark Freeman
Nonequilibrium physics
Canada Research Chair
CoreNano (2006-present)
iCORE Professor, Nanocore (2001-2005)
Fellow, CIAR Program in Nanoelectronics (1999-present)

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Dr Massimo Boninsegni	Theoretical condensed matter and statistical physics	Canada Research Chair
Dr Frank Hegmann	Terahertz spectroscopy	CFI award
Dr Frank Marsiglio	Superconductivity	Director of TPI, Visiting Professor at University of Geneva, September 2005 – July 2006
Dr Al Meldrum	Nanoparticles and nanomaterials	University of Alberta Students' Union "Professor of the Week" Rutherford Award for Undergraduate Teaching, 2006

PostDoctoral Fellows

Name	Role/Topic	Awards/Special Info
Dr Fabian Giesen	Ultrafast interferometry on nanomechanical systems	Now at Max Born Institute, Berlin
Dr Amena Khan	The influence of isolated adsorbates on silicon (100) surface at low temperatures	Avadh Bhatia Postdoctoral Fellowship
Dr Wonkee Kim	Research Associate, Quantum mechanics of spin transfer to nanomagnets	
Dr Sulan Kuai	Electroluminescence from silicon nanoclusters	Avadh Bhatia Postdoctoral Fellowship
Dr Marcus Walther	Near-field terahertz spectroscopy	Now faculty at Instit of Physics, Albert-Ludwigs-Universitat Freiburg

PhD Candidates		
Name	**Role/Topic**	**Awards/Special Info**
Grey Arnup	Single-shot ultrafast microimaging	
Robert Bryce	Viscoelastic flow in microchannels	NSERC, NRC Grad Student Scholarship, Q E II
Kar Mun Cheng	Mapping NEMS with STM	
Zhigang Liu	Magnetic modes in confined structures	
Joseph Losby	Nanoelectromechanical Device Actuation and Detection Using Stroboscopic Interferometry	
Allan MacDairmid	Molecular hydrogen on silicon	

MSc Candidates

Name	Role/Topic	Awards/Special Info
Jacob Burgess	Time resolved spin polarized scanning tunneling microscope	NSERC Canada Graduate Scholarship, Alberta Ingenuity Scholarship

Other Team Members

Name	Role/Topic	Awards/Special Info
Lynn Chandler	Administrative Assistant	
David Fortin	Administrator/Technical	
Dr Mohammed Hedayatipoor	Microwave dielectric measurements of proteins	Visiting Professor
Ross Lockwood	Computational simulations of interacting silicon nanocrystals (undergraduate)	NSERC USRA
Jen Moroz	StroboNEMS (undergraduate)	NSERC USRA
Steven Olson	Microfluidic/nanoelectronic interface	Internship, Physics
Dr Prasanth Ravindran	Visitor, optical transduction in NEMS	

Supported Graduate Students of Faculty Team

Name	Role/Topic	Awards/Special Info
Rahma Al Harthy	MSc, Ultrafast carrier dynamics of Si nanocrystals	
Giang Bach	PhD, Dynamical mean field theory of interacting electrons	
Cindy Blois	Wave packet absorption due to complex potentials	NSERC undergrad summer student
Kai Choy	MSc, Silicon nanocrystals	CGS award
Tyler Cocker	MSc, THz spectroscopy of GaAs nitrides	
David Cooke	PhD, Terahertz spectroscopy	Dissertation Fellowshp
Lucian Covaci	PhD, Inhomogeneous superconductivity	
Fatih Dogan	PhD, Electron-phonon systems using DMRG method	
Jianbo Gao	Photoresponse of organic photodetectors	
Aaron Hryciw	PhD, Silicon nanocluster photonics	Dissertation Fellowship, NSERC Postdoctoral Fellowship, Governor General's Gold Medal
Florian Lenz	Silicon nanocluster waveguides	
Peng Li	Radiation damage to organic compounds	
Andrea MacDonald	MSc, Luminescence of silicon nanocluster glasses	
Fabio Mezzacapo	Superfluidity of hydrogen clusters	
Aaron Slepkov	PhD, Nonlinear optical properties of organics	NSERC PGS/PDF; AIF; NSERC PDF
Joseph Turnbull	Superfluidity of para-hydrogen films	
Feng Wang	PhD, Magnetic nanoparticles	Killam Scholarship
Xiongyao Wang	Electron microscopy of silicon nanoclusters	

GRADUATES

Name	*Research Topic*	*Current Position*
PhD Graduates		
David Cooke	Time-Resolved Terahertz Spectroscopy of Bulk and Nanoscale Semiconductors	Postdoc in Peter Uhd Jepsen's group, COM*DTU, Technical University of Denmark
Lucien Covaci	Numerical Simulations of Surfaces and Nanoscale Superconducting Devices	Postdoctoral fellow at UBC
Aaron Hryciw	Optical Properties of Rare-earth-doped Silicon Nanocomposites	NSERC Postdoc award; postdoc at Stanford
Aaron Slepkov	Two-Photon Absorption in Conjugated Organic Molecules	NSERC Postdoc award; postdoc at Cornell
MSc Graduates		
Nicole McDonald	Photoluminescence Study of Nd Enriched Si-Nanocluster Glass	Not Reported

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
U of A: ECE Dr K Westra	Advanced e-beam lithography
U of A: Physics and Chemistry Dr JB Green Dr R Tykwinski Dr R Wolkow	Molecular conductors
U of A: Chemistry Dr R Tykwinski	Organic materials
U of A: Physics Dr R Sydora	Micromagnetic modeling
U of A: Electrical and Computer Engineering Dr R DeCorby	Developing rare-earth-doped silicon nanocluster glasses as possible waveguide amplifiers

Participants	*Nature of Collaboration*
National Collaborations	
McGill University Dr P Grütter	Magnetic nanostructures
INRS/University of Quebec Dr T Ozaki RM Dotti	Extreme terahertz sources and applications
University of Manitoba Dr D Thomson	Dielectric measurements on single cells
NINT Dr M Malac	Electron holography
NINT Dr W Hiebert	Nanomechanics
Brock University Dr A. Knigavko	High temperature superconductors
McMaster Dr J Carbotte	High temperature superconductors
University of British Columbia: Physics Dr Tom Tiedje	Gallium arsenide (GaAs) nitrides and bismides
Queen's University Dr B Gooding	High temperature superconductors
Simon Fraser University Dr B Heinrich	Dynamic coupling in magnetic multilayers
International Collaborations	
Cal Tech Dr M Roukes	NEMS interferometry
La Sapienza, Rome Dr L Benfatto	High temperature superconductors: optics
La Sapienza, Rome Dr E Cappeluti	Spin-Hall effect, high temperature superconductors
University of Geneva Dr F Carbone Dr AB Kuzmenko Dr HJA Molegraaf Dr E van Heumen Dr J Teyssier Dr V Lukovac Dr D van der Marel	High temperature superconductors: optical properties

Participants	*Nature of Collaboration*
International Collaborations Cont'd	
Rutgers Dr K Haule Dr G Kotliar	High Temperature Superconductors:optics and Dynamical Mean Field Theory
Lausanne, Dresden Dr C Grimaldi	Spin-Hall Effect
University of Bristol Dr I Manners	Direct-written organometallic nanomagnets
Chinese University of Hong Kong Dr Q Li	Advanced electron microscopy
Institut fur Laser und Plasma-physik, Univ Duisburg-Essen Dr M Horn von-Hoegen	Dynamics of electrons in nanostructures
Seagate, Pittsburgh Dr X Zhu	Magnetization dynamics
University of Kentucky: Chemistry Dr J Anthony	Terahertz spectroscopy of organic semiconductors
University of Massachusetts Amherst Dr BV Svistunov Dr NV Prokof'ev	Supersolid phase of helium
ETH Zurich Dr M Troyer	Supersolid phase of helium
Industrial Collaborations	
Norcada Dr Y Ning Mr G McKinnon	Nanomechanics
Applied Nanotools Dr M Aktary	Electron beam lithography
Micralyne and TR Labs, Edmonton Dr R DeCorby Dr C Haugen	Silicon nanoclusters for microphotonics (NSERC Strategic Program)

INTELLECTUAL PROPERTY

Patents	Title/Name	Status
US 5,451,863	Fiber optic probe	Awarded prior to this year
US 5,663,652	Magneto-optic current sensor	Awarded prior to this year

FUNDING

Dr Mark Freeman has a five year iCORE Professor award ($1.5M). This year he has federal funding from NSERC, NRC and CFI ($1.5M), provincial funding from Alberta Science and Research Investments Program ($975K), and a Tier 1 Canada Research Chair ($200K). He shares the funding from an NSERC facilities grant with Dr Michael Brett ($245K).

PUBLICATIONS

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Feng Wang, Marek Malac, Ray F. Egerton, Alkiviathes Meldrum, Peng Li, Mark R. Freeman, and Jonathan G.C. Veinot , "Controlled Growth of Silicon Oxide Nanowires from a Patterned Reagent", *J. Phys. Chem. C111* (5), 2007, pp. 1865 – 1867.

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B.C. Choi, J. Rudge, M.R. Freeman, Y.K. Hong, and Q.F. Xiao, Nonequilibrium Magnetic Domain Structures as a Function of speed of Switching Process in $Ni_{80}Fe_{20}$ thin-Film Element", *IEEE Trans Mag 43* (1), 2007, pp. 2 -5.

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SPECIAL/INVITED PRESENTATIONS

F. Marsiglio, "The Optics of Superconductivity" at the *CAP conference*, Brock University, June, 2006, St. Catharines, Ontario.

M. Freeman, "Dynamics Of An Ising Chain Under Local Excitation" at the *CAP Conference*, Brock University, June, 2006, St. Catharines, Ontario.

M.R. Freeman "Using an STM to Connect Silicon and Magnetism: Dynamics of an Ising Chain Studied at a Semiconductor Surface", Ohio State University, Department of Physics, June, 2006.

Frank A. Hegmann, David G. Cooke, and Markus Walther; "The Nature of Terahertz Conductivity in Nanomaterials", *OTST 2007* (OSA Topical Meeting on Optical Terahertz Science and Technology Topical Meeting), Orlando, FL, March 18-21, 2007.

F. Hegmann, "Probing Semiconductor Nanostructures with Terahertz Pulses", Technical University of Denmark, Center for Nanotechnology (COM-DTU), Sept. 11, 2006.

F. Hegmann, "Probing Organic Semiconductors with Terahertz Pulses", Max Planck Institute for Polymer Research, Mainz, Germany, Sept.14, 2006.

M.R. Freeman, "Dynamics of an Ising Chain Under Local Excitation", *International Conference on Magnetism*, Tokyo, 18-27 August, 2006.

INVITED TALKS BY GROUP MEMBERS

Xiaobin Zhu, Vitali Metlushko, Zhigang Liu, and Mark Freeman "Transient Magnetic Field Induced Dynamics Coupling in Patterned Magnetic Bilayers", *2007 MMM/Intermag Joint Conference*, Baltimore, MD (Abstract AE-01) January 7 – 11, 2007.

F. Hegmann, "Ultrafast Carrier Dynamics and Terahertz Conductivity in Nanocrystalline Silicon", *ICOOPMA 2006*, International Conference on Optical and Optoelectronic Properties of Materials and Applications, Darwin, Australia, July 17-21, 2006, (given by David Cooke).

THESES

David Cooke, PhD, 2006, "Time-Resolved Terahertz Spectroscopy of Bulk and Nanoscale Semiconductors", now a postdoc in Peter Uhd Jepsen's group, COM*DTU, Technical University of Denmark.

Aaron Slepkov, PhD, 2006, "Two-Photon Absorption in Conjugated Organic Molecules", now a postdoc in Professor Gaeta's group in Cornell, Dept of Physics.

Nicole McDonald, MSc, 2006, "Photoluminescence Study of Nd Enriched Si-Nanocluster Glass", accompanied partner for postdoc at Copenhagen.

Lucien Covaci, PhD, 2006, "Numerical Simulations of Surfaces and Nanoscale Superconducting Devices", now a postdoctoral fellow at UBC.

Aaron Hryciw, PhD, 2007, "Optical Properties of Rare-earth-doped Silicon Nanocomposites", now a postdoc at Stanford.

Quantum Information Science

Quantum information science is an interdisciplinary field comprising computer scientists, physicists, mathematicians, and engineers who aim to revolutionize communication and computation by exploiting the remarkable quantum aspects of nature.

The goal of this revolution is to create quantum devices that can perform tasks that are thought to be impossible without quantum devices, which quantum information researchers refer to as classical communication and classical computation. Four discoveries highlight the importance and promise of quantum information: these discoveries have revolutionary impacts on information security and also show that quantum information is feasible on the grand scale provided that it works well on a small scale.

Two of the four monumental quantum information discoveries concern information security: quantum cryptography enables communication to be impervious to any computational attack ever, and a quantum computer would make every known scheme of public key cryptography completely vulnerable.

The third discovery is fault tolerant quantum error correction, which demonstrates that, if a small-scale quantum computing device can be created, it can be extended to a full quantum computer. The fourth major discovery is that a quantum computer can efficiently simulate the dynamics of any quantum system whereas a classical computer probably cannot. Thus a quantum computer will enable testing of theories for large quantum systems, which will impact development of new materials and address outstanding questions in quantum physics.

The Institute for Quantum Information Science (IQIS) is an interdisciplinary centre addressing the full spectrum of quantum information research. Led by Dr Barry Sanders, there are seven faculty members in experimental and theoretical physics, computer science and mathematics, including two Canada Research Chairs, one iCORE Professor, and one iCORE/NSERC Industrial Research Chair. The Institute's goals are to conduct leading research in key theoretical and experimental topics of quantum information science, to provide excellent education, training, and outreach in quantum information, and to foster linkage between the Institute and other partners.

The Institute has the dual objective of applying quantum physics to produce revolutionary advances in information and communication science and technology and to advance understanding and methods in quantum physics by applying breakthroughs in quantum information research. The Institute and its members are partners in NSERC's Innovation Platform QuantumWorks, the Canadian Institute for Advanced Research and the Australian Centre of Excellence for Quantum Computer Technology.

The most outstanding results from the group this past year have been the following: proposing a giant optical nonlinearity using Rubidium gas to make quantum optical switches; a theory for avoiding decoherence in generic optical systems; and a complete theory for a quantum computer to simulate arbitrary physical systems. In addition to these scientific developments, two patents were filed that resolve, from a commercial perspective, the two obstacles to adopting quantum cryptography, namely the need for information-theoretic security of authentication and overcoming the distance barrier for quantum key distribution.

Also a four-minute animated movie on solid-state quantum computing was produced for the United States Army Research Office, to be used for informing, educating and performing outreach. Furthermore the Institute grew by the addition of two new faculty members in the past year: Gilad Gour in the Department of Mathematics and Statistics and Wolfgang Tittel, who is an iCORE/NSERC Industrial Research Chair, co-funded by General Dynamics Canada.

Research Program Overview

The goals of the quantum information research program are to discover and enhance the capabilities of quantum information and to translate these potentials into experimental reality and ultimately into practical and commercial realization. To achieve these goals, Dr Sanders and the team focus on four research planks:

i. "enabling technologies", which identify and resolve key technological obstacles that prevent quantum information protocols from working in the laboratory,

ii. "implementations", which proposes, designs, and realizes quantum information tasks when all relevant technologies are working,

iii. "resources", which identifies and quantifies requirements and consumable resources for quantum information processing such as entanglement, distinguishability, and quantum measurement protocols, and

iv. "algorithms", which identifies specific computational problems that are efficiently solvable on a quantum computer and believed not to be efficiently solvable on a "classical" (i.e. non-quantum) computer and develops corresponding quantum algorithms to solve these problems efficiently. These research activities are theoretical, experimental, or both.

The "enabling technology" research plank is primarily focused on the interface between optical fields and matter because quantum communication is the most important medium-term application of quantum information science, with quantum cryptography being an excellent example, and the medium of choice for sending quantum information over long distances is the optical, or electromagnetic, field. Control, storage, and processing of light during its preparation, transmission, and readout, are crucial technologies for making quantum communication work. Thus the main emphasis of this research plank is on interfaces between light and matter, and using matter to control light. Various types of matter are considered, including atoms, ions, plasmas in metal and optical cavities.

The "implementations" research plank is concentrating on three key areas where experiments are sufficiently sophisticated to realize quantum information tasks. Specifically these three areas are optical quantum information in the so-called continuous variable framework, superconducting charged qubits in circuit quantum electrodynamics, and laser tweezer manipulations and entangling of neutral atoms.

Optical quantum information in the continuous variable setting makes use of Gaussian quantum states, passive optics, squeezing, and homodyne detection. IQIS team member Dr Alex Lvovsky's laboratory in Calgary is one of the best in the world, so his laboratory is capable of realizing these implementations. The two main implementations under investigation are continuous variable quantum cryptography and continuous variable quantum secret sharing, which are both important for information security applications, especially over short distances such as local area network configurations.

The superconducting charged qubit technology is being studied in collaboration with Dr Blais at l'Université de Sherbrooke, and the goal is to realize the first quantum walk, and circuit quantum electrodynamics offers the best prospect for success. The study of neutral atoms in tweezers is conducted in collaboration with Dr Raizen's experimental group at the University of Texas at Austin and seeks to implement a fast controlled-NOT (exclusive OR) gate via atomic collisions, with the view to performing a loophole-free Bell inequality violation in the laboratory. The specific atoms under investigation are Ytterbium and Strontium, which provide fast, long-lived optical transitions and so can be used for fast quantum information processing and yet avoid decoherence.

The "resources" research plank is focused primarily on studies of entanglement, measurement, reference frames, and decoherence. Entanglement provides a resource that is consumed by performing quantum teleportation, and many-particle entangled states can be used as a resource for performing quantum computation simply by sequential measurements of particles. Fundamental research on entanglement is a key component of this research plank.

The other resources are equally important. Because of complementarity, accessing full information about a quantum state is challenging, and the techniques are known as "tomography" because of the mathematical analogue with tomography in medical imaging. Quantum states can be quite complicated so efficient tomography is both important and challenging. Reference frame research is vital because quantum information may be encoded in timing or orientation or location of particles, and all parties in quantum communication need to know which way is up or what time it is, and quantum resources for these reference frames are consumed. Finally coherence is an important resource to ensure that quantumness is robust, and the IQIS has a strong collaboration with Dr Whaley's group at the University of California at Berkeley on avoiding decoherence.

The goal of the final research plank, "algorithms", is to develop protocols for a quantum computer to solve efficiently computational problems that are inefficient for classical computers. The first important computational problem for a quantum computer will be to simulate various quantum dynamical systems to test physical theories for poorly understood states of matter such as high-temperature superconductivity. The Institute is designing quantum algorithms for solving such generic problems and assessing their performance limits and working to saturate these bounds.

Research Projects

Giant optical nonlinearity

Producing a giant optical nonlinearity is important for creating optical switches that will function as optical gates and for optically controlled quantum memory. IQIS has shown how a giant nonlinearity, and consequently strong cross-phase modulation, can be achieved between optical pulses using a Rubidium-87 gas medium. The simulation has been extended to treat pulsed sources and is modelled with realistic parameters for Dr Lvovsky's laboratory in Calgary so that they can test the proposal, beginning with the prediction of double electromagnetically induced transparency, which has not yet been observed in a laboratory.

Monogamy of entanglement of assistance

One important property of entanglement is that it does not like to be shared, and this limitation is known as "monogamy" and is quantified by the "tangle". Studies of entanglement monogamy are important because they lead to bounds on what is achievable in quantum information processing using entanglement. IQIS turned the problem on its head by considering how agents in many-particle systems can help with providing entanglement to subsets of the system and, by considering this problem, the team established bounds on the "tangle" itself and provided new insights into the potential and limitations of entanglement.

Decoherence free subspaces in extended systems

The quantum information state will degrade unless it is entirely contained within decoherence free subspace. IQIS has developed a theory of decoherence free subspaces for extended systems, that is for the realistic case that many-particle systems extend beyond a single point in space, and assumed reasonable properties of the reservoir such as its properties being unchanged under translation in space, and developed an algorithm for finding spatial configurations that admit decoherence free subspaces. IQIS also proved the unfortunate result that decoherence free subspaces cannot exist for a wide variety of conditions, which at least leads to a focused efforts by experimentalists on the smaller class of systems that do admit decoherence free subspaces.

Optimal state determination

The inference of the quantum state for a system is complicated because of complementarity, namely that measurements are mutually incompatible and in general destructive. The goal of optimal state determination is to find fast ways to learn the quantum state within the acceptable error tolerance and to identify bounds on how efficiently a state can be learned. One major result generalizes the notion of mutually unbiased bases so that efficient measurements can now be constructed for dimensions of spaces that defied mutually unbiased bases constructions before. Another major result extends tomography to work efficiently for partially distinguishable systems. The IQIS team is found an efficient way to test whether distinguishability meets the threshold condition and simultaneously performs tomography.

Symmetries and simplifications of generic interferometry with squeezers

One of the most important systems for first implementations of quantum information tasks has been a combination of optical squeezers (quantum noise quenchers) with linear optics in a multi-channel interferometer. IQIS has employed Lie group theory to greatly simplify the mathematics for computing output states from the interferometer that includes one squeezer, given any input state.

Efficient algorithms for quantum simulations

The team discovered an efficient quantum algorithm for simulating the evolution of a quantum state for any sparse, time-independent Hamiltonian. IQIS found that the resources for the near-optimal algorithm scale nearly linearly in the evolution time and nearly constant in the size of the system for fixed sparseness of the Hamiltonian matrix. One impact of IQIS' work is that the team firmly places the problem of simulation in a framework that is amenable to rigorous computer science study, which is important to figure out and quantify what it means to say that a quantum computer can efficiently simulate quantum dynamics whereas a classical computer cannot. An important application of the work will be to assess efficiency and resource use for adiabatic quantum computation, which is one of the alternatives to gate-based quantum circuits.

Optical processing of single-rail qubits

Quantum information can be encoded into light in various ways. Dr Lvovsky's laboratory is especially well equipped to manufacture and manipulate single-rail qubits, which corresponds to encoding quantum information into a superposition of no photon ("nothing") and one photon ("something"). Truncating the state so that no more than one photon is present can be done with "quantum scissors", and phase sensitive readout of the superposition of "something" with "nothing" is performed using homodyne detection.

IQIS has been investigating the processing of single-rail qubits with particular emphasis on the efficiency of such processes so that quantum error correction can be incorporated into the analysis; quantum error correction is needed to convert the process from an approximate procedure to a nearly exact transformation for quantum information processing purposes. IQIS obtained a convincing upper bound to efficiency for single-rail qubit processing for a variety of ways to manipulate single-rail optical qubits.

Perfect state transfer with spinor bosons

In quantum information processing, spatial transference of a state is an important primitive operation. By exploiting a mathematical analogy between spinor bosons, such as ultracold atoms, on a lattice, Dr Feder has shown that near-perfect quantum state transfer can be achieved using ultracold atoms in optical lattices under realistic conditions. One advantage of this scheme is that it readily sends multiple identical states down the same channel.

Distributed authentication and relaying for secure networks

IQIS introduced a simple, efficient, practical approach with asymptotic information-theoretic security to solve quantum key distribution's two major security weaknesses: distance limitations and the requirement of an authenticated classical channel to prevent "man-in-the-middle" attacks, using secret sharing and partially trusted intermediaries.

Objectives for Next Year

In addition to the research highlights below, outreach and education continue to be important: new graduate courses in quantum information are planned, and a new fifteen minute movie built from last year's four minute animated movie on the solid state quantum computer will be produced.

Distributed authentication and relaying for secure networks

IQIS will develop numerical simulations to test the simple, efficient, practical approach to solve quantum key distribution's two major security weaknesses. First the team will simulate the security of networks under various topologies as the cost of bandwidth is expected to be topology-dependent. This simulation will take place on a network of existing linux-operated computers in the group. The goal is to collaborate with iCORE Chair Dr Wolfgang Tittel's team to test these proposals in real world settings. Licensing arrangements with various companies are being explored.

Giant optical nonlinearity

IQIS will explore the production of a giant optical nonlinearity from media other than gases. These latter media are important to enable fixed circuits with giant optical nonlinearities to be possible in the future. The researchers will also adapt models to accommodate pulses rather than just continuous wave sources. Experiments are being set up with Rubidium-87 gas as the medium to test part of the proposal, namely the existence of double electromagnetically-induced transparency.

Efficient algorithms for quantum simulations

The team will extend efficient quantum algorithms for simulating the evolution of a quantum state for time-dependent Hamiltonians. In particular IQIS will study the simulation of adiabatic quantum evolution, which is at the heart of some quantum computer developments including work at D-Wave System's in Vancouver. The goal is to identify conditions for whether the time-dependent Hamiltonian can be efficiently simulated, to write the circuit-based algorithm for doing so for generic adiabatically evolving Hamiltonians, and to assess the resources consumed during this evolution.

Quantum walk in superconducting circuit quantum electrodynamics

IQIS' goal with circuit quantum electrodynamics with superconducting charge qubits coupled to niobium resonators is to propose a feasible experiment that will observe, for the first time, a quantum walk, and will include controllable decoherence. The quantum walk is important as a primitive in quantum information, and its realization in the laboratory will connect the concept to experimental reality and ultimately lead to its practical use.

Neutral atom graph states

IQIS plans to complete work on a loophole-free test of local realism using neutral Ytterbium or Strontium atoms manipulated by laser tweezers. IQIS will use lasers to manipulate rapidly the states of individual atoms (qubits) and to entangle atoms by making them collide via laser tweezer manipulation. Graph states provide a so-called entangled substrate from which universal quantum computation can take place solely via measurement and feedforward of measurement results for subsequent measurements and for information processing at the end of the readout phase. The goal will be to propose a scheme for creating specific graph states on demand, which can then be used for specific purposes in quantum computing.

Outreach

Conference/Workshop/Award Committees

Committee	Conference/Workshop/Award	Location	Dates
Member: A. Lvovsky, K.-P. Marzlin			
Organizing Committee	The American Physical Society Division of Atomic, Molecular, and Optical Physics Annual Meeting (DAMOP 07)	Calgary, Alberta	June 5 - 9, 2007
Member: A. Rezakhani			
Organizing Committee	International Iran Conference on Quantum Information (IICQI 2007)	Kish Island, Iran	September 7 – 10, 2007
Member: B. C. Sanders			
Program Committee	SPIE Conference on Quantum Communications and Imaging III	San Diego, United States of America	August 13 – 17, 2006
Advisory & Award Committees	Quantum Communication, Measurement and Computing (QCMC2006)	Tsukuba, Japan	November 28 – December 3, 2006
Program Committee	SPIE Symposium "Fluctuations and Noise"	Florence, Italy	May 20 – 24, 2007
Treasurer, Organizing Committee	The American Physical Society Division of Atomic, Molecular, and Optical Physics Annual Meeting (DAMOP 07)	Calgary, Canada	June 5 – 9, 2007
Program Committee	International Conference on Quantum Information (ICQI07)	Rochester, United States of America	June 10 – 13, 2007
Chair, Steering Committee	Photons, Atoms, and Qubits (PAQ07)	London, United Kingdom	September 2 – 5, 2007
Co-Chair, Organizing Committee	International Iran Conference on Quantum Information (IICQI 2007)	Kish Island, Iran	September 7 – 10, 2007
QELS Subcommittee 02: Quantum Information	Conference on Lasers and Electro-Optics / Quantum Electronics and Laser Science Conference (CLEO/QELS 2007)	Baltimore, United States of America	May 6 – 11, 2007
Technical Program Sub-Committee	Seventh Pacific Rim Conference on Lasers and Electro-Optics (CLEO-PR 2007)	Seoul, Korea	August 26 – 31, 2007

Society and Publications Activities

Name	Role/Topic	Journal/Society
H. Carteret	Member, Advisory Panel	Journal of Physics A
K.-P. Marzlin	Associate Editor	Canadian Journal of Physics
B. C. Sanders	Member, Editorial Board	Physical Review A
B. C. Sanders	Member, Editorial Board	New Journal of Physics
B. C. Sanders	Secretary-Treasurer	American Physical Society Topical Group on Quantum Information Science

Media Coverage

Source	Title of Articcle	Location	Date
On Campus Weekly	Highlight of the four-year budget and business plan		April 7, 2006
Calgary Inc.	Quantum progress, bit by bit: Alex Lvovsky, Barry Sanders	P 27	July/August 2006
Innovation Canada	Quantum leap: A chance encounter between a computer-science professor and a physicist launches new field of quantum cryptography	Issue 24	September – October 2006
Netera Alliance	Points of interest: Maria Lantin	pp. 24-25	05/06 Annual Report
Netera Alliance	Points of interest: Barry Sanders	pp. 18-19	05/06 Annual Report
University of Waterloo Daily Bulletin	National quantum network launched	2nd item	September 26, 2006
Calgary Sun	Online security nets quantum reap at U of C: Dr. Wolfgang Tittel, Dr. Barry Sanders		January 26, 2007
Calgary Herald	U of C researchers study quantum leap in security: Dr. Wolfgang Tittel, Dr. Barry Sanders		January 26, 2007
Grande Prairie Daily Tribune	Swiss quantum physicist joins Calgary university to work on Internet security: Dr. Wolfgang Tittel, Dr. Barry Sanders		January 26, 2007
CBC Homestretch with Jeff Collins	Regarding the upcoming announcement from D-Wave: Dr. Barry Sanders		February 9, 2007

Research Team Members and Contributions

Team Leader
Professor Barry Sanders
iCORE Professor of IQIS
Fellow, American Physical Society
Elected member of the Theoretical Physics Institute, U of A
Elected Secretary-Treasurer for the American Physical Society Topical Group for the Quantum Information, Concepts, and Computation.
Appointed member of the Editorial Board of *Physical Review A*
Elected Member of the Scientific Review Panel for the Pacific Institute for the Mathematical Sciences.

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Dr David Feder	Assistant Professor, Physics and Astronomy	
Dr Gilad Gour	Adjunct Assistant Professor Mathematics & Statistics	
Dr Alexander Lvovsky	Canadian Research Chair, Physics and Astronomy	

Research Associates

Name	Role/Topic	Awards/Special Info
Dr Somshubhro Bandyopadhyay	PostDoctoral Research Associate: Theory of entanglement	iCORE/MITACS NCE/CIAR (Sanders)
Dr Hilary Carteret	PostDoctoral Research Associate: Quantum information	iCORE (Sanders)
Dr Dmitry Korystov	PostDoctoral Research Associate: Storage of squeezed light in atomic vapour	NSERC (Lvovsky)
Dr Karl-Peter Marzlin	Senior Scientist and Adjunct Professor: QI Technology	iCORE (Sanders)
Dr Andrew Scott	PostDoctoral Research Associate: Quantum measurement	MITACS NCE (Cleve/ Sanders)
Dr Frank Vewinger	PostDoctoral Research Associate: Light atom interface	CIAR (Lvovsky)
Dr Peng Xue	PostDoctoral Research Associate: Cavity quantum electrodynamics	NSERC (Sanders)
Dr Anning Zhang	PostDoctoral Research Associate: Engineering and characterization of nonclassical light	AIF (Lvovsky)

PostDoctoral Fellows

Name	Role/Topic	Awards/Special Info
Dr Ali Rezakhani	Quantum Information	iCORE (Sanders) PIMS (Rezakhani)
Dr Aidan Roy	Quantum Information	NSERC (Roy) MITACS (Høyer)
Dr René Stock	Quantum information	CIAR (Sanders) AIF (Stock)
Dr Peter Turner	Quantum information resources	AIF (Turner)/ CIAR (Sanders)
Dr Jonathan Walgate	Distinguishability	PIMS (Walgate) AIF (Walage)

PhD Candidates

Name	Role/Topic	Awards/Special Info
Mark Adcock	Continuous variable quantum networks	General Dynamics Canada /MITACS (Sanders)
Jürgen Appel	Exchange of quantum information between light and atomic ensembles	NSERC (Lvovsky)
Sergey Babichev	Quantum technology of light	NSERC (Lvovsky)
Jérémie Choquette	Quantum information	NSERC (Sanders)/NSERC (Marzlin)
E. V. Figueroa-Barragan	Quantum source of light for experiments with atoms	NSERC (Lvovsky)/2007 Physics Department Scholarship
Iyad Mahmoud	Collective effects in dense gases	NSERC (Sanders)
Alexis Morris	Topological quantum computing	NSERC (Feder)/iCORE (Sanders)/2007 Physics Department Scholarship
Xuesong Qi	Entanglement in cavity quantum electrodynamics	NSERC (Sanders)
Zengbin Wang	Electromagnetically-induced transparency with single photons	iCORE (Sanders)/NSERC (Sanders)/2007 Physics Department Scholarship
Nathan Wiebe	Quantum simulation	iCORE (Sanders)

MSc Candidates

Name	Role/Topic	Awards/Special Info
Nathan Babcock	Quantum error correction	iCORE (Sanders)/2007 Physics Department Scholarship/NSERC Canada Graduate Scholarship D/NSERC Canada Postgraduate Scholarship M/Alberta Ingenuity MSc Student Scholarship
Jop Briet	Many-qubit stabilizer states	CIAR (Høyer)/NSERC (Briet)/ NSERC (Feder)
Michaël Durocher	Quantum information	iCORE (Sanders)
Adam D'Souza		NSERC (Feder)/2007 Physics Department Scholarship
Tim Friesen	Quantum Information Science & Quantum Works	NSERC (Friesen)/2007 Physics Department Scholarship
Mike Garrett	Measurement-based one-way quantum computing & cluster states	NSERC (Garrett)/2007 Physics Department Scholarship

MSc Candidates Cont'd		
Name	**Role/Topic**	**Awards/Special Info**
Gina Howard	Limitations of long-distance quantum key distribution	iCORE (Sanders)
Andrew McRae	Giant nonlinearities in electromagnetically-induced transparency	NSERC (Lvovsky)/CIAR (Lvovsky)
Simon Poole	Quantum information with mesoscopic states of light	
Sarah Rugheimer	Bose Einstein Condensates	
Michael Skotiniotis	Quantum information	iCORE (Sanders)/2007 Physics Department Scholarship
Zahra Shaterzadeh Yazdi	Continuous variable multipartite quantum states	iCORE (Sanders)
Michael Underwood	Quantum memory in optical fibres	iCORE (Sanders)/NSERC (Marzlin)/ Queen Elizabeth II Graduate Scholarship

Undergraduate Students

Name	Role/Topic	Awards/Special Info
Geoff Campbell	Exchange of quantum information between light and atomic ensembles	NSERC (Campbell) Supervised by A. Lvovsky
Peter Gagliardi	QViz	IQIS Supervised by B. Sanders
Chris Healey	Exchange of quantum information between light and atomic ensembles	NSERC (Lvovsky) Supervised by A. Lvovsky
Dallas Hoffman	Quantum technology of light	NSERC(Lvovsky) Supervised by A. Lvovsky
Yuval Sanders	Entangled rings	NSERC (Sanders)/iCORE (Sanders) Supervised by B. Sanders/H. Carteret

Other Team Members

Name	Role/Topic	Awards/Special Info
Catherine Avramenko	Administrator, IQIS	IQIS
Wolfgang Dobler	Technical Support, IQIS	IQIS
Gina Howard	Web Support, IQIS	iCORE
Nancy Jing Lu	Administrative Assistant, IQIS	iCORE

Visitors

Name	Dates of Visit	Home Institution
Georg Günter	September 1, 2005 – August 15, 2006	University of Konstanz, Konstanz, Germany
Wolfgang Tittel	March 30 –April 8, 2006	University of Genève, Genève, Switzerland
Shohini Ghose	April 10 – 17, 2006	Wilfrid Laurier University, Waterloo, Canada
Terry Rudolph	April 13 – 21, 2006	Imperial College, London, United Kingdom
Peter Knight	April 30 – May 3, 2006	Imperial College, London, United Kingdom
Martin Oberst	May 1– 27, 2006	Technische Universität Kaiserslautern, Kaiserslautern, Germany

Visitors Cont'd

Name	Date of Visit	Home Institution
Dominic Berry	May 7 – 21, 2006	The University of Queensland, Brisbane, Australia
Mayank Maheshwari	May 8 – July 17, 2006	Institute of Technology, BHU, Varanasi, India
Daniel Terno	May 8 – 13, 2006	Perimeter Institute for Theoretical Physics, Walterloo, Canada
Aidan Roy	May 9 – 12, 2006	University of Waterloo, Waterloo, Canada
Anne Broadbent	May 14 – 19, 2006	Université de Montréal, Montréal, Canada
Anirban Pathak	June 4 – July 19, 2006	Jaypee Institute of Information Technology, Uttar Pradesh, India
Emanuel Knill	June 6 – 9, 2006	National Institute of Standards and Technology, Gaithersburg, United States of America
Gilad Gour	June 12 – 22, 2006	University of California, San Diego, United States of America
Raisa Karasik	July 3 – August 24, 2006	University of California at Berkeley, Berkeley, United States of America
Viv Kendon	July 25 – July 29, 2006	University of Leeds, Leeds, United Kingdom
Robert Raussendorf	July 28, 2006	Perimeter Institute for Theoretical Physics, Waterloo, Canada
Anirban Roy	August 2 – October 29, 2006	The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy
Anning Zhang	August 10 – 12, 2006	University of Toronto, Toronto, Canada
Howard Wiseman	August 16 – 20, 2006	Griffith University, Griffith, Australia
Elinor K. Irish	August 20 – 25, 2006	University of Rochester, Rochester, United States of America
Andrew Greentree	August 23 – 24, 2006	The University of Melbourne, Melbourne, Australia
Chris Vo	September 8 – 12, 2006	Stanford University, Stanford, United States of America
Raisa Karasik	September 9, 2006 – January 14, 2007	University of California at Berkeley, Berkeley, United States of America
Austin Fowler	September 17 – 30, 2006	University of Waterloo, Waterloo, Canada

Visitors Cont'd

Name	Date of Visit	Home Institution
Dmitry Korystov	September 20 – 23, 2006	University of California at Santa Barbara, Santa Barbara, United States of America
Shohini Ghose	September 21 – 22, 2006	Wilfrid Laurier University, Waterloo, Canada
Anning Zhang	September 28 – 30, 2006	University of Toronto, Toronto, Canada
Jonathan Dowling	October 3 – 6, 2006	Louisiana State University, Baton Rouge, United States of America
Shannon Mayer	October 4 – 6, 2006	The University of Portland, Portland, United States of America
Dmitri Maslov	October 9 – 13, 2006	University of Waterloo, Waterloo, Canada
Birgitta Whaley	October 17 – 20, 2006	University of California at Berkeley, Berkeley, United States of America
Troy Lee	October 29 – November 3, 2006	Université de Paris-Sud, Orsay Cedex, France
Gus Gutoski	November 14 – 19, 2006	University of Waterloo, Waterloo, Canada
Félix Bussières	November 14 – 25, 2006	Université de Montréal, Montréal, Canada
Sun-Hyun Youn	December 15, 2006 – December 15, 2007	Chonnam National University, Korea
Dmitry Gavinsky	January 10, – January 12, 2007	University of Waterloo, Waterloo, Canada
Félix Bussières	January 16, – December 14, 2007	Université de Montréal, Montréal, Canada
Mirko Lobino	January 24, – January 30, 2007	Politecnico di Milano, Milano, Italy
Stephen Bartlett	January 25, – February 8, 2007	University of Sydney, Sydney, Australia
Martin Roetteler	February 16, 2007	NEC Laboratories America, Inc., Princeton, United States of America
Patrick Hayden	February 21, 2007	McGill University, Montréal, Canada
Pavel Kolchin	February 27, 2007 – March 3, 2007	Stanford University, Stanford, United States of America
Matthew D. Eisaman	March 22 – 25, 2007	National Institute of Standards and Technology, Gaithersburg, United States of America

GRADUATES

Name	*Research Topic*	*Current Position*
PhD Graduates		
Sergey Babichev	Quantum-optical technology at the single-photon level	Technologist at Airbus, Hamburg
MSc Graduates		
Jop Briet	Stabilizer representations of entangled pure states	Research Assistant University of Calgary
Michael Garrett	Stochastic one-way quantum computing with ultra cold atoms in optical lattices	PhD Student University of Calgary

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
Dr Wolfgang Tittel's Research Group (IQIS) Wolfgang Tittel	Academic collaboration on joint research
Centre for Information Security and Cryptography (CISaC) Hugh Williams, Renate Scheidler	Academic collaboration on joint research
Advanced Technology Information Processing Systems (ATIPS) Laboratory Graham Jullien	Academic collaboration on joint research
National Collaborations	
Perimeter Institute for Theoretical Physics Jonathan Walgate, Daniel Terno	Academic collaboration on joint research
QuantumWorks (NSERC Innovation Platform)	QuantumWorks is a NSERC research innovation platform for a nework of research groups
Université de Montréal André Méthot, Anne Broadbent	Academic collaboration on joint research
University of Waterloo Richard Cleve	Academic collaboration on joint research
Wilfrid Laurier University Shohini Ghose	Academic collaboration on joint research

Participants	*Nature of Collaboration*
International Collaborations	
Commonwealth Science and Industrial Research Organization, Sydney Trevor Bird	Academic collaboration on joint research
Fujian Normal University Xiumin Lin, Meiying Chen, Zhihua Chen, Xinghua Li	Academic collaboration on joint research
Imperial College, London Terry Rudolph, Jens Eisert	Academic collaboration on joint research
Institute for Scientific Interchange Paolo Zanardi	Academic collaboration on joint research
Macquarie University James Cresser Peter Brooke Andrew Weily Karu Esselle Dominic Berry	Quantum information science and in dielectric antennas with electromagnetic band gaps
Masaryk University Tomáš Tyc	Academic collaboration on joint research
Nicolaus Copernicus University Wojciech Wasilewski Konrad Banaszek	Academic collaboration on joint research
Sharif University of Technology Omid Akhavan Mehdi Golshani	Academic collaboration on joint research
Stanford University Yoshihisa Yamamoto	Academic collaboration on joint research
University of Cambridge Robert Spekkens	Academic collaboration on joint research
University of California at Berkeley Birgitta Whaley Raisa Karasik Travis Beals	Academic research, student/faculty exchange, proposal for National Science Foundation funding to support collaboration and exchanges
University of California at San Diego David Meyer	Academic collaboration on joint research
University of Isfahan Reza Afzali	Academic collaboration on joint research

Participants	*Nature of Collaboration*
International Collaborations Cont'd	
University of London Rüdiger Schack	Academic collaboration on joint research
University of New Mexico Ivan Deutsch Paul Alsing Ian Reichenbach Andrew Silberfarb Carlton Caves	Academic collaboration on joint research
University of Science and Technology of China Yunfeng Xiao	Academic collaboration on joint research
University of Southern California Todd Brun	Academic collaboration on joint research
University of Sydney Stephen Bartlett	Academic collaboration on joint research
University of Vienna Anton Zeilinger	Academic collaboration on joint research
Institute of Physics, Bhubaneswar Arun Kumar Pati	Academic collaboration on joint research
University of Western Australia Gordon Royle	Academic collaboration on joint research
Warsaw University Czeslaw Radzewicz	Academic collaboration on joint research

INTELLECTUAL PROPERTY

Patents/Author	*Title/Name*	*Status*
T. Beals/B. Sanders	Distributed encryption methods and systems	Patent pending
T. Beals/B. Sanders	Distributed encryption authentication methods and systems	Patent pending
B. Sanders (producer)	Solid state quantum computer in Silicon	Four minute animated film

FUNDING

Dr Barry Sanders has a five year iCORE Professor award ($2.3M). This year he received federal funding from NSERC, CFI, CIAR, MITACS and PIMS ($520K) and provincial funding from Alberta Ingenuity ($229K). He also received funding from the University of Calgary ($95K) and others ($58K).

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Quantum Cryptography and Communication

The establishment of the new Quantum Cryptography and Communication Laboratory (QC2Lab) expands the Institute for Quantum Information Science (IQIS).

Through partnership between iCORE, General Dynamics Canada (GDC) and the University of Calgary (U of C), and based on support from the Southern Alberta Institute for Technology (SAIT), the QC2Lab research program allows the important interfacing of the world-class academic research with the demand of the society for provable secure communication systems, and is indispensable given the strategic importance of self-sufficiency in information security. It leads to pioneering advances in practical quantum cryptography (QC), and to significant benefits for Albertan and Canadian society and industry, U of C, and SAIT.

Quantum information science is concerned with revolutionary implications of quantum devices and systems to information and communication science and technology. Although the field is still in an embryonic stage and implementations are difficult, the advance of experimental capabilities coupled with new technologies are bringing it closer each day to actual realizations. In particular, the tremendous progress in the information-theoretically secure distribution of quantum keys during the last decade underlines the expectations that secure communication, invincible to future technological or algorithmic improvements, can be achieved. Yet, Canada cannot rely on importing working QC systems due to trade restrictions and imported technology be fully trusted because of the risk of "backdoor" information leakage. Furthermore, current quantum key distribution (QKD) systems lack from small key rates and limited distance, and the integration into networks is still to be accomplished. In short, investigation into QC systems that are made in Canada is indispensable.

The research program allows the building of fibre-based QC systems for up to 50 km distance with unprecedented key rates, and integration into classical communication infrastructure and networks. It also targets the development of quantum relay and repeater technology to extend QC across Alberta and ultimately across the nation. This includes novel techniques for rendering photonic quantum communication primitives practical, plus hitherto unrealized means for efficient and reversible transfer of quantum information between photons and atoms for temporal storage.

The first nine months of Dr Tittel's employment at the U of C were primarily devoted to securing the requisite funds for running an experimental research group consisting of approximately 12 researchers, setting up and equipping of the new world-class laboratories at the U of C and SAIT, attracting of students and postdoctoral researchers, and establishment of various collaborations, necessary to achieve the research goals. This installation phase now being sucessfully completed, next year's activities will be dominated by various QC related research projects.

Research Program Overview

Today, QC is limited in terms of bit-rate, distance, and extension from dedicated point-to-point links to multi-user networks. The goal of the Chair research program is to conduct leading edge research into high bit-rate and long-distance quantum cryptography and to investigate the building of a quantum secured communication network to the benefit of the Albertan and ultimately Canadian society. This includes the:

- Development of high-speed, point-to-point quantum cryptographic systems based on attenuated laser pulses and operating on widely available standard telecommunication fibres over distances of twenty of kilometers.
- Integration of quantum cryptographic systems with secure encoding algorithm for

the building of complete, quantum secured communication systems.

- Extension of point-to-point system to networks.
- Development of versatile and robust quantum communication primitives like sources of entangled photons and quantum teleportation units.
- Development of a quantum memory as needed for a quantum repeater.

Experimental work on quantum key distribution quantum relays and quantum memory has begun. Dr Tittel's team now comprises one BSc student, five MSc students (including co-supervised students), two PhD students (including a long-term visitor), one post-doctoral fellows, one SAIT Instructor, and Dr Tittel.

Research Projects

The QC2Lab can be divided into five categories: (i) general, (ii) quantum cryptography, (iii) integration and networks (iv) quantum relays, and (v) quantum memory.

General

Various collaborations necessary to achieve the research goals have been established.

Laboratory work commenced in January 2007. The laboratories will be supplied with filtered air and are set-up in a low vibration environment. A specifically designed electrical cirquit with "clean-ground" will allow highly sensitive measurements that will not be perturbed by electronic noise from other electronic equipment at the U of C. The three laboratories contain six experimental tables, including four optical, air supported tables. All tables are connected via fibre optical cables, and a raised floor provides great flexibility to install additional connections in the future. A separate compressor room allows hosting a noisy compressor (being part of a cryogenic system) off the main working area.

An additional laboratory at SAIT is currently being renovated. It will host one experimental table plus appropriate workspace for the collaborative development of networking components such as clock recovery circuits by SAIT personnel and students.

A pair of dark fibres will be set up by Bell to connect the laboratories at the U of C and SAIT. This link will allow testing of various QC setups in a real-world environment, as required to bridge the gap between academic research and commercial grade technology.

Quantum Cryptography

Current point-to-point QC systems based on faint laser pulses and qubits typically feature secret key rates over a distance of a few tens of km below one Kbps, orders of magnitude smaller as compared to classical telecommunications. This prevents from online interfacing with the highly key-consuming one-time pad, and limits the key regeneration rate for AES based encoding. Secret key rates in the Mbps range will be required for reasonably fast information-theoretically secure encoding, and to allow for more frequent replenishing of key material (i.e. for higher security) in high rate, AES-based communication. Limitations to higher rates include inefficient QKD protocols, poor detector performance, and low-speed implementation of classical post-processing algorithms. Co-ordinated work on all components of a QC system is required to solve the rate problem.

Experimental work has already started on a fibre-optical QKD system. It is based on the so-called four-state protocol and polarization states encoded into faint laser pulses, compatible with standard telecommunication fibre infrastructure, and will feature decoy states, a recently discovered method to counter a powerful eavesdropping attack in a very efficient way. It will allow preparation of photon states at Gbps rates, incorporate a novel method to actively stabilize time-varying polarization transformations during transmission in optical fibres, and will be set-up to allow future implementation into optical networks.

At the same time the team has started investigating a highly efficient method to correct errors during QKD. Traditionally, error correction is implemented via "Cascade", a two-way error correction protocol that was invented in the early nineties. However, Cascade requires several rounds of communication, and will become the limiting factor in future, high rate quantum key distribution schemes. In collaboration with iCORE Chair Dr Graham Jullian, Dr Tittel and the team have started investigating forward error correction based on low-density parity check matrices with the goal of a high-speed hardware implementation. Furthermore, QC2 recently teamed up with iCORE Chair Dr Hugh Williams, whose post-doctoral fellow Dr Shaoquan Jiang will try to optimize the error correction algorithm from a mathematics point of view. This collaboration between the three iCORE Chairs will ultimately lead to high performance implementation of classical error correction and thereby remove a foreseeable bottleneck in future implementations of QKD.

Integration and Networks

The integration of quantum secured communication links into communication networks is still at a very early stage. Various network node families must be considered, consisting of classical measurement nodes, optical switching nodes, or fully quantum enabled nodes.

Together with SAIT personnel, the QC2Lab has started studying QKD networks consisting of passive switching nodes.

Quantum Relays

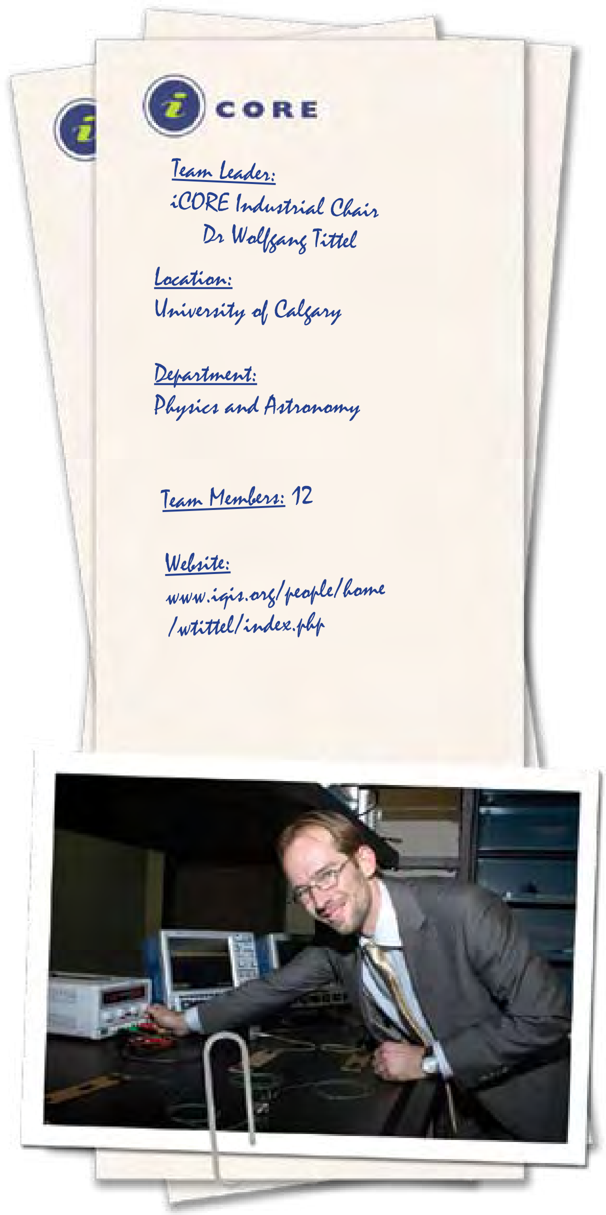
A major contribution to existing QC technology concerns the transmission distance. The concept of a quantum relay is based on several key elements, which are the creation and distribution of pairs of "entangled" photons over sub-sections of the complete link, entanglement purification within each sub-section, and swapping to extend (or teleport) the entanglement over the whole channel. This enables the generation of entanglement with high fidelity between distant nodes of a network. It can then be used for any kind of quantum communication task, such as quantum cryptography.

The team conducted a literature survey on various entanglement generation schemes. Phase-matching conditions that allow the generation of photon pairs at widely separated wavelengths in a periodically poled LiNbO3 crystal was investigated.

The team investigated the possibility of creating pairs of entangled photons via four-wave mixing in optical fibres with two (instead of one) pump laser. This so-far unexplored approach is promising for the generation of photons that are widely separated in wavelengths, as required for quantum channels consisting of free-space links (requiring photons at around 800 nm wavelength), and fibre-optics links (requiring photons at around 1550 nm wavelength).

An experimental setup that allows transformation of time-bin qubits was devised. These qubits are well suited for transmission through optical fibres. The transformation allows them to be mapped unto polarization qubits, which are better adapted to free-space transmission.

Theoretical studies of the optimum configuration assuming present or near future technology for QKD over a given transmission distance were started. A method to model the detection of faint laser pulses with non-perfect, i.e. realistic detectors, has been developed. It will now be extended to the detection



of quantum bits and entangled quantum bits, and will result in a realistic description of a quantum relay.

Quantum Memory

The realization of a reversible quantum state transfer between atoms and photons is one of the most important challenges in the field of quantum communication. It is a necessary requirement for a quantum repeater, which promises transmission distances beyond what is achievable using quantum relay technology. Many schemes for storage of non-classical light have been proposed. However, efficient, reversible transfer of quantum information between different species has not been accomplished yet.

An original protocol for a quantum memory in solid state material is based on "controlled reversible inhomogeneous broadening" (CRIB) of a single atomic absorption line, and has been proposed in an international collaboration lead by the group at the Université de Genéve, Switzerland. The protocol is particularly interesting in view of its enhanced bandwidth capacities as compared to other approaches and is now studied in several laboratories world-wide.

Erbium doped optical fibres or crystalline waveguides are interesting candidates for the realization of CRIB, as long interaction lengths, up to hundreds of meters in the case of fibres, can easily be achieved, allowing for large absorption even at low doping concentration. However, very little work has been done to characterize properties of Erbium doped fibres with respect to CRIB, and investigations of crystalline waveguides are completely missing.

Together with his former group at the University of Geneva in Switzerland, Dr Tittel could demonstrate optical coherence times exceeding one μsec in an Erbium doped optical fibre through application of a magnetic field and cooling to 150 mK. This constitutes the longest coherence time for a rare-earth-ion doped amorphous medium reported to date, and is important in view of the possible storage time for quantum information.

An additional step towards CRIB based quantum state storage was the investigation of broadening a single atomic absorption line through the application of an electric field in amorphous and crystalline waveguides. The new findings demonstrate the possibility for storage of quantum information encoded into photonic wave-packets as short as 10 ns.

Storage and recall of strong light fields via stimulated photon echoes in an Erbium-doped crystalline waveguide was investigated, leading to the result that the relative phase and amplitude ratio of data pulses can be preserved during storage in the optical memory, and that storage can be combined with projection measurments. This is of high importance and interest for quantum communication and computation schemes.

At the U of C, two students will be working on the quantum memory project. The research team has started looking into the basic concepts of quantum state storage based on CRIB in rare-earth ion doped solids.

Objectives for Next Year

The activities during the next year will be dominated by research into quantum cryptography, quantum relays, and quantum memory.

Quantum Cryptography

The QC2Labwill continue work on the polarization-based QKD system, which will lead to a complete QC system. The laboratory-type setup will comprise standard single photon detectors and run at a clock frequency of a few MHz. It will be implemented on the U of C - SAIT test-bed link, and will allow the demonstration of the principles of QC and yield important information for future packaging and development of commercial grade technology.

The Quantum Memory Lab at the U of C.

The QC2Lab will start work on quantum key distribution based on encoding of quantum information in superposition of faint laser pulses located in different "time-bins".

Integration and Networks

The team will continue studies for integrating QKD with Internet protocols, and into networks.

Quantum Relays and Repeaters

The QC2Lab will develop a realistic theoretical model that allows the team to simulate the performance of various QKD schemes based on quantum repeater technology, and that will guide the researcher's activities in future.

Quantum Relay

The QC2Lab will develop sources of pairs of entangled photons that feature time-bin entanglement, polarizatin entanglement, or entanglement between time-bin qubits and polarization qubits.

Quantum Memory

The team will start work on storage of classical (strong) light pulses in cold rare-earth ion doped solids based on a standard photon echo approach, and conduct research into the individual steps required for CRIB. The research will include spectroscopic investigations of various material properties.

Outreach

Jan 25, 2007: Dr Wolfgang Tittel was formally announced as the new iCORE/General Dynamics Canada Industry Research Chair in Quantum Cryptography and Communication. The launch event showcased Dr Tittel's research to around 100 guests, and included presentations by Dr Ron Dyck (Assistant Deputy Minister Research, Alberta Advanced Education and Training), Mark Adcock (Senior Scientist, GDC), Dr Harvey Weingarten (President, U of C), Dr Randy Goebel (President and CEO, iCORE), and Dr Tittel.

The iCORE launch triggered extensive coverage in print media, radio, and television:

Date	*Outlet/Reporter*	*Secondary Hits*
Print		
January 26	Calgary Herald (Jamie Komarnicki), Calgary Sun (Tarina White), Canadian Press	
February 16	IT World Canada.com (Nestor Arellano)	Various websites
April 3	Globe and Mail Innovation Page (Dawn Walton, Report on Business)	
Pending	Globe and Mail (Bill Atkinson, Science Writer)	
Pending	Alberta Ventures magazine (Doug Baisley, Edmonton Sun freelancer)	Scheduled for May
Television		
January 25	Breakfast Television/CITY TV (Dean)	
January 26	Shaw TV (Lisa) Global TV (Dave Goucher) SAIT TV CFCN TV (Kevin Green) Canada AM (CTV national news)	CTV NewsNet with Kate Wheeler. Footage used on Canada AM

Date	Outlet/Reporter	Secondary Hits
Radio		
January 26	AM 660 radio (Cormack McSwinney) CHQR/AM QR77 (Bruce)	
January 31	C-FAX Newsline with Terry Moore	West coast radio network
February 13	CBC Radio Wild Rose Country (Calgary) with Cathy Little	
February 17	Innovation Alberta (CKUA Radio, 580 AM) (weekly research news updates, Saturdays, 8:30 am)	Posted as Program #226 at http://www.innovationalberta.com/archives.php
Other		
	Brent Gilmore (photographer for iCORE publications and Website)	http://www.icore.ca/research_quantumcrypt.htm
U of C		
1/26/07	OnCampus	
Jan 26-29	Web homepage	

Feb 9, 2007: The quantum cryptography project was officially presented to the SAIT Management Council. The presentation was done by Steve Hosier, Principle QC Investigator at SAIT, in the presence of Dr Wolfgang Tittel.

March 6, 2007: The quantum cryptography project was presented to the SAIT Information Services Department. The presentation was done by Steve Hosier (SAIT), in presence of Dr Xiaofan Mo and Itzel Lucio (both from Dr Tittel's group).

Research Team Members and Contributions

Team Leader
Professor Wolfgang Tittel
iCORE/GDC Industrial Research Chair in Quantum Cryptography and Communication
NSERC Discovery Grant

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Steve Hosier	Instructor and Principle QC Investigator	

PostDoctoral Fellows

Name	Role/Topic	Awards/Special Info
Xiaofan Mo	Experimental quantum key distribution	iCORE

PhD Candidates

Name	Role/Topic	Awards/Special Info
Félix Bussières	Hybrid entanglement	NSERC graduate scholarship
Erhan Saglamyurek	Quantum Memory	Currently via teaching assistantship

MSc Candidates

Name	Role/Topic	Awards/Special Info
Philip Chan	Fast classical post-processing of a quantum key	NSERC graduate scholarship
Ahdiyeh Delfan	Quantum Memory	Currently via teaching assistantship
Gina Howard	Long-distance quantum key distribution with realistic devices	iCORE (Dr Sanders)
Itzel Lucio Martinez	Experimental quantum key distribution	Conacyt Fellowship (Mexican Government)
Joshua Slater	Entanglement	NSERC graduate scholarship

BSc Students

Name	Role/Topic	Awards/Special Info
Alisson Rubenok	Entanglement	

Visitors		
Name	**Date**	**Home Institution**
Félix Bussières	Nov 19 - Nov 25	Ecole Polytechnique Montréal

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
SAIT, Mr Hosier	Quantum Cryptography
U of C, IQIS, Dr Sanders	Studies of long-distance quantum communication with realistic devices
U of C, ATIPS Lab, Dr Jullien	Fast classical post-processing for quantum cryptography
U of C Centre for Information Security and Cryptography, Dr Williams	Optimization of forward error correction based on low density parity check matrices
National Collaborations	
Polytechnique Montréal, Département de génie physique, Dr Godbout	Entanglement and quantum teleportation
International Collaborations	
University of Geneva, Switzerland, Group of Applied Physics, Dr Gisin	Quantum Memory
University of Geneva, Switzerland, Département de Physique de la Matière Condensée, Dr Jaccard	Quantum Memory
University of Nice, France, Laboratoire de Physique de la Matière Condensée, Dr Baldi	Quantum Memory
University of Paderborn, Germany, Group of Applied Physics, Dr Sohler	Quantum Memory

FUNDING

Dr Wolfgang Tittel has a five year iCORE Industrial Chair award ($750K). This year, he received funding from the University of Calgary ($1.3M) and Alberta Ingenuity ($628K), and federal funding from NSERC and CFI ($985K).

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

S. R. Hastings-Simon, M. U. Staudt, M. Afzelius, P. Baldi, D. Jaccard, W. Tittel and N. Gisin, Controlled Stark shifts in Er3+-doped crystalline and amorphous waveguides for quantum state storage, Optics Communications 266(2): 716-719, 15 October 2006.

M. U. Staudt, S. R. Hastings-Simon, M. Afzelius, D. Jaccard, W. Tittel and N. Gisin, Investigations of optical coherence properties in an Erbium-doped silicate fiber for quantum state storage, Optics Communications 266(2): 720-726, 15 October 2006.

M. U. Staudt, S. R. Hastings-Simon, M. Nilsson, M. Afzelius, V. Scarani, R. Ricken, H. Suche, W. Sohler, W. Tittel and N. Gisin, "Fidelity of an Optical Memory Based on Stimulated Photon Echoes", Physical Review Letters 98: 113601 (4 pp.), 14 March 2007.

ABSTRACTS

W. Tittel, M. Afzelius, N. Gisin, S. Hastings-Simon, and M. Staudt, "Investigations of an Erbium doped fiber for quantum state storage", IEEE LEOS Summer Topicals 2006 in Quebec.

PRESENTATIONS

8 Mar 2007, W. Tittel, M. U. Staudt, S. R. Hastings-Simon, M. Afzelius, V. Scarani and N. Gisin, Investigations of an optical memory based on stimulated photon echoes, V33:000002, 2007 APS March Meeting (APS 2007), Colorado Convention Center, Denver, Colorado, 5 Mar 2007 - 9 Mar 2007.

7 Mar 2007, M. U. Staudt, S. R. Hastings-Simon, B. Lauritzen, M. Afzelius, H. De Riedmatten, N. Sangouard, C. Simon, W. Tittel and N. Gisin, Coherence investigations of Erbium doped in wave-guide structures for a quantum memory, S32:00007, 2007 APS March Meeting (APS 2007), Colorado Convention Center, Denver, Colorado, 5 Mar 2007 - 9 Mar 2007.

7 Mar 2007, S. R. Hastings-Simon, M. U. Staudt, B. Lauritzen, M. Afzelius, H. De Riedmatten, N. Sangouard, C. Simon, W. Tittel and N. Gisin, Three level systems for quantum memories in Erbium doped materials, S32: 00010, 2007 APS March Meeting (APS 2007), Colorado Convention Center, Denver, Colorado, 5 Mar 2007 - 9 Mar 2007.

18 Sep 2006, W. Tittel, M. Afzelius, N. Gisin, S. R. Hastings-Simon and M. U. Staudt, Towards Quantum Memory (invited), Optical Science and Engineering Conference, Bozeman, Montana, USA, 18 Sep 2006 - 19 Sep 2006.

18 Jul 2006, W. Tittel, M. Afzelius, N. Gisin, S. R. Hastings-Simon and M. U. Staudt, Investigation of an Erbium doped optical fiber for quantum state storage, TuB2.5, IEEE/LEOS Summer Topical Meeting on Quantum Communication in Telecom Networks, Quebec City, Canada, 17 Jul 2006 - 19 Jul 2006.

E-Prints (arXiv.org e-Print archive)

M. U. Staudt, S. R. Hastings-Simon, M. Nilsson, M. Afzelius, V. Scarani, R. Ricken, H. Suche, W. Sohler, W. Tittel, N. Gisin, "Fidelity of an optical memory based on stimulated photon echoes", arXiv:quant-ph/0609201.

SPECIAL/INVITED PRESENTATIONS

3 Apr 2007, W. Tittel, Quantum Cryptography - Distinguished Lecture Series - CISaC & CMSS (invited), University of Calgary, Department of Mathematics and Statistics.

16 Nov 2006, W. Tittel, Quantum cryptography, entanglement and teleportation: experiments with photons (invited, colloquium), University of Waterloo, Department of Physics and Astronomy .

15 Sep 2006, W. Tittel, Quantum cryptography, entanglement and teleportation: experiments with photons (invited, colloquium), Montana State Univesity, Department of Physics.

8 Sep 2006, W. Tittel, QC2 lab: the quantum cryptography and communication laboratory, University of Calgary. PHYS.020 Research Day.

10 Aug 2006, W. Tittel, Practical quantum cryptography and communication , Sixth Canadian Summer School on Quantum Information Processing, Calgary, Canada, 7 Aug 2006 - 11 Aug 2006.

Nanoscale Information and Communication Technologies

In the past four years the iCORE Chair in Nanoscale Information Communications Technology (NICT) has made great progress towards its goals.

With comparable resources from the National Institute for Nanotechnology (NINT) and other sources, a tremendous team and state of the art facilities have been assembled, placing the iCORE Chair in Nanoscale Information Communications Technology among the world's leaders. The Molecular Scale Devices Group under the iCORE Chair in NICT uses scanning tunneling microscopy (STM) and advanced quantum mechanical computation, together with expertise in condensed matter physics, surface chemical physics, organic synthesis and instrument engineering to gain a detailed understanding of, and atom-scale control over hybrid silicon-molecule structures. The knowledge gained in this venture will underpin revolutionary devices capable of new function and miniscule power consumption that will be fabricated – and later disassembled - using "green" processes. While initially the group faces a great array of formidable challenges, the brain-like computational power and sensing functions created will more than repay the investment.

While half of the last year was devoted to moving five NINT and three Physics-based labs to new buildings, the NICT team gained substantial results. One achievement that stands out was the development of the sharpest electron-emitting object made by man. The work was judged by the American Institute of Physics to be among the top stories of the year – the only Canadian work so recognized. Newspapers, blogs, e-magazines around the world reported on this work. Mass distributed journals such as Popular Mechanics, Popular Science, and PC Magazine also featured the work. So numerous were downloads of movies showing the atom-by-atom crafting process that university web administrators threatened to shut down the iCORE Chair in NICT website. The site remained open because this, like other high profile work, has significantly enhanced Alberta's reputation in the area of nanotechnology and has helped draw the very best students to the team.

The NICT team plans to report that metal contacts can be automatically and precisely grown onto the end of the team's molecular lines – a major step toward building of complex and functional ICT structures. The NICT team also plans to reveal a most dramatic development: that single electrons can be spatially isolated and controllably moved. Crucially, this is done on a standard silicon surface and at room temperature. The team believes this is a substantial step toward realization of radically new computation concepts such as quantum cellular automata (QCA) and possibly qubits for solid-state quantum computers.

Research Program Overview

The research program seeks means for understanding and controlling matter at the nano-scale to enable revolutionary ICT devices. The focus is the enormously rich territory formed by hybrid silicon-molecule structures – an area the NICT team pioneered and leads. Because the approach builds upon silicon technology, and because the aim was initially to enhance rather than supplant silicon, a viable path for adoption of new ideas was created. Work is organized along three streams: Chemistry, Physics and Engineering, but there is overlap among these streams of people, facilities, and objectives. Briefly, projects within the Chemistry grouping explore revolutionary fabrication approaches. Physics projects explore properties relevant to future ICT applications. Engineering projects include both state of the art instrument development and explorations of applications of the capabilities, materials and structures created within the Chemistry and Physics projects.

While techniques now exist that enable atom-by-atom crafting of structures, to be viable, nano-structured devices must largely self-assemble. The NICT team is set to discover ways to set the stage, and then to provide a "spark" that causes desired structures to assemble precisely how and where they need to be. Though entirely different than conventional manufacturing processes that place, carve and fix "building blocks" into place, this self-assembly idea is not new – it is an emulation of nature's methods. Determination to do more than make interesting one-off research structures is a key and differentiating point in NICT's work. This demand of the research does set the bar much higher, but the pay-off will be great. Despite the greater challenges, remarkable progress has been made toward this goal. The researchers have invented a process that allows pre-defined multi-molecular structures to be automatically formed wherever a scanned probe is "pointed". In numerous publications the NICT team has shown the substantial and expanding scope and power of their approach.

Despite the time used relocating all of NICT's labs, great progress has been achieved. In the chemistry section, various improvements in the ability to controllably grow nano-structures are described. The goal is to be able to "point" at initiation points and then through simple controls grow many like entities of pre-defined function.

The NICT team moved closer to understanding molecular lines of mixed composition. It is worth mining this area because theory predicts and experiments make clear that fascinating new properties are created at the interfaces built into these entities.

A years-long sustained effort has gone into tuning the properties of individual "dangling bond" atoms. These are special atoms in that they have some properties of the continuous crystal that they sit upon but also have unique and widely tunable character due to their particular configuration. These entities have long been seen as defects with deleterious properties (in traditional silicon technology). The NICT team recognizes that these dangling bond atoms hold great promise for future technologies. As a result the NICT team is trying, and is getting closer and closer, to showing what these special atoms can do and how to control them. In the coming year the NICT team expects major developments – specifically, to tune chemistry of such atoms, to show that such atoms can in turn tune the electrical properties of juxtaposed molecules, and even to show that dangling bonds can localize and participate in the exchange of single electrons.

The engineering efforts of the past year show the maturing of several on-going projects. The multi-probe microscope, an instrument of NICT's design, has begun to operate – a thrill after years of design and fabrication. Many aspects remain to be debugged but in the coming year the instrument will produce useful and, the NICT team hopes and expects, famous data.

The impact of NICT's nanotip – on lay and scientific audiences – has been great. Numerous extensions of the work have been made and several more are continuing into next year. The NICT team aims to create

a powerful new kind of microscopy that will greatly advance the group's work and the work of an entire community too.

All the results now emerged and those coming ever closer are what they were predicted to be. World-leading science has been done time and again, the NICT team has stimulated growth and benefited the prestige of the campus, the best students are being drawn to NICT and are being superbly trained, IP is being created, and revolutionary new technologies look ever closer to hand. The only substantial deviation from the plan is that the iCORE Chair in NICT is ahead of schedule.

Research Projects

Chemistry

Directional Control of Nano-Structure Growth

A substantial advance was recently made by the Kawai group of Japan who modified the NICT team's multi-molecular nanostructure growth process. The Kawai team found a process that grows at a right angle (with respect to the axes defined by the crystalline silicon substrate) to the structures the team had grown. The NICT team has now gone one step further, to grow contiguous lines of molecules that turn a corner (precisely 90°). Using controls, molecules can be titrated to grow along one pre-defined direction - then, by turning off that valve and opening another, molecules are fed in that continue the growth, but in a different direction. This process, in principle, allows unlimited numbers of similar structures to be grown simultaneously. Though an exciting development, much work remains to be done - the current process still results in too many errors in growth. A paper has been submitted for publication.

No experimental progress on planned electrostatically governed growth has yet been made, but the researchers have succeeded in designing appropriate molecules and have a test procedure planned.

Dangling Bond Capping

The NICT team's palette of materials has been made richer through the investigation of Diethylhydroxylamine as a gentle source of H atoms for termination of surface silicon dangling bonds. Several means to achieve this termination have been created, each with a niche application. These capabilities are necessary elements in the team's toolkit for atom-scale control. A further paper, contrasting two capping procedures, is complete and soon to be submitted.

Dangling Bond Formation

Dangling bonds are central elements of the NICT team's fabrication approaches. Building on the pioneering work of Tucker and Lyding, the NICT team has advanced the understanding of the formation of single and groups of dangling bonds, revealing the remarkable ease of formation of particular groupings – a result reminiscent of "magic numbers" revealed in other areas of science. For the particular case of 2 H atom removal the atoms are claimed from adjacent dimers, not from one dimer, the seemingly more attractive source of 2 H atoms. Step by step, the researchers improve their ability to fabricate at the atom scale.

Single Dopants

The ability to theoretically describe single dopant atoms has progressed. Experimental studies of local effects of thermal dopant deactivation have been performed successfully. Work toward control over single dopants is ongoing.

Extending Classical Poisson's calculations to non-equilibrium

The NICT team's proposal to work with Randal Feenstra of Carnegie Mellon to model electrical transport from a silicon substrate, through particular surface states with a rigorous inclusion of charging phenomena has progressed. Theorist Werner Hofer of Liverpool has been added to the mix. He headed a grant application that proposed connecting the three groups to pursue this goal. That grant was successful, allowing staffing and inter-group travel to soon commence.

Physics

Electrical Characterization of Molecular Lines

In this past year much effort has gone into further characterization of molecular lines as conductors. The NICT team's theoretical work has led to better understanding of the details of molecular configuration. George Kirczenow further advanced his transport calculations. Experimental studies have reproduced the dramatic features associated with one dimensional heterostructures that the researchers observed in the previous year – allowing them to be confident of their observations. New heterostructures were fabricated, again showing beautiful local tuning of electronic properties. The work is on-going and a little more progress is required before the researchers can state their conclusions.

Molecule-Molecule Tuning

As planned, the NICT team's advanced substantially toward demonstrating and understanding molecule-molecule tuning effects. Dramatic experimental and corresponding theoretical work is in hand. In essence this work shows that the composites the team grows are different than the sum of the (molecular) parts – subtle, controlled interactions among the participants create new hybrid features. Nature does exactly this all the time, but what is unique here is an ability to purposefully call upon such tunings to achieve desired properties and function.

Tuning Local Electronic Structure – "Alchemy"

A goal in last year's report was to show the capacity to locally tune the electronic and chemical character of single atoms. Such a capability would be like alchemy in that a single element could be caused to act differently. The NICT team is a large step closer to achieving such a tuning by an all-electrical means, literally changing the nature of an atom by the turn of a button. More work is required, but awaits full operation of the new multi-probe instrument.

Advancing the Concept for a Single Molecule Transistor

The same capabilities described in the preceding section moved the NICT researchers a big step closer to gaining true temporal control over a single-molecule transistor – that is to turn it on and off at will. A little progress has been made toward the goal of a surface-lateral molecular transistor configuration, which in turn will lead to a multi-molecular integrated circuit – a giant achievement when reached. Work is ongoing.

Localizing and Manipulating Single Electrons

For two years the NICT team has reported that evidence is accumulating of controllable positioning of single electrons with atom-scale spatial control. The team has speculated that if such localization can be achieved it might lead to the ability to poise groupings of electrons and allow them to interact – or "compute" – at the smallest conceivable, lowest energy-consuming level, as in the "quantum cellular automata" (QCA) scheme. Though outside of the time frame of this report it was noted that solid proof was gained that electrons can be placed and moved. This is a very important advance, described more under "Objectives for Next Year".

Structural Assignment

Some of the questions asked during the team's research require new physical characterization tools. In the recent paper "A simple and accurate approach for calculating the vibration spectra of molecules on surfaces: Comparisons to high resolution electron energy loss data for ethylene on silicon", Surface Science 2006, 600, L209-L213, the team describes an improved combined experiment/theory method for using vibration spectroscopy to identify the precise structure of molecules attached to a surface..

Metal-Silicon Contacts

NICT has devoted much effort to the problem of nano-scale metal-semiconductor contacts. Last year, the NICT team was on the verge of completing this research, but numerous challenges and uncertainties emerged and the group has only recently arrived at a robust description of the physics of the problem. It was found that traditional descriptions of such structures offer a starting point but full predictive understanding and control of the smallest possible metal-semiconductor junctions requires awareness of new phenomena inherent to the nano-scale. Though slow moving, this project has not been abandoned because it is essential to NICT's and the field's, progress.

Computational Methods

Theory and computation work is central to all of the NICT team's physics projects. In the past, quantum mechanical computation skills have been focused on energies and geometries of nano-scale systems – in this area the NICT team's skills are top-notch. In last year's report it was mentioned that the team had learned plane-wave, semi-infinite slab methods which describe energies and structures related to continuous crystalline materials. Those techniques are now routinely, confidently used and have been incorporated in published work.

The capacity to perform "transport" calculations, which describe electricity in nano-scale entities, have advanced greatly in the past year as a result of working closely with Hong Guo of McGill University. The NICT team expects to be able to publish in this area in the coming year.

Engineering

Scanner Design

The group continues to advance the machinery that enables the scanned probe microscopes. The NICT team describes nano-scale scanning devices through improved predictive capacity.

Multi-probe Instrument

As predicted in last year's plans, the multi-probe microscope became operational for the first time this past year. All mechanisms, electronics and software of this extraordinary instrument are of the NICT team's design. It allows independent scan-able probes to image or touched-down to electrically characterize on the nano-scale. Each of the independent tips can be atomically characterized with an integral field ion microscope to allow optimal control over probe-sample contact. The instrument includes the world's only in-ultra high vacuum active noise isolator to achieve extraordinary noise reduction (100x reduction at 1 Hz). Noise reduction leads directly to better measurements that lead to better understanding. Some modes of operation have yet to be tested and debugged but this is the year, after three years of design and building, when the instrument will begin to produce data.

Nano-Tips

The NICT team's nano-tips were reported on briefly last year and have since been published (after patent pending protection was established). The scientific and lay response was enormous (see Outreach section). The nano-tip is unique in that it is extremely sharp and chemically terminated in such a way that only the single apex atom is a source of emitted ions or electrons. In addition to being extremely bright (emission current is concentrated in a small solid angle) the emission is also spatially coherent – one property of laser light – and that property may enable a supremely powerful new holographic microscopy.

Objectives for Next Year

Chemistry

Diversity of Chemical Function

Over the last several years the NICT team has substantially expanded the range of molecular functions that can be incorporated into multi-molecular nanostructures on silicon. As the palette of materials expands, the team approaches the capacity to build structures of the complexity that future devices will require. The near term extension of that effort focuses on substituted benzophenones, which contain both electron donating and electron withdrawing groups. The team expects to automatically juxtapose such molecules in a perfectly ordered line on silicon. It is anticipated that such structures will display enhanced and tunable intermolecular conductivity – a property the team seeks as it moves closer to functioning devices.

The plan is also to explore lines that contain strongly interacting molecules (sharing H-bonds for example) to enforce stronger electronic coupling of aromatic functions.

Molecules as Mechanical Elements

Still other designs will explore "mechanical" coupling of molecules in a line. The NICT team pictures a Venetian blind-like structure that causes the enforced configuration of one molecule to determine that of others at a distance.

Electric Field Controlled Growth

The NICT team aims to make a first attempt at the use of electric fields to control nanostructure growth direction. If successful this approach to biased-self-assembly would be most powerful, as it would allow control over another dimension of structure. This approach meets the challenging goal of supporting parallel fabrication of numerous like structures.

Physics

Localized Electrons

The NICT team is considering IP implications now. Subsequent studies will explore building blocks for logic function, possibly fulfilling the quantum cellular automata framework, which in turn underpins a revolutionary (theorized) computing platform.

Molecular Diode Construction

The NICT team will continue studies of molecular lines of mixed composition. The group will also study the electrical characteristics of these one-dimensional heterostructures seeking indications of rectifying behavior. Such a diode will be an important circuit element in future multi-molecular integrated circuits.

Engineering

Nano-Tips

In the NICT team's new multi-probe instrument, probe sharpness determines how closely probes can be spaced and therefore how small an entity can be probed. The probes promise the smallest possible spacing between probes. This is an important activity as the demand for such exacting characterization skills and tools is sure to grow with time. Tests will commence in several months.

Four additional nano-tip projects are underway:

i. With Hitachi, the NICT team is working to establish the practical capabilities of the tips (under the terms of a written agreement). All tests to date show that the NICT team's tips are superior to any previous electron emitters used in electron microscopy. Hitachi sends their premium commercial emitters that are sharpened to achieve greater brightness and lower onset voltage. The tip is not merely a laboratory curiosity - it can be shipped around the world, subsequently be characterized by independent researchers, and survive to reveal its wonderful properties. One Hitachi researcher has visited the NICT labs several times already.

ii. The NICT team seeks to better characterize the helium ion emission character of the tips, with the aim of gaining a licensing arrangement with a manufacturer of a helium ion microscope. Preliminary discussions with that company have taken place.

iii. The group has designed and is now building a holographic microscope that will exploit the extraordinary spatial coherence properties of the nano-tips. A paper describing the design criteria has been submitted for publication. The NICT team anticipates that the instrument will reveal 3-dimensional, atom-resolved images of nano-scale objects.

Research Team Members and Contributions

Team Leader
Professor Robert A. Wolkow
Directs all activity and serves in managerial roles at NINT
Professor in Physics at University of Alberta
Adjunct Professor of Chemistry
Principal Research Officer and Molecular Scale Devices group leader at National Institute for Nanotechnology (NINT), NRC

Outreach

Dr Wolkow was elected to be chair of future Gordon Research Conference on Nanostructure Fabrication, volunteered to lecture on Ethics and Academic Integrity, Department of Physics, fall 2006, gave several presentations for local and provincial organizations, reviewed numerous manuscripts for several top-tier international journals,m and he has co-organized Science Fair at a school in Edmonton.

The University of Alberta (U of A) and NINT gained much recognition though coverage of the NICT team's procedure for making the sharpest ever metal tips.

Professional journals covering the result included:

- Chemistry World, the Royal Society of Chemistry's magazine.
- Chemical and Engineering News, "Method whittles sharp metal tips", 12 June 2006

Newspaper covering this development included:

- The Toronto Star
- Berliner Zeitung, 13 Aug 2006 "Die spizeste Nadel der Welt: Sie wurde bis auf ein einziges Atom werjungt"

The nano-tip was described in Magazines such as:

- Popular Science (Nov 2006, "Atomic Pencil Sharpener")
- Popular Mechanics
- PC Magazine

Radio and television coverage:

- Global television news, Aug 2006
- "Earth and Sky" Fall 2006 – a widely distributed radio item (on CKUA in Alberta)

- Research on new nano-tips was featured in many electronic technical magazines, ranging from Physorg to Slashdot. Professional and lay interest was enormous. The real-space, atom-scale movies of the tip formation process resulted in hundreds of gigabytes of downloads from the U of A web site in 2006.
- The American Institute of Physics (AIP) "Physics Update" column featured the NICT team's result
- The AIP ranked the NICT team's work as one of the most notable of the year – the only Canadian work so recognized

Service on committees

- WestGrid Local Executive Committee
- Condensed Matter Physics lecture series organizer
- Committee to recruit condensed matter physics theorist – succeeded in hiring first choice candidate
- University of Alberta President's committee for Canadian Research Chair renewal
- Provided a "Nanotechnology Case Study" for the National Computing Platform CFI proposal
- Chemical Institute of Canada, Edmonton Local Executive Committee: Plans and executes a number of chemistry-related activities in Edmonton including lay-accessible and scientific seminars, student activities, tours and events related to Nation Chemistry Week
- National Research Council Research Officer/ Research Council Officer Professional Institute of the Public Service of Canada Group Executive Member. Tour other NRC Institutes and discuss various issues with staff
- Member of the Committee for Safety and Health at NINT
- Hiring committee at NINT
- Organizing Committee – International Conference on Nanoscience and Technology, Basel 2006
- Organizing Committee, NanoForum, Canada's national nano-science annual meeting
- NINT NRC Internal Strategic Advisory Committee
- NINT NRC Project Selection Committee

Faculty Team Members		
Name	**Role/Topic**	**Awards/Special Info**
Martin Cloutier	Permanent staff technician	Contributes to the running and maintenance of all the labs Expertly aided in complex lab relocations of the past year
Gino DiLabio	Permanent staff scientist at NINT, theorist, quantum mechanical calculations of molecules and silicon probing electronic and chemical properties	Contributes substantially to near all of the group's projects Manages the group's computer facilities, aids in institute and university (Westgrid) computer facility management, supervises graduate students, and liaises extensively to make the NICT team's skills available to the wider community
Jason Pitters	Permanent staff scientist at NINT, experimentalist, specializes in scanning tunneling microscopy and atom-scale control of surface chemical modifications of silicon	Responsible for all ultra high vacuum scanning tunneling microscopy and related laboratories, and for day-to-day guiding of postdocs and students. Also supervisor of group technician Liaises extensively to make group's particular expertise more widely accessible to the local community. Time was dominated this year by lab move requirements Played a central role in a demonstration that single electrons can be spatially isolated, and, controllably repositioned
Mark Salomons	Permanent Staff at NINT, Instrument Design Engineer Designs state of the art instruments that cannot be purchased, and opening the door to commercialization opportunities	Completing a new multi-probe nanoscale measurement tool, allowing the NICT team to simultaneously monitor and/or manipulate matter on the atomic scale, while also measuring electrical transport properties This machine will give the NICT team a lead in the ability to gain practical measurements relating the nano-scale to the macro world
Judy Xu	Group Administrator	

PostDoctoral Fellows

Name	Role/Topic	Awards/Special Info
Adam Dickie	Completing studies of nano-scale electrical contacts to silicon	Several papers are in sight: two describing the extraordinary physics of smallest possible metal-silicon contacts; one describing contacts as molecular sensors
Stanislav Dogel		Three papers completed; one describes improved methodology for combined STM and electron energy loss spectroscopy; others describe advances in controlling surface states on silicon Will soon leave for a job in Germany
Baseer Haider	Explores of silicon surface states	
Luca Ramoino		Gained new insights into intermolecular ordering effects, extended work on one-dimensional molecular heterostructures, discovered new nanoscale molecular electronic tuning effects, and has found a way to automatically grow a metal contact onto a well defined molecular structure
Mohamed Rezeq		Created the sharpest electron-emitting object ever, gaining patent pending status and worldwide attention Has taken an academic job in Singapore.
Radovan Urban	Creates ultra-fine probes (as started by Rezeq)	Works with Hitachi, USA and Japan, in evaluating the NICT team's extraordinary tips as superior electron field emitters Evaluating ion emission character and attempting to create spin-polarized among other sources Likely to go to Hitachi's Japanese labs

PhD Candidates

Name	Role/Topic	Awards/Special Info
Janik Zikovsky		Has helped bring the new multiprobe instrument to completion, a machine is so powerful that the NICT team expects near every subject probed with it will lead to exciting, world-wide noted results

MSc Candidates		
Name	**Role/Topic**	**Awards/Special Info**
Amsalu Anagaw		Guided by Gino DiLabio Successfully completed all formal requirements for MSc A fine thesis has resulted and a paper is in the works that describes the practical, local and well-defined tuning of silicon surface electronic structure through addition of molecules
Josh Mutus		Awarded the CGS scholarship Near completion of the design of a remarkable new microscope – a holographic electron microscope that will reveal 3D atomic level structure, including internal structure, of diverse nanoscale objects This machine is a direct offshoot of the NICT team's nano-tip discovery
Shoma Sinha		In Chemistry
Manuel Smeu		Guided by Gino DiLabio Performs nano-scale electrical transport computations Will finish a Masters degree in a few months and will then continue studying before moving to McGill (Wolkow is adjunct there) – to be co-supervised by theorist Hong Guo A paper is expected from MSc work

GRADUATES

Name	*Research Topic*	*Current Position*
MSc Graduates		
Amsalu Anagaw		Completed all requirements of MSc Will not formally graduate until the next reporting period

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
U of A, Physics Prof Mark Freeman	Brings time-resolved scanned probe and magnetism expertise
U of A, Physics Prof Frank Hegmann	The same joint effort as above to explore ultra fast scanned probe methods, Hegmann brings ultra fast laser expertise and he led the effort to gain substantial CFI and related funding for the team
U of A, Chemistry Prof Rik Tykwinski	Exploring highly electrically conjugated molecules as candidate molecular wires, and more Student Janik Zikovsky has now achieved impressive preliminary results showing individual and nano-crystals of the molecules
National Collaborations	
Simon Fraser University Prof George Kirczenow, Renowned mesoscopic physics and transport theorist	Coupled experimental-theoretical electrical transport study of hybrid silicon-molecule structures, one paper published, another underway, discussing means to observe quantum interference effects, which would have profound implications for molecular devices, with Kirczenow postdoc David Cardamone

Participants	*Nature of Collaboration*
National Collaborations Cont'd	
University of Calgary, Electrical Engineering Prof Qiao Sun, Expert in control systems, finite element analyses and robotics	Jointly designing new instrument noise isolation techniques. One paper is now published and in testing, the vacuum active isolator achieved a 100x noise reduction at 1 Hz. A capability no other lab has
NRC, Steacie Institute for Molecular sciences K. U. Ingold	NICT's projects are regularly discussed with Keith Ingold, one of Canada's greatest living scientists. Over the last decade his expertise with radicals has led to powerful insights
University of Western Ontario Kim Baines	Completed a study of the mechanism of substituted alkynes addition to silicon dimers
International Collaborations	
Prof P. Christiansen, Clarkson University and Dr M. Hurley, US Army Research Labs	Advancing Quantum Capping Potentials
St. Andrew's and Leiden: Dr J. Walton, Dr P. Mulder	Continue to explore radicals and solvent effects
Institute for Microelectronics Stuttgart Prof Dr. Joachim N. Burghartz, Director and Chairman of the Board	Last year described anomalously low Schottky barriers for atom-scale metal-silicon contacts made with an STM tip The effect was reproduced in a lithographic implementation. Attempts to to test within a CMOS device have been hampered by lack of funds on the European side. Progress is slow but the team has not given up. Adam Dickie's work directly impacts this effort.
Liverpool , Physics Prof Werner Hofer	Theoretical study of molecule-silicon electronic properties – a coauthor on the NICT team's recent Nature publication Theoretical approaches compliment the team. Succeeded in gaining a new grant that will finance continued collaborative work. Been named an associate of the CIAR nano-electronics program (Wolkow is a fellow of that) – ensuring two paid-for face-to-face meetings each year (principals and students too).

FUNDING

Dr Robert Wolkow has a five year iCORE Chair award ($3.75M). This year he received federal funding from NSERC, NRC, CFI and CIAR ($1.7M), provincial funding from ASRA ($61K) and funding from the University of Alberta ($50K).

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

Theoretical study of the thermochemistry and kinetics of the addition of silyl radical to ethylene", O. J. Clarkin and G. A. DiLabio, *Chemical Physics Letters*, **2006**, 425, 201-204.

"Construction of a stable N-heterocyclic phosphenium cation with an electron-rich framework and its complexation to rhodium", H. A. Spinney, G. P. A. Yap, I. Korobkov, G. A. DiLabio, and D. S. Richeson, *Organometallics*, 2006, 25, 3541-3543.

"Effect of ring substitution on the S-H bond dissociation enthalpies of thiophenols. An experimental and computational study", P. Mulder, O. Mozenson, S. Lin, C. E. S. Bernardes, M. E. Minas da Piedade, A. F. L. O. M. Santos, M. A. V. Rideiro da Silva, G. A. DiLabio, H.-G. Korth, and K. U. Ingold, *J. Phys. Chem. A* **2006**, 110, 9949-9958.

"A simple and accurate approach for calculating the vibration spectra of molecules on surfaces: Comparisons to high resolution electron energy loss data for ethylene on silicon", G. A. DiLabio, S. A. Dogel, R. A. Wolkow, *Surface Science* **2006**, 600, L209-L213.

"Bond strengths: The importance of hyperconjugation", K. U. Ingold and G. A. DiLabio, *Organic Letters* **2006**, 8, 5923-5925.

"Isomerization of triphenylmethoxyl and 1,1-diphenylethoxyl radicals. Revised assignment of the electron-spin resonance spectra of purported intermediates formed during the ceric ammonium nitrate mediated photooxidation of aryl carbinols", K. U. Ingold, M. Smeu, and G. A. DiLabio, *Journal of Organic Chemistry* **2006**, 71, 9906-9908.

"A theoretical and experimental investigation of some unusual intermolecular hydrogen-bond IR bands - Appearances can be deceptive", G. Litwinienko, G. A. DiLabio and K. U. Ingold, *Canadian Journal of Chemistry* **2006**, 84, 1371-1379.

"Theoretical and spectroscopic study of the reaction of diethylhydroxylamine on silicon(100)-2×1", G. A. DiLabio, S. A. Dogel, A. Anagaw, J. L. Pitters, and R. A. Wolkow, *Physical Chemistry Chemical Physics* **2007**, Published to the web Feb. 07.

Electron-induced H atom desorption patterns created with a scanning tunneling microscope: Implications for controlled atomic-scale patterning on H–Si(100), Xiao Tong and Robert A. Wolkow, Surface Science, **600**, L199-L203 (2006)

Three-dimensional displacement analysis of a piezoelectric tube scanner through finite element simulations of a tube assembly, Qiao Sun and Robert A. Wolkow, Rev. Sci. Instrum. **77**, 113701-10 (2006).

Tungsten nanotip fabrication by spatially controlled field-assisted reaction with nitrogen, Rezeq M, Pitters J, Wolkow R, J. Chem. Phys., **124**, 204716 (2006)

PRESENTATIONS

Invited Talks given by Wolkow

Hybrid silicon-molecule device concepts, The NINT-CeNS Winter School on Nanotechnology Convergence, a gathering of scientists and students from Munich Germany and Edmonton, Edmonton 14-21 Mar 2007.

Field regulation of single-molecule conductivity by a charged atom, College of Nanoscale Science and Engineering, University at Albany, State University of New York, 18-19 January 2007.

Field regulation of single-molecule conductivity by a charged atom, Schloss Ringberg Discussion meeting on one-dimensional materials, hosted by Max Plank Institutes, Tegernsee, Germany, 15-18 Oct. 2006.

Field regulation of single-molecule conductivity by a charged atom, ACS meeting, San Francisco CA, Sept. 2006

Field regulation of single-molecule conductivity by a charged atom, Gordon Research Conference on Nanostructure Fabrication, July 16 – 21, 2006, New Hampshire, USA

Field regulation of single-molecule conductivity by a charged atom, CREST workshop on physics of single molecules, 16-18 May 2006, Shonnan international village, Kanagawa, Japan

Invited Talks by DiLabio

"Modulation of Current by a Single Localized Electron Through Linear Organic Nanonstructures On Silicon." 18th IUPAC Conference on Physical Organic Chemistry, Warsaw, Poland, Aug. 20-25, 2006.

"Modulation of Current by a Single Localized Electron Through Linear Organic Nanonstructures On Silicon." Netera Days, Edmonton, Alberta, Canada. Oct. 31, 2006.

Invited Talks by Postdoc Adm Dickie

"Molecular Sensing Using Point Contact Conductivity Modulation", 4th Molecular Conduction and Sensor Workshop, Charlottesville, VA, USA, July 2006.

Advanced Digital Media for Education

There is a tremendous opportunity to investigate new ways of improving student performance through the use of multimedia educational content, as opposed to traditional printed material.

Figure 1 *Some screenshots from Google Earth.*

Instead of computer games, animations, cartoons, and videos being used only for entertainment, the Advanced Digital Media for Education (ADME) iCORE chair's focus is now on using some of these media for educational purposes. Along with content creation, multimedia has potential use in "innovative testing." Audio, video and graphics are being integrated as alternative means for more effective testing rather than traditional pen-and-paper tests.

The University of Alberta (U of A) benefits by increasing its profile in applied multimedia research, being able to attract and retain high quality academic personnel, and increasing the graduate and undergraduate enrollment in multimedia disciplines. Over the last decade, the Computing Science department at the U of A has achieved various milestones in the Multimedia area, including setting up a multimedia curriculum sponsored by HP, a CAVE visualization facility, the Multimedia Advanced Computing Facility, and several multimedia panoramic and 3D research projects. The proposed research chair has been the project leader in several projects, and a principal investigator in many other major initiatives, including the TeleLearning NCE.

The ADME team researches how image, graphics, haptic and audio tools can be used for innovative testing. The researcher's incorporates perceptual factors for optimizing transmission and visualization of multimedia for delivery over low-bandwidth and unreliable networks. The University-Industry research program makes it possible for the team's industrial partner, Castle Rock Research, to accelerate an already successful Alberta company to a company with national and international recognition for its innovative R&D pursuits.

Research Program Overview

The focus of this program is to research optimized techniques for content delivery over heterogeneous and wireless networks for high stakes multimedia transmission, and to advance computer adaptive testing with innovative multimedia item types along with improved algorithms and methods for adaptive testing. The industrial sponsor, Castle Rock Research (CRR), has developed a niche market for its educational notes and test items for K-12 students in Alberta. CRR now needs to focus on web-based multimedia adaptive testing and robust, efficient multimedia delivery in a real-world (high stakes) environment. Unlike other online notes and test items, the multimedia developments undertaken by the research chair consider what factors are important for human perception of multimedia and design the stored data to scale in a perceptually optimal manner based on available bandwidth, and considering packet loss in the case of wireless transmission.

CRR provides additional support on project management, research and technical support, and space for some of the staff coordinating the project, plus meeting and demonstration space in the best real-estate location (Manulife Place) in Edmonton.

The ADME team depends on prior studies in this area to guide their research direction, and CRR conducts field trials at their own cost with Alberta Education to evaluate the effectiveness of the ADME team's research in the long term.

Research Projects

The projects to be pursued under the Industrial Research Chair (IRC) umbrella will focus more on representation, transmission, and testing following a perceptually adaptive strategy.

Robust, Perceptually Optimized Multimedia Transmission for High Stakes Delivery

Overview of need

CRR is currently working on creating many multimedia and animation items for online student learning. The U of A partnership will not help in the multimedia content creation process; rather, the ADME team's focus will be on research on transmission of multimedia content in a way that takes perceptual factors into account and is also robust against network errors and packet loss. The need for CRR and U of A collaboration in this area is to position CRR as a company that is different from the many other educational multimedia development companies, through its pursuit of advanced R&D rather than dependence on free web sites and tools. The current CRR adaptive testing environment is built for low-stakes environment where students try out tests in a trial website in their schools under the guidance of their instructors.

Perceptually optimized multimedia transmission is important because it is interactive. A good example of this is the widespread adoption of Google Earth (GE) over Mapquest and other similar products. Figure 1 shows some screenshots from quickly zooming into a map with GE; the updates are almost instantaneous compared to Mapquest, which often gets stuck in the process of updating a map. Some of this update efficiency could be credited to more powerful server networks of GE; however, both products are often limited by the similar Internet bandwidth to a client

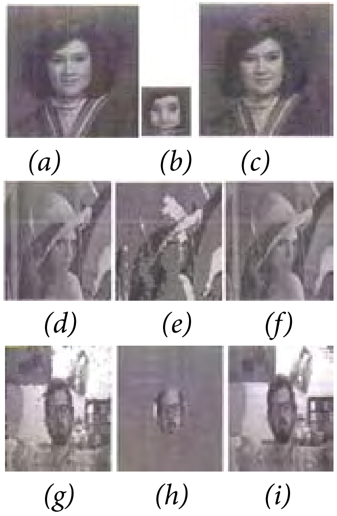


Figure 2 *Some results from past research on foveated compression and lossy transmission.*

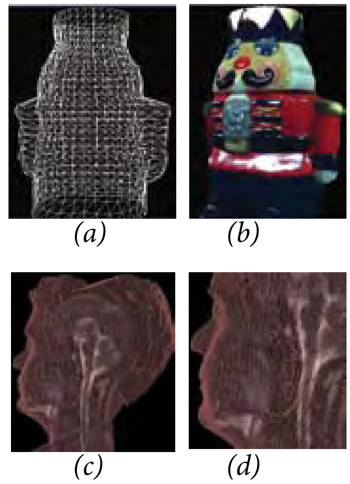


Figure 3 *(a) 3D mesh structure of Nutcracker object; (b) texture-mapped version of (a); (c) MRI video sequence of swallowing inside a 3D head structure; and (d) close up of (c).*

computer. There is a vast difference in performance between the two because not all areas of the map are displayed with equal clarity in GE: areas near the centre are made clearer first before the outer parts, and this strategy continues as a viewer zooms into a map. The techniques used by GE are actually similar to the ADME team's earlier research on foveated image and video compression some results of which are shown in Figure 2.

Figure 2 shows some of the results from the group's past research: (a) shows the original portrait of a girl, (b) transformed image with more details on the face, (c) image reconstructed from (b); (d) LENA image, (e) JPEG compressed LENA at very low bitrate, (f) combination of foveation and JPEG at the same bit rate as in (e); (g) packetized image transmitted over ATM network with all packets having same priority, (h) foveated packet loss with face as region-of-interest, (i) packets created with foveation and priority dithering.

Brief review of background research

Various issues in multimedia transmission must be accounted for when optimizing multimedia transmission at low bandwidths. For video, maintaining smoothness may be the most important factor, while for 3D objects represented by both texture and mesh the relative importance of texture versus mesh given an estimated bandwidth needs to be considered. For transmitting lectures it is important to maintain the realistic nature of facial expressions.

In addition to these factors, the ADME team will also apply a fundamentally different concept to Quality-of-Service based multimedia education content delivery over the Internet by supporting a new framework of Statistical QoS (sQoS) following the research framework described in a previous publication. The researchers system will support the framework of foveation and prioritization to introduce additional efficiencies over low-bandwidth connections. The ADME team are also considering developing algorithms compatible with emerging standards that allow reference to more than two other frames.

A general framework for 3D transmission and visualization

One of differences in the approach that the researchers intend to follow is consideration of an integrated framework of different types of media including texture, mesh, and video. The ADME team will also design formats that are interchangeable between volume and surface representations for 3D. For example, in Figures 3 (a) and (b) the structure and texture mapped versions of the object nutcracker is shown; while Figures 3 (c) and (d) show time-varying MRI of swallowing registered inside a 3D scanned structure of a head.

If necessary, mesh data can also be converted back to the volume space by filling the interior of the mesh with blocks. For example, Figure 4 illustrates how the mesh of a spherical shape can be converted to a volume space. The algorithm works as follows:

i. The mesh is enclosed in a minimum cube (block).

ii. The block is divided into eight sub-blocks using three orthogonal planes (in 1 iteration).

iii. Empty blocks outside the mesh are thrown away.

iv. Steps (2) and (3) are repeated until the desired number of iterations is reached.

The flexibility of interchanging between volume and surface space enables data to be modeled and analyzed taking advantage of the techniques developed for different data spaces.

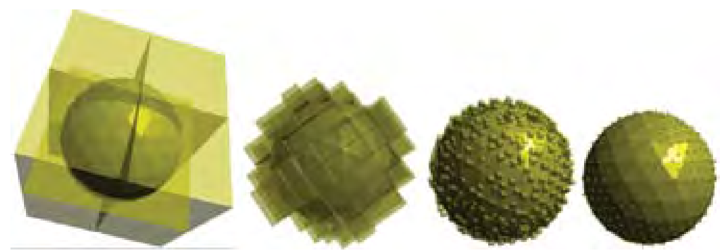


Figure 4 *A spherical shape is partitioned into half in each of the x-, y- and z- directions (in 1 iteration). From left to right: the results after 1, 3, 5 and 6 iterations are shown.*

Proposed research advances

- Registration of different types of media: One of the major challenges lies in the registration of different types of media. The ADME researchers have been exploring the possibility of registering MRI video with a 3D structure of a face, for example, using active contour tracking followed by robust detection of features on the face. Augmenting video into a virtual scene could be achieved by robust feature tracking in video. Substantial work still needs to be done to make the algorithms robust and applicable in a more general environment.
- Interchangeable representation between surface and volume formats: This approach is different from current methods that use DICOM for volume and OBJ format for mesh, for example. Initial results using a modified sphere-tree construction algorithm, to voxelize a 3D mesh are shown in Figure 4. By increasing the number of iterations, the voxels get smaller and smaller, and thus the surface silhouettes get smoother. When converting voxels back to a mesh representation, interior voxels of the volume are discarded and only those lying on the surface are extracted.

Perceptual optimization for 3D transmission

Review of 3D Mesh Coding

3D meshes are widely used in visualization applications, including manufacturing, architecture, medical imaging, military, geographic information systems, and entertainment. A 3D mesh is represented by geometry and connectivity. An uncompressed representation, such as the VRML ASCII format, is inefficient for transmission. In general 3D mesh compression schemes handle geometry data following three steps: quantization, prediction, and statistical coding. However, they are different from each other with regard to connectivity compression.

Among the many 3D mesh compression schemes proposed, the valence-driven approach is considered to be the state-of-the-art technique for 3D mesh compression. For mesh compression, the valence-driven approach is still among the best. However, this approach is restricted to manifolds. A number of 3D mesh compression algorithms have been accepted as international standards.

Touma and Gotsman proposed the valence-driven algorithm to compress 3D meshes, which was then enhanced. The algorithm begins by randomly selecting a triangle. Starting from a vertex of that triangle and traversing all the edges in a counter-clockwise direction (Figure 5), the visited vertices are pushed into an

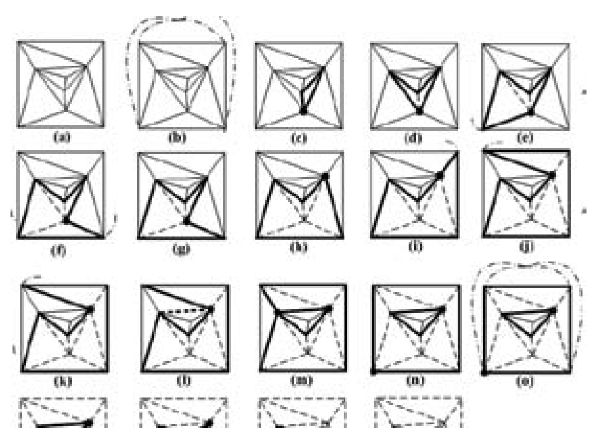


Figure 5 *An example of a run of the valence-driven connectivity-encoding algorithm. Thick lines indicate the active lists, and dashed lines indicate edges already visited.*

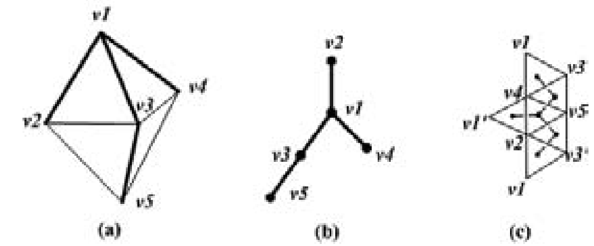


Figure 6 *An example of a vertex spanning tree and a triangle spanning tree for a tetrahedron mesh: (a) A tetrahedron mesh; (b) The vertex spanning tree; (c) The cut and flattened mesh with its triangle spanning tree depicted by dashed lines.*

active list. After visiting the associated edges, the next vertex is popped from the active list, and the process is repeated. The valence (or degree) of each processed vertex is output. From the stream of vertex valences, the original connectivity can be reconstructed.

A topological surgery method to compress mesh connectivity was proposed. The connectivity is represented by vertex spanning trees and triangle spanning trees. Figure 6 shows an example of vertex spanning tree and triangle spanning tree for a tetrahedron mesh.

To achieve progressive transmission of 3D meshes, the Progressive Forest Split method was proposed. The 3D mesh data is structured into multiple layers: one base layer and one or more enhancement layers. The Topological Surgery algorithm encodes the base layer. The enhancement layers use Forest Split operations to refine the model by cutting existing edges in the forest, creating new triangles in the crevices, and displacing the new vertices to their new positions (Figure 7).

Current 3D mesh coding techniques mainly focus on coding efficiency, i.e. compression ratio, by transmitting incremental data. This approach is good without packet loss but is vulnerable to channel errors for irregular meshes. In the Edgebreaker 3D mesh coding method, with one error character in the connectivity stream, the decoded mesh can change significantly and can be impossible to reconstruct.

To transmit compressed 3D meshes over a lossy network, there are two approaches. The first approach is to compress 3D meshes in an error-resilient way.

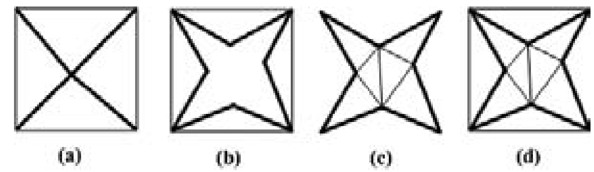


Figure 7 *An example of the Forest Split operation: (a) A low resolution mesh with a forest depicted by thick lines; (b) cutting the mesh along the forest edges and forming a crevice; (c) triangulation of the crevice; (d) the refined mesh.*

Taubin and Rossignac proposed partitioning a mesh into pieces with joint boundaries and encode each piece independently. However, if packets are lost, there are holes in the mesh resulting from missing pieces. The ADME team's second approach is to use error protection to restore lost packets.

Instead of transmitting duplicate packets to reduce the effect of packet loss, the group adopted a perceptually optimized statistical approach in which adjacent vertices and connectivity information are transmitted in different packets so that the possibility of losing a contiguous segment of data is minimized. Furthermore, the ADME team's model takes into consideration both geometry and texture data, while previous approaches discuss only geometry. Experimental results using both regular and irregular meshes show that perceptual quality is better preserved using the team's approach when data packets are lost over an unreliable network. Next, the researchers will review their statistical model, which optimizes the overall visual quality of a 3D object by allocating bandwidth appropriately between geometry and texture data.

3D Perceptual Quality Optimization for regular meshes

In the area of image compression, Mean Square Error (MSE) is commonly used as a quality predictor. However, past research has shown that MSE does not correlate well to perceived quality based on human evaluation. Since this study a number of new quality metrics based on the human visual system have been developed.

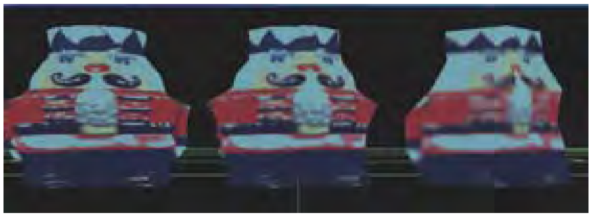


Figure 8 *Evaluation Example*

Several 3D objects were used as stimuli in the ADME team's experiments.

Figure 8 illustrates two referential stimuli (left and right) and one target stimulus (center) in the experiment.

Considering perceptual evaluations, the team observed that perceived quality varies:

i. Linearly with texture resolution (Figure 9, top);

ii. Following an exponential curve for geometry (Figure 9, bottom). Scaling the texture (t) and geometry (g) between 0 and 1, it can be shown that:

$$Q(g,t) = \frac{1}{\frac{1}{m+(M-m)t} + \left(\frac{1}{m} - \frac{1}{m+(M-m)t}\right)(1-g)^{c}} \quad (1)$$

Details of the perceptual evaluations and metric derivation can be found in prior work. Other approaches to joint texture-mesh transmission have been discussed. The approach is based on view-dependent rate-distortion optimization, whereas the ADME team's approach is view-independent. The team's approach does not need to guarantee delivery of certain packets in order to make other packets useful.

The ADME team chose the relative proportion of texture and mesh to create a 3D model in many different ways, as long as Equation (2) is satisfied. Equation (1) can be further simplified to:

$$Q(g,t) = \frac{1}{\frac{1}{1+4t} + \left(1 - \frac{1}{1+4t}\right)(1-g)^{2.7}} \quad (3)$$

Considering that b is the estimated total bandwidth for the transmission time interval, T is the texture and G is the geometry file sizes, possibly compressed, at maximum resolution, to utilize the bandwidth completely it must be: $b = t^2 T + g^2 G$ (2)

Maximizing Equation (3) is equivalent to minimizing the inverse of this equation; considering this and Equation (2), optimizing quality reduces to minimizing:

$$Q_{b,G,T}(t) = \frac{1}{1+4t} + \left(1 - \frac{1}{1+4t}\right)\left(1 - \sqrt{\frac{b - t^2 T}{G}}\right)^{2.7} \quad (4)$$

Where b, G and T are parameters:

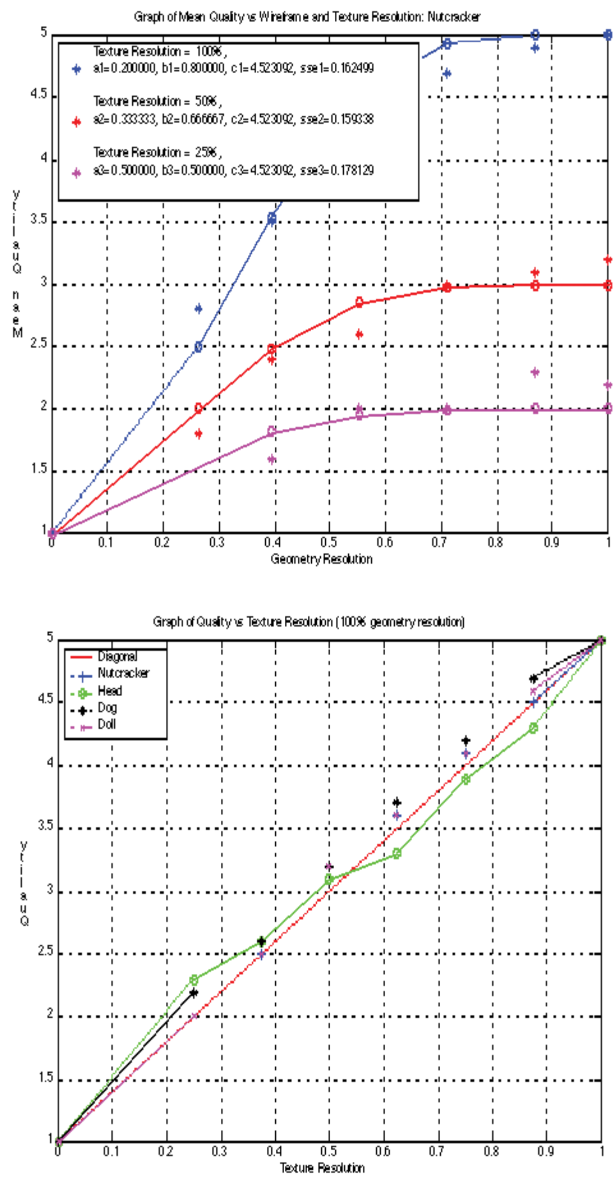


Figure 9 *(Top) Quality vs. Texture Resolution (100% Geometry Resolution); (Bottom) Quality vs. Geometry for various texture resolutions.*

Figure 10 *Applying stripification to a cow mesh. Different colors represent different triangle strips.*

To simplify the model of wireless transmission, the ADME team assumes that data is sent in packets of equal size and there is a possibility that a certain proportion of these packets may be lost. Various protocols suggest re-transmission approaches in case of packet loss; however, re-transmission is not conducive to time bound real-time applications, such as 3D visualization for online games. The group considered several possible strategies for packet construction in wireless 3D transmission, and then analyzed the pros and cons of each. Breaking up a 3D image into fragments can cause voids; progressive transmission necessitates receiving packets at lower levels before packets at higher levels can become useful; and sending duplicate copies of base layer packets in progressive transmission increases bandwidth requirements. The ADME team thus focuses on the two following strategies for regular mesh transmission.

Strategy A:

3d Partial Information Transmission (3PIT): In this approach the texture is broken up and meshed into packets by sub-sampling into overlapping but non-identical components.

Strategy B:

3d Perceptually Optimized Partial Information Transmission (3POPIT): This approach extends 3PIT by taking perceptual quality into account. The algorithm modifies Strategy A by a bandwidth estimation step followed by perceptually optimized packet creation. Without any packet loss, the transmission bandwidth would be used to compute the optimum texture and mesh scaling factors. When packets are lost the remaining packets may not be perceptually optimal for the effective bandwidth after packet loss. The researchers thus form packets that are optimal at a lower bandwidth.

Proposed research advances

- *Determining texture-mesh trade-off for regular meshes incorporating packet loss:* The ADME team still needs to address the process of estimating the parameters of the perceptual quality function for different classes of objects, and how to classify objects into perceptually similar groups. Also, the group needs to investigate the possibility of finding algorithms that can automatically generate reasonable estimates of the perceptual quality function of an object.
- *Incorporating video into the framework of perceptual optimization:* The research described above includes only texture and mesh. The team next needs to include video into the analysis.
- *Including foveation and region-of-interest processing:* Finally, how can the perceptual optimization framework be extended when certain regions, shapes, or features may be of greater interest compared to others. Also, the group needs to consider what kinds of models of foveation provide better quality and under what conditions.

Robustness to packet loss for arbitrary mesh structures

When transmitting irregular mesh data, not only vertex information but also connectivity information plays a crucial role in 3D reconstruction. In order to preserve the original geometry of the object, many transmission algorithms suggest retransmission of the base layers to safeguard the successful transmission of important features of the object. Any discontinuity in the data received makes the rest of the mesh difficult to reconstruct. The ADME researchers also use an incremental approach, but in order to increase robustness against packet loss the group restricts the adverse effect of packet loss locally without propagation. The team focuses on the following criteria:

1. Efficient compression based on stripification – In order to avoid the memory bus bandwidth bottleneck in the processor-to-graphics pipeline and maintain high compression ratio, compres-

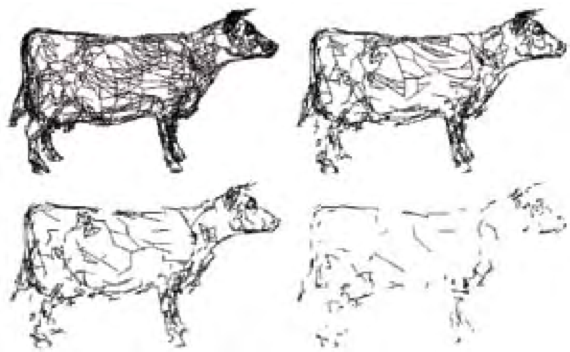


Figure 11 *A Cow mesh highlighting the packet loss region before interpolation: 30% (Top Left), 50% (Top Right), 60% (Bottom Left) and 80% (Bottom Right) packet loss.*

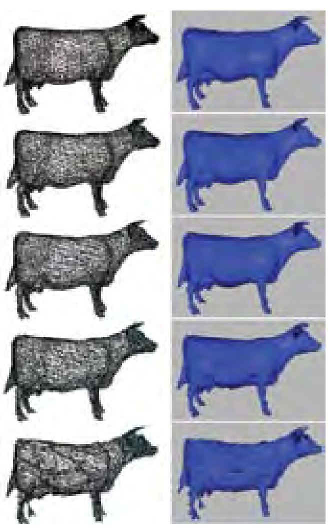


Figure 12 *From top to bottom, 0%, 30%, 50%, 60% and 80% randomly selected packet loss was applied to a Cow mesh (Left). The corresponding mesh mapped with color is shown on the right.*

sion algorithms often employ a "tristrips" encoding method, which virtually specifies a triangulation cost of one vertex per triangle instead of sending three vertices per triangle, as shown in Figure 10. High compression ratio can be achieved if a mesh can be broken down into a few long continuous strips. In the ADME team's approach, the group traverses the vertices following the valence-driven method because this algorithm generates long continuous tristrips.

2. Robustness to packet loss based on even distribution – In addition to stripification, there is a need to distribute neighbouring vertex and connectivity information into different packets to minimize the risk of losing data affecting a large neighbourhood. The possibility of losing adjacent vertices creating a large empty region is reduced. If packet(s) containing valence information are lost they are re-transmitted.

Experimental results for irregular meshes

In Figure 11 it is difficult to recognize the object as a cow when over 60% of the packets are lost in the bottom row.

In Figure 12 the lost geometry was interpolated based on neighbouring vertices and valence information, which is transmitted without error. Smoothness on the object surface begins to deteriorate at about 60% packet loss. Visual degradation becomes more obvious at 80% packet loss, but the object is recognizable as a cow, unlike in Figure 11.

Figure 13 shows the effect of packet loss on a model with photo-realistic texture, rather than the color per vertex representation in Figure 12. The differences in shapes here are more obvious because following the team's research on Just Noticeable Difference (JND) for 3D perception a relative change of more than 10% is easily noticeable.

In Figure 13 the cost of re-transmission of the connectivity information for this real example is less than 1%. To avoid the delays in requesting re-transmission of packets, it may be wiser to send duplicate packets containing the connectivity information so that real-time visualization of photo-realistic texture mapped 3D objects at high packet loss can be facilitated.

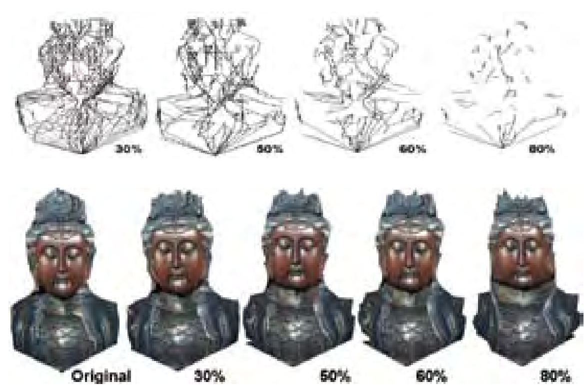


Figure 13 *Top row: 30%, 50%, 60% and 80% randomly selected packet loss was applied to the Queen mesh. The corresponding mesh mapped with texture is shown at the bottom.*

Objectives for Next Year

Robust wireless multimedia transmission:

Without the need to retransmit the base layer in irregular mesh data, the ADME team's goal is to find a trade-off between compression rate and robustness to packet loss.

- Modification and improvements to the existing strategy based on test results over handheld devices;
- Introducing viewpoint dependent predictive models to further improve performance in interactive applications;
- Designing algorithms based on point cloud representation for robustness against connectivity loss.

Adaptive Multimedia Testing:

- Automatic question generation;
- Automatic estimation of difficulty level of questions;
- Creating animations based on video, for realistic yet cost effective content creation.

Outreach

Castle Rock Research (CRR) has already launched their Adaptive Testing Initiative at a major event in Telus Centre in April 2006. All school board representatives across Canada were invited to this event and many attended. In 2007, simple multimedia adaptive test items will be made available for testing for students in Alberta. The commercialization will take place in collaboration with CRR.

Team Members and Contributions

Team Leader
Professor Anup Basu
Advanced Digital Media for Education Chair

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Dr Walter Bischof	Computing Science	
Dr Carlos Flores-Mir	Clinical Associate Professor	
Dr Paul Major	Orthodontic	
Dr Mrinal Mandal	Electrical Engineering	

PostDoctoral Fellows

Name	Role/Topic	Awards/Special Info
Xiao Dong Wen		

PhD Candidates

Name	Role/Topic	Awards/Special Info
Manuel Lagravere		(Orthodontic)
Sharmin Nilufar		NSERC scholarship
Meghna Singh		Killam scholarship
Tao Wang		iCORE scholarship
Gang Wu		RA (part-time)
Lihang Ying		

MSc Candidates

Name	Role/Topic	Awards/Special Info
Eric Frimpong	MS Internetworking, RA	
Xiaoyong Liao	MS Internetworking, RA	
Saul Rodriguez	MS	
Rui Shen	MS	
Xingdong Yang	MS	

Alberta Education Participants		
Name	**Role/Topic**	**Awards/Special Info**
Kent Marcellus		
Deanna Shostak		

Other Team Members		
Name	**Role/Topic**	**Awards/Special Info**
Alexey Badalov	Undergrad, RA	
Matt Bates	BSc, RA	
Xuefen Chen	BSc, RA	
Dr Irene Cheng	Associate	NSERC fellowship
Darcy Faulkner	Undergrad, RA	
Ivan Filippov	Summer Intern	
Sally Fu	MSc, RA	
Leslie Jia	MSc, RA	
Chris Kerr	BSc, RA	
Hiep Ngo	Undergrad, RA	
Garrett Rieger	Undergrad, RA	
Vivek Sail	Undergrad, RA	
Michael Stadnyk	Summer Intern	

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
Athabasca University Profs. Terry Anderson and his group	Educational Multimedia
International Collaborations	
Prof. Guido Cortelazzo Padova, Italy	Robust multimedia transmission
University of Pennsilvania, USA Prof. Kostas Daniilidis	3D vision and graphics
University of Pennsilvania, USA Prof. Jianbo Shi	Segmentation
Prof. Satish Tripathi SUNY Buffalo, USA	Multimedia communication with packet loss

Participants	*Nature of Collaboration*
Industrial Collaborations	
Castle Rock Research	Industrial Prototyping & Commercialization
HP Labs, Palo Alto Tom Malzbender	Advanced 3D Imaging Techniques

INTELLECTUAL PROPERTY

Software licensing arrangement on Multimedia Adaptive Testing being worked out with Castle Rock Research. The group expects revenues for the U of A to be generated through royalties in the near future.

A. Basu, "Method and apparatus for high resolution 3D scanning of objects having voids," Canadian Patent # 2,369,710, 25 pages, Sep. 19, 2006.

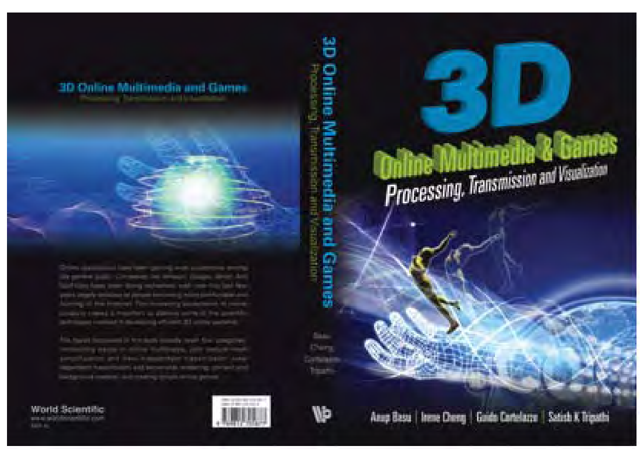
FUNDING

Dr Anup Basu has a five year iCORE Industrial Chair award ($500K). This year he received funding from industry partner Castle Rock Research ($100K), and from NSERC ($40K) and ASRA ($90K).

PUBLICATIONS

BOOKS

A. Basu, I. Cheng, G. Cortelazzo and S. Tripathi, "3D Online Multimedia and Games," *World Scientific Press,* 350 pages (estimate), 2007 (in press).



REFEREED JOURNAL PUBLICATIONS

T. Wang and A. Basu, "An improved fully parallel 3D thinning algorithm," (T. Wang and A. Basu), *Pattern Recognition Letters,* 501-506, Vol. 28, 2007.

I. Cheng and A. Basu, "Perceptually optimized 3D transmission over wireless networks," *IEEE Transactions on Multimedia*, 386-396, Feb. 2007.

I. Cheng, L. Ying and A. Basu, "Packet loss modeling for perceptually optimized 3D transmission," *Advances in Multimedia*, 10 printed pages, in press, 2007.

M. Singh, A. Basu and M. Mandal, "Event dynamics based temporal registration," *IEEE Transactions on Multimedia*, 9 printed pages, in press, 2007.

I. Cheng and P. Boulanger, "Adaptive Online Transmission of 3D TexMesh Using Scale-space and Visual Perception analysis," *IEEE Transactions on Multimedia,* Vol. 8, No. 3, 12 transactions pages, June 2006.

REFEREED CONFERENCE PROCEEDINGS

A. Basu, I. Cheng, M. Prasad & G. Rao, "Multimedia adaptive computer based testing: An overview," *IEEE Int. Conference on Multimedia*, July 2007.

I. Cheng and W. Bischof, "Multimedia item type design for assessing human cognitive skills," *IEEE Int. Conference on Multimedia*, July 2007.

G. Wu and I. Cheng, "An interactive 3D environment for computer based education," *IEEE Int. Conference on Multimedia*, July 2007.

I. Cheng and A. Basu, "Improving Multimedia Innovative Item Types for Computer Based Testing," *IEEE Int. Symposium on Multimedia*, Dec 2006, (8 pages) San Diego.

S. Rodrigues, I. Cheng and A. Basu, "Multimedia games for learning and testing physics," *IEEE Int. Conference on Multimedia*, July 2007.

T. Wang and A. Basu, "Automatic estimation of 3D transformations using skeletons for object alignment," *IAPR/IEEE International Conference on Pattern Recognition*, 4 pages, Hong Kong, August 2006.

I. Cheng, R. Shen et al. "Perceptual Analysis of Level-of-Detail: The JND Approach," *IEEE Int. Symposium on Multimedia*, Dec 2006, (8 pages) San Diego, USA.

I. Cheng and A. Basu, "A Perceptual Approach to Texture Scaling based on Human computer Interaction," *EUROGRAPHICS*, Short Paper, 4 pages, Sep 2006, Vienna, Austria.

I. Cheng, S. Nilufar, A. Basu and R. Goebel, "Shape Tracking and Registration for 4D Visualization of MRI and Structure," *International Symposium on Visual Computing*, Lake Tahoe, Nevada, 2006, 10 LNCS pages.

T. Wang and A. Basu, "Iterative Estimation of 3D Transformations for Object Alignment," *International Symposium on Visual Computing*, Lake Tahoe, Nevada, 2006, 10 LNCS pages.

M. Singh, A. Basu and M.K. Mandal, "Temporal Alignment of Time Varying MRI Datasets for High Resolution Medical Visualization," *International Symposium on Visual Computing,* Lake Tahoe, Nevada, 2006, 10 LNCS pages.

I. Cheng, L. Ying and A. Basu, "Packet Loss Modeling for Perceptually Optimized 3D Transmission," *IEEE International Conference on Multimedia and Expo*, 4 pages, Toronto, July 2006.

M. Singh, R. Thompson, A. Basu, J. Rieger and M. Mandal, "MRI video interpolation," *IEEE International Conference on Image Processing*, 4 pages, Atlanta, USA, October 2006.

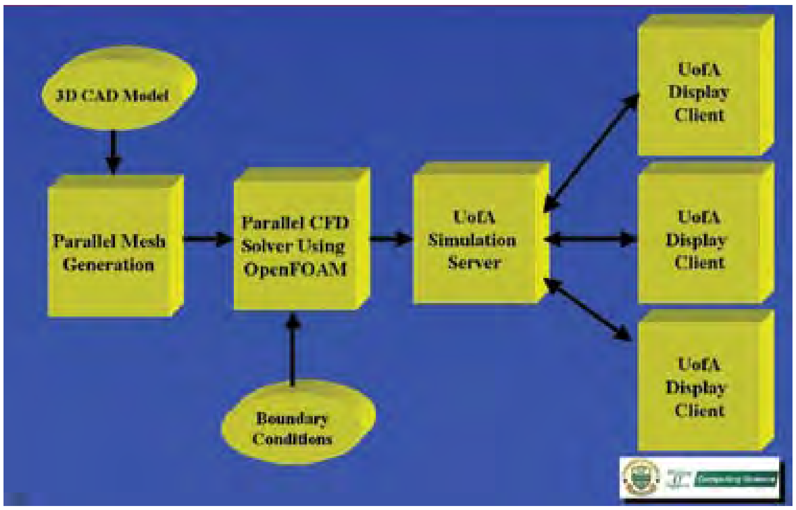
I. Cheng, L. Ying and A. Basu, "A Perceptually Driven Model for 3D Transmission over Unreliable Networks," *3rd Int'l Symposium on 3DPVT*, 8 pages, June 2006, North Carolina, USA.

SPECIAL/INVITED PRESENTATIONS

- Special session organizer and chair in Int'l Symposium on Multimedia conference (I. Cheng) Dec 2006 San Diego, USA
- Special session organizer and chair in Int'l Symposium on Visual Computing (I. Cheng) Nov 2006 Lake Tahoe, USA
- Invited presentation at Siemens, Pennsylvania (A. Basu) and U. Penn (I. Cheng).

Collaborative Virtual Environments

This last year the Collaborative Virtual Environments (CVE) group successfully finalized two main projects financed partially by this chair and by CANARIE's Advanced Research Program.



U of A Virtual Wind Tunnel Architecture

The first project, Media Light Paths network (MLP) demonstrated how User Controlled Light Paths (UCLP) can be used to transmit advanced media information cost-to-cost with very low latency (speed of light) and very high bandwidth via direct optical connections. MLP was made in collaboration between Simon Fraser University (SFU), the University of Calgary (U of C), the University of Alberta (U of A), the University of Québec, and Dalhousie University. The main contribution of the CVE group was to explore how advanced computing technologies and networking could allow scientists and engineers to solve complex Computational Fluid Dynamics (CFD) problems creating in effect an advanced Collaborative Virtual Wind Tunnel (CVWT). During the course of this two year project, the CVE group did numerous demonstrations such as the one at the prestigious iGRID 2005 conference in San Diego California and in 2006 at the Super Computing conference in Tampa Florida. The team continues participating in the Global Lambda Visualization Facility an NSF sponsored project. This project led by the Electronic Visualization Laboratory (EVL) at the University of Illinois and aims at developing new advanced collaborative environments based on all optical networks and the latest in display technologies. In the last year, the CVE group did some work on developing a high definition video application for the Access Grid environment.

The second project was to develop shared Hapto-visual-Audio-Virtual Environments (HAVE) capable of digitizing the operating environment and replicating every move of a teaching ophthalmic surgeon to remote trainee surgeons connected with the trainer using a UCLP connection. Using this new revolutionary technology, trainees can follow remotely through haptic devices and auto-stereo displays every move of the training surgeon allow them to learn the fine hand-eye coordination necessary to be a good eye surgeon. This project was a collaboration between the CVE group, the University of Ottawa Ophthalmology Department, and the University of Ottawa DISCOVERY group. An official demonstration of this project was successfully performed on March 10, 2007. During the course of this project, the CVE group had significant interest from researchers at the U of A's Faculty of Medicine who would like to improve training of surgeons using this new and exciting technology. The CVE team is currently negotiating with them the next phase of deployment into a real operating room. The researchers applied with COMPRU an oral and maxillofacial surgery clinic in Edmonton and with iCORE Industry Chair Dr Christopher Sensen's research group in Calgary for a Canadian Foundation for Innovation (CFI) grant to upgrade the Virtual Reality (VR) facilities and to equip COMPRU and Dr Sensen's laboratory with advanced VR facilities. In addition, the CVE team also applied with COMPRU and the Department of Radiology and Diagnostic Imaging at the U of A's Faculty of Medicine for a CIHR/Capital Health team grant that will pay for students and technicians that are necessary to operate those large training facilities.

The CVE Chair started in September 2006 and research collaborated with Hewlett Packard (HP) in Palo Alto California. This project consists in developing with them the next generation of video-conferencing system based on tele-immersive technology. The technology developed during this project is to be included in the new HALO system one of the first commercial tele-presence system. The project is well on its way and the CVE team has demonstrated a TRLabs-HP connection with HALO to show how HALO technology performs using public networks. The team received a lot of interest from TRLabs's partners to start the construction of the first Canadian laboratory dedicated to tele-presence. It is planned in 2007 to expand this activity and to focus the work on medical training. The CVE team has also applied for an NSERC strategic grant to help finance its activity. This new laboratory already has the industrial support of CANARIE, Netera Alliance, SGI, HP, Telus, 3DI, and BigBangWidth. If this grant application is successful it should bring $1.6 M to further equip the tele-presence laboratory at TRLabs and to pay for graduate students and technicians.

At the beginning of 2006, the CVE team also started a Precarn Industrial project to work with two companies Creaform 3D and Camoplast to develop a new deformable part inspection system. This is a critical issue in industry today as more and more parts are now fabricated with non-rigid materials such as composite materials or soft plastics. With the help of the Laval University 3D vision group, the team is developing for those two companies the hardware and the software capable of performing dimensional inspection on deformed parts. The team has also received great interest for this project by GM Canada and Air Bus Industries in France . In 2006, the researchers developed the registration code and were able to make a successful demonstration at the annual Precarn meeting in Montreal in May 2007.

In 2006, the CVE team also continued to participate to the Canadian Design Research Network. The team's main contribution was to demonstrate how virtual prototyping using the development of the Virtual Wind Tunnel could be used to help in better automotive design.

In 2006, the CVE researchers published 23 papers in peered reviewed journals and conferences and trained 13 graduate students.

Research Program Overview

The advent of high-capacity storage devices, powerful computer workstations, and high-speed networks is enabling (both technically and economically) a variety of multimedia communications services. Applications in training, medicine, education, and concurrent engineering design have quickly emerged and are characterized by large multimedia documents

that have to be communicated with very short delays. Computer-controlled cooperative projects, whereby a group of users can jointly create, edit, view, and produce collaborative work with multimedia documents, characterize many current and future research activities. In many new multimedia technology systems, VR is now being used to display a multitude of information in a form that can be easily interpreted, shared, and manipulated.

One of the hottest topics in VR research is in the field of Collaborative Virtual Environments. In CVE, a simulated world runs on several computer systems, each running a compatible application. The computers are connected over a network and people using those computers are able to interact and collaborate in real-time, sharing the same virtual world. Some tele-immersive CVE systems recognize the presence and movements of individuals and objects, process those images, and then project them in realistic, multiple, geographically-distributed virtual environments where individuals can interact with each other and with computer-generated models.

CVE systems raise a number of resource allocation problems, including high-speed networks, clusters of large computers, data storage distributed over a grid, and advanced visualization tools such as the U of A VizRoom. The advent of grid computing/visualization facilities such as WestGrid provides fresh challenges and opportunities for collaborative visualization, including the close coupling of simulation, visualization, and Internet communication tools in a steering environment capable of creating the equivalent of a real-time physics experiment.

In some systems, CVE aims to enhance a video conferencing environment with access to visualization facilities. At the most basic level, pre-generated visualization may be shared through a shared whiteboard tool. Richer approaches enable users to share control of the visualization/simulation process allowing for true exploration of the simulation space.

The main goal of this Chair is to conduct research and development on the various issues relating to implementation of CVE systems. The key scientific and technical challenges that have to be solved will require an expansion of the boundaries of computer vision, low latency networking, real-time tracking, stereo display, haptics, and real-time rendering technologies.

Research Projects

Multi-Modal Interface for Collaborative Visualization

In this project, the CVE team will investigate the development of multi-modal interactions interface for collaborative visualization in the medical and engineering fields. Several technologies are being combined and evaluated from the leading edge to consumer scale, including PC-based passive stereo wall- and table-mounted large touch-screen displays, high-resolution desktop systems, laptops, haptics interface, handheld trackers, pen-based computing tablets, even paper.

The research goals that underpin this project centre around the study of how heterogeneous devices may be combined into device suites for particular complex information tasks, and what tasks these suites and enriched environments may aid or impede. Using multi-modal interfaces, the researchers will analyze and try to understand how different combinations of tools may be useful as device suites for particular kinds of tasks, both collaborative and singular, in both face-to-face and remote situations; the analysis and development of novel interaction techniques to span, share and control diverse devices; and the implementation of an adaptive infrastructure that maximizes a collaboration's Quality of Experience (QoE) for the end user across a wide range of technology platforms. As a research focus, the CVE team is exploring the use of multi-modal interfaces (visual, auditory, and haptics) for the exploration of CFD solutions or radiological volumetric data sets (CT, MRI, fMRI). The interface consists in transforming data into multi-modal perceptions that are meaningful for a human operator. The team is also exploring how this information can be shared in a collaborative environment.

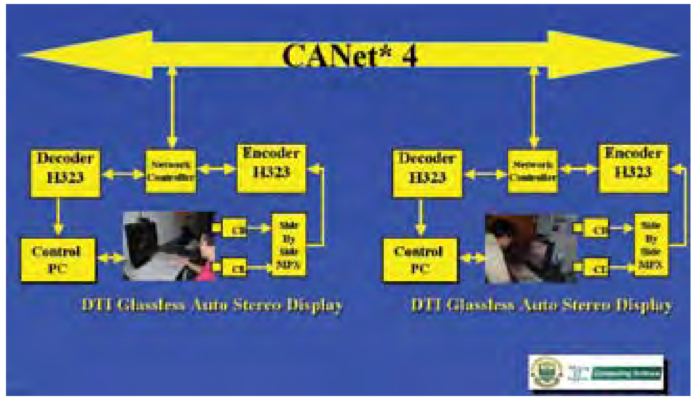
In addition to the Virtual Wind Tunnel applications, the team is also developing similar interfaces for radiology data set. In this project, the CVE team is exploring new algorithms to display in real-time, volumetric data using volumetric shaders based on GPUs. The team is also exploring new specialized haptics and sonification interfaces especially design for radiological analysis. The Department of Radiology and Diagnostic Imaging in Medicine, the Department of Orthodontic surgery in Dentistry, and COMPRU are collaborating with the CVE team in this project.

Collaborative Visualization and Steering of Large Simulations using the WestGrid Infrastructure

In this project the CVE team will develop a real-time environment for the collaborative visualization and steering of complex physical simulation using the WestGrid infrastructure;

Advances in computer processing power and networking over the past few years have brought significant changes to the modeling and simulation of complex phenomena. Problems that formerly could only be tackled in batch mode can now be monitored in progress using graphics. In certain cases it is even possible to alter parameters of the computation whilst it is running. This ability to monitor and change parameters of the computational process at any time and from anywhere is called computational steering. By combining this capability with advanced communications tools it is now possible for a group of scientists and engineers located across various continents to work collaboratively on simulations, allowing them to compare ideas and to share their experience. This is a key advance as the notion of a scientist and an engineer working alone in a laboratory is disappearing as problems get larger and more complex. New multidisciplinary teams of experts working collaboratively are the only way to solve today's complex science/engineering problems.

One of the critical components for usability of collaborative simulation on a grid is to design a visualization/simulation system in such a way that it can run relatively independent of the original simulation code time scale.



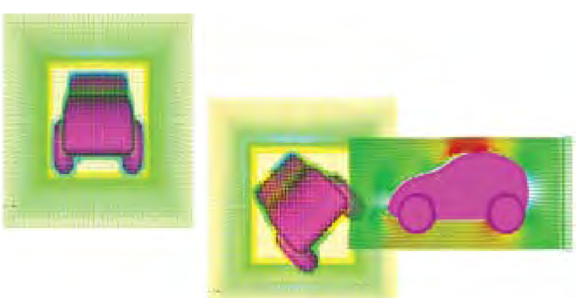
Immersive Desktop Stereo Video Display and Visualization over High Speed Network

In particular, the system architecture should allow three-dimensional (3D) rendering of scalar and vector fields to occur independently of the data production process. This means that data production delays should not cause delays in manipulation of the visual representation, such as object rotation and the exploration of vector fields.

The main components of the proposed architecture are:

- A simulation program: the code that need to be computationally steered;
- A simulation controller: responsible for controlling various services requested by the clients and by the simulation process;
- A client manager: responsible for offering to each client: simulation, filtering, and graphical services;
- A client display program: responsible for connecting to the server and to display to the user the most up-to-date simulation results.

Here the simulation controller directs which data coming from the simulation will be processed. The simulation services converts simulation output for further processing by the visualization program located at each client site. The first three run on a large multiprocessor shared memory machine or on clusters distributed along the grid whereas the last subsystem may be run on a remote PC or high-end workstation. The data transfer from the large shared memory machine where the simulation server reside and the clients graphic computers is facilitated by data compression, which is performed by an extra service offered by the system.



Real-time air flow calculation for a car at various orientations

One of the numerous challenges associated to this project is to link collaborative technologies, simulation tool, and design tools into a truly integrated environment. WestGrid computing and communication infrastructures, in addition to new emerging standard for CFD and FEM simulation, can make this possible. This project is being supported by SGI Canada, Creaform 3D, GM Canada, and the CDRN center of excellence.

Next Generation Virtual Video Conferencing System Based on Tele-Immersion

With the collaboration of HP, the researchers are developing a new generation of tele-communication technology aimed at giving to participants in a meeting (local and remote) the illusion that they are in the same room. Contrary to current videoconference technologies, tele-immersive systems will allow participants in a meeting to remotely express non-verbal communication clues: a critical element to create a real sense of remote presence.

Tele-immersion presents a series of challenges in many research areas in computing science such as computer vision, computer graphics and rendering, haptic systems, display technologies, tracking systems and real-time network communications.

In general, tele-immersive systems are composed of the following elements:

- A system that senses the position of a participant in each location and establishes a common reference point where each participant can be located;
- A network of video cameras at each location to capture at least two different perspectives of a participant;
- Algorithms that process the video streams and produces a video stereo pair according to each participant's position and inter-ocular distance;
- A communication platform allowing the video and other multimedia information to be sent to the participants;
- Algorithms that process the information received and display the information according to each participant's position with respect to the common reference point.

In order to achieve tele-immersion, each participant must have at least two viewpoints from each remote site to create a sense of depth perception. Every participant segmented from the surroundings must be sensed from all directions using the bank of cameras. This information is then sent to other participants and then rendered from their personal viewpoint.

In order to be able to generate new views and to integrate those views in the virtual meeting room tele-immersive system must first localize and segment the various participants from their background. In a situation where the scene viewed by the cameras remains constant in time and where the only changes correspond to the participants being present, background subtraction techniques can be used to segment a participant from his background. This project involves the collaboration of four industrial partners: BigBang-Width, HP, Telus, and Creaform, who are interested in using this system for an application that will be involving many of Creaform industrial partners world. With the help of TRLabs, the CVE team is also building the first Canadian laboratory on tele-immersive systems.

Surgical trainers Using Tele-Immersive Technology

This project oversees the development of a surgical trainer using tele-immersive technology. The goal of this project is to develop shared HAVE with advanced multi-point 3D video conferencing, new display and interface technologies that will be used for collaborative surgical planning and training. The expected result is the demonstration and evaluation of a realistic HAVE immersive collaborative virtual environment application for the training of surgeons and the pacification of complex surgeries, linking the VR CAVE systems located at COMPRU, the Department of Radiology and Diagnostic Imaging at the Faculty of Medicine, and the AMMI laboratory at the Computer Science Department. This innovative project will create collaborative training environments in which training surgeons can learn and plan virtual surgical procedures on real and virtual body using real/virtual surgical instruments, while receiving immediate sensory feedback from multi-modal interfaces that simulates real tissue resistance and facilitates the learning of exact hand-to-eye coordination. HAVE tele-surgery applications will enable junior surgeons to be trained by remote experts and deliver improved patient care and reductions in training costs and risks. The benefit to the community is that surgeons do not have to stay in large centers to keep their surgical skills, as remote training will allow them to access continuous surgical training.

Real-Time Networking for CVE

This project oversees the development of real-time networks capable of dealing with the demands of collaborative visualization applications especially for real-time applications.

This project requires access to high quality of network service. There are two main criteria that define real-time network quality: bandwidth and latency. For most of the CVE applications latency is a dominating factor as real-time constraints of the systems require that it to be minimized, or at least constant. Unfortunately, current networks, even high-bandwidth ones, are plagued by non-constant latencies that are disastrous for any multimedia applications. During this project and with the help of Netera Alliance and TRLabs, the CVE team is planning to expand the length of this network by using TRLabs new experimental network capable of transmitting at 10Gb/s. The team is also planning to add new functionalities to these networks such as real optical multicast. This work may result in the redefinition of real-time networking for multimedia applications.

Objectives for Next Year

Multi-Modal Interface for Collaborative Visualization

In 2006, a Master's student with the CVE team finished the development of the multi-modal interface specialized in the exploration of CFD data. During this project, she explored different strategies to transform pressure, vorticity, and speed into sound that can be easily identified. A comprehensive usability study to identify how efficient each sonification algorithms are at identifying various features in the flow field was performed. How visual information combines with auditory information to enhance the localization of vortices was performed. It is planned to add to this interface haptic-rendering capability and to perform a similar usability study to show how, once haptics is combined with auditory and visual, a further improvement in efficiency can be experimentally observed. Another of Master student with the CVE team finished the first phase of his thesis and was able to demonstrate that volumetric rendering can be accelerated significantly using pixel shaders in GPU. The student was able to achieve real-time performance for MRI volumes of size 256x256x256. The student is now adding this rendering algorithm in the VRJuggler environment and it is planned by the end of the summer that the CVE team will have a first version of a true radiology CAVE. The team is also planning to do a usability study of this new CAVE to determine experimentally how efficient radiologists can find important details in a volumetric data set.

Trainer Digitizing Station

Collaborative Visualization and Steering of Large Simulations using the WestGrid Infrastructure

One of the ultimate goals is to create a truly interactive virtual wind tunnel system for teaching and design. By code optimization, computer upgrade, and more advanced parallel algorithm the CVE team is planning to push the boundary on computer speed further.

In the new architecture for the Virtual Wind Tunnel a CAD model represented as a triangulated mesh is provided to the system and transformed into a volumetric mesh by a parallel volumetric mesh generator capable of producing 2M volumetric elements per second on an eight CPUs computer. Following the production of the volumetric mesh, the system adds boundary conditions to the mesh and then saved the attributed model in OpenFOAM format on a share disk with the solution server computer using CXFS file management system. OpenFOAM running on a large HPC machine (256 CPUs shared memory system) located to a remote location then read this file and solved the CFD solution for the various time steps requested by the users. The OpenFOAM simulator is controlled by the simulation server allowing various clients to connect to the simulation and to share their results. Now that many of the elements of the virtual wind tunnel are in place, the CVE team is planning to optimize each element for speed and to test the system with simple cases to illustrate its capabilities. The team is planning to add new steering capabilities such as mesh resolution, control on fluid density, wind directions, and many more.

Next Generation Virtual Video Conferencing System Based on Tele-Immersion

In 2006, the desktop stereo-video conferencing system was tested as part of a demonstration with HP. This system was built with two video cameras connected to a Tanberg codec. The output of the codec is then connected to a stereo-video conferencing system in a side-by-side mode where a user can see his/her interlocutor in 3D. The problem with the current system is that it is limited to two cameras and to peer-to-peer. This sytem needs to be scaled to more cameras and more people by been able to generate new view through the process of view morphing.

In order to be able to generate new views and to integrate those views in the virtual meeting room, tele-immersive system must first localize and segment the various participants from their background. In a situation where the scene viewed by the cameras remains constant in time and where the only changes correspond to the participants being present, background subtraction techniques can be used to segment a participant from the background. This process aims at segmenting changing regions in an image using robust image segmentation techniques.

Last year the CVE team started collaborations with HP research in Palo Alto, California to solve these problems. A PhD student with the CVE team went at the end of November 2006 to be trained on the software development environment used for developing HALO. This environment was then ported to the CVE's and integrated with the multi-cameras system. Following this integration, the team is currently developing new real-time view morphing and calibration algorithms using GPU hardware. The plan for next year is to have a new desktop version of the system, but this time with real-time view morphing to generate the stereo pairs. The team is also designing and implementing a new foreground/background segmentation system based on infrared lighting. By controlling lighting in using non-visible light wavelength, the team hopes that the segmentation of the foreground can be made simple and robust to ambient lighting.

Surgical trainers Using Tele-Immersive Technology

The expected result of this CANARIE funded project was to demonstrate and to evaluate how realistic a HAVE immersive collaborative environment can be used for

Outreach

This last year, the CVE team has made 25 demonstrations of the laboratory to group of people ranging from high-school students to VIP. The Chair also presented at various conferences:

1. P. Boulanger, "Tele-Immersive Systems for Design Review", National University of Colombia, August 2006.
2. P. Boulanger, "The Virtual Wind Tunnel Project", EAFIT University August 2006.
3. P. Boulanger, "An Advanced Collaborative Infrastructure for the Real-Time Computational Steering of Large Scientific Simulations", Keynote speaker, HPCS conference, May 2006.
4. P. Boulanger, "Collaborative Computational Steering: The Next Generation of Super-Computing Interface", invited speaker, BCNET Conference, April 2006.
5. P. Boulanger, "The HAVE Project: Remote Surgical Training Over Advanced High-Speed Networks, invited speaker, BCNET Conference, April 2006.
6. P. Boulanger, Medical Collaborative Virtual Environments for Training and Data Visualization, Seminar presented at the Faculty of Medicine, June 2006.

the training of ophthalmic residents in cataract surgery between the U of O and the U of A. The first prototype is working very well. The CVE team was able to remotely capture subtle moves from the training surgeon. The team was also able to demonstrate that the network delay does not influence the performance of the system. The next step is to perform a formal usability study of this interface to demonstrate that one can perform true surgical skill transfer over very large distances using haptic training. The following studies are planned:

- An analysis of skill transfer of gesture using remote haptic training with and without visuals;
- An analysis of the effect of delay and bandwidth limitations on skill transfer;
- A comparison with simulator vs. tele-immersive training for skill transfer.

In addition, last summer the team developed a new multi-resolution technique that will compare 3D gesture from a trainer to a trainee. This analysis is based on a multi-resolution curvature analysis of 3D trajectories of surgical instruments.

There is a lot of interest by the Space Agency to use this system to assist surgeons in future space missions. By prerecording typical operations with the digitizing system and then playing it back in the spaceship, a crew member with medical training could first learn the functional aspect of a medical procedure with standard VR simulators and then learn the fine motor skills with the immersive system. The system can also be used to certify his skill level by comparing his gesture with the advanced surgeon gesture.

For collaborative training sessions, the CVE team was also able to demonstrate that UCLP performed well as its bandwidth and delay were well in line with this very challenging application.

Real-Time Networking for CVE

The network performance requirements in many of those projects are challenging. HAVE network data, for example, is mostly streaming media:

- High-definition stereo video (600Mb/s);
- Access Grid (10 Mb/s);
- Haptic signals (5 Mb/s).

The end points are about 4000 km apart, which means that the minimum delay one way will be approximately 40 ms. In the case of voice and video, this is not a problem, but for haptic this is critical. If not compensated by proper delay compensation algorithms this could be a severe problem for the project.

The CVE team finished configuring the optical networking environment using BigBangWidth switches. With this configuration, The team was able to successfully test the UCLP connection to Ottawa as well as the one to SFU. The experiment showed that there is a connection of 621Mb/s with a latency of 50ms. The CVE team plans to test the network connection with HP in Palo Alto and with TRLabs.

Research Team Members and Contributions

Team Leader
Professor Pierre Boulanger
System Architect
iCORE, NSERC, ASRA, Canarie ARP, CFI, and Precarn awards

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Walter Bischof	Perceptual Issues	NSERC
Jason Carey	Physical Modeling	NSERC
Janelle Harms	Networking Issues	NSERC, CFI Department of Mechanical Engineering

PostDoctoral Fellows

Name	Role/Topic	Awards/Special Info
Jeff Mahovsky	Advanced Rendering	Financed by Ingenuity Fund

PhD Candidates

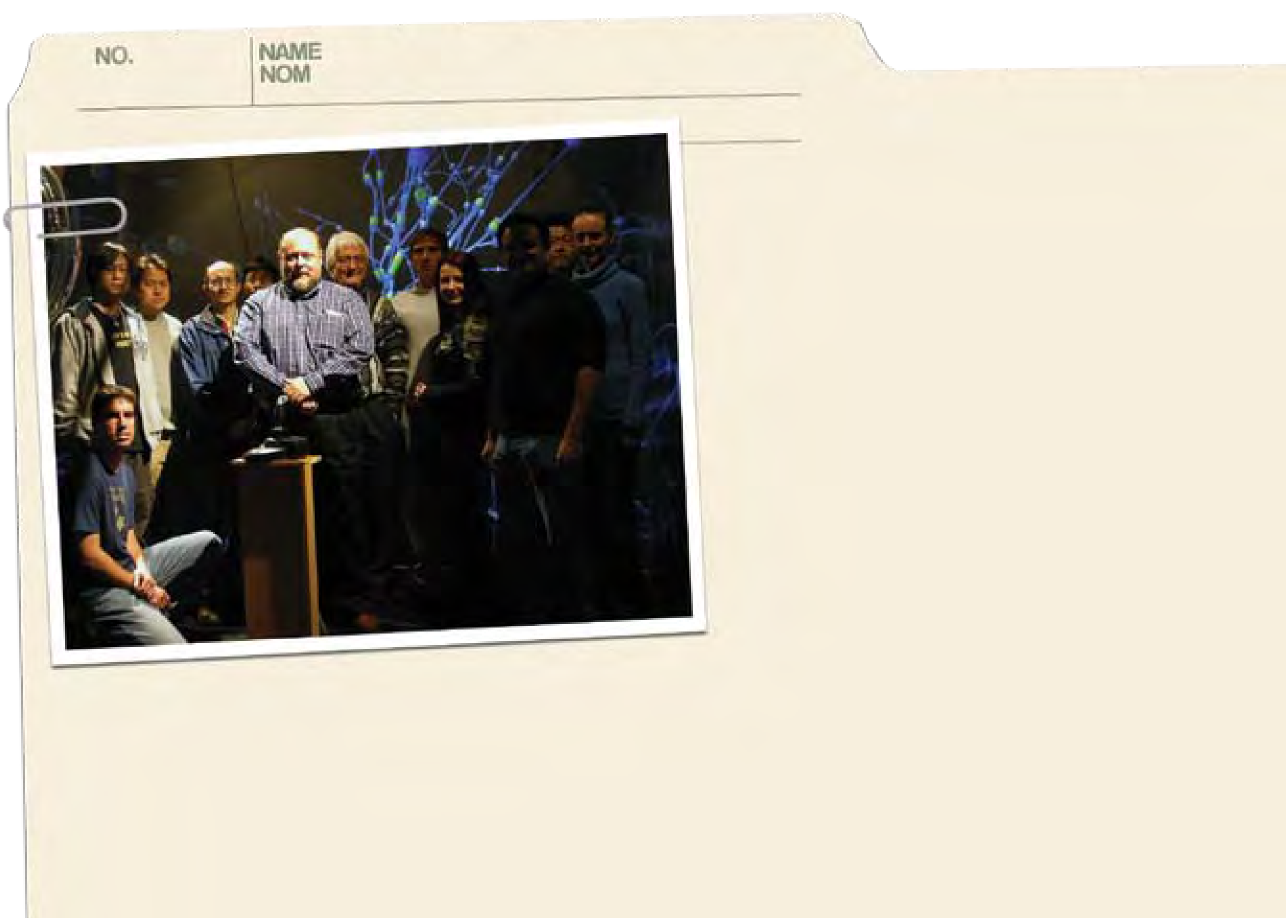
Name	Role/Topic	Awards/Special Info
Baochum Bai	Networking Issue for Tele-Immersion	Ingenuity Funds
Jacques-André Boulay	Tele-Immersion	NSERC
John Branch	Range Image Processing	National University of Colombia, Department of System Engineering (PhD defended successfully in 2007)
Victor Ochoa	Gesture Recognition	CONACIT
Robyn Taylor	Sound Visualization	NSERC, Ingenuity Funds
Andres Eleazar Jaramillo Velasquez	Deformable Part Inspection Using Spring-Mass System	National University of Colombia, Department of System Engineering (Passed entrance exam successfully in 2006)

MSc Candidates

Name	Role/Topic	Awards/Special Info
Steven Eliuk	Medical Imaging	
Mariya Kasakevich	Sonification Interface	Defended MSc thesis successfully in 2006
Qiong Wu	Tele-Immersion	iCORE
Rui Shen	Medial Imaging	iCORE
Matthew Hamilton	Simulation Server Development	NSERC
Xing Dong Yang	HCI analysis of the medical trainer	

Other Team Members

Name	Role/Topic	Awards/Special Info
Jeff Ryan	Programmer	
Guo Wu	Chief Programmer	



GRADUATES

Two students graduated this year:

- John Branch, "Reconstruction of Free Form Objects From Range Images Using A Net of NURBS Patches", School of Mines, National University of Colombia, Medellin, Colombia
- Maryia Kasakevich, "Enhanced Rendering of Fluid Field Data Using Sonification and Visualization", Department of Computing Science, University of Alberta

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
U of C, Prof. Richard Levy	Collaborator in CRDN and Canarie MLP Projects
Banff Centre, Maria Lantin	VR for the ARTS
U of A, Dentistery, Dr. Carlos Flores Mir	Medical Imaging
U of A, Radiology Dept, Dr. Michelle Norga	Medical Imaging
U of A, Dentistery, Dr. Paul Major	Medical Imaging
COMPRU, Dr. John Wolfaardt	Surgeon
National Collaborations	
McGill University, EE Prof. Jeremy Cooperstock,	Collaboration on the Tele-Immersion Project
Laval University, EE Prof. Patrick Hebert	Collaboration of the 3D Part Inspection Project
University of Ottawa, Photonics Group Prof. Trevor Hall	Collaboration of the CANARIE's HAVE Project
University of Ottawa, DISCOVER Lab Prof. Nicolas D. Georganas	Collaboration of the CANARIE's HAVE Project
SFU Brian Corrie	Collaborator for WestGrid and CANARIE's MLP Project
International Collaborations	
LIMSI Lab, CNRS, Orsay, France Prof. Patrick Bourdot	Multi-modal Interfaces
Ecole des Mines de Paris, France Prof. Claude Laurgeau	3D Image Processing
INSA, Lyon, France, Prof. Tanneguy Redarce	3D Imaging and Medical Trainer
University of Illinois, USA, EVL Lab Prof. Jason Leigh	GLVF Project
EAFIT University, Medellin, Colombia Prof. Manuel Garcia	Virtual Wind Tunnel Project

Participants	*Nature of Collaboration*
International Collaborations Con't	
EAFIT University, Medellin, Colombia Prof. Helmut Trefftz	Virtual Wind Tunnel Project
Los Andes University, Bogota, Colombia Prof. Pablo Figueroa	Virtual Wind Tunnel Project
National University, Manizales, Colombia Prof. Flavio Prieto	3D Image and Inspection Project
Industrial Collaborations	
BigBangWidth, Brian Moore	Optical Networking
3DI, Armand Cadieux,	Advanced Rendering
Creaform 3D, Charles Mony	Advanced Manufacturing
SGI Canada, Dan St-Germain	Virtual Wind Tunnel Project
HP Research, Tom Malzbender	Tele-Immersion Project
InnovMetric, Canada, Marc Soucy	Advanced Manufacturing

FUNDING

Dr Pierre Boulanger received a five-year iCORE Industrial Chair award ($250K). This year he received funding from NSERC ($26K), AET ($98K), industry ($309K), and from PRECARN and CANARIE ($221K).

PUBLICATIONS

ARTICLE IN A CONFERENCE PROCEEDINGS

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Kasakevich M., Boulanger P., Bischof W.F., and Garcia M., "Multi-Modal Interface for a Real-Time CFD Solver, HAVE'2006," *IEEE International Workshop on Haptic Audio Visual Environments and their Applications*, Ottawa, Canada 4-5 November 2006.

Boulanger P., Wu G., Bischof W.F., and Yang X.D., "Hapto-Audio-Visual Environments for Collaborative Training of Ophthalmic Surgery Over Optical Network, HAVE'2006," *IEEE International Workshop on Haptic Audio Visual Environments and their Applications,* Ottawa, Canada 4-5 November 2006.

Sanchez, G., Branch, J.W., Boulanger, P. "Reconstrucción De Objetos De Topología Arbitraria Mediante Selección De Centros Para La Interpolación Con Fbr," *Revista Dyna Facultad de Minas*, Universidad Nacional de Colombia. Número 150, November 2006. ISSN: 0012-7353.

Boulanger P., Garcia M., Badke C., and Ryan, J. "An Advanced Collaborative Infrastrcture for the Real-Time Computational Steering of Large CFD Simulations," E*uropean Conference on Computational Fluid Dynamics ECCOMAS CFD 2006,* TU Delft, The Netherlands, September 2006.

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Taylor R., Boulanger P., and Torres, "Responsive Visualization for Musical Performance," *Proceedings of The Bridges Conference: Mathematical Connections in Art, Music, and Science,* London, England, August 2006.

Garcia M., Boulanger P., Henao M. and Betancour M., "Structural Optimization of Reversed Engineered Structures," *7th World Congress on Computational Mechanics*, Los Angeles, July 18-24, 2006.

Branch J., Prieto F. and Boulanger P. "Robust Three-Dimensional Registration of Range Images Using a New Genetic Algorithm," *GMP 2006 Geometric Modeling and Processing 2006*, Pittsburgh, Pennsylvania, U.S.A, pp. 528 – 535, July 26 - 28, 2006.

Taylor R. and Boulanger P., "Deep Surrender: Musically Controlled Responsive Video," *6th International Symposium on Smart Graphics*, Vancouver, Canada, pp. 62-69, July 24-27, 2006.

Taylor R., Boulanger P., and Torres, D. "Real-Time Music Visualization using Responsive Imagery," *8th Laval Virtual Conference in Laval* (France), pp. 62-69, 18th to the 22th of April 2006.

Garcia M. and Boulanger P., "Low Altitude Wind Simulation Over Mount Saint Helens Using NASA SRTM Digital Terrain Model", *3DPVT 2006 Third International Symposium on 3D Data Processing, Visualization and Transmission,* University of North Carolina, Chapel Hill, USA, June 14-16, 2006.

Branch J., Prieto F. and Boulanger P. "Automatic Hole-Filling of Triangular Mesh Using Local Radial Basis Function," *3DPVT 2006 Third International Symposium on 3D Data Processing, Visualization and Transmission*, University of North Carolina, Chapel Hill, USA, June 14-16, 2006.

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Diaz, I. Branch, J., Boulanger, P. "A Genetic Algorithm to Segment Range Image by Edge Detection," *International Conference on Industrial Electronic and Control Applications*. Quito – Ecuador. ISBN: 0-7803-9420-8. IEEE Catalog Number: 05EX1175C, November 29-December 2, 2005.

Branch, J., Prieto, F., Boulanger, P. "Correspondence Method for Registration of Range Images Using Evolutionary Algorithms," *International Conference on Industrial Electronic and Control Applications*. Quito – Ecuador, ISBN: 0-7803-9420-8. IEEE Catalog Number: 05EX1175C, November 29 – December 2, 2005.

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Acar R., and Boulanger P., "Digital Marbling: A Multiscale Fluid Method," *IEEE Transactions on Visualization and Computer Graphics*, Vol. 12, No. 4, July/August 2006.

Figueroa P., Bischof W.F., Boulanger P., Hoover J. Efficient comparison of platform alternatives in interactive virtual reality applications. Int. J. Human-Computer Studies 62, pp. 73–103, 2005.

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Jason Leigh, Luc Renambot, Andrew Johnson, Byungil Jeong, Ratko Jagodic, Nicholas Schwarz, Dmitry Svistula, Rajvikram Singh, Julieta Aguilera, Xi Wang, Venkatram Vishwanath, Brenda Lopez, Dan Sandin, Tom Peterka, Javier Girado, Robert Kooima, Jinghua Ge, Lance Long, Alan Verlo, Thomas A. DeFanti, Maxine Brown, Donna Cox, Robert Patterson, Patrick Dorn, Paul Wefel, Stuart Levy, Jonas Talandis, Joe Reitzer, Tom Prudhomme, Tom Coffin, Brian Davis, Paul Wielinga, Bram Stolk, Gee Bum Koo, Jaeyoun Kim, Sangwoo Han, JongWon Kim, Brian Corrie, Todd Zimmerman, Pierre Boulanger, and Manuel Garcia, "The global lambda visualization facility: An international ultra-high-definition wide-area visualization collaboratory. Future Generation Computer Systems," *The International Journal of Grid Computing: Theory, Methods and Applications,* Volume 22, Issue 8, (October 2006), pp 964--971.

Manuel J. Garcia, Mario A. Gomez, Oscar E. Ruiz S., Boulanger P. "Spring-particle Model for Hyperelastic Cloth," *Revista Dyna*. No 151, pp 137--145. ISSN 0012-7353

Interactive Technologies

Modern society demands that people manage, communicate and interact with digital information and digital devices at an ever-increasing pace.

Dr Carpendale and another Interactive Technologies researcher demonstrate interactive tabletop hardware and software.

The problem is not with the information itself, but rather with its sheer volume and the unwieldy ways now provided to present, exchange, view, and interact with it.

The iCORE/Smart Technologies team attacks this problem with the objective to design, develop, and evaluate interactive technologies so that they support everyday-world practices of how people view, represent, manage, collaborate with and interact with information.

This broad objective is realized by two inter-related research themes. First, interactive visualization investigates the possibilities the digital world affords for peoples' exploration of dense and complex information spaces. The overall goal of an effective interactive visualization is to promote comprehension by providing people with appropriate interactive technologies and digital displays that help them transform information into knowledge. Second, embodied interaction considers how the technology that displays this information can be designed as a truly integral part of the real world environment. The overall goal is to create new interactive displays and computational devices that fit, support and participate in – rather than ignore – the everyday-world social practices of people and their surrounding environment. Both themes are tightly intertwined: interactive visualization considers the fundamental nature of information and how people can effectively interact with it through technology, while embodied interaction considers how these technologies manifest themselves in ways that exploit the everyday practices and routines of people.

This last year, academically, the team published many papers on the research described in the iCORE proposal, most with graduate students. Grantwise, the iCORE/Smart Technologies team has applied for the matching NSERC Industrial Chair, and has just completed the site visit. The team (along with collaborator Prof Sharin) just received an NSERC Research Tools and Instruments Grant for a Vicon Motion Capture setup. With industrial partners, the team finalized the intellectual property agreement, engaged in discussions over research products, and worked with them to run an important conference.

Research Program Overview

Interactive Visualization

This theme includes the design, development, and evaluatation of interactive visualization of information that address some of people's challenges as part of an informative society, and to enhance individual's cognitive and communicative abilities: to see the invisible, to comprehend vast information spaces, to manipulate abstract concepts, to appreciate the beauty of information structure, and to support decision making and collaborative processes. Interactive visualizations are successful when they can help people interpret and understand information, steps which are integral in the processes of developing knowledge:

i. Visualizing uncertainty
ii. Visual decision support
iii. Interactive information exploration through semantic zooming
iv. Social visualization

Embodied Interaction

This theme includes the design, development, and evaluatation of interactive technology such that it supports and participates in – rather than ignores – the everyday-world practices of people. Social groups will use these systems to pursue and maintain their long-term collaborations within their real world context.

i. Understanding social practices
ii. Groupware interaction technologies
iii. Infrastructure for embodied interaction

Research Projects

Overview

During this last year the iCORE/Smart Technologies Chairs worked on a variety of projects as listed in the proposal and as detailed below. Many of these projects were, of course, continuations of research begun before the Chair award but that now fall under the Chair mandate. Many projects have produced quality research outcomes. Specific project outcomes during this reporting period within these themes are:

- Production of a rapid prototyping toolkit for ubiquitous computing, single display groupware, and other tools that enable creativity in interactive technologies
- Development of algorithms for rapid updates on very high resolution displays
- Production of a journal special issue on digital tabletop research
- Various publications concerning the design of digital tables and corresponding software, including multimodal interfaces to table, interface currents, shallow-depth 3D manipulation, and interactive annotations
- Foundational studies of domestic environments and healthcare settings
- Development of ubiquitous appliances for domestic environments, including location-dependant appliances, home messaging and home calendars (with Microsoft Research)

- Development of interactive techniques for interacting with display walls, and for non-photorealistic artwork
- Development of particular information visualization methods for graph viewing, for typed communication, for message posting and for team programming
- Development of methods for information sharing and awareness between distant-separated work groups via several means, including: posting and seeing daily multimedia updates; observing a group's computer activities; hearing other's activities through an audio-based media space; reviewing video histories of other's activities; and by using robots to act as a distant surrogate of oneself in the group setting
- Connecting digital tables and walls together, and methods that enhance people's ability to communicate through them

Objectives for Next Year

Administratively, the first reporting period primarily involved getting the Chair into place. Two large and time-consuming hurdles were setting up the Intellectual Property Agreement, and writing the matching NSERC Industrial Chair grant proposal. Now that both are in place, the team's main administrative objectives for the coming year are to hire two post doctorate/senior researchers if the NSERC IRC is accepted, putting into play the various obligations that come with it (e.g., hiring, program set up).

Several new students will be arriving in the fall, and they will be invited to assume various projects as described in the iCORE proposal. Students will have a significant stake in these projects, and thus the team expects details to evolve as the students become vested in them.

Outreach

Community Events:

A graduate student recruitment day was held, starting January 24, where the Chairs invited a variety of prospective graduates students and a Post Docs to both interview and attend a Demonstration Day. The Demonstration Day was held on January 25, where the Chairs and their students demonstrated various projects to about 50 visitors and industrial sponsors.

The Chairs, their students, and the iCORE/Smart Technologies team's industrial sponsor had a major involvement with the ACM Conference on Computer Supported Cooperative Work, held in Banff, Alberta. To take advantage of this local conference, almost all students in the laboratory were involved in either demonstrating their work at the formal (refereed) demonstration session, or through the formal (refereed) video session, or through paper presentations with exposure to the International Community. One external report of the conference explicitly described and included a photo of one of Smart Technologies demonstrations (Interactive Currents on a Digital Table), where it was listed as the most popular demonstartion of the conference.

Similarly, students and faculty took advantage of the CSCW conference to attend workshops (by invitation) on themes relevant to the Chair.

The NSERC Nectar Research Grant held its Annual General Meeting/Demonstration Day immediately following the conference. Because the Chair research overlaps with Nectar, the team took advantage of this opportunity to have all students present either demonstrations or posters over the day. Students and faculty from several other Canadian universities were also at this event.

Finally, Carpendale and a large group of the team's students attended IEEE Information Visualization and IEEE Visualization, which were held back to back in Baltimore. The major venue for the team's students was the interactive poster session. These demonstrations caused considerable excitement and line ups of people waiting for hours even after the demonstration session was formally over.

Public Presentations by Visitors to the Chairs:

Name	Role/Topic	Location/Date
Prof Tim Bell	Computer Science Unplugged	Dept Computer Science University of Canterbury, NZ October 2006
Andrea Bunt	Supporting Interface Customization Using a Mixed-Initiative Approach	Computer Science Department at the University of British Columbia January 2007
Gregor McEwan	Supporting teams collaborating remotely	National ICT Australia (NICTA) November 2006
Dr Hiroaki Ogata	Computer supported ubiquitous learning in the context of language learning	Tokushima University October 2006
Dr Catherine Plaisant	Network Visualization: Seeking Alternatives to the Traditional Node Link Diagram	Human-Computer Interaction Laboratory of the University of Maryland Institute for Advanced Computer Studies January 2007
Mary (Missy) Cummings and Stacey Scott	Decision and Collaboration Support for Time-Critical Unmanned Vehicle Operations	Humans and Automation Lab (HAL) at the Massachusetts Institute of Technology in Cambridge, MA March 2007
Prof Stephen Viller	Lo-fi Matchmaking: A Study of Social Pairing for Backpackers	Inf. Environments Program U. Queensland, Australia October 2006

Significant Media Exposure

There was a media event for the iCORE Chair Launch held at the Interactions Lab in the U of C on March 8, 2007. Media coverage appeared in the Calgary Herald, CTV News, and an interview with Carpendale and Greenberg was held with Cheryl Croucher for Innovation Alberta. The University television station (NUTV) also did a segment on the Chairs that was aired April 2007. Greenberg was interviewed for a technology column on CBC radio.

Other Activities

Major academic service by the Chairs included:

- Co-Chair, Program Committee ACM CSCW (Greenberg)
- Member, EPSRC Panel Review for ICT Research in the UK (Greenberg)
- Program Committee Member, Interacción '2006 (Greenberg)
- Video Chair, ACM CSCW (Carpendale)

- Interactive Posters/Video Co-Chair IEEE Information Visualization (Carpendale)
- General Co-Chair, Computational Aesthetics 2007 (Carpendale)
- Tang, C., gave a presentation on Observations on Nurses' Shift Change at Ward of the 21st Century's 2006 fall retreat
- Many students gave presentations associated with their publications at conferences

New Initiatives:
A new graduate course on Ubiquitous Computing was created. This is relevant because:

- the content of the course explored the theoretical grounding behind the research in Theme 2
- the course was attended by three Smart Tehnologies, Inc. staff for its duration via an official audit.
- A new fourth year undergraduate course on Computer Science, Fine Arts Inter-disciplinary Collaboration is currently being developed. This year 2006/2007 pilot full course is currently in progress.

Research Team Members and Contributions

Team Leader
Professor Sheelagh Carpendale
Associate Professor
Canada Research Chair Information Visualization

Team Leader
Professor Saul Greenberg
Full Professor

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Robin Arseneault	Team Member	
Steve Jenkins	Part time technical assistant	
Mark Watson	Team Member	

PostDoctoral Fellows

Name	Role/Topic	Awards/Special Info
Tobias Isenberg		Alberta Ingenuity Post-Doctoral fellowship
Carman Neudstaedter		Awarded PhD in Computer Science

PhD Candidates

Name	Role/Topic	Awards/Special Info
Christopher Collins		NSERC PGS-D Co-supervisors: Penn (U of T), Carpendale
Mark Hancock		Supervisor: Carpendale NSERC PGS-D, Alberta Ingenuity, iCORE Supervisor: Carpendale
Petra Neumann		Alberta Ingenuity and iCORE Supervisor: Carpendale
Charlotte Tang		Alberta Ingenuity and iCORE Supervisor: Carpendale
Eward Tse		Alberta Ingenuity and iCORE Supervisor: Greenberg
Torre Zuk		NSERC IPS Gave a presentation on Visualization of uncertainty for the diagnosis of pulmonary embolism in an evidence-based medicine decision making framework at Ward of the 21st Century's 2006 fall retreat Supervisor: Carpendale

MSc Candidates

Name	Role/Topic	Awards/Special Info
Tim Au Yeung		Awarded NSERC Scholarship, March 31 2007 Supervisor: Greenberg
Rob Diaz-Marino		Supervisor: Greenberg
Katherine Elliot		Designer, Smart Technologies, Inc.
Uta Hinrichs		iCORE , Alberta Ingenuity (awarded March 2007) Supervisor: Carpendale
Jereon Keijser		Supervisor: Carpendale
Michael Nunes		NSERC PGS-M Scholarship Supervisor: Greenberg
Eric Penner		NSERC CGS-M, Alberta Ingenuity (awarded March 07), iCORE Supervisor Carpendale
Annie Tat		Supervisor Carpendale
Kimberly Tee	Internship at Microsoft Research, March – June 2007	NSERC PGS-M Scholarship Alberta Ingenuity Scholarship Supervisor: Greenberg
Matthew Tobiasz		Supervisor: Carpendale

Other Team Members

Name	Role/Topic	Awards/Special Info
Marian Dörk	Visitor	Visiting research student
Martin Schwarz	Exchange Student	Visiting research internship, requirement for the University of Magdeberg Supervisor: Carpendale

Visitors

Name	Role/Topic	Awards/Special Info
Marian Dörk	Visitor	Visiting research student
Stephen Viller	Visitor	Visited several months, Fall 2007

GRADUATES

Name	*Research Topic*	*Current Position*
PhD Graduates		
Carman Neudstaedter	Domestic Awareness and the Role of Family Calendars.	Postdoc Research Associate, U of C
MSc Graduates		
Kathryn Elliot	Contextual locations in the home	Interaction Designer, Smart Technologies, Inc.
Gregor McEwan	Community Bar: Designing for Informal Awareness and Casual Interaction.	Research Engineer, National ICT Australia (NICTA)

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
University of Calgary (U of C), Faculty of Fine Arts	Carpendale on hiring committee for the new interdisciplinary CRC position in New Media and Creative Practices.

Participants	*Nature of Collaboration*
Provincial Collaborations Cont'd	
U of C, Department of Art	Carpendale is working towards the development of interdisciplinary programs. Annie Tat is an Interdisciplinary MSc student, Supervisor Carpendale, Co-supervisor P. Woodrow
U of C, EVDS	Ron Wardell of EVDS is a member of Caprendale's PhD student C. Tang's committee.
U of C, Department of Physics	Two students under Carpendale's supervision are visualizing Astro-physics data. The collaborator is Russ Taylor
U of C, Departments of Radiology and Clinical Neurosciences	Dr. J. Ross Mitchell is working with MSc student E. Penner of visualizing his medical (brain scan) data.
Banff Centre for the Arts, Banff New Media Institute	Carpendale is working towards the development of interdisciplinary programs. Two weeks of this course were held as intensives at the Banff centre. CAe will be held at Banff Centre and collaboration around this is on going. Carpendale is involved with helping Banff replace their senior research and helping write job adds.
Alberta College of Art & Design	Carpendale is working towards the development of interdisciplinary programs. This initive is joint with ACAD. Three ACAD students are attending the pilot course. Most of the final projects will result as installations in the ACAD end of year show.
Ward of the 21st Century	Carpendale is a member of the Steering Committee. Carpendale has two active research projects on W21C
National Collaborations	
University of British Columbia	Carpendale paid for UBC PhD student A.Tang to spend two weeks in ilab to work on a research project with PhD student P. Neumann
University of Toronto	Both Greenberg and Carpendale associated via NECTAR. Carpendale co-supervising U of T PhD student
University of Victoria	Carpendale has invited Prof A. Gooch to be a member of PhD candidate Neumann's team. Carpendale co-chair of CAe with Brian Wyvill
International Collaborations	
University of Magdeberg, Germany	Regular research student exchange
University of Queensland, Australia	Research Visitor, Stephen Viller

Participants	*Nature of Collaboration*
Industrial Collaborations	
Autodesk	Student Internships
Intel	Student Internships
Microsoft Research, Redmond	Student Internships
Mitsubishi Electric Research Laboratories, Boston	Student Internships
Smart Technologies	Sponsor

INTELLECTUAL PROPERTY

Spinoff Companies	*Nature of Company*
Phidgets, Inc.	Established several years ago, with ongoing relationship to Greenberg
Idelix	Established several years ago, has an ongoing relationship with Carpendale

FUNDING

Dr Carpendale and Dr Greenberg were co-awarded a five year iCORE Industrial Chair ($500K). Yearly funding was provided by SMART Technologies Inc ($100K), NSERC and CFI ($277K). Funding was also provided by Dr Carpendale's Tier 2 CRC Research Chair award ($100K).

PUBLICATIONS

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Greenberg, S. (2007) "Toolkits and Interface Creativity," *Journal Multimedia Tools and Applications*, 32(2), February. Kluwer. Special Issue on Groupware.

Greenberg, S. (2006) "Creating Stories Over Distance," Commentary. *THEN Journal: Technologies, Humanities, Education, & Narrative*, Issue 4, September, 2006.

Scott, S.D., Carpendale, S. Co-editors, "Special Issue on Interacting with Digital Tabletop," *IEEE Computer Graphics and Applications*, 26(5), September/October 2006.

Scott, S.D., Carpendale, S. "Introduction: Interacting with Digital Tabletops," *IEEE Computer Graphics & Applications: Special Issue on Interacting with Digital Tabletops*, 26(5): 24-27, September/October 2006

Shen, C., Ryall, K., Forlines, C., Esenther, A., Vernier, F.D., Everitt, K., Wu, M., Wigdor, D., Morris, M.R., Hancock, M., and Tse, E. "Informing the Design of Direct-Touch Tabletops," *IEEE Computer Graphics and Applications*, 26(5):36-46, September/October 2006.

FULLY REFEREED CONFERENCE PAPERS

Elliot, K., Neustaedter, C. and Greenberg, S. (2007) "StickySpots: Using Location to Embed Technology in the Social Practices of the Home," *Proc. 1st International Conference on Tangible and Embedded Interaction*. (Feb 15-17, Baton Rouge, Louisiana, USA).

Marquardt, N. and Greenberg, S. (2007) "Distributed Physical Interfaces with Shared Phidgets," *Proc. 1st International Conference on Tangible and Embedded Interaction*. (Feb 15-17, Baton Rouge, Louisiana, USA).

Keijser J., Carpendale, S., Hancock, M.S., Isenberg, T. (2007). "Exploring 3D Interaction in Alternate Control-Display Space Mappings," In press: *Proc. IEEE Symposium on 3D User Interfaces*, 3DUI'07

Wong, N., Carpendale, S. (2007) (in press) "Supporting Interactive Graph Exploration Using Edge Plucking," *Proc. Conference on Visualization and Data Analysis*, SPIE-IS&T Electronic Imaging.

Neustaedter, C., Elliot, K. and Greenberg, S. (2006) "Interpersonal Awareness in the Domestic Realm," *Proc. OZCHI*, (Sydney, Australia, Nov 20-24), 2006.

Smale, S. and Greenberg, S. (2006) "Transient Life: Collecting and sharing personal information," *Proc. OZCHI* (Sydney, Australia, Nov 20-24), 2006.

Tang, A., Neustaedter, C. and Greenberg, S. (2006) "VideoArms: Embodiments for Mixed Presence Groupware," *Proceedings of the 20th BCS-HCI British HCI 2006 Group Conference* (Sept 11-15, Queen Mary, University of London, UK).

Tee, K., Greenberg, S. and Gutwin, C. (2006) "Providing Artifact Awareness to a Distributed Group through Screen Sharing," *Proceeding of the ACM CSCW'06 Conference on Computer Supported Cooperative Work*, ACM Press, November

Tse, E., Greenberg, S. and Shen, C. (2006) "GSI DEMO: Multiuser Gesture/Speech Interaction over Digital Tables by Wrapping Single User Applications," *Proc Eighth International Conference on Multimodal Interfaces* (ICMI'06), (Nov 2-4, Banff, Canada), ACM Press.

FULLY REFEREED VIDEOS (INCLUDES VIDEO AND TWO PAGE PAPER SUBMISSION)

Diaz-Marino, R. and Greenberg, S. (2006) "Cambience: A Video-Driven Sonic Ecology for Media Spaces," *Video Proceedings of ACM CSCW'06 Conference on Computer Supported Cooperative Work*, November, ACM Press. Video and two-page summary. Duration 3:52

Elliot, K., Neustaedter, C. and Greenberg, S. (2006) "Sticky Spots: A Location-Based Messaging System for the Home," Video Proceedings of *ACM CSCW'06 Conference on Computer Supported Cooperative Work*, November, ACM Press. Video and two-page summary. Duration 4:55

Greenberg, S. and Tse. E. (2006) "SDGToolkit in Action," Video Proceedings of *ACM CSCW'06 Conference on Computer Supported Cooperative Work*, November, ACM Press. Video and two-page summary. Duration 7:14

Hinrichs, U., Carpendale, S., Scott, S.D. "Interface Currents: Supporting fluid face-to-face collaboration," Video Proceedings of *ACM CSCW'06 Conference on Computer Supported Cooperative Work*, November, ACM Press. Video and two-page summary.

Neustaedter, C., Brush, A.J. and Greenberg, S. (2006) "LINC, An Inkable Digital Family Calendar: The Video," Video Proceedings of *ACM CSCW'06 Conference on Computer Supported Cooperative Work*, November, ACM Press. Video and two-page summary. Duration 3:32

Nunes, M., Greenberg, S., Carpendale, S. and Gutwin, C. (2006) "Timeline: Video Traces for Awareness," Video Proceedings of *ACM CSCW'06 Conference on Computer Supported Cooperative Work*, November, ACM Press. Video and two-page summary. Duration 4:44

Tee, K., Greenberg, S., Gutwin, C. and McEwan, G. (2006) "Shared Desktop Media Item: The Video," Video Proceedings of *ACM CSCW'06 Conference on Computer Supported Cooperative Work*, November, ACM Press. Video and two-page summary. Duration 4:00

Tse, E., Greenberg, S. and Shen, C. (2006) "Motivating Multimodal Interaction Around Digital Tabletops," Video Proceedings of *ACM CSCW'06 Conference on Computer Supported Cooperative Work*, November, ACM Press. Video and two-page summary. Duration 3:25.

FULLY REFEREED DEMONSTRATIONS (INCLUDES LIVE DEMO AND TWO PAGE PAPER SUBMISSION)

Carpendale, S., Isenberg, T., Scott, S.D., Hinrichs, U. Miede, A., Kruger, R., Habelski, S., and Inkpen, K. "Collaborative Interaction on Large Tabletop Displays," Demo, *Adjunct Proc ACM CSCW* 2006.

Diaz-Marino, R. and Greenberg, S. "Demonstrating How to Construct a Sonic Ecology for Media Spaces through Cambience," Demo, *Adjunct Proc ACM CSCW* 2006.

Neumann, P, Tat, A., Zuk, T., and Carpendale, S. "Visualization of Typed Communication," Demo, *Adjunct Proc ACM CSCW* 2006.

Neustaedter, C., Brush, A.J. and Greenberg, S. "A Demo of Family Calendaring using LINC," Demo, *Adjunct Proc ACM CSCW* 2006.

Nunes, M., Greenberg, S., Carpendale, S. and Gutwin, C. "Demonstrating Timeline: Video Traces for Awareness," Demo, *Adjunct Proc ACM CSCW* 2006.

Seniuk, A., and Carpendale, S. "Astral: A System for Immersive Team Programming," Demo, *Adjunct Proc ACM CSCW* 2006.

Tee, K., Greenberg, S., McEwan, G. and Gutwin, C. "Sharing Desktops with the Community Bar," Demo, *Adjunct ProcACM CSCW* 2006.

Tse, E., Greenberg, S., Shen, C. "Multi User Multimodal Tabletop Interaction over Existing Single User Applications," Demo, *Adjunct Proc ACM CSCW* 2006.

Tse, E., Greenberg, S., Shen, C. "Exploring Interaction with Multi User Speech and Whole Handed Gestures on a Digital Table," Demo, *Adjunct Proc ACM UIST* 2006

Young, J., McEwan, G., Greenberg, S. and Sharlin, E. "Aibo Surrogate - A Group-Robot Interface," Demo, *Adjunct Proc ACM CSCW* 2006.

FULLY REFEREED POSTERS (INTERACTIVE POSTERS INCLUDE: POSTER, LIVE DEMO, AND TWO PAGE PAPER SUBMISSION)

Isenberg, T., Neumann, P., Carpendale, S., Nix, S., Greenberg, S. "Interactive Annotations on Large, High-Resolution Information Displays," *Interactive Poster: IEEE InfoVis* 2006, November.

Neumann, P., Tat, A., Zuk, T., Carpendale, S. "Personalizing Typed Text through Visualization," *Interactive Poster: IEEE InfoVis* 2006, November.

Seniuk, A. Carpendale, S. "Visualizing Program Syntax to Support Agile Programming," *Interactive Poster: IEEE InfoVis* 2006, November.

Tat, A., Kruger, R., Carpendale, S., Dunning, A. "Plant Post: Visualizing Temporal Aspects of Message Posting," *Interactive Poster: IEEE InfoVis* 2006, November.

WORKSHOPS, REFEREED BY WORKSHOP COMMITTEE

Greenberg, S. and McEwan, G. (2006) "Reflecting on Several Metaphors for Media Spaces," in *Proc. CSCW'06 Workshop on Media Space - Reflecting on 20 Years*. Steve Harrison, Organizer.

Tang, C. and Carpendale S. (2006). "Healthcare Quality and Information Flow during Shift Change," In *Proc. Ubicomp'06 Workshop on UbiHealth 2006: Pervasive Healthcare*, Jakob E. Bardram, Thomas Riisgaard Hansen, Ilkka Korhonen, Organizers.

OTHER PUBLICATIONS

THESES

Nuestaedter, C. (2007) "Domestic Awareness and the Role of Family Calendars," PhD Thesis, Department of Computer Science, University of Calgary, Calgary, Alberta CANADA T2N 1N4. February.

Elliot, K. (2006) "Contextual Locations in the Home," MSc Thesis, Dept. Computer Science, University of Calgary, Calgary, Alberta, Canada. December.

McEwan, G. Community Bar: Designing for Informal Awareness and Casual Interaction. MSc Thesis, Department of Computer Science, University of Calgary, Calgary, Alberta, Canada T2N 1N4. September, 2006.

TECHNICAL REPORTS

Nunes, M., Greenberg, S., Carpendale, S. and Gutwin, C. (2007) "What Did I Miss? Visualizing the Past through Video Traces," Report 2007-855-07, Dept. Computer Science, University of Calgary, Calgary, Alberta, Canada. March. 21 pages.

"Modeling with Rendering Primitives: An Interactive Non-Photorealistic Canvas," 2007-851-03, Martin Schwarz, Tobias Isenberg, Katherine Mason and Sheelagh Carpendale; February 9, 2007.

Elliot, K., Watson, M., Neustaedter, C. and Greenberg, S. (2006) "Location-Dependant Information Appliances for the Home," Report 2006-848-41, Department of Computer Science, University of Calgary, Calgary, Alberta, Canada T2N 1N4. December.

DOCTORIAL CONSORTIUMS

Tang, C. "Designing Technology to Support Information Flow for Asynchronous Co-located Medical Shift Work," *Doctorial Consortium, Adjunct Proc. ACM CSCW* 2006. November.

Tse, E. "Multimodal Co-located Collaboration," *Doctorial Consortium, Adjunct Proc ACM UIST* 2006. November

NSERC NECTAR RESEARCH NETWORKS POSTERS

The following posters were produced for the Annual NSERC NECTAR Research Networks AGM, held after the ACM CSCW Conference in November 2006.

Hancock, M. and Carpendale S. Interaction in Shallow Depth 3D.

Hinrichs, U. and Carpendale, S. Interface Currents.

Isenberg, T. and Carpendale, S. Maintaining Interactive Rates on Large High Resolution Displays.

Marquardt, N. and Greenberg, S. Shared Phidgets: A developer's toolkit for rapid prototyping of distributed tangible user interfaces

McEwan, G. and Greenberg, S. Community Bar

Neumann, P., Tat, A., Zuk, T. and Carpendale, S. Visualization of Typed Communication.

Neustaedter, C., Brush, A.J. and Greenberg, S. LINC: A Digital Family Calendar

Nunes, M., Greenberg, S., Carpendale, S., and Gutwin, C. Timeline: Video Traces for Awareness

Seniuk, A., and Carpendale, S. Visualising Program Syntax to Support Agile Programming.

Tang, C. and Carpendale, S. Observing Information Flow during Nurses's Shift Change.

Tee, K., Greenberg, S. and Gutwin, C. Screen Sharing with Community Bar

INVITED TALKS

Note: this list does not include talks associated with papers at conferences and workshops, or media interviews.

Other Team Members

Name	Role/Topic	Awards/Special Info
Dr Greenberg	Keynote Presentation:	Interaccion 2006 (Spain) November, 2006
Dr Greenberg	Invited Presentation (with Ben Shneiderman, University of Maryland)	Cadius – Professional Group on Human Computer Interaction (Madrid, Spain) November, 2006
Dr Greenberg	Distinguished Lecture Series	Univ. Washington January 2007
Dr Greenberg	Industrial Seminar	Smart Technologies Inc. Mach 2007
Dr Greenberg	Department Seminar	University of Avairo, Portugal March 2007
Dr Greenberg	Department Seminar	University of Lisbon Portugal March 2007
Dr Greenberg	Opening Keynote	HCI Educators Conference (Portugal) March 2007

Biocomplexity and Informatics

To properly reflect the work that has evolved and been accomplished to date, the mission of the Institute for Biocomplexity and Informatics (IBI) has been anchored and refined.

The original Spring 2005 vision was to explore and develop general principles that govern the dynamics of cellular regulatory networks. The IBI's mission now is to understand the living state from the perspectives of Systems Biology and non-equilibrium thermodynamics, based on physics, chemistry, biology, computer science, and mathematics.

Having now commenced its third year of operation, the IBI has the first phase of its strategic experimental laboratory plan completed, equipped, and readied for action. This leading-edge laboratory now permits iCORE Chair Dr Stuart Kauffman and the IBI's expanding research team to launch unprecedented experimental work including high-throughput screening and image analysis of cancer cell lines to seek novel drug targets, and to better understand and utilize new knowledge about the regulatory networks and mechanisms of cell differentiation in both healthy and diseased states.

This experimental work is taking place in concert with the theoretical, mathematical, and computer simulation work being carried out by a team of current staff plus new hires: physicists, biologists, medical doctors, mathematicians, and theorists who are developing useful experimental approaches and techniques, new algorithms, models, and exploration methods.

New IBI faculty is being hired through the Departments of Biological Sciences, Physics, and Astronomy. Plans for acquiring additional computing, meeting, office, and laboratory space adjacent to the present IBI facility are being developed. Formative and established networks of scientific collaboration are in place and continue to be built at the University of Calgary (U of C), throughout Alberta, across Canada, and internationally. Faculty and staff of the IBI continue to publish extensively in respected journals in Biological Sciences, Physics, and other fields. Present research findings have occurred in a wide variety of venues, and two patents have been filed as a result of intensive theoretical work. New Master's and Doctoral students and an increasing number of post-doctoral fellows continue to join the IBI, adding strength to its teams, research, publication capacities, and interdisciplinary foundation.

Science policy networking continues as a major outreach thrust of the IBI, with ongoing meetings, consultations and science policy work at local, provincial, national, and international levels. This outreach has resulted in increased awareness and collaborative potential among policy actors, industrial partners, and other experimental and theoretical teams, of the significance of understanding the relationship between the emerging "new science on the ground" and the shaping and evolution of long-term science policy that supports and helps new science develop.

In order to achieve desired results and meet its goals, the IBI will continue to build four basic things: a gradual strategic expansion in concert with other leading edge research efforts especially increasing collaborations at the U of C and throughout Alberta further developing its experimental, theoretical, and simulation research capacities, productivities, and program efforts; shaping its program in terms of research, partnerships, collaborations and outputs to emphasize the training, support and growth of highly-trained scientists, the generation of leading-edge knowledge in the Systems Biology and related fields, and potential benefits for all Albertans in terms of improved health care, wellness, diversified economic growth, and overall quality of life; and ongoing correction of and accounting for all project management and financial accounting errors and omissions that have occurred to date in establishing the IBI, thus ensuring that a full, coordinated, accurate and complete project management and financial accounting system is appropriately developed and implemented to meet all future project planning, execution, and accounting requirements.

Research Program Overview

The research program of the IBI began in early 2005 with a generalized focus on the intention to explore the dynamics of genetic regulatory networks of cells. The explicit goal in the early phases of the IBI's development was to begin exploration and novel development of the sciences of genetic regulatory networks to better understand how to control or eliminate cancer through manipulation of cell differentiation mechanisms.

The IBI was without a laboratory during the first two years of operation. Although greatly appreciated, laboratory-based collaboration at the U of C proved to be far too limited to be of great value. With the experimental component of the IBI's burgeoning program by default critically under-activated, the theoretical work of the IBI developed quickly and productively during the first two years of operation. New algorithms were developed and utilized in extensive simulations, suggesting a variety of experimental approaches appropriate to the time when the IBI laboratory would be operational with new directions for theoretical exploration of simulated cellular systems.

The first phase of the planned laboratory configuration of the IBI was completed in March of 2007. The first cell lines are now being grown as a "shake down cruise" of both methodologies and equipment. The custom-made high throughput screening robot has been tested and fine-tuned by the manufacturer and is now ready to begin work in earnest. The leading-edge microscopy and image analysis system has been tested in preparation for receipt of experimental products that will be generated from the robotic high throughput screening activities. All other aspects of laboratory setup have been completed and are now poised to begin a program of extensive screening and analysis. The mathematical and simulation work of the theoretical arm of the IBI has undertaken a long-term investigation of image analysis methods and technologies, and has already begun to examine plausible mathematical enhancements to programs used to run and generate results from this equipment.

The IBI's new hires reflect the logical expansion and development of the institute's research program. Dr. Sui Huang will be arriving from the Harvard Children's Hospital and Medical Schoolwork to co-establish the Laboratory for Functional Genomics [LFG] at the IBI. This facility, to be built over the forthcoming year, and will share strategic planning responsibilities for the overall scientific direction of the institute. Work will address expansion of the IBI's existing Systems Biology efforts toward massively-parallel analyses of other "layers" of "omics" in cell information processing and their integration into the genome-wide genetic regulatory system. This includes analysis of signal transduction, histone modification and transcription factor-DNA binding, microRNA, and metabolites.

The central goal remains the same: to develop and refine novel high thoughput techniques to establish, infer, and test the control logic of the regulated gene in addition to the regulatory connections. This will also require a tighter integration of the IBI's current and planned improvements in network inference from microarray-based expression profiles and other data, to the modeling of genetic network dynamics. As part of the quest for general principles that govern network dynamics and simple synthetic human genetic regulatory networks in mammalian cell systems, such as gene switches, the IBI will also study the actual in vivo dynamics of networks with defined architecture when they are exposed to a noisy environment.

Experimentalist Dr Gordon Chua will be arriving from the University of Toronto in July 2007. In collaboration with the IBI, Dr Chau's plans include co-establishing the aforementioned LFG. Chua will build microarray and Synthetic Genetic Array [SGA] Facilities to enable large-scale mapping of transcriptional-regulatory and genetic-interaction networks, two areas at the forefront of Systems Biology research that have received extensive attention and hold great promise for major biomedical discoveries. The LFG infrastructure will facilitate the utilization and applications of these high throughput genomic technologies in Alberta by offering other research labs the specialized expertise and accessibility of experimentation involving custom-designed, affordable Agilent microarrays and SGA. Moreover, the large datasets generated by the LFG will provide useful functional information on individual genes and biological processes that will overlap with the research interests of other labs and foster synergistic collaborative relationships between molecular and computational biologists. Furthermore, the research carried out by the LFG will lead to new genomic platforms including a compendium of human therapeutic expression profiles and bar-coded deletion and over expression fission yeast arrays that will be highly beneficial in the functional characterization of genes and the mapping of biological networks by the Systems Biology community.

The IBI is also planning to acquire a high-end modular computing cluster to aide in the exploration of the features, characteristics and dynamics of proteins comprising cellular membrane transport mechanisms, an enhanced understanding of which is crucial to the overall research program of the IBI regarding cancer and healthy cell differentiation.

In the Fall of 2007, Dr Dennis Salahub, who is currently the Vice President Research at the U of C, will begin his move into the IBI to take up the pursuit of quantum chemistry research related to the mechanisms of cell differentiation. Recent theorems in quantum computing suggest that, despite the expectations of most physicists, quantum coherence effects may persist at body temperature. This has powerful implications for an expanded line of inquiry at the IBI having to do with cellular dynamics. Dr Salahub plans to bring with him onto the IBI team a number of graduate students and post doctoral fellows (PDFs).

Research Projects

Over the past year, the IBI has achieved significant advances in four areas of theory and one area of experimental work. The theoretical domains include:

- analysis of criticality in model genetic regulatory networks with extension to the initial evidence that eukaryotic cells are dynamically critical;
- development and deployment of two inference algorithms to infer the regulatory structure and logic of genetic regulatory networks from gene expression array data;
- development and deployment of chemical master equation models of genetic regulatory networks studied using the Gillespie algorithm; and,
- molecular dynamical studies of membrane channel proteins and ubiquitin that includes the discovery of an enhanced diversity of modes of motion of ubiquitin at its evolved temperature.

On the experimental front, the preliminary experiments have begun and are continuing with respect to knock-down of specific gene expression with siRNA and initial attempts to induce cell differentiation through such alterations of gene expression in HL60 cells.

This research and other work undertaken by IBI personnel and their collaborators over the past fiscal year has resulted in a total of 61 publications, conference presentations, and invited talks.

Objectives for Next Year

For the upcoming fiscal year, the IBI aims to achieve the following five objectives:

- to pursue the goal of understanding the living state from the perspective of Systems Biology and far-from-equilibrium thermodynamics via its theoretical and experimental research programs;
- to begin to function as a coherent whole with a full complement of seminar programs, guest speakers, institute meetings, and other aspects of a communal intellectual life;
- to outreach programs to the U of C campus and beyond, to embed itself firmly in the University, and further enhance national and international collaborative efforts;
- to commence development of an interdisciplinary curriculum in Systems Biology for courses that are expected to come on-line in the fourth year of the IBI's operation;
- to make one further faculty appointment shared between the IBI and the Department of Physics and Astronomy.

New IBI faculty is being hired through the Departments of Biological Sciences, and Physics and Astronomy. Plans for additional computing, meeting, office, and laboratory space adjacent to the present IBI facility are being developed.

The overall goal is to relate the dynamics of complex molecular networks to global cell behavior. These efforts include theory work based on chemical master equations of genetic regulatory networks to understand the stochastic dynamical behavior of integrated genetic circuits, and computational efforts to develop the capacity to infer the regulatory connections and "logic" among human genes from time static and time series gene expression data. One aim of this work is to test for the existence of a possible new general law by showing that cells are in a poised state between dynamical order and dynamical chaos that may be selected to maximize the correlated gene activities and causal, work-related events that can occur in cells.

Goals this forthcoming year focus on discovering the regulatory connections among genes in yeast and human haemopoetic cells, a well-formulated and recognized challenge in current Systems Biology. But beyond finding connections, the logics that govern how the multiple connections act in concert on one gene target will also be evaluated using novel perturbation approaches. The research team also aims to determine whether cell types are stochastic dynamical attractors. The IBI's new high throughput technology will be used in a novel fashion: screening is to be conducted not with sheer brute force, but in conjunction with predictive network-based models that will be designed, evolved, and aimed to restrict the search space and confirm "hits".

At the theoretical level, the IBI is beginning to approach the fundamental properties of the cell as an open, thermodynamical, far-from-equilibrium system. In particular, the IBI team will attempt to understand the quantum mechanics of many quantum particle systems in cells.

Research Team Members and Contributions

Team Leader
Professor Stuart Kauffman
Team Leader and Director
Author or co-author of 41 publications published or in process including ten invited lectures and conference presentations, plus one book in process
One patent filed [with Andrecut]

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Bob Este	Deputy Director	Author or co-author of 15 publications published or in process including five invited lectures and conference presentations; initiated IBI Steering Committee; initiated successful long-term industry collaborative relationship with IBM at University, Provincial, National, and International levels; initiated successful student internship[s] with MITACS and IBM; initiated long-term science policy function; Ph.D near completion
Kate Leatherbarrow	Administrative Assistant	Led and co-managed financial completion of laboratory; strategic planning with Kauffman, Lyons, Huang and Chua regarding Phases II and III; led and is now establishing complete IBI financial management system; now solving old tracking problems and eliminating any future ones; attended or coordinated three special training sessions; two conferences attended
Tarrah Lyons	Laboratory technician	Led and co-managed technical planning and completion of laboratory; strategic planning with Kauffman, Lyons, Huang and Chua regarding laboratory Phases II and III; initiated, coordinated and attended five special training; two conferences attended
Sergei Noskov	Professor, Biological Sciences	Author or co-author of eight articles published or in process; one invited conference presentation; one PDF hired; computational cluster planning and coordination for purchase; successful NSERC grant funding

Research Associates

Name	Role/Topic	Awards/Special Info
Mircea Andrecut		Author or co-author of 14 publications published or in process; one conference attended; two patents filed

PostDoctoral Fellows

Name	Role/Topic	Awards/Special Info
Andre Ribeiro		Author or co-author of 14 publications published or in process; five conferences attended; five presentations
Julia Subbotina		
Julie Thoms		Co-managed final stages of laboratory planning and setup; strategic planning with Kauffman, Lyons, Huang and Chua regarding laboratory Phases II and III; initiated laboratory and safety policy manual program; completed all new equipment training; one conference attended

Visitors

Name	Role/Topic	Awards/Special Info
Peter Grassberger	iCORE Visiting Professor	

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
U of A, and iCORE Randy Goebel	Paper co-authorship; extensive strategic planning
National Collaborations	
McGill University Leon Glass	Models of genetic regulatory networks
University of Ottawa Mads Kearns Daniel Figeys, University of Toronto Brenda Andrews	National White Paper on Systems Biology in Canada
University of Toronto Robert P. Logan [retired]	IBI Senior Fellow [end of term]; paper co-authorship
McGill University Roy Wilds	Guest Lecturer
International Collaborations	
Duke University Josh Socolar Bjorn Samuelsson	Visiting scholars-in-residence, July 2006
George Mason Universiy John Grefenstette	Visiting Scholar-in-residence, September - December, 2006
Universidad Nacional Autónoma de México Max Aldana	Visting Scholar, June 2006
Harvard Medical School Children's Hospital Sui Huang	Visting Scholar, June 2006
Columbia University Daniel Cloud	Visting Scholar, October 2006; self-supported PDF [Kauffman] January-March 2007
Tampere University of Technology Tiina Manninen	Visting Scholar, October 2006
Tampere University of Technology Antti Lehmulossa	Visting Scholar, October 2006
Istanbul Technical University Ayse Erzan	Guest Lecturer, February 2007 [co-hosted with Maya Paczuski, PHAS]

Participants	*Nature of Collaboration*
Industrial Collaborations	
IBM Canada Roger Piquette, Don Aldridge IBM Functional Genomics and Systems Biology Group, New York Gustavo Stolovitzky	Collaborative workshops with IBI, other participants; strategic planning for technical, service, student education and science policy advice/support

INTELLECTUAL PROPERTY

Patents/Author	*Title/Name*	*Status*
Andrecut and Kauffman	Network Inference Methods	Applied for this fiscal year
Andrecut	Analogue Random Coding	Applied for this fiscal year

FUNDING

Dr Stuart Kauffman received a his five year iCORE Chair award ($4.6M) and receives yearly funding from CFI ($710K) and ASRA ($1.1M).

PUBLICATIONS

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Aldana, M., Balleza, E., Kauffman, S. A., Resendis, O., "Robustness and evolvability in genetic regulatory networks," *Journal of Theoretical Biology* [2007, in press]

Aldana, M, Kauffman, S.A., "Distributed Robustness in Genetic Nets," *PNAS USA*, [submitted 2006]

Andrecut, M., Cloud, D., Kauffman, S. A., "Monte Carlo simulation of a simple gene network yields evolutionary insights not available from analytic models," *Physical Review Letters* [submitted 2007]

Andrecut, M., "New deconvolution algorithms for well test and production data analysis," *Journal of Reservoir Engineering* [2007, accepted, in press]

Andrecut, M., Kauffman, S. A., "A physical analogy of the genetic toggle switch," *Journal of Computational Biology* [2007, accepted, in press]

Andrecut, M., Kauffman, S. A., "Chaos in a discrete model of a two-gene system," *Physics Letters A* [2007, accepted, in press]

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Andrecut, M., Kauffman, S. A., "Mean field model of genetic regulatory networks," *New Journal of Physics* 8, 148 [2006]

Andrecut, M., Kauffman , S. A., "Noise in genetic toggle switch models," *Journal of Integrative Bioinformatics* 3(1), 0023 [2006] Online Journal: http://journal.imbio.de/index.php?paper_id=23

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Clayton, P., Kauffman, S.A., "Agency, Emergence and Organization," *Biology and Philosophy* 21:501-521 [2006]

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Grefenstette, J., Kauffman, S. A., "An Analysis of the Class of Gene Regulatory Functions Implied by a Biochemical Model," *Biosystems* 84:81-90 [2006]

Hanel, R., Kauffman, S. A., Thurner, S., "Towards a physics of evolution: Existence of gales of creative deconstruction in evolving technological networks" [submitted 2007]

Kauffman, S. A., Logan, Robert K., Este, Robert A., Goebel, Randy, Hobill, David, Shumelvich, Ilya, "Propagating Organization: An Enquiry", *Biology and Philosophy,* Springer Heidelberg, available on-line: http://dx.doi.org/10.1007/s10539-007-9066-x [accepted in 2007 for publication in 2008]

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Kauffman, S. A., "Systems Chemistry Sketches. Chemical Evolution: Chemical Change Across Space and Time," in Zaikowski, L. and J. M. Friedrich (Eds.), *American Chemical Society Symposium Series* [2007, in press]

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Este, Robert A., "Engineering Innovation Through the Policy Process: an 'Institute for Advanced Studies' Scenario," invited conference keynote address, *Association for Integrative Studies annual conference,* Tempe, Arizona [forthcoming, September 27-20, 2007]

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Ribeiro, Andre S., Lloyd-Price, J., Chan, W., Bratland, M., Zhu, R., Andrecut, M., Este, Robert A., Kauffman, S. A., "Unraveling the Gene Regulatory Network: Boolean Modeling and inferring, Stochastic Modeling, Spatial Modeling, Searching for attractors and Information propagation", conference at the *iCORE 2006 Banff Summit*, May 23-25, 2006, Banff, Alberta, Canada

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Ribeiro, Andre S., Lloyd-Price, J., Este, Robert A., Kauffman, S. A., "Measuring Information Propagation and Retention in Boolean Networks and its Implications to a Model of Human Organizations", *6th WSEAS Int. Conf. on Simulation, Modeling and Optimization* (SMO '06), Lisbon, Portugal, Sept. 22-24, 2006

Ribeiro, Andre S., Lloyd-Price, J., Bratland, Murray, Chan, W., Noskov, S., Charlebois, D., and Kauffman, S. A., Models of Gene Regulatory Networks, (poster), conference on *Progress in Systems Biology*, Ottawa, Nov 9-10, 2006

Serra, R., Villani, M. Graudenzia, A., Kauffman, S. A., Colaccici, A., "The influence of the topology of regulatory networks on the distribution of avalanches in gene expression data," *European Conference on Complex Systems* [submitted 2007]

Serra, R., Villani, M., Daminani, C., Graudenzia, A., Kauffman, S. A., Colaccici, A., "Interacting Random Boolean Networks," *European Conference on Complex Systems* [submitted 2007]

WORKSHOPS

Este, Robert A., "The Significance of Long-term Science Policy Considerations in the Development of Systems Biology," conference presentation, *IBI/IBM Systems Biology Workshop*, IBM Industry Solutions Lab, Hawthorne, NY, USA, Sep. 18-20 [2006]

Este, Robert A., "An Exploration of the Relationship Between the Emergence of Innovation Theory and the Policy Process," Ph.D Dissertation, Graduate Division of Educational Research, Faculty of Education, The U of C. Supervisor: Ian Winchester [forthcoming, Summer 2007]

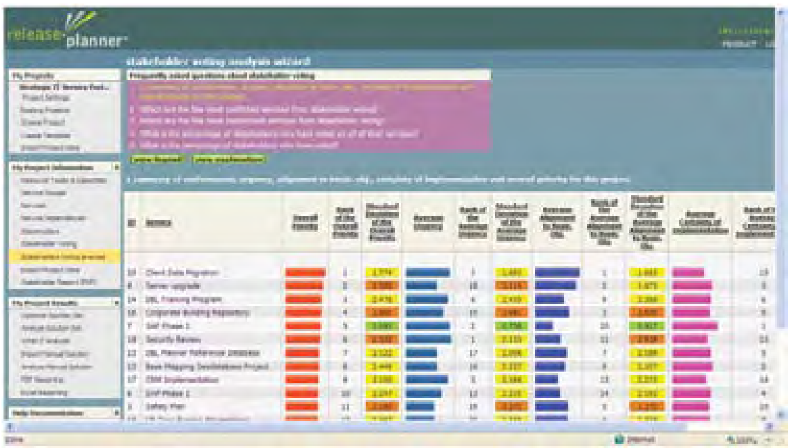
Este, Robert A., "Innovation Theory and Innovation Practice: Systems of Enhancement", invited private consultative presentation, The Ewin Marion Kauffman Foundation, Kansas City, Missouri [forthcoming, September 10-11, 2007]

Ribeiro, Andre S., Kauffman, S. A., "Modeling Strategies of Gene Regulatory Networks", *IBI/IBM Systems Biology Workshop,* Hawthorne Industry Solutions Lab, NY, USA, Sep. 18-20, 2006

Serra, R., Villani, M., Graudenzi, A., Kauffman, S. A., "On the Distribution of Small Avalanches in Random Boolean Networks," *Workshop on Computational Systems Biology*, Tampere University of Technology, Tampere, Finland [submitted 2007]

Software Engineering Decision Support

The Laboratory of Software Engineering Decision Support (LabSEDS) has continued to study foundations, methods, tools, and techniques for cognitively and computationally complex decision problems in the context of software systems.



A screenshot of ReleasePlanner™, a decision support system completed with Siemens Corporate Technology, City of Calgary, Chartwell Technologies, and ProcessPathways.

For that purpose, the LabSEDS team is following a multi-disciplinary research approach. The team has integrated concepts and approaches from software engineering, decision science, artificial intelligence, knowledge management, and computational intelligence to achieve novel results.

The team of LabSEDS consists of three professors, seven PhD, three MSc, five undergraduate students, and two research associates. Main achievements of the research team over the last year have been results in the area of intelligent support for early stage decisions in software system and product development. Research in the reporting year has mainly been done in the areas of software product and project planning (resource optimization, effort estimation, release and design decisions, software product lines), selection of component off-the-shelf software products, as well as scenario-driven solution of wicked planning problems. The research has been presented at major journals and conferences in the field and has resulted in 12 journal publications and 20 publications at conferences or workshops.

The NSERC Collaborative Research and Development project on "Intelligent support for Release and Design Decisions for Evolvable Software-Intensive Systems" has been continued. A new discovery grant application devoted to "Planning and Re-Planning of Software Releases" was approved. Further progress was achieved in the enhancement, implementation, evaluation, and pre-commercialization of the decision support system ReleasePlanner™. Collaborations and trial projects were done with Siemens Corporate Technology (Muenich), City of Calgary, Chartwell Technologies (Calgary), and ProcessPathways (Calgary). The commercialization effort was supported by the NSERC funding as part of the program "Idea to Innovation (I2I)" Phase 2a. A new NSERC CRD initiative was prepared called "An Electronic Process and Decision Guide for the Design and Analysis of IT Services".

Research Program Overview

The idea of going beyond all the former efforts devoted to modeling, measurement, simulation, experimentation and knowledge management in software and system development towards software engineering decision support has created substantial interest over the last years. Workshops, conference sessions, panel discussions and an increasing number of publications devoted to this subject matter are an indicator of this tendency.

The paradigm of hybrid intelligence suggests evolutionary problem formalization and the application of computationally efficient algorithms for approximate solution. The emphasis of LabSEDS's research was on specific aspects of this paradigm in specific domains of release and design decisions. The results of this research have led to the further enhancement, implementation, evaluation, and pre-commercialization of the decision support system ReleasePlanner™.

Main achievements of the research team over the last year have been results in the area of intelligent support for early stage decisions in software system and product development. Research in the reporting year has mainly been done in the areas of software product and project planning (resource optimization, effort estimation, release and design decisions, software product lines), selection of Component-Off-The-Shelf (COTS) software products, as well as scenario-driven solution of wicked planning problems.

Advancing Software Engineering Decision Support Methodology

The paradigm of hybrid intelligence was further developed and refined. The advantage of the human intelligence based approach is that it is able to better handle soft and implicit objectives and constraints. The advantage of computer-based approach is exactly where the human based approach fails: to cover a large portion of the solutions space. The LabSEDS team hybrid approach is designed to combine the strength of both human and computational intelligence. The methodology of software engineering decision support has been further enhanced by making synergy between decision-making and the contributions of simulation, reasoning, explanation and different optimization techniques (genetic algorithms, linear programming, integer programming, branch and bound, heuristics).

Uncertainty is an important issue in decision support and is one of its key characteristics in software engineering. The LabSEDS team is particularly interested in decision problems that are not completely understood, have a large solution space and/or uncertain data such as planning problems. LabSEDS has integrated the diversification principle into the evolutionary problem solving approach EVOVLE*. It is intended to facilitate the participation of human's expertise into the decision process without explicitly integrating it into formal models.

Intelligent Support for Release and Design Decisions

After designing and appling the paradigm of hybrid intelligence to the wicked problem of release planning, the LabSEDS team has transferred these principles to more classes of decision problems:

- selecting COTS products based on optimized resolution of mismatches
- deciding about release time in dependence of quality criteria
- integrating release and design decision in incremental product development.

Decision Support System Development and Empirical Validation

The functionality of the ReleasePlanner™ decision support system was enhanced by allowing multi-criteria based optimization, by providing cumulative voting on a flexible number of self-defined prioritization criteria, by offering the possibility of cumulative resource allocation through across release implementation of objects, supporting to run comprehensive what-if analysis, and by supporting comprehensive pre-analysis of project data and stakeholder priorities. Successful trial projects for the ReleasePlanner™ decision support systems were completed with Siemens Corporate Technology (Munich), City of Calgary (DBA), Chartwell Technologies (Calgary), and ProcessPathways (Calgary).

Research Projects

Resource and Release Optimization

Optimized Resource Allocation for Software Release Planning

Release planning for incremental software development assigns features to releases such that technical, resource, risk, and budget constraints are met. The LabSEDS team assumes a given pool of human resources with different degrees of productivity to perform different types of tasks. In the context of release planning, the question studied in this research is how to allocate these resources to the tasks of implementing the features such that the value gained from the released features is maximized. LabSEDS has named this problem Resource Allocation for Software Release Planning (RASORP). The NP-complete knapsack problem is shown to be a special case of RASORP.

LabSEDS proposes a two-phased optimization approach called OPTIMIZERASORP that combines the strength of two existing solution methods. Phase 1 applies integer linear programming to a relaxed version of the full problem. Phase 2 uses genetic programming in a reduced search space to generate operational plans to schedule all the tasks and to assign them to the available human resources. The hybrid solution method allows the LabSEDS team to generate release plan and resource allocation solutions with a proven degree of optimality and to reduce the overall computational effort needed for generating release plans by reducing the search space in Phase 2.

The industrial applicability of the approach is primarily directed towards mature organizations having systematic development and measurement processes in place. The method is initially evaluated for a series of 600 randomly generated problems with varying problem parameters. The expected practical benefit of the planning method is to provide release plan solutions that achieve a better overall business by better allocation of resources.

A Systematic Approach for Solving the Wicked Problem of Software Release Planning

Release planning is known to be a cognitively and computationally difficult problem. Different kinds of uncertainties make it hard to formulate and solve the problem. The LabSEDS team's solution approach called EVOLVE+ mitigates these difficulties by:

- an evolutionary problem solving method combining rigorous solution methods to solve the actual formalization of the problem combined with the interactive involvement of human experts
- offering a portfolio of diversified and qualified solutions at each iteration of the solution process
- the application of a multi-criteria decision aid method (ELECTRE IS) to assist the selection of the final solution from the set of qualified solutions

iCORE

Team Leader:
iCORE Professor
Dr Guenther Ruhe

Location:
University of Calgary

Department:
Electrical and Computer Engineering and Computer Science

Team Members: 26

Website:
www.seng-decisionsupport.ucalgary.ca/

Members of the LabSEDS team (left to right): PhD Candidate Jingzhou Li, Team Leader Professor Guenther Ruhe, and PhD Graduate Ahmed Al-Emran

At the final stage of the process, an out-performance relation is created among the final set of qualified candidate solutions to address existing soft constraints or objectives. The proposed method and results are not limited to software release planning, but can be adapted to a wider class of wicked planning problems.

A System Dynamics Simulation Model for Analyzing the Stability of Software Release Plans

Release planning for incremental software development assigns features to releases such that most important technical, resource, risk and budget constraints are met. This research is an element of a three-staged procedure, in addition to an existing method for:

- strategic release planning that maps requirements to subsequent releases
- more fine-grained planning that defines resource allocations for each individual release
- stability analysis, which analyzes fine-grained plans of individual releases with regards to their sensitivity to planning errors

Planning errors can relate to alterations in expected personnel availability and productivity, feature and task specific work volume, and degree of task dependency. The focus of this research is on stability analysis of proposed release plans. A simulation model called 'Release Plan Simulator, Version 1' was developed.

Effort Estimation by Analogy

Impact Analysis of Missing Values on the Prediction Accuracy of Analogy-based Software Effort Estimation Method AQUA

Effort estimation by analogy (EBA) is often confronted with missing values. LabSEDS former analogy-based method AQUA is able to tolerate missing values in the data set, but it is unclear how the percentage of missing values impacts the prediction accuracy and if there is an upper bound for how big this percentage might become in order to guarantee the applicability of AQUA. Impact analysis is conducted for seven data sets being of different size and having different initial percentages of missing values. that the following were the major results:

- it was confirmed that the intuition that the more missing values, the poorer the prediction accuracy of AQUA;
- there is a quadratic dependency between the prediction accuracy and the percentage of missing values;
- the upper limit of missing values for the applicability of AQUA is determined as 40%

These results are obtained in the context of AQUA. Further analysis is necessary for other ways of applying EBA, such as using different similarity measures or analogy adaptation methods from those used in AQUA.

Analysis of Attribute Weighting Heuristics for Analogy-based Software Effort Estimation Method AQUA+

For this research LabSEDS understands EBA as a meta-method, which needs to be instantiated and customized at different stages and decision points regarding a specific context.

This research proposes a decision-centric process model for EBA by generalizing the existing EBA methods. Typical decision-making problems are identified at different stages of the process as part of the model. Some existing solution alternatives of the decision-making problems are then studied. The results of the decision support analysis can be used for better understanding of EBA related techniques and for providing guidelines for implementation and customization of general EBA.

Software Effort Estimation by Analogy Using Attribute Selection Based on Rough Set Analysis

In order for LabSEDS to improve the estimation accuracy of the former proposed EBA method AQUA, which supports data sets that have non-quantitative and missing values, an attribute weighting method using rough set analysis is proposed in this research. AQUA is thus extended to AQUA+ by incorporating the proposed attribute weighting and selection method. Better prediction accuracy was obtained by AQUA+ compared to AQUA for five data sets. The proposed method for attribute weighting and selection is effective in that it supports data sets that have non-quantitative and missing values; it supports attribute selection as well as weighting; and it helps AQUA+ to produce better performance.

Combined Release and Design Decisions for Evolving Systems

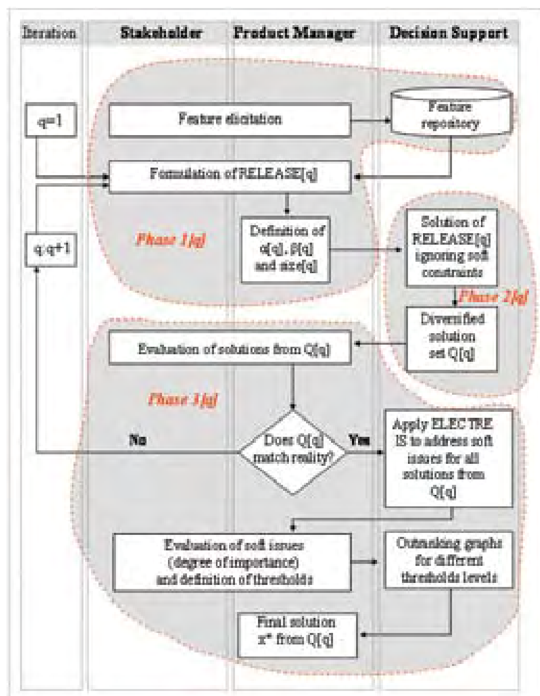
Evaluating the Modifiability of Architectural Designs using Expert Judgment

This research presents an architectural design evaluation technique called EBEAM (Expert-Based Evaluation of Architecture for Modifiability) that assists experts in articulating their knowledge of architectural designs and expressing the knowledge in measurable terms. The EBEAM supports the evaluation of different architectural design versions for modifiability. In addition, the EBEAM supports relative comparison between these design versions and the target design. The EBEAM is developed as a generalized technique that can be reused for evaluating other architectural design attributes.

Bi-Objective Release Planning for Evolving Software Systems

The release planning (RP) problem can be investigated from two dimensions – what to release and when to release. LabSEDS investigated the "what" to release decision in terms of which new features or change requests should be assigned and implemented in which releases of a software system. RP for evolving systems is challenging, because the new features might require changes to the existing system. A major drawback of existing RP methods is that, they do not consider the existing systems in making RP decisions.

In this research, the LabSEDS team presents a technique to detect coupling between features based on relatedness of the components that would implement the features. The components implementing the features are derived from change impact analysis. The team integrates the results from feature coupling into a RP strategy that encourages the assignment of highly coupled features in the same release. This helps to avoid haphazard implementation of related features.



Release Planning for Evolving Systems

The researcher's Bi-Objective Release Planning for Evolving Systems (BORPES) is aimed at optimizing the value of release plans from both the business perspectives and the implementation perspectives. This research presents BORPES in detail and reports on a case study that investigates the efficacy of the proposed approach. The bi-objective optimization offers a set of Pareto-optimal solutions.

Optimized Mismatch Handling for the Selection of COTS

MiHOS: An Approach to Support Handling the Mismatches between System Requirements and COTS

In the process of selecting COTS products, it is inevitable to encounter mismatches between system requirements and COTS products. These mismatches occur as a result of an excess or shortage of the COTS attributes. This research proposes a decision support approach, called Mismatch Handling for COTS Selection (MiHOS), which aims at addressing COTS mismatches during and after the selection process. MiHOS can be integrated with existing COTS selection methods at two points:

- for evaluating COTS candidates: MiHOS estimates the anticipated fitness of the candidates if their mismatches are resolved
- mismatch resolution after selecting a COTS product: MiHOS suggests alternative plans for resolving the most appropriate mismatches using suitable actions, such that the most important risk, technical, and resource constraints are met.

Sensitivity Analysis in the Process of COTS Mismatch Handling

In Mismatch Handling for COTS Selection (MiHOS), several input parameters need to be estimated such as the resource constraints, the level of mismatches, and the amount of resources required to resolve them. These estimations are subject to uncertainty, which may threat the validity of the results. In this research, LabSEDS proposed an approach called Sensitivity Analysis for MiHOS (MiHOS-SA) that aims at helping decision makers gain insights about the impact of input uncertainties on the validity of MiHOS' results, and thus improve the effectiveness of related decisions. MiHOS-SA draws on existing sensitivity analysis techniques such as Monte Carlo analysis to address the problem.

Method for Customer Oriented Product Evolution

This research is related to release planning for software product lines (RP-PL). Initial investigation identified the differences between RP-PL and release planning for traditional software product development. LabSEDS has been working on the development of a decision support approach called Customer Oriented Product Evolution (COPE) for evolving a single software product into a family of related products using stakeholders' input. COPE is an instantiation of hybrid intelligence approach EVOLVE*. Based on the analysis of customers' priorities on potential product features, COPE identifies groups of customers having similar product expectations. This information is combined with the evaluation of the business and architectural impact of defining various products as suggested by the clusters of customers.

Explanation and Reasoning for Computationally and Cognitively Complex Planning Problems

Knowledge-based Decision Support for Wicked Planning

This research is concerned with providing knowledge-based decision support to improve decision-making in release planning. As the fundamental basis of this research, a family of four evolving experiments has been conducted to understand the knowledge needs of the decision makers in release planning. In order to provide the knowledge-based decision support system, a four-layer knowledge base has been designed. A set of methodologies has been proposed to build such knowledge using different knowledge extraction techniques from various knowledge sources.

Literature surveys and empirical studies have been used to elicit the generic knowledge. Rough set analysis, as a type of machine learning technique, along with more empirical studies are used to build specific knowledge. A goal-oriented dialogue approach has also been proposed to make the knowledge-based decision support efficient and effective. It aims to facilitate the communication between the knowledge-based decision support system and the decision makers in order to provide necessary knowledge support at appropriate time. A question-answer scheme has been designed to carry out such dialogues.

A Dialogue Approach for Solving Wicked Planning Problems

In this research the LabSEDS team is considering an interactive and explanation based dialogue approach to complex and 'wicked' planning problems. Wicked problems are essentially imprecisely formulated problems having no clearly defined goals and constraints. The dialogue approach is aimed at reducing the problem complexity during interaction with the human expert. The comparison of the actual and the ideal plan looks at aspects of interest for the stakeholder such as resource consumptions or structural properties of the plan. The proposed approach is generic and was applied and customized to three classes of wicked problems: release planning, investment planning, and urban planning.

Objectives for Next Year

Overview

Main objective for the next year is fundamental and applied research in the areas of decision support for

- planning and re-planning of software releases
- methodology for combined release, design and resource decisions
- process and decision guide for the analysis and design of IT Services
- intelligent decision support system for release, design and resource decisions.

The team's main goal is to maintain and extend a leading position in the area of intelligent decision support for the design of software systems. The proposed multi-disciplinary research topic is integrating concepts and approaches from the software engineering, system science, decision science, optimization, simulation, empirical research, artificial intelligence, and knowledge management fields.

Decision support for planning and re-planning of software releases

Resource-centric planning is related to project management and combines aspects of scheduling. Resource-centric planning of features looks into all the tasks necessary to implement features. Dependencies between the tasks and features are considered as well as resource constraints. For fixed release dates, the issue becomes one of maximizing a utility function defined on the features to be provided.

In the case of planning across projects, the problem is to perform individual release planning for different products and to provide synchronization of the individual product plans. Although there is increasing interest and a number of substantial research results in this area, the question of actually planning releases is either ignored or handled informally in an ad hoc manner.

Re-planning of releases requires a method that can react in a flexible manner to changes in the problem parameters or other settings. There is also no significant method for release planning allowing hierarchical structuring of objects and non-additive objective and/or resource functions. This work ties in with previous LabSEDS work done on business value-related release planning and with external research on value-based software engineering.

The objective for non-linear planning is to extend existing methodology based on EVOLVE* towards the more general case allowing hierarchical dependencies between planning objects as well as non-additive characteristics of both the objective and the resource consumption function(s).

Methodology for Combined Release, Design and Resource Decisions

Both rational and intuitive decision-making are contributing to release and resource decisions in the design and implementation of evolving software systems. For the rational part of design and resource decision-making, problem specific meta-heuristics such as genetic algorithms, tabu-search, simulated annealing, greedy randomized adaptive search procedures, and Bayesian belief networks, are studied for their capability to generate solution alternatives. Their flexibility potentially allows solving even complex questions including time slicing, team structure, and robustness of resource assignments.

Here, the LabSEDS team extends the existing AQUA framework by a process-centric support system offering the different options at the different stages of the process and giving recommendations which option appears to be best in which situation.

A Process and Decision Guide for Analysis and Design of IT Services

Process Pathways Inc. (PPI) provides software IT services offered to its customer organizations in the domain of higher education, health science and research administration. These services facilitate the business processes of the organization. As with requirements elicitation in general, understanding of the customer service needs is as crucial as it is difficult to ascertain. The fundamental research question is how to qualify this process to the domain of service needs elicitation. As there are time and resource constraints for providing these services, the service portfolio offered by the software needs to be optimized in terms of fulfilling the customers' most important needs in a timely manner.

The main goal of this three-year project is to develop a methodology and a prototype decision support system called the Electronic Process and Decision Guide (EPDG). The EPDG is a web-based intranet solution guiding processes and their related decisions in the early stages of defining and planning IT services. Another goal is to increase the likelihood that services will meet customers' expectations and that the services can be provided with the resources available. The resulting EPDG will be applied during the pre-development stages of the IT service development.

By careful modeling, analysis and optimization of processes and decisions, the key results of the proposed research are expected to be:

- Method for process-centric decision support for customer needs analysis and resource-aware design of IT services.
- Prototype for an EPDG-supporting understanding, communication, and analysis of processes and decisions.
- Empirical evaluation and packaging of results: In vivo (PPI and two trial projects with lead customers) and in vitro experiments at U of C and American University of Sharjah (Dr Eberlein).

Development and Validation of an Intelligent Support System for Release and Design Decisions

The paradigm of decision support provides tools and techniques that help decision makers to make more informed decisions, to improve transparency, and to achieve better results from given resource investments. Operational prioritization is a refinement of strategic planning at a more detailed level. In addition to assigning tasks to time-intervals, the issue is to prioritize the tasks to effectively allocate sparse resources necessary to perform them.

All the research in this area includes comprehensive studies to prove the validity and the applicability of the methods and techniques able to allocate human and non-human resources to tasks belonging to the features to be planned.

Research Team Members and Contributions

Team Leader
Professor Guenther Ruhe
Director of LabSEDS

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Dr Armin Eberlein		Department of Electrical and Computer Engineering, U of C
Dr Michael Richter		Department of Computer Science, U of C
Dr Zhigang Wang	Visitor (Post-doc)	Department of Computer and Mathematics, Human University

Research Associates

Name	Role/Topic	Awards/Special Info
Dr An Ngo-The	Research Associate	Alberta Ingenuity Industrial Associate
Kornelia Streb	Research Associate	

PhD Candidates

Name	Role/Topic	Awards/Special Info
Ahmed Al-Emran	Dynamic re-planning for software releases	Special Issue for Best Papers at ICSP 2006 and ICSP 2007
Gengshen Du	Explanation and reasoning for computationally and cognitively complex planning problems	Department of Computer Science Research Award (U of C), NSERC CGS-D Scholarship, iCORE Graduate Student Scholarship
Jingzhou Li	Effort estimation by analogy	
Jim McElroy	Non-linear and time-dependent product release planning	Department of Computer Science Research Award (U of C)
Abdallah Mohamed	Decision support for selecting COTS software products	Special Issue for Best Paper at ICC BSS 2007
Omolade Saliu	Supporting software release planning decisions for evolving systems	NSERC CGS-D Scholarship, iCORE Graduate Student Scholarship
Irfan Ullah	Customer oriented product evolution	Department of Computer Science Research Award (U of C)

MSc Candidates

Name	Role/Topic	Awards/Special Info
Thamer Al Bourae	Light-weight method for re-planning of software releases	Defense in August 2007
James Ambler	Planning of product releases	
Kendra Hamilton	(Course-based)	
Fazlul Chowdury	(Course-based)	

Undergraduate Students		
Name	**Role/Topic**	**Awards/Special Info**
Eric Bauld		
Martin Echtner		
Johannes Fischer	Exchange student from University Mannheim, Germany	
David Goodladd		
Mark Przepiora		NSERC USRA 2006, 2007

GRADUATES

Name	*Research Topic*	*Awards*
Abdallah Mohamed	Decision Support for Selecting COTS Software Products Based on Comprehensive Mismatch Handling (PhD Thesis, April 2007)	Best Presentation Award, Faculty of Engineering Annual Grad Conference (U of C)
PhD Graduates		
Ahmed Al-Emran	Dynamic Re-planning of Software Releases (December 2006)	iCORE International Graduate Student Scholarship
Pankaj Bhawnani	An Integrated Method for “When-to-release” Decisions based on Reliability (July 2006)	iCORE International Graduate Student Scholarship
MSc Graduates		
Yongxue Cai	Course-based (June 2006)	

COLLABORATIONS

Participants	Nature of Collaboration
Fraunhoder IESE and Fraunhofer-Center Maryland	Omolade Saliu was invited as a visiting research student to the Fraunhofer Center for Experimental Software Engineering (FC-MD), Maryland, USA, from July 3 - August 2, 2006. Joint research was devoted to architectural design evaluation to perform modifiability evaluation of architectural design candidates derived from a real-life project. The results were prepared in a research that has been submitted for publication
Industrial Collaborations	
Siemens Corporate Technology	Technology transfer case study with Siemens Corporate Technology, Systems and Engineering in Munich, Germany in which intelligent decision support was provided for road mapping of the services provided To provide roadmaps for optimal success in order to achieve maximum market competitiveness and customer satisfaction while simultaneously balancing the resources, business rules, risks, constraints and priorities of different stakeholders and customers around the world. The case study investigated how ReleasePlanner™ was used to provide decision support
City of Calgary	A pilot study to test the effectiveness of ReleasePlanner within The City of Calgary environment. Analysis of the results from this project suggests that ReleasePlanner exceeded the objectives to which it was tasked • ReleasePlanner was used by DBA to improve how they prioritize, estimate and communicate their strategic projects • The DBA Management Team used ReleasePlanner to vote on 47 strategic projects • ReleasePlanner identified resource constraints for the DBA Management Team and IT to be resolved • The established systematic planning process allowed DBA to re-plan road-maps when new projects were added • The total time required from each individual manager was reduced by a third (approximately) • The defined priorities had a much stronger tie to available resources
Chartwell Technology Drs Far, Maurer, Ruhe (PI) and Walker	The NSERC CRD project "Intelligent Support for Release and Design Decisions of Evolvable Software-Intensive Systems" involves different tools have been developed based on research on methods and techniques devoted to release planning and design, which are applicable at different stages of the planning life-cycle. All these methods and techniques are aimed at providing support for making better decisions in the respective context
Process Pathways Inc.	Process Pathways Inc. is a work systems design and automation company focused on IT services for improving administrative workflows primarily in the Research, Higher Education, and Health Sciences sectors. The collaboration between Process Pathways Inc. and LabSEDS was established in 2005 and has grown since that time. Exchange of expertise (presentations of MacDonald to students as part of software engineering courses, presentations by Ruhe to PPI project teams) and experience in technology transfer (trial applications of the release planning technology developed at LabSEDS for PPI) has matured into this proposal. Recently, a joint proposal for Collaborative Research and Development has been prepared and submitted to NSERC for funding support

INTELLECTUAL PROPERTY

The ReleasePlanner™ technology builds on a web-based approach; it has also been designed and developed to be easily customizable for the different types of users and different application scenarios. United States and Canada patent protection is pending. The research will also produce additional, valuable intellectual property such as the know-how generated through broad-ranging applications of the technology.

FUNDING

Dr Ruhe had an iCORE Professor award of $1.75 M over five years, which has expired.

PUBLICATIONS

JOURNAL PUBLICATIONS

A. Ngo-The, G. Ruhe: "Optimized Resource Allocation for Software Release Planning", Submitted to IEEE Transactions on Software Engineering

O. Saliu, M. Lindvall, C. Ackermann, and G. Ruhe: "Evaluating the Modifiability of Architectural Designs using Expert Judgment", Submitted to IEEE Transactions on Software Engineering

J. Li, G. Ruhe: "Analysis of Attribute Weighting Heuristics for Analogy-based Software Effort Estimation Method AQUA+", Submitted to Empirical Software Engineering (Best papers ISESE'06)

J. Li, G. Ruhe: "Software Effort Estimation by Analogy Using Attribute Weighting Based on Rough Sets", Appears in Software Engineering and Knowledge Engineering

J. Li, G. Ruhe: "Comments on 'COCOMO-Based Effort Estimation for Iterative and Incremental Software Development'", by Oddur Benediktsson, et al., Submitted to Software Quality Journal

D. Pfahl, A. Al-Emran, and G. Ruhe: "A System Dynamics Simulation Model for Analyzing the Stability of Software Release Plans", Appears in Journal Software Process Improvement and Practice (Best papers SPW/ProSim 06)

A. Mohamed, G. Ruhe, A. Eberlein: "MiHOS – An Approach to Support Handling Mismatches between Requirements and COTS Products", Appears in Requirements Engineering Journal, see http://dx.doi.org/10.1007/s00766-007-0041-5

J. Li, G. Ruhe, A. Al-Emran, M. M. Richter: "A Flexible Method for Effort Estimation by Analogy", Empirical Software Engineering, Volume 12(2007), No 1, pp 65-106

Y. Wang, G. Ruhe: "The Cognitive Process of Decision Making", Cognitive Informatics and Natural Intelligence, 1(2), April-June 2007, pp 73-85

A. Ngo-The., G. Ruhe: "A Systematic Approach for Solving the Wicked Problem of Software Release Planning", Appears in: Soft Computing 2007.

G. Du, M. M. Richter, G. Ruhe: "An Explanation Oriented Dialogue Approach and its Application to Wicked Planning Problems", Computing and Informatics, Vol 25 (2006), pp 223-249

J. Momoh, G. Ruhe: Release planning process improvement - an industrial case study, Software Process: Improvement and Practice Volume 11, Issue 3, 2006, pp 295-307

CONFERENCES AND WORKSHOPS

A. Al-Emran, K. Khosrovian, D. Pfahl, and G. Ruhe: "Simulation-Based Uncertainty Analysis for Planning Parameters in Operational Product Management", accepted for IDPT' 2007

A. Al-Emran, D. Pfahl, G. Ruhe, "DynaReP: A Discrete Event Simulation Model for Re-planning of Software Releases", Conference on Software Processes ICSP'2006, LNCS 4470-0246

J. Li, A. Al-Emran, G. Ruhe: "Impact Analysis of Missing Values on the Prediction Accuracy of Analogy-based Software Effort Estimation Method AQUA". Accepted for Symposium on Empirical Software Engineering and Measurement (ESEM) 2007

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Applied Bioinformatics

The goal of the iCORE/Sun Microsystems Chair in Applied Bioinformatics and the Applied Bioinformatics laboratory is to build the next generation of bioinformatics tools for data exploration, information integration, and advanced 4D visualization.

The diverse set of large-scale data currently produced by genome research efforts needs new data integration approaches to reveal their full potential. At the same time, the laboratory also seeks innovative solutions to several other underlying technical challenges: high degree of usability through fully visual and fully portable interaction; scalability of the visualization through the use of semantic zoom and level-of-detail management; a number of security provisions; and platform-independence.

The Applied Bioinformatics laboratory is working in two general directions: creating the computational environment for next-generation bioinformatics in collaboration with computer scientists, mathematicians, and industrial partners; and creating models of biological systems in collaboration with clinical and wet-lab researchers. The users of the newly developed tools include life science researchers, both at the University of Calgary (U of C) and other institutions, as well as students and trainees whose work involves biological data exploration.

Research Program Overview

The Applied Bioinformatics laboratory has two major research themes, which often overlap: the development of 2D bioinformatics tools and the development of 4D bioinformatics tools.

The 2D bioinformatics research is focused on the integration of tools for the analysis and annotation of genomic data, including partial and complete genomes, as well as enhanced sequence tags and protein sequences. The major tools that have been developed thus far are called MAGPIE and Bluejay.

The Bluejay system was upgraded from Java 1.4 to Java 1.5 to enable the use of the latest language features. Several improvements were made to enhance the robustness of this new version: full or partial legend display; robust data control when loading a genome, microarray data, and multiple genomes; clearer splash screen and more relevant initial message screen upon launching Bluejay; context-dependent enabling/disabling of "Comparison" menu items; more stable cross-links between MAGPIE and Bluejay; and accurate canvas refocus on some semantic zoom operations.

The newest line of development in Bluejay is the text view mode capability (Figure 1). This capability provides an extreme close up view of a genome sequence and allows the user to examine a relatively short subsequence of individual nucleotides at a time. To make this view mode more useful, the existing waypoint functionalities were extended so that a waypoint can be set on a whole gene and also on any base position.

In the text view mode, the user can also select a contiguous set of nucleotides, enabling operations such as expanding or contracting the boundaries of an existing gene. This feature will prove useful because many genes are currently annotated inaccurately or new information may become available after the initial annotation of the sequence. Bluejay now offers an intuitive method of selecting a new text region within a gene to contract the gene bounds or selecting a chunk of contiguous bases adjacent to a gene to expand the gene bounds.

MOBY-S is an important bioinformatics standard for semantic Web Services, and the Applied Bioinformatics laboratory has played an important role in its development. MOBY-S is finally reaching a version 1.0 status (manuscript submitted), based on the coordinated efforts of developers in more than a dozen countries. Bluejay was one of the first pieces of client software supporting the MOBY-S protocol, and in the last year, this work has grown into the development of a highly interactive, standalone MOBY-S client called "Seahawk". Seahawk is open source software, and components of it have been integrated into software projects at other institutions. A manuscript for Seahawk is currently in the final stages of review.

The Applied Bioinformatics laboratory is also hosting a growing number of MOBY services for public use. A framework for MOBY service provision, developed in the Applied Bioinformatics laboratory, has been published. The exemplary service used in this publication is one that was developed in collaboration with the industrial partner SemBioSys Genetics Inc., Calgary.

The team has also developed new software for various types of microarray analysis, in collaboration with external researchers. The Applied Bioinformatics laboratory published the results of a 70-base oligomer microarray study elucidating the transcript profile of the *Sulfolobus spindle-shaped virus 1*, and a second manuscript on the UV-light response of the *Sulfolobus* host has been submitted. A second microarray analysis collaboration involves the processing of massive numbers of Affymetrix microarrays (a.k.a. GeneChips), with a new software package dubbed "Merlin". Merlin helps overcome technical limitations of large-scale GeneChip analysis by parallelizing and improving established statistical software. Merlin is being used by the University of Alberta (U of A) kidney transplant team as part of a new technique in a clinical setting to identify transplant rejection type of transplanted kidneys early, rather than by pathology alone.

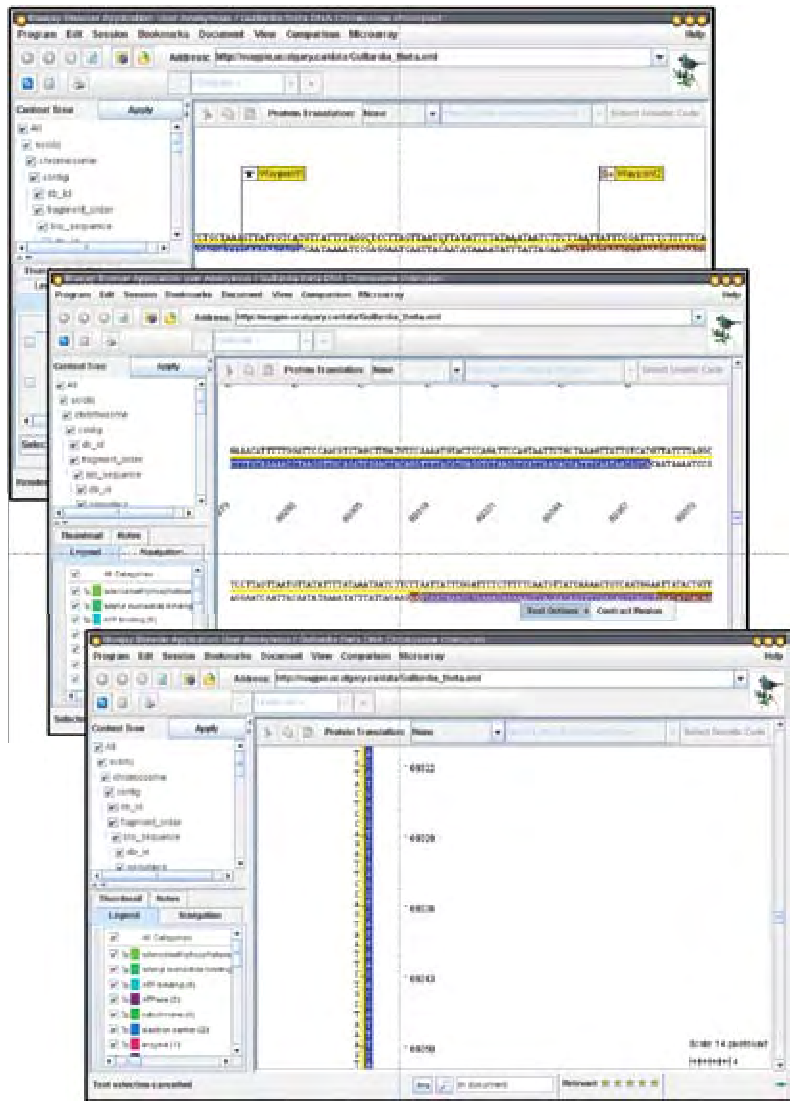

Figure 1 *Three kinds of text views available in Bluejay: (top to bottom) horizontal sequential, horizontal breakable, and vertical sequential. The first view shows two waypoints, each on a different gene, set for a base position. The user has set a unique icon for each waypoint to easily tell one from another. The second view shows selected base pairs and the available text operation.*

The second thrust of the iCORE/Sun Microsystems Chair's research is focused on the development of novel tools for 4D bioinformatics. Over the last year development progressed along several lines:

- Hardware: The Applied Bioinformatics laboratory has been using their mobile virtual-reality solution, called VRCO Full Circle™, in both public museums and industry exhibits. The system consists of a laptop, two digital data projectors with polarized filters, and a silver-coated screen to achieve the (passive) stereo effect. Using three-dimensional visualization and audio narration, the exhibits illustrate the importance of genomics, proteomics and pharmaceutical experiments, and their relationship to the anatomical changes in a human body. These activities complement the team's on-going usage of the Java-enabled CAVE exploration environment, which remains the main test bed for biomedical studies in virtual reality.
- Middleware: The research team has improved their middleware layer JABIRU through additional functionality, such as a mouse emulator. As a result, mouse interactions are now available through a regular CAVE 3D joystick wand device, which opens the way of using common Java 2D Swing GUI objects without leaving the CAVE immersion.
- Medical Atlas: The Applied Bioinformatics team is in the final stages of developing a 3D digital atlas, of the anatomy of an adult male human. The model is equipped with data-integration features for biochemical and imaging data types. The system uses virtual reality techniques and standard ontology support for the integration of molecular datasets onto the anatomical context of a human body. The notable advantage of the anatomical components of the atlas is that they can be cross-referenced with other biomedical data sources via standard data-processing interfaces. The atlas then can serve as a common context for the explorations of many bioinformatics and medical datasets. Thanks to Java portability, the explorations may be performed in a virtual reality environment or on a common desktop.
- Applications: Through Genome Canada-funded collaborative work, the Applied Bioinformatics team is now using this virtual body for pilot studies on metabolomics, pharmacokinetics, and multiple sclerosis. For example, the team began the visualization using the pharmacodynamics example of aspirin. This allows the digestion of aspirin, its breakage into biochemical products, and their transfer between the relevant body systems and fluids to be traced.

The Applied Bioinformatics' hardware architecture was upgraded in January 2006 and now features the first four-tiered data storage system in an academic lab in

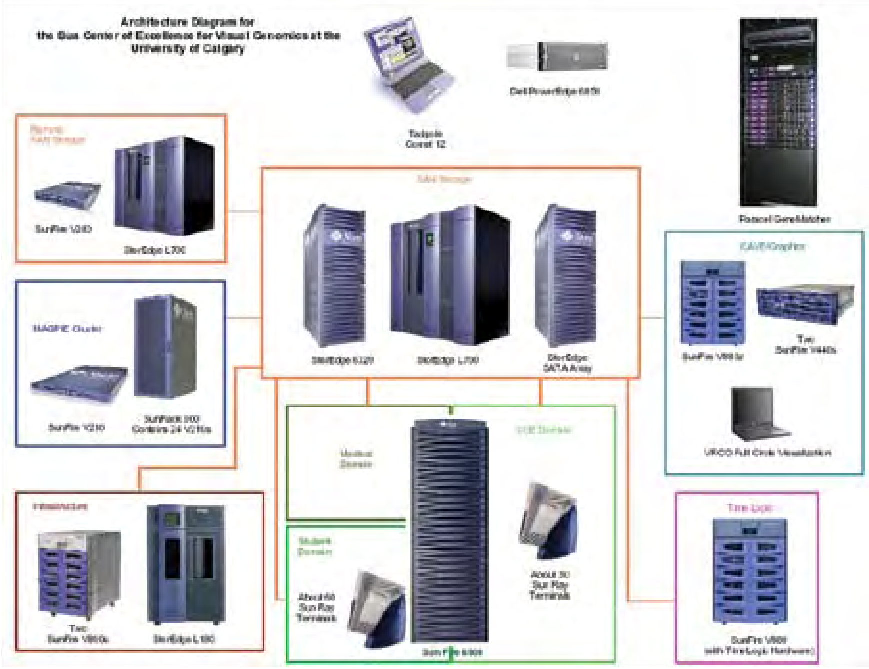

Figure 2 *Computer hardware configuration at the Sun Center of Excellence for Visual Genomics, as of January 2007 (Courtesy Ariane Mather).*

Canada (Figure 2). The total storage capacity at the Sun Center of Excellence for Visual Genomics (COE) now exceeds one Petabyte (over a thousand Terabytes).

Research Projects

The laboratory has created a 4D atlas-based system prototype of the adult male human body for the exploration of heterogeneous biomedical data. This work provides a solid foundation for applying the team's experimental technology to collaborative projects. The work of the laboratory builds on the strengths of an existing project that created a 3D atlas of human anatomy suitable for mapping genomic and medical information. The laboratory also provides scientific leadership of the overall 4D Initiative for other co-investigators. In particular, the Applied Bioinformatics team developed a unified research strategy for the duration of the project that details patterns of data exchange, workflow co-ordination, and mutual relationships between all collaborators.

3D Anatomical Atlases

The 3D Human Body Atlas is in the final stages of development. The internal organs of a human (male) body are represented as Java 3D objects and are in a hierarchy that follows the semantic structure of *Terminologia Anatomica* (TA), an international standard for the description of the human anatomical terminology. Anatomy experts examined all 3D objects in the CAVE virtual-reality environment to ensure anatomical correctness. The creation of the 3D Atlas was done in collaboration with Kasterstene Inc. of Red Deer, Alberta.

A 3D Mouse Atlas is in the early stages of design. This work is done in collaboration with the 3D Morphometrics laboratory at the Faculty of Medicine, U of C, led by Dr. Benedikt Hallgrimsson. The Applied Bioinformatics team will focus on visualizing these models, morphing and animating their relationships. 3D scans will help create full visual representation of mouse development.

Data Mapping Mechanism

The Applied Bioinformatics team has integrated a powerful, free, and highly regarded Visualization Toolkit (VTK) suite for image processing. The VTK operations include image segmentation, thresholding, surface extraction, polygonal decimation, and a broad range of other tools.

The team has developed a prototype visualization component for biochemical data mapping using pharmacodynamics data supplied by the Metabolomics Toolbox project, a Genome Canada project led by Dr. David Wishart at the U of A. This is an example of a successful extension of the team's software system to support new data types. The team began the visualization using the pharmacodynamics example of aspirin. After the completion of the aspirin test case, the plan is to advance to other pharmacokinetic and pharmacodynamic models involving more complex drugs.

Visual Interactions

The team adopted 2D GUI interactions into the CAVE virtual reality environment. The Applied Bioinformatics team has created a 3D wand mode that controls the mouse movement and generates mouse events from within the immersive environment. As a result, mouse interactions are now available through a regular CAVE 3D joystick wand device, which opens the way of using common Java 2D Swing GUI objects without leaving the CAVE immersion. Many 3D applications contain 2D GUI elements such as menus, buttons, check boxes, and radio buttons and therefore require mouse-based interactions, which this work has now made available.

The team held several design sessions with the collaborators from the Genome Canada projects to jointly detail visual interactions required by biomedical researchers.

The Applied Bioinformatics team made substantial progress in the accuracy of medical image mapping onto the 3D Human Body Atlas. Since the original release of the 4D software prototype in February 2006, the team is able to guide the 3D image registration by aligning the generic 3D models from the 3D Human Body Atlas on one hand, and landmarks extracted from real medical images on the other hand (see Figure 3). These are the first and very promising steps towards 3D registration of many medical imaging models and the Atlas for a variety of applications.

Figure 3 *The elements of the immersive working in the CAVE on the 3D image registration, outlining the patient's skull.*

Figure 4 *A user explores gene expression data in endothelial cell lines with respect to the new 3D cardiovascular system. The exploration is performed in a virtual reality CAVE using a joystick-enabled virtual wand (yellow). Clustering models are visualized as animated color schemas directly on the chosen organs. Traditional 2D graphs and GUI controls are also provided (top left corner).*

The elements of the immersive virtual scene are the generic 3D Skull model from the Human Body Atlas (grey), a stack of a patient's MRI images (heat map), and a set of semi-automatically extracted landmarks outlining the patient's skull.

Ontology Support

The team developed an XML meta-vocabulary for the unified access, cross-annotation and retrieval of the 4D biomedical data. The Applied Bioinformatics group has used the Web Ontology Language (OWL) mechanism for hierarchical management of data and the placement of objects onto the 3D atlas. The focus has thus far been on supporting automated operations with gene expression data and pharmacokinetic data through the local-ontology metadata management (Figure 4). The team has also established a scenario that relates data between several renowned knowledge bases.

Portability to Desktops

The 3D Human Body Atlas and associated software is converted into the Java 3D™ format suitable for the Java 3D-enabled CAVE at the COE, and is portable to other Java 3D environments. The team has streamlined the mechanism of converting X3D files into Java 3D objects and ensured that semantic names are preserved in the created Java 3D structures. All 3D components and related software have been tested extensively using JABIRU technology in four visualization settings: a four-screen immersive CAVE, a single-screen VRCO Full Circle stereo display system, a UNIX thin client, and a common Windows laptop.

Automated Quality Assurance

Substantial progress has been made in terms of the Quality Assurance for the team's software: the software now includes its own JUnit testing modules for automated regression testing, including those for the GUI functionality (typically the hardest part in automated testing). New automated tests are being added regularly as the development progresses.

4D Genomic Exhibits

The team has created a 3D virtual-reality exhibit entitled "4D Inside Genomics", which was on display at the Telus World of Science, Calgary, from September 13, 2006 to January 30, 2007. The exhibit used stereo visualization to demonstrate three-dimensional anatomical, genomic, and proteomic models with the appropriate narration.

Thereafter, the team created a new virtual-reality exhibit with a strong pharmacokinetic component, emphasizing the range of possible applications of the new Human Body system. The exhibit is now on display at the Sun Executive Briefing Center at the Sun Microsystems headquarters. The exhibit demonstrates models of metabolism of drugs and the possibilities of pharmacokinetic explorations using our Java 3D system.

Objectives for Next Year

Over the next year, the laboratory will continue working with collaborators from the Genome Canada project on several case studies, which will use the human body model and the upcoming mouse model. Specifically, these will be:

- Mapping of human metabolite distributions on the human
- Combining drug studies and gene expression patterns for Multiple Sclerosis
- Studying the genetic background of facial development in mice and humans to identify key genes that define facial shapes
- Studying the genetic background of obesity in mice to identify key genes that are responsible for obesity in certain mouse strains

In addition to the case studies, the laboratory will focus on two main groups of tasks: manipulation of 3D anatomical models, and the standardization of biochemical data mapping.

In the manipulation of 3D anatomical models, the team will expand the interactive capabilities of the virtual body atlases in both human and mouse. The development of 3D image landmarking, registration, and morphing will continue. The team will also enhance the existing software modules that map experimental medical imaging data onto the atlases. These efforts will specifically include image analysis in the context of pathologies, and cross annotation of salient features between the atlas and external datasets. The team remains committed to the expansion into the micro-level, mapping histology and micro-CT datasets onto the macro-level anatomical structures.

In the standarization of biochemical data mapping, the Applied Bioinformatics team will continue the ongoing efforts in mapping patterns of molecular genomics onto the 4D context. The team has already developed a generic Application Programming Interface (API) for comparative biochemistry in 4D, separating the common comparison tasks from the specific type of the chemicals under study whenever possible. The team will address the issues of data standards, ontology support, and automated localization of a wide range of chemicals within anatomical tissues.

Outreach

The team organized and chaired a Special Track on Bioinformatics Visualization in 3D, as part of the 19th IEEE International Symposium on Computer-Based Medical Systems. This was the first such Track in the history of the annual CBMS Symposia. The event took place in Salt Lake City, UT, on June 22 - 23, 2006.

On June 20, 2006, the team organized an anatomy training seminar, given by Dr. Benedikt Hallgrimsson, Department of Cell Biology and Anatomy, to the 3D Human Body Atlas development team from Kasterstener Inc. The session was held in the Gross Anatomy lab of the U of C.

The team hosted a high profile Southeast USA Omics (genomics, proteomics, metabolics, and bioinformatics) and Nano-Bio Mission to Alberta (AB) and British Columbia (BC), which comprised government policy makers, academic researchers and industry experts. COE was the only research facility in Calgary selected to host the Mission during their six day tour of AB and BC. The team conducted extensive demonstrations of the latest 2D and 4D visual bioinformatics technologies to the US delegation and engaged them in productive discussions.

The Applied Bioinformatics group has created a 3D virtual reality exhibit entitled "4D Inside Genomics". It has been on display from September 13, 2006 to January 30, 2007 at the Telus World of Science (Calgary). The exhibit used stereo visualization equipment (VRCO Full Circle) to demonstrate three-dimensional anatomical, genomic, and proteomic models, with the appropriate narration. The general theme was to illustrate the importance of genomics and proteomics and their relationship to the anatomical changes in a human body.

The team created a new virtual-reality exhibit with a strong pharmacokinetic component, emphasizing the range of possible applications of the new Human Body system. The exhibit is now on display at the Sun Executive Briefing Center at the Sun Microsystems headquarters. The exhibit demonstrates models of metabolism of drugs and the possibilities of pharmacokinetic explorations using our Java 3D system.

Research Team Members and Contributions

Team Leader
Professor Christoph Sensen
Director of Appled Bioinformatics

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Dr Jung Soh	Research Associate	iCORE
Dr Quang Trinh	Research Associate	Genome Canada projects
Dr Andrei Turinsky	Research Associate	Human Body Team Leader

PhD Candidates

Name	Role/Topic	Awards/Special Info
Paul Gordon	Research Assistant	Computer Science

Undergraduate Students		
Name	**Role/Topic**	**Awards/Special Info**
Krzysztof Borowski	Summer Student	BHSc, Bioinformatics
Morgan Taschuk	Summer Student	BHSc, Bioinformatics (graduated with honours)

Other Team Members		
Name	**Role/Topic**	**Awards/Special Info**
Lisa Bicek	Administrative Coordinator, Bioinformatics Initiatives	Genome Alberta
Theron Dekok	Assistant Systems Administrator	
Xiaoli Dong	Research Programmer	
Marianne Hang	Program Director, Bioinformatics Initiatives	Genome Alberta
Jackie Irwin	Laboratory Technician	
Shelby Kadnar	Administrative Secretary	
Ariane Mather	Head Systems Administrator	
Julia Trangeled	Executive Administrative Assistant	

GRADUATES

Name	*Research Topic*	*Current Position*
Masters Graduates		
Paul Gordon	Semantic Web Service for non-programmers	
Hong Chi Tran	Competitive analysis of Bluejay	
Anguo Dong	Multiple genome comparison in Bluejay	Bioinformatics Support Specialist, NRC Plant Biotechnology Institute, Saskatoon, Saskatchewan
Julie Stromer	Volume rendering and interaction in immersive 4D bioinformatics	
Xueling Shu	Agile methods in bioinformatics projects	Computer Science (co-supervision with Frank Maurer)
Stephen Wat	Crf4 mutation and developmental basis	

COLLABORATIONS

Participants	Nature of Collaboration
Industrial Collaborations	
Kasterstener Inc. (Red Deer, AB)	Completion of the virtual human body
Sun Microsystems	Collaboration continues in the areas of graphics and large-scale storage solutions. Dr Sensen visited Palo Alto in March 2007 and initiated further interactions with Sun. A virtual reality-based genomic exhibit has been set up at the Executive Briefing Center at Sun Microsystems headquarters.

INTELLECTUAL PROPERTY

The commercialization effort regarding the oligonucleotide selection engine, called "Osprey", was reported last year. TimeLogic Inc. has licensed this for distribution with their high-throughput database search engines (DeCypher machines). The Applied Bioinformatics team is currently working with the company on the industrial version pending siRNA design module, to be completed summer 2007.

FUNDING

Dr Christoph Sensen has a five year iCORE Industrial Chair award ($500K). This year he received federal funding from Genome Canada ($4.3M), CFI ($3.8M), and WEPA($325K) and others ($4.2M). He received provincial funding from ASRA and Alberta Ingenuity ($1.3M). He also receives industry funding from Sun Microsystems of Canada ($100K/year).

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N.J. Ruecker, S.L. Braithwaite, E. Topp, T. Edge, D.R. Lapen, G. Wilkes, W. Robertson, D. Medeiros, C.W. Sensen, and N.F. Neumann, "Tracking Host Sources of Cryptosporidium spp. in Raw Water for Improved Health Risk Assessment," *Applied and Environmental Microbiology*, vol. 73, pp. 3945-3957.

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A. Dong, A.L. Turinsky, A. Ah-Seng, M. Taschuk, P.M.K. Gordon, K. Hochauer, S. Fröls, J. Soh, and C.W. Sensen, "Enhancing Bluejay with Scalability, Genome Comparison and Microarray Visualization," *Advances in Data Analysis: Proc. 30th Annual Conf. German Classification Society* (GfKl 2006), R. Decker and H.-J. Lenz, eds., Springer, 2007, pp. 557-568.

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C. W. Sensen. "Three-Dimensional Presentation of Data," Plenary Lecture at the *Canadian Federation of Biological Sciences 49th Annual Meeting*, Saskatoon, SK, June 14-18, 2006.

C.W. Sensen, "From 2D to 4D Bioinformatics," Invited Talk at the *Canadian Food Inspection Agency*, Lethbridge, 2007.

C.W. Sensen, S. Czub, C. Graham, E. Schütz, and H. Urnovitz, "Preliminary Characterization of Chronic Wasting Disease in Elk," *PrP Canada 2007 – Canada's Prion Research Conference*, Calgary, 2007.

ABSTRACT COLLECTION

J. Collado-Vides, R. Hofestädt, and C.W. Sensen, "Integrative Bioinformatics – Aspects of the Virtual Cell," *Dagstuhl Seminar Proceedings 04281*, 17 pages, ISSN 1861-4405, 2006.

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P. Gordon, "Enhancing the Web Browser Paradigm to Facilitate Semantic Web Service Use by Non-Programmers," master's thesis, Dept. of Computer Science, Dalhousie Univ., 2006.

S. Wat, "The Crf4 Mutation and the Developmental Basis for Variation in Facial Length," master's thesis, Dept. of Physiology, Univ. of Calgary, 2006.

J. Stromer, "Software-Based Volume Rendering and Interaction in Immersive 4D Bioinformatics," master's thesis, Dept. of Computer Science, Univ. of Calgary, 2007.

A. Dong, "Multiple Genome Comparison in Bluejay," master's thesis, Dept. of Computer Science, Univ. of Calgary, 2007.

Computer Process Control

Process control performance is a cornerstone of operational excellence in Canada's refining, petrochemicals, pulp and paper, and mineral processing industries.

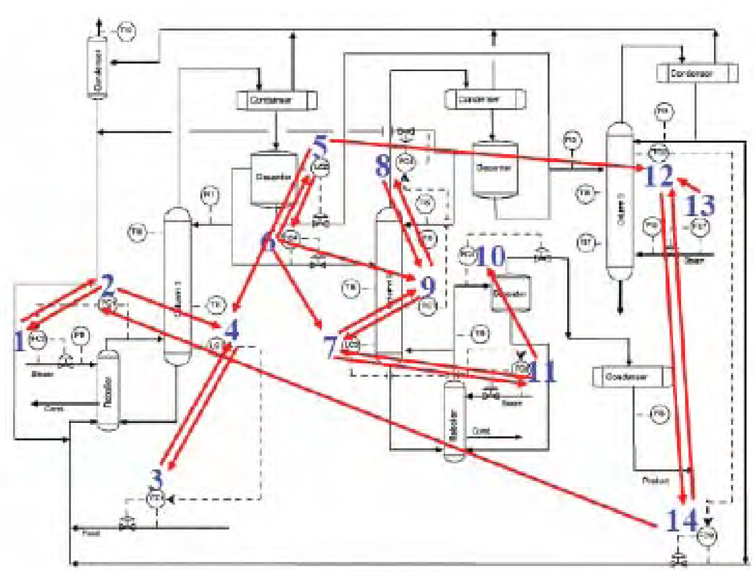


Figure 1 *New Graph theoretic methods have been developed to capture process flow sheet information for fault detection and diagnosis.*

Control performance assessment and monitoring applications have become mainstream in these industries and are changing the maintenance methodology surrounding control assets from predictive to condition based. In the typical process industry, operators are responsible for monitoring several hundreds or even thousands of control loops. With such a wide span of control, operator responsibility forces them to work in an "alarm-driven" mode, principally depending on computerized systems to inform them of problems when or after they occur. A majority of such unexpected disruptions are due to common faults such as sensor/actuator failures, sticky control valves, plugged lines, compressor imbalance, and fouled heat exchangers. Such common faults render the most sophisticated advanced control strategies useless with the result that benefits due to reduced energy expenditure and reduced quality variance may not accrue.

The main objective of this iCORE Industrial Chair in Computer Process Control (CPC) is to continue the development and evaluation of tools, based on fundamental multivariate statistical temporal and spectral techniques, for effective process and performance monitoring strategies, i.e. develop strategies that help to do preventative abnormal process detection and diagnosis. An equally important objective is to demonstrate the utility of these tools in the Canadian process industry. The end goal is to develop practical tools that industrial personnel can use for knowledge discovery from process data and use them effectively towards process and performance monitoring.

Research Program Overview

The intent of data analysis is to model processes in their 'normal' state of operation and use such models to monitor processes for impending faults. Performance monitoring is concerned with maintaining process operation in an optimal state with minimum energy usage in an environmentally sustainable way.

Dr Shah's experience in working with industrial data sets over the last six years has revealed that real process data is invariably compressed with many missing values and, more often than not, asynchronous. Multivariate statistical techniques used in the analysis of such data are predominantly used in a temporal framework. Spectral transformation of process data and its subsequent analysis offers a different and unique insight into the information contained in such data. Dr Shah's work is concerned with developing a theoretical and practical framework for temporal and spectral analysis of process data for fault or event detection and diagnosis.

In the context of biological data analysis or bioinformatics, the plan is to build suitable tools that will be useful in the analysis of Nuclear Magnetic Resonance (NMR) data generated from various body fluids with the main focus on developing disease diagnosis procedures from NMR data.

The projects that Dr Shah's team has undertaken, as described below in more detail, involve fundamental theoretical development of signal processing methods, followed by practical evaluation of these techniques on data from real processes as made available by industrial (Matrikon and Suncor) and academic collaborators.

Research Projects

The emphasis on the research projects is to work on methods of knowledge discovery from industrial data, i.e. data mining, and managing this knowledge in real-time for optimum and economic process operation. The end goal of the group's effort is to develop new time and frequency-domain methods for real-time applications-driven, closed-loop monitoring of industrial processes. Dr Shah's team intends to develop from fundamental theory, time and frequency domain based fault detection and isolation methods that will be able to deal with missing and non-uniformly sampled data. The algorithms will have immediate practical appeal.

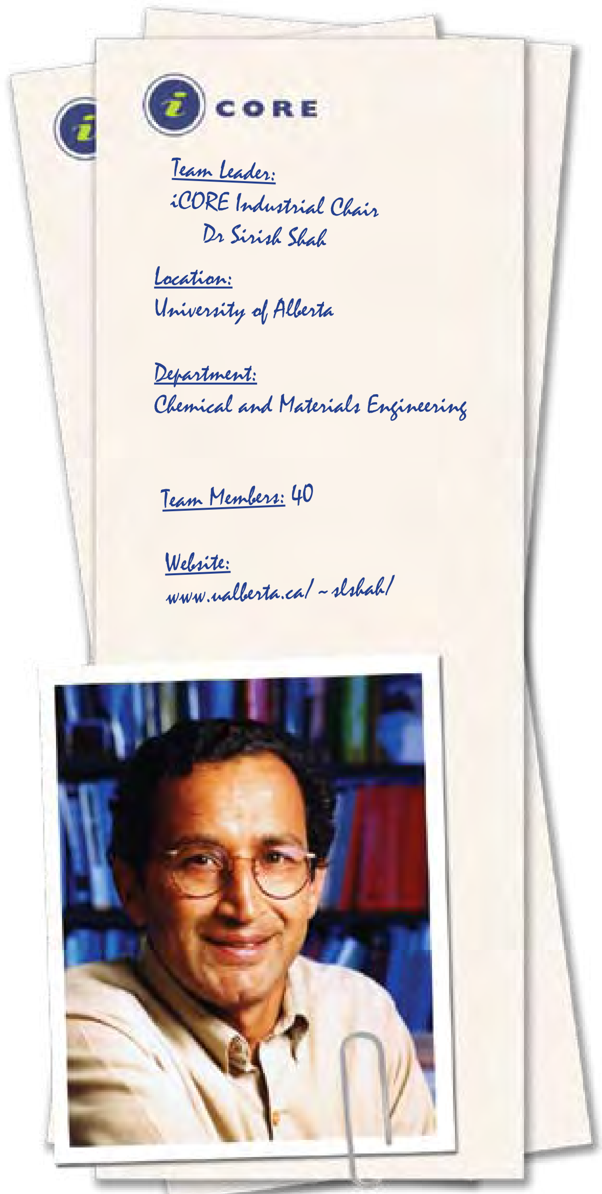
Control relevant closed-loop model validation based on the two-model divergence method

This project is concerned with model validation and detection of parameter changes under closed-loop operating conditions. Two control relevant validation algorithms have been developed based on the two-model divergence method. The algorithms are only sensitive to plant changes that affect closed-loop performance. The first algorithm is sensitive to changes in both plant dynamics and disturbance dynamics. If the plant dynamics is the only concern, then the second algorithm is more appropriate because it is only sensitive to the changes in plant dynamics, irrespective of changes in disturbance dynamics. For the situation where the changes in plant dynamics are not a concern, then algorithms can also be applied for fault detection. Simulations as well as experimental applications on a pilot scale process have evaluated the developed algorithms.

The main goal of this project is to be able to develop a diagnosis method for the detection of model-plant mismatch for model-based predictive control applications.

Root cause diagnosis of plant-wide oscillations using the adjacency matrix

Oscillations are a common type of plant-wide disturbance whose effects can propagate to many units and



thus may impact the overall process performance. This project is concerned with the development of a new method to diagnose the root cause of plant-wide oscillations using adjacency matrix. A distinguished feature of the new method is that it is not data-based and can be carried out without using any data. Combination of the new method and other data-based methods can provide powerful diagnosis of plant-wide oscillations. A complete procedure for detection and diagnosis of plant-wide oscillation has been developed and evaluated on two industrial case studies to demonstrate the utility and applicability of the proposed procedure.

Reconstruction of missing data using wavelet transform and spectral techniques

It is not uncommon to be involved in analyzing process data where data may be missing due to sensor malfunctions, compression problems, irregular sampling, or outliers. Rather than delete an entire row of otherwise good data when only a few observations may be missing in one or a few sensors, it is better to reconstruct the missing data. Towards this end the CPC team has carried out the following tasks:

- Simple spectrum methods have been implemented using Matlab to test their efficiencies in reconstructing missing data, and the method has been evaluated on simulated and industrial data.
- A new method for reconstructing missing data has been developed based on the discrete wavelet transformation and successfully evaluated by application to simulated and industrial data.
- The current focus of this project is to develop a new method for missing data reconstruction based on multiple layer wavelet method which the team hopes will be even more efficient than the earlier method based on single layer wavelet transformation.
- Development of a temporal method of reconstructing missing data using an iterative PCA algorithm.

All of these methods have great practical appeal. These algorithms are being implemented in the CPC team's Matlab-based DVA (Data visualization and analysis) toolbox.

Figure 2 *Type of gear faults.*

Time domain averaging across all scales: a novel method for detection of faults in rotating machineries:

Rotating machines, such as pumps, compressors, turbines, and gearboxes are common units in most industrial processes. They are also expensive in terms of the original investment and maintenance. In this study the CPC team has taken the gearbox as a typical representation of rotating machinery.

The vibration signal of a gearbox carries the signature of the fault in the gears, and early fault detection of the gearbox is possible by analyzing the vibration signal using different signal processing techniques. Time synchronous averaging can extract the periodic waveforms of a noisy vibration signal, whereas wavelet transformation is able to characterize the local features of the signal at different scales. The study has proposed

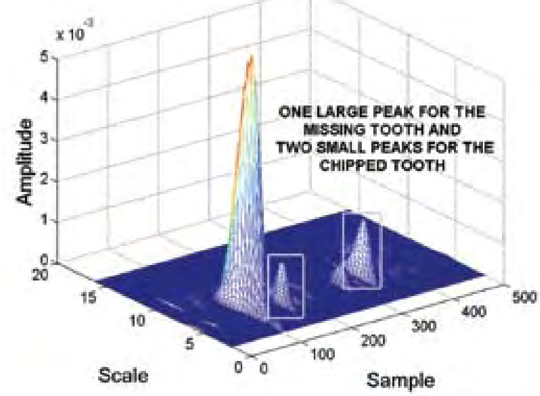


Figure 3 *'Time Domain averaging across all scales' method applied to a fault detection and diagnosis technique is able to identify the type of gear faults.*

a new technique, Time Domain Averaging across all Scales, which combines the time synchronous average and wavelet transformation together to extract the periodic waveforms at different scales from noisy vibration signals. The technique efficiently cleans up noise and detects both local and distributed faults simultaneously. A pilot plant case study has been conducted to demonstrate the efficacy of the proposed technique.

Image based interface level control in a separation cell

Separation cells used in primary extraction in the oil sands industry are a core component of the overall process.

Good control of the interface between the bitumen froth and the middlings in these cells at an optimum level can result in a significant improvement in bitumen recovery and reduction in the variability of the process downstream. The major impediment in the implementation of such a control system is the lack of reliable sensors for interface level detection. Traditional instruments such as nuclear gauges, capacity probes, and pressure transmitters were largely unsuccessful due to the harsh environment inside the separation cell. A novel technique is to use image processing on images captured from a sight glass via a video camera for real time interface level detection and control. One specific project focuses attention on the development of such a real time image processing system considering the various practical problems that arise in an operating separation cell. Simple image processing methods have been combined with the powerful Bayesian (particle) filtering framework to provide estimates of the current interface level and its quality.

This soft sensor has already been successfully tested on Suncor's Line 6 and efforts are currently underway to close the control loop to maintain an optimum interface level. Preliminary results show the stability of the algorithm and the reduced variability in the interface level when the estimates from the algorithm were used in an automatic control loop.

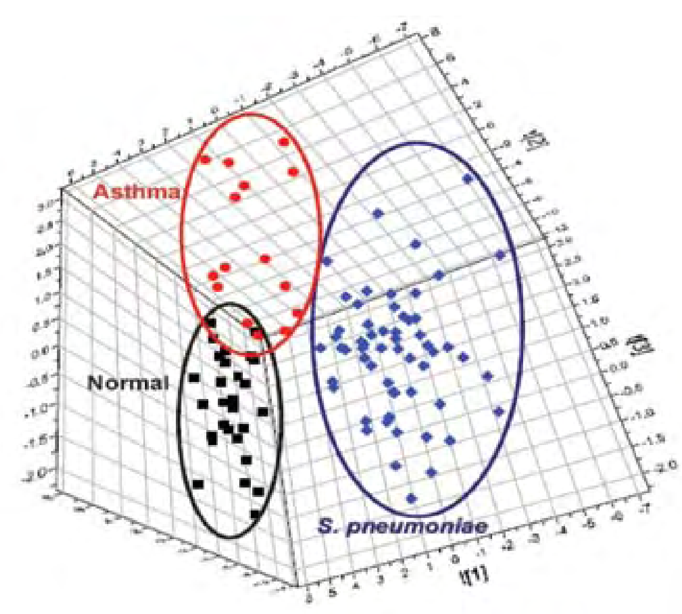


Figure 4 *Support vector machines based NMR data analysis to show the separation that can be achieved for a 3-class problem consisting of Controls, Pneumonia, and Asthma*

Feature Selection and Classification of Metabolomic Data Using Support Vector Machines

The main task of data analysis is to extract meaningful information in a way that facilitates the understanding of complex biological processes. In order to do this, algorithms and techniques have to be developed that can be trained to learn rules and form patterns from the available data sets and then apply these rules to analyze new data. This is known as machine learning. In this study, the applicability of one such machine learning technique, namely support vector machines to analyze and classify metabolomic NMR data is explored. The CPC team has explored some of the feature selection algorithms that help determine important biomarkers or metabolites in data sets obtained from clinical records. These biomarkers can be related to certain diseases and in this way the SVM analysis of NMR data from bio-fluids can be used as a diagnosis tool.

Support Vector Regression for nonlinear system identification

The basic objective is regression in a multivariable framework with an approach that is quite different from the classical method of least square regression. In the support vector regression formulation, a more generic and flexible cost function is minimized with a set of well-chosen constraints to fit a function to the data. The algorithm has parameters to control the trade off between good fit and testing performance. One of the good features of the method is its direct applicability to nonlinear regression due to the use of Kernel functions for mapping the input vectors to a feature space where the input-output relationship becomes linear. In addition, the optimization problem is quadratic and hence does not suffer from the problem of local minima even in the case of nonlinear regression. One of the areas in data based modeling where the CPC team can take advantage of this feature of SVR is the development of soft sensors based on steady state input-output plant data.

Objectives for Next Year

Objectives for the upcoming year

- Evaluation and analysis of multivariate statistical techniques that can be applied to missing and multirate data;
- Development of a detection and isolation strategy for model-plant mismatch in MPC-based multivariate control loops;
- Analysis of multivariate data in the spectral domain and use of non-negative factorization (NMF) techniques to ensure positive spectra in the transformed basis space;
- Experimental evaluation of the temporal, spectral, and combined temporal and spectral (i.e. wavelet-based) monitoring algorithms on computer-controlled pilot scale processes.

Long term research objectives

The general theme of this project is to use temporal and spectral methods for analyzing process data for the purpose of fault detection and diagnosis (FDD). More specifically, this CPC project is concerned with sensor or data fusion methods for analyzing process data for model-building and process monitoring.

The CPC team's efforts are directed towards developing methods that allow knowledge discovery (e.g. model building) from process data and using these models to carry out process and performance monitoring. Towards this end the long-term objectives of the program are:

- Development of a general methodology for fault detection and isolation in non-uniformly sampled multirate systems (including segments of missing data);
- Development of a practical tool for the diagnosis of poor performance of a multivariate control loop;
- Extension of the 'Data Visualization and Analysis' toolbox as an integrated monitoring system toolbox that uses temporal and spectral analysis of process data, e.g. for plant wide oscillation detection and condition-based maintenance of rotating machinery;
- Experimental evaluation and transfer of the newly developed technology to Canada's chemical, pulp and paper, mining and metallurgical and other manufacturing industries.

Outreach

- Received the 2006 D.G. Fisher award from the Systems and Control division of the Canadian Society for Chemical Engineering, for outstanding contributions.
- Plenary, keynote, invited talks, and also talks and workshops delivered at IITM (India), NUS (Singapore), SIMTECH (Singapore), ICES (Singapore), NTU (Singapore), UTP and USM (Malaysia), SICE (Society of Instrumentation and Control Engineers), process and performance monitoring conference organized by Saudi Aramco (Bahrain), Texas and Wisconsin Model and Control Consortium, U of Texas (Austin)
- National organizing committee Chair for Adconip to be held in Jasper, May 2008
- Member of the international program committee for 2009 Adchem
- Elected to the editorial board of IEE Journal of Control Theory and Applications.

Research Team Members and Contributions

Team Leader

Professor Sirish Shah
Principal Investigator and Chair

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Dr Weihua Li	Research Manager	
Dr Harigopal Raghavan	Research Associate	

Research Associates

Name	Role/Topic	Awards/Special Info
Iman Izadi	FDI of non-uniformly sampled systems	AI Industrial Research Fellow
Liqian Zhang	Missing data reconstruction	

Faculty Collaborators		
Name	**Role/Topic**	**Awards/Special Info**
Professor A. Benzvi	Co-supervisor of project on monitoring a tubular reactor.	CME
Professor T. Chen	Co-supervisor of project on missing data reconstruction.	(ECE)
Professor F. Forbes	Co-supervisor of project on Economics of Performance Assessment	(CME)
Professor B. Huang	Co-supervisor of project on MPC monitoring.	(CME)
Professor U. Sundararaj	Co-supervisor of project on Polymer reactor control and monitoring.	(CME)
Professor B. Sykes and Professor D. Adamko, (Medicine)	Analysis of NMR data	Faculty of Medicine
Professor M. Zuo (ME)	Co-supervisor of project on fault detection and diagnosis of rotating machineries	Mechanical Engineering

PhD Candidates		
Name	**Role/Topic**	**Awards/Special Info**
Salim Ahmed	System Identification	
Ian Alleyne	Control of Polymer Reactors	
David Chang	Analysis of NMR data	
Saneej Chitralekha	Data fusion and multivariate statistics	
Enayet Halim	Monitoring of rotating machinery	
Syed Imtiaz	Treatment of missing data	
M. Iqbal	Identification and Control of a Twin Screw Extruder	AI Scholarship
Hailei Jiang	Spectral envelope methods	
Sankar Mahadevan	NMR data analysis via Machine learning	
Karteek Popuri	Machine learning for fault detection	
Venkat Raghavan	PCA Analysis of reverse flow reactors	
S. Reddy	Smart Alarm Monitoring Strategies	
M. Sahebsara	Control in a networked environment	AI Industrial Research Fellow
Rumana Sharmin	Monitoring of Polymer Reactors	AI Scholarship
Phanindra J. Verma	Bayesian filtering for state estimation	

MSc Candidates

Name	Role/Topic	Awards/Special Info
P. Grower	Economics of performance assessment	
Mridul Jain	Evaluation of cost and benefits of performance and process monitoring	

Other Team Members (International Visiting Students)

Name	Role/Topic	Awards/Special Info
Marcelo Farenzena	Variability matrix identification in performance monitoring	Federal University of Rio Grande do Sul, Brazil
Jitendra Kanodia	Non-negative factorization methods (NMF) in PCA	IIT-Madras
Boyi Ni	Identification from multirate data	Tsinghua University, Beijing
Magnus Nilson	MPC control and monitoring	Chalmers University, Sweden

Visiting Professors

Name	Role/Topic	Awards/Special Info
Dr Y. Ohnishi	Performance Driven adaptive control	JSPS Visiting Fellowship Kure Institute of Technology, Kure, Japan
Professor S. Patwardhan	Fault tolerant control	May 2007 to June 2007; IIT-Bombay, Mumbai, India
Dr J. Praksh	Boyscast Fellowship. Working on Bayesian filters	Boyscast Fellow Madras Institute of Technology, Chennai, India
Dr T. Yamamoto	Memory-based PID controllers	JSPS Visiting Fellowship, Hiroshima University, Japan

GRADUATES

Name	*Research Topic*	*Current Position*
PhD Graduates		
Salim Ahmed		PDF with this team
Ian Alleyne		Shell Canada, Sarnia
S. Imtiaz		AspenTech Inc., Calgary
M. Sahebsara		PDF with this team
MSc Graduates		
M. Jain		Matrikon Inc.

COLLABORATIONS

Participants	*Nature of Collaboration*
Inernational Collaborations	
Faculty member at IIT-Madra Dr A. Tangirala	Collaborative work on non-negative matrix factorization (NMF) for data analysis in the spectral domain)
Tsinghua University, China Dr Deyun Xiao	Identification of process models from irregularly sampled data
National University of Singapore Dr L.Samavedham	Process analytics and health informatics for personalized 'point-of-care' medicine.
Imperial College, UK Professor N. Thornhill	Detection of process nonlinearities using higher order statistics
Industrial Collaborations	
Matrikon Dr David Shook and Dr R. Patwardhan Suncor Energy Dr R. Kadali and T. Hrycay	Part of the partnership between Matrikon and Suncor for process and performance monitoring.

INTELLECTUAL PROPERTY

- Image based softsensor currently under evaluation at Suncor Energy
- Patent filed in Japan with Professor Z. Iwai (a method for tuning PID loops using adaptive control)
- Development of a Matlab based toolbox: DVAtool

FUNDING

Dr Sirish Shah has a five year iCORE Industrial Chair award ($500K). This year he received NSERC funding ($210K), cash and contributions from Suncor and Matrikon ($330K), and contributions from the University of Alberta ($23K).

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S.L. Shah, "Plant Health Management: The Role of Digital Automation Systems in Process Monitoring", Plenary Talk delivered at the *Process Performance Monitoring & Data Analysis Symposium*, November 2006, Bahrain.

S. Imtiaz, M.A.S. Choudhury and S.L. Shah, "How to Undo the Detrimental Effects of Data Compression", Talk delivered at the *Process Performance Monitoring & Data Analysis Symposium*, November 2006, Bahrain.

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Jain, M., "Practical issues in controller performance monitoring", MSc. thesis, Department of Chemical and Material Engineering, U of A, Fall 2006

Sahebsara, M., "Filtering and Estimation in Modern Computer Control Systems", PhD thesis, Department of Electrical and Computer Engineering, U of A, Spring 2007

Reinforcement Learning and Artificial Intelligence

A vast number of problems of economic and scientific interest involve sequences of actions where the effects of one action influence the expected utility of subsequent actions.

Sequential decision problems include such diverse applications as inventory management, robots, industrial processes, and backgammon, all of which are made more challenging because of their sequential and stochastic aspects. Reinforcement learning is a new body of theory and techniques for solving sequential decision problems, based on classical methods such as dynamic programming and inspired by animal learning theory that enables larger and more diverse problems to be solved.

The objectives of the iCORE reinforcement learning and artificial intelligence (RLAI) researchers are to create new methods for reinforcement learning that remove some of the limitations on their widespread application, and to develop reinforcement learning as a model of intelligence that could approach human abilities.

The primary focus of the research program has been on how intelligent machines represent their knowledge of the world. The key question is how to organize the knowledge such that it can be verified, learned, and used autonomously without continual tending by human experts. This project has pursued an unusual approach in which knowledge is expressed in terms of the machines' sensors and actuators, thereby enabling it to be compared directly to experiential data. Substantial progress was made this year toward formalizing the core learning algorithms and developing planning algorithms.

Dr Csaba Szepesvari joined the iCORE RLAI team this year as a fourth principal investigator and new associate professor in the computing science department at the University of Alberta (U of A). Dr Szepesvari is internationally recognized as one of the foremost theorists in reinforcement learning.

Overall, the RLAI team grew to about 50 members, of which 31 are graduate students and 12 of these are recipients of major scholarships. The output of the research program has remained strong, with 38 papers published or accepted for publication in archival venues during the reporting period. Four MSc students graduated.

The project has created a new web site this year known as the RL-Library. This site is meant to become an international repository for reinforcement learning software based on the RL-Glue standard interface the RLAI introduced last year and has now become widely used for research and education in reinforcement learning.

Research Program Overview

The iCORE research program in RLAI pursues an approach to artificial intelligence (AI) and other engineering problems in which they are formulated as Markov Decision Processes (MDPs) and approximately solved using Reinforcement Learning (RL). RL is a new body of theory and techniques for solving MDPs that has been developed in the last 20 years, primarily within the machine learning and optimal-control research communities. RL researchers have developed novel methods to approximate solutions to MDPs that are too large or too ill-defined for classical solution methods such as dynamic programming.

The RLAI research team has four focus areas for investigation on each of which substantial progress was made this year. One proposed focus was the role of state in AI systems, in particular on predictive state representations and on planning in large state spaces:

Predictive State Representations

Predictive state representations are a new idea for modeling sequential decision problems that are not Markov, that is, for which an appropriate state representation is not available a priori but must be constructed from the stream of raw sensor data. In previous years the RLAI has introduced a new formulation of predictive state representations, temporal-difference networks, that enables the representation of compositional predictions, a qualitative increase in abstraction abilities.

This year the team conducted further systematic studies of compositional learning systems. The most significant aspect of this work was the thorough merging of temporal-difference networks with temporal abstraction.

Planning with the kind of function approximation needed for large state spaces is largely an open problem. One approach, called Dyna, is to create hypothetical experience using the world model and then learn from it using RL algorithms just as if it had actually occurred. This year the RLAI team developed the first Dyna-style planning methods extended to use linear function approximation. The team completed an initial set of experiments with the new methods, culminating in Cosmin Paduraru's MSc thesis.

Expressive Representations

A second proposed focus of the research program was on building powerful, expressive representations of the world, in particular, on the extension of RL beyond the flat and low-level representations commonly used with MDPs to the more flexible, structured, and higher-level representations used by AI systems. Last year the team combined the theory of temporal abstraction ("options") with temporal-difference networks and explored corresponding learning algorithms.

This year the RLAI team has started the predictive empirical abstract knowledge (PEAK) project, in which high-level knowledge is related more explicitly to low-level sensations and actions.

Approximantion and Generaliztions in RL

A third proposed focus of the research program was broadly concerned with approximation and generalization in RL. Approximation is required in all large-scale applications, yet is incompletely understood in both theory and practice. Most of the RLAI's work to date has focused on developing software to improve practice. Last year the RLAI extended the RL toolkit with RL-Glue, a new interface standard that has become a de-facto international standard for RL competitions.

The RL-Library was created this year, a central site for storing and organizing RL code based on standards such as RL-Glue. Such sites exist for other branches of machine learning, but it has not been possible to create it without a standard such as RL-Glue.

Robotics Applications

The fourth proposed area of investigation was the demonstration of advances in robotics applications. The RLAI robotics laboratory has a variety of robots including a robot Segway, Kato. Last year Kato was used to demonstrate robot geo-caching—the locating of a hidden cache through knowledge only of its GPS coordinates.

This year the RLAI team has begun replacing key components of Kato with more robust learning-based approaches. In particular, the RLAI is exploring extending the idea of sensor bootstrapping—defining the meaning of one sensor in terms of its dynamic, causal relationship to another sensor.

Research Projects

Very Large or Continuous Action Spaces

Within the realm of on-line learning, large action spaces have been studied in a model in which the MDP is degenerate in the sense that it has a single state. Such problems are called stochastic bandit problems and despite their simplicity have numerous applications, ranging from experiment design for clinical trials to finding the correct setting of the parameters of an industrial plant. The RLAI team has proposed a new variation on existing methods for bandit problems with large numbers of actions, and shown that the rate of convergence is better that that of previous methods. The RLAI team plans to explore if these results can be extended to the case where extensive prior knowledge is not available.

The RLAI team has been developing the upper confidence-bounds based tree (UCT) algorithm due to Levente and Szepesvari (before coming to Alberta). UCT is a search algorithm for large, discrete action spaces with a hierarchical structure. The researchers proved that UCT's rate of convergence for deterministic environments depends on the difficulty of the search. UCT is the first search algorithm that adapts to the difficulty of the search problem and has proven to be very practical.

The RLAI team has combined RL algorithms with the UCT-based Computer Go program MoGo to produce what is currently the world's best Go playing program. This is currently a very active area of research for RLAI and for the international research community.

Computational Models of Animal Learning

This year the RLAI group added an experimental component to their research program by teaming with Professor Jim Kehoe of the University of New South Wales. Dr Kehoe's area of specialization is in the temporal structure of prediction processes in animal learning (classical conditioning), which makes his work particularly relevant to this project. There are striking relationships between animal learning models and computational reinforcement learning algorithms; The RLAI team is exploring ways in which animal learning behavior may yield new insights leading to better algorithms. This has happened several times in the past, leading to some of the most effective modern algorithms such as TD(λ) and Q-learning.

Reinforcement Learning for Hybrid Vehicles

The RLAI team has been exploring the use of RL technology for improving the fuel efficiency of gas-electric hybrid cars. Whenever developing a major application, new issues arise that feed into, inform, and ultimately direct ongoing research. In this application the team seeks to minimize fuel consumption without interfering with the car's performance. The challenge is that the driver will impact performance in ways outside of the learning algorithm's control. The driver may ask for accelerations that can be delivered only with poor fuel efficiency. The team's challenge is to design a learning agent that can separate the effects of its decisions from the effects of the driver's decisions.

The RLAI team has formulated this challenge as an instance of the more general problem of control learning with disturbances. Disturbances are aspects of the world that impact performance but which cannot be affected by the learning agent.

The RLAI team has developed a new algorithm for RL with disturbances and has shown in simplified cases that it can significantly improve performance. This work is still in its initial stages and the team expects to explore several different algorithms before determining which are most effective in general and in particular in the hybrid-car domain.

Dual Representations for Reinforcement Learning

Algorithms for dynamic programming and reinforcement learning are usually formulated in terms of value functions—representations of the long run expected value of a state or state-action pair. This past year the RLAI group has begun a systematic exploration of an alternative approach.

The dual approach to dynamic programming and reinforcement learning is based on maintaining an explicit representation of a stationary distribution instead of a value function. The dual approach allows well-developed techniques to be exploited for representing, approximating, and estimating probability distributions without running the risks associated with divergent value function estimation. A second advantage is that some distinct algorithms for the average reward and discounted reward cases become unified under the dual representation. The RLAI team has developed a modified dual of the standard linear program to guarantee that a globally normalized state visit distribution is obtained. With this reformulation, the research team has derived novel dual forms of dynamic programming, including policy evaluation, policy iteration and value iteration. The RLAI team has also derived dual formulations of temporal-difference learning to obtain new forms of Sarsa and Q-learning. Finally, the team has explored the scaling of these techniques to large domains by introducing function approximation. The dual view seems to yield a viable alternative to standard value-function-based techniques.

Objectives for Next Year

A major focus for next year will be on planning with linear function approximation. Planning is a core topic for the entire research program, corresponding roughly to reasoning in people and to optimal decision making in control theory. Much of the research program has been directed toward constructing flexible, expressive, multi-scale approximate models of the world to support decision-making. There are a number of possible approaches arising out of the RLAI group's previous work in iLSTD and in Dyna-style planning systems. The team will develop these both theoretically and experimentally over the next year. The primary objective for the year will be a general and sound planning algorithm for worlds with linearly approximated dynamics at a single time scale. If this is achieved then the team will extend to multiple time scales and predictive state representations will be attempted.

A new focus for RLAI group next year will be on treating reinforcement learning as a tracking problem. Conventionally, in machine learning, it is assumed that the goal is to converge to a single optimal solution. In contrast to this, the team's preliminary results suggest that in large problems a time-varying solution may perform better than any fixed solution, even if the underlying problem being solved is stationary. The RLAI team's objective for next year is to demonstrate this phenomena in a state of the art Computer Go program.

The RLAI group continues to seek software and algorithms that make RL easier to apply without expert knowledge. All of the software systems the team has developed – the RL-Toolkit, RL-Glue, and the RL-Library – are towards this goal. The goal for the next year is to increase these software system's user-friendliness and use in education.

In concert with the software effort the RLAI team will develop a long-term focus on "black box" RL algorithms. These are algorithms that have no parameters or settings of any kind and can be used without knowledge of what is going on inside. The RLAI group's goal for next year is to develop RL algorithms that require only meta-parameters – parameters for setting the other parameters.

The RLAI team also seeks to develop and publish a new model of animal learning (classical conditioning) based on the temporal-difference learning algorithm and an extended temporal representation the team has termed micro-stimuli. Micro-stimuli turns a simple sensory event into a temporally extended and multi-component representation which enables precise timing of responses. The objective is to develop this model through comparisons with empirical data from animal learning and neuroscience.

In robotics, The RLAI team's focus over the next year or more will be integrating ideas from ongoing research into a robot system capable of completing the Turkey Trot, a four-kilometer walk for charity that happens every fall at the U of A. The system will require robust positioning, local and global navigation, and obstacle avoidance, all over a long challenging route.

Outreach

Team member Dan Lizotte exhibited a joint research project with team member Michael Bowling on automatically tuning robotic gaits using experience at the Smithsonian Institute's Folklife Festival in Washington, D.C., highlighting Alberta.

Dan Lizotte also presented an introductory robotics lecture and demo to the grade eight science classes of Richard S. Fowler Catholic Junior High School.

Team member Anna Koop conducted a session for "Choices - A Conference for Grade Six Girls," giving them hands-on RL experience.

Anna Koop also conducted a session for "Women in Technology," a program for grade nine female students to participate in IT workshops.

Team member James Neufeld conducted Segway Robot demonstrations for the students from Augustana University, Brander Gardens Elementary school, and Edmonton high school teachers.

Team member Jacqueline Jean was a WISEST (Women in Scholarship, Engineering, Science and Technology) summer student.

Research Team Members and Contributions

Team Leader
Professor Richard Sutton
Principal investigator
NSERC and AICML awards

Faculty Team Members		
Name	**Role/Topic**	**Awards/Special Info**
Michael Bowling	Principal investigator Robotics, games, reinforcement learning	NSERC, AIF New Faculty, AICML Awarded an Alberta Ingenuity New Faculty grant to pursue "Subjective Models for Autonomous Robots"
Dale Schuurmans	Principal investigator Probabilistic methods in artificial intelligence, machine learning	CRC II Chair, NSERC, AICML
Csaba Szepesvari	Principal investigator Nonparametric learning, statistical techniques	NSERC, AICML Awarded an Alberta Ingenuity New Faculty grant to pursue "on-line learning and sequential decision making in stochastic environments"
Mark Ring	Visiting professor, Chapman University Continual learning, neural networks, sequence learning	

PostDoctoral Fellows		
Name	**Role/Topic**	**Awards/Special Info**
Yaakov Engel	Gaussian process reinforcement learning	Alberta Ingenuity Fellowship
Mohammad Ghavamzadeh	Hierarchical reinforcement learning, Bayesian policy-gradient reinforcement learning	
Yuxi Li	Computational Finance	
Elliot Ludvig	Computational models of animal learning Integrating approaches to natural and artificial intelligence	
Martin Zinkevich	Minimal regret algorithms	

PhD Candidates		
Name	**Role/Topic**	**Awards/Special Info**
Arash Afkanpour	Function approximation and feature discovery in reinforcement learning	iCORE
Amir massoud Farahmand	Manifold learning methods for reinforcement learning problems	PhD Academic Achievement Award, Provost Doctoral Entrance Award
Alborz Geramifard	Least-squares reinforcement learning methods and planning	
Yuhong Guo	Learning bayesian networks	
Jiayuan Huang	Spectral clustering and semi-supervised learning	University of Waterloo
Feng Jiao	Bayesian methods	Google
Daniel Lizotte	Bayesian global optimization	Killam, iCORE
Adam Milstein	Localization and mapping	University of Waterloo
David Silver	RL in computer GO	iCORE, FS Chia, AIF
Ivett Szabo	Bandit algorithms	Budapest University of Technology and Economics

PhD Candidates Cont'd

Name	Role/Topic	Awards/Special Info
Brian Tanner	Experience oriented reinforcement learning	NSERC CGS-D, Killam, AIF, AIF Bill Bridger iCORE, Walter H. Johns
Qin Wang	Learning structured classifiers for statistical dependency parsing	
Tao Wang	New representation and approximations for sequential decision making	SIGART/AAAI Doctoral Consortium Scholarship
Adam White	A benchmarking system for reinforcement learning	AIF, iCORE
Dana Wilkinson	Subjective mapping	Ontario Graduate Scholarship, President's Scholarship from University of Waterloo
Linli Xu	Convex large margin training techniques	University of Waterloo

MSc Candidates

Name	Role/Topic	Awards/Special Info
Yasin Abbasi-Yadkori	Bandit problem in the continuous action space	
Andrew Albert	Machine learning and games	NSERC CGS-M, Walter H. Johns
Nolan Bard	Agent modeling using state estimation	
Kate Davison	Generating bidding strategies in bridge	
Varun Grover	Applying shaping and transfer leaning to reinforcement learning	
Michael Johanson	Opponent modeling in poker	
Brad Joyce	Reinforcement learning with continuous action	iCORE, NSERC PGS-M, Walter H. Johns, Dept Academic Award
Armita Kaboli	Bayesian calibration for robot localization	ECE student
Anna Koop	Predictive features for knowledge abstraction	AIF, iCORE, NSERC CGS-M, Walter H. Johns
Volodymyr Mnih	Efficient stopping rules	NSERC CGS-M, iCORE, Walter H. Johns

MSc Candidates		
Name	**Role/Topic**	**Awards/Special Info**
Gergely Neu	Inverse reinforcement learning	Budapest University of Technology and Economics
James Neufeld	Autonomous outdoor navigation	
Cosmin Paduraru	Planning with approximate and learned MDP models	iCORE
Eddie Rafols	Temporal abstraction in temporal-difference networks	NSERC PGS-M, Walter H. Johns
Masoud Shahamiri	Disturbance in reinforcement learning	

Other Team Members	
Name	**Role/Topic**
Andrew Butcher	
Steve Fraser	
Akiko Green	
Jacqueline Jean	
Mark Lee	
Nelson Loyola	
Jason Roberts	Segway programming
Christian Smith	Simulation programming
Mike Sokolsky	Robot engineer
Lori Troop	Program administrator
Stephen Walsh	Segway hardware

GRADUATES

Name	*Research Topic*	*Current Position*
Alborz Geramifard	iSLTD	PhD student at U of A
Cosmin Paduraru	Planning with Approximate and Learned MDP Models	PhD student at McGill with Doina Precup
Eddie Rafols	Temporal Abstraction in Temporal-difference Networks	
AdamWhite	A Benchmarking System for Reinforcement Learning	PhD student at U of A

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
Alberta Ingenuity Center for Machine Learning	R. Sutton, D. Schuurmans, Cs. Szespesvari and M. Bowling are among the eight principle investigators at the U of A
National Collaborations	
McGill University Doina Precup Prakash Panangaden Shie Mannor University of Montreal Yoshua Bengio	NSERC Collaborative Research and Development Grants-Project, "Learning and prediction in high-dimensional stochastic domains"
Jonathan Schaeffer, Robert Holte, Duane Szafron, and Michael Buro University of Alberta	NSERC Strategic Grant, "Intelligent Agents for Interactive Entertainment"
International Collaborations	
Indian Institute of Science, Bangalor Shalabh Bhatnagar	Joint research with R. Sutton, M. Ghavamzadeh, and M. Lee on actor-critic RL algorithms
University of Paris South Sylvain Gelly	Joint research with D. Silver on the use of RL in Computer Go
Jean-Yves Audibert	Joint research with C. Szepesvari on variance estimation in bandit problems
University of New South Wales, Australia E. James Kehoe	Joint research with R. Sutton, E. Ludvig and J. Neufeld on the relationship between reinforcement learning and learning in animals
University of Michigan Satinder Singh	Joint research with R. Sutton on predictive state representations and temporal-difference networks
Industrial Collaborations	
Michael James, Toyota Motor Corporation	With R. Sutton and M. Shahamiri exploring the use of reinforcement learning technology for improving the fuel efficiency of gas-electric hybrid cars

RESEARCH COLLABORATIONS

Role	*Conference/Journal/Activity*
M. Bowling	
Volunteer chair	23rd International Conference on Machine Learning
Senior program committee	22nd National Conference on Artificial Intelligence
Program committee	20th Annual Conference on Neural Information Processing Systems
Program committee	20th International Joint Conference on Artificial Intelligence
Program committee	Journal of Field Robotics
Program committee	24th Annual International Conference on Machine Learning
Program committee	2007 Robotics: Science and Systems Conference
M. Ghavamzadeh	
Program committee	20th Annual Conference on Neural Information Processing Systems
Program committee	20th International Joint Conference on Artificial Intelligence
Program committee	6th International Joint Conference on Autonomous Agents and Multiagent Systems
Program committee	24th International Conference on Machine Learning
Program committee	22nd National Conference on Artificial Intelligence
D. Schuurmans	
Associate editor	Artificial Intelligence Journal
Senior program committee	22nd Conference on Artificial Intelligence
Senior program committee	21st Annual Conference on Neural Information Processing Systems
Program committee	20th International Joint Conference on Artificial Intelligence
Program committee	Conference on Empirical Methods in Natural Language Processing Conference on Computational Natural Language Learning
R. Sutton	
Senior program committee	23rd International Conference on Machine Learning
Program committee	20th Annual Conference on Neural Information Processing Systems

Role	*Conference/Journal/Activity*
Cs. Szepesvari	
Associate editor	AI Communications
Senior program committee	17th European Conference on Machine Learning
Program committee	20th Annual Conference on Neural Information Processing Systems
Program committee	20th International Joint Conference on Artificial Intelligence
Program committee	23rd International Conference on Machine Learning
Program committee	24th International Conference on Machine Learning
Program committee	21st National Conference on Artificial Intelligence
Program committee	22nd National Conference on Artificial Intelligence
Program committee	20th Annual Conference on Learning Theory
B. Tanner	
Organizer and co-chair	Grounding Perception, Knowledge, and Cognition in Sensori-motor Experience, a workshop at the 20th Annual Conference on Advances in Neural Information Processing Systems
Program committee	5th International Joint Conference on Autonomous Agents and Multiagent Systems
A. White	
Organizer and co-chair	The First Annual Reinforcement Learning Competition, a workshop at the 20th Annual Conference on Advances in Neural Information Processing Systems

RLAI team members hosted many prominent short-term visitors during the reporting period, including: Scott Sanner (University of Toronto), Pascal Poupart (University of Waterloo), Doron Tal (Research Institute for Advanced Computer Science at NASA Ames Research Center), Koby Crammer (University of Pennsylvania), James Kehoe (University of New South Wales), Kocsis Levente (Computer and Automation Research Institute, Hungarian Academy of Sciences), Eva Czabarka (University of South Carolina), Laszlo Szekely (University of South Carolina), Liang Huang (University of Pennsylvania), Alex Strehl (Rutgers University), Sylvain Gelly (University of Paris South), Peter Auer (University of Leoben), Wenye Li (The Chinese University of Hong Kong), Jean-Yves Audibert (Centre d'Enseignement et de Recherche en Technologies de l'Information et Systèmes, Ecole Nationale des Ponts et Chaussées)

FUNDING

Dr. Richard Sutton received a five year iCORE Chair award ($3M). This year he and his team received federal funding from NSERC ($373K), provincial funding from Alberta Ingenuity ($964K), and funding from other sources ($342K). One of his team members, Dr. Schuurmans, received a Tier 2 Canada Research Chair ($100K/year).

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

A. Antos, Cs. Szepesvári and R. Munos, "Learning Near-optimal Policies with Bellman-Residual Minimization Based Fitted Policy Iteration and a Single Sample Path," *Machine Learning Journal*, to appear.

A. Blum, T. Sandholm, and M. Zinkevich, "Online Algorithms for Market Clearing," *Journal of the ACM*, Sept. 2006, Vol. 53, No. 5, pp. 845-879.

E.A. Ludvig, K. Conover, P. Shizgal, "Effects of Reward Magnitude on Timing in Rats," *Journal of Experimental Analysis of Behavior*, Mar. 2007, 87, pp. 201-218.

M. Zinkevich, A. Greenwald, M. Littman, "A Hierarchy of Prescriptive Goals for Multiagent Learning," *Artificial Intelligence*, to appear.

HIGHLY REFEREED ARCHIVAL CONFERENCE PROCEEDINGS

P.Auer, R. Ortner and C. Szepesvári, "Improved Rates for the Stochastic Continuum-Armed Bandit Problem Time Associative Bandit Problems," *Proc. of the 20th Annual Conf. on Learning Theory*, (COLT-07), to appear. 43% acceptance rate.

N. Bard, M. Bowling, "Particle Filtering for Dynamic Agent Modelling in Simplified Poker," *Proc. of the 22nd Conf. on Artificial Intelligence* (AAAI-07), 2007, to appear. 27% acceptance rate.

S. Bergsma and Q. Wang, "Learning Noun Phrase Query Segmentation," *Proc. of EMNLP-CoNLL 2007,* to appear. 17% acceptance rate of oral presentations.

I. Biro, Z. Szamonek and C. Szepesvári, "Sequence Prediction Exploiting Similarity Information, *Proc. of the 20th Int'l Joint Conf. of Artificial Intelligence,* (IJCAI-07), 2007, to appear. 35% acceptance rate.

L.Cheng, SVN. Vishwanathan, D. Schuurmans, S.Wang, and T. Caelli, "Implicit Online Learning with Kernels," *Proc. Neural Information Processing Systems 20* (NIPS-06), 2006. 24% acceptance rate.

S. Gelly, and D. Silver, "Combining Online and Offline Knowledge in UCT," *Proc. of the 24th Int'l Conf. on Machine Learning*, (ICML-07), 2007, to appear. 29% acceptance rate.

A. Geramifard, M. Bowling, M. Zinkevich, and R.S. Sutton, "iLSTD: Eligibility Traces and Convergence Analysis," *Proc. Neural Information Processing Systems 20* (NIPS-06), 2006. 24% acceptance.

M. Ghavamzadeh, and Y. Engel, "Bayesian Policy Gradient Algorithms," *Proc. Neural Information Processing Systems 20* (NIPS-06), 2006. 24% acceptance rate.

M. Ghavamzadeh and Y. Engel, "Bayesian Actor-Critic Algorithms," *Proc. of the 24th Int'l Conf. on Machine Learning* (ICML-07), 2007, to appear. 29% acceptance rate.

A. Ghodsi, F. Southey, and D. Wilkinson, "Improving Embeddings by Flexible Exploitation of Side Information," *Proc. of the 20th Intl. Joint Conf. on Artificial Intelligence* (IJCAI-07), 2007, to appear. 35% acceptance rate.

Y. Guo, and D. Schuurmans, "Convex Structure Learning for Bayesian Networks: Polynomial Feature Selection and Approximate Ordering," *Proc. of the 22nd Conf. on Uncertainty in Artificial Intelligence* (UAI-06), 2006. 31% acceptance rate.

A. György, L. Kocsis, I. Szabó, and C. Szepesvári, "Continuous Time Associative Bandit Problems," *Proc. of the 20th Int'l Joint Conf. of Artificial Intelligence* (IJCAI-07), 2007, to appear. 35% acceptance rate.

J. Huang, A. Smola, A. Gretton, K. Borgwardt, and B. Schoelkopf, "Correcting Sample Selection Bias by Unlabeled Data," *Proc. Neural Information Processing Systems 20* (NIPS-06), 2006. 24% acceptance rate.

J. Huang and D. Schuurmans, "Information Marginalization on Subgraphs," *Proc. 17th European Conf. on Machine Learning and the 10th European Conf. on Principles and Practice of Knowledge Discovery in Databases* (ECML/PKDD-06), 2006. 14% acceptance rate.

J. Huang, T. Zhu, and D. Schuurmans, "Web Community Identification From Random Walks," *Proc. 17th European Conf. on Machine Learning and the 10th European Conf. on Principles and Practice of Knowledge Discovery in Databases* (ECML/PKDD-06), 2006. 14% acceptance rate

F. Jiao, S. Wang, C. Lee, R. Greiner, and D. Schuurmans, "Semi-Supervised Conditional Random Fields for Improved Sequence Segmentation and Labeling," *Proc. Joint Conf. of the Int'l Committee on Computational Linguistics and the Association for Computational Linguistics* (COLING/ACL-06), 2006. 23% acceptance rate.

F. Jiao, J. Xu, L. Yu, and D. Schuurmans, "Protein Fold Recognition Using the Gradient Boost Algorithm," *Computational Systems Bioinformatics Conf.* (CSB-06). 19% accep-tance rate.

L. Kocsis and C. Szepesvári, "Bandit Based Monte-Carlo Planning," *Proc. of the 17th European Conference on Machine Learning* (ECML-06), 2006, LNCS/LNAI 4212, pp. 282-293. 14.5% acceptance rate.

R.S. Sutton, A. Koop, and D. Silver, "On the Role of Tracking in Stationary Environ-ments," *Proc. of the 24th Int'l Conf. on Machine Learning*, (ICML-07), 2007. 29% acceptance rate.

C. Lee, S. Wang, F. Jiao, D. Schuurmans, and R. Greiner, "Learning to Model Spatial Dependency: Semi-Supervised Discriminative Random Fields," *Proc. Neural Infor-mation Processing Systems 20* (NIPS-06), 2006. 24% acceptance rate.

M. Littman, N. Ravi, A. Talwar, and M. Zinkevich, "An Efficient Optimal-Equilibrium Algorithm for Two-Player Game Trees," *Proc. of the 22nd Conf. on Uncertainty in Artificial Intelligence* (UAI-06), 2006. 31% acceptance rate.

D. Lizotte, T. Wang, M. Bowling, and D. Schuurmans, "Automatic Gait Optimization with Gaussian Process Regression," *Proc. of the 20th Int'l Joint Conf. on Artificial Intelligence* (IJCAI-2007), 2007, to appear. 35% acceptance rate.

A. Milstein and T. Wang, "Localization With Dynamic Motion Models: Motion Model Parameters Dynamically in Monte Carlo Localization," *Proc. of the 3rd Intl. Conf. on Informatics in Control, Automation and Robotics* (ICINCO 2006), 2006. 10% acceptance rate.

N. Ratliff, J. Bagnell, and M. Zinkevich, "Maximum Margin Planning," *Proc. of the 23rd Int'l Conf. on Machine Learning* (ICML-2006), 2006. 20% acceptance rate.

N. Ratliff, D.Bagnell, M. Zinkevich, "Subgradient Methods for Structured Prediction," *Artificial Intelligence and Statistics 11* (AISTATS-07), 2007.

D. Silver, R.S. Sutton, and M. Mueller, "Reinforcement Learning of Local Shape in the Game of Go," *Proc. of the 20th Int'l Joint Conf. on Artificial Intelligence*, (IJCAI-07), 2007. 35% acceptance rate.

F. Southey, W. Loh, and D. Wilkinson, "Inferring Complex Agent Motions from Partial Trajectory Observations," *Proc. of the 20th Int'l Joint Conf. on Artificial Intelligence* (IJCAI-2007), 2007. 35% acceptance rate.

B. Tanner, V. Bulitko, A. Koop, and C. Paduraru, "Grounding Abstraction in Predictive State Representations," *Proc. of the 20th Int'l Joint Conf. of Artificial Intelligence* (IJCAI-07), 2007. 35% acceptance rate.

Q. Wang, D. Lin, and D. Schuurmans, "Simple Training of Dependency Parsers via Structured Boosting," *Proc. Neural Information Processing Systems 20* (NIPS-06), 2006. 24% acceptance rate.

Q. Wang, D. Lin and D. Schuurmans, "Simple Training of Dependency Parsers via Structured Boosting", *Proc. of the 20th Int'l Joint Conf. of Artificial Intelligence* (IJCAI-07), 2007, pp. 1756-1762. 35% acceptance rate.

L. Xu, D. Wilkinson, F. Southey and D. Schuurmans, "Discriminative Unsupervised Learning of Structured Predictors," *Proc. of the 23rd Int'l Conf. on Machine Learning* (ICML-06), pp. 1057-1064. 20% acceptance rate.

D. Zhou, J. Huang, and B. Schoelkopf, "Learning with Hypergraphs: Clustering, Classification, and Embedding", *Proc. Neural Information Processing Systems 20* (NIPS-06), 2006. 24% acceptance rate.

M. Zinkevich, M. Bowling, N. Burch, "A New Algorithm for Generating Equilibria in Massive Zero-Sum Games," *Proc. of the 22nd National Conf. on Artificial Intelligence* (AAAI-07), 2007, to appear. 27% acceptance rate.

SPECIAL INVITED PRESENTATIONS

May, 2006, "Learning to Cooperate using Hierarchical Reinforcement Learning," presented at the workshop on Hierarchical Autonomous Agents and Multi-Agent Systems (H-AAMAS), at the *fifth Int'l Joint Conf. on Autonomous Agents and Multiagent Systems* (AAMAS-2006), Hakodate, Japan, Mohammad Ghavamzadeh.

June 13, 2006, "Learning to Control an Octopus Arm with Gaussian Process Temporal Difference Methods," *Gaussian Processes in Practice workshop*, Bletchley Park, UK, Yakov Engel.

June 29, 2006 “Gaussian Process Temporal Difference Learning - Theory and Practice,” *Kernel machines and Reinforcement Learning workshop*, ICML’06, Pittsburgh, PA., Yakov Engel.

July 10, 2006, “Incremental Least-Squares Temporal Difference Learning,” AI seminar at *Carnegie Mellon University*, Michael Bowling.

July 12, 2006, “Convex Training Algorithms for Hard Machine Learning Problems,” Plenary Lecture at the *Center for Language and Speech Processing, summer workshop*, Johns Hopkins University, Dale Schuurmans.

August 24, 2006, “Predictive Action Descriptions from Experience,” presented at *Inductive Logical Programming 2006* in Santiago de Compostela, Spain, Brian Tanner.

November 8, 2006, “Games, Optimization, and Online Algorithms,” *Session on Online Convex Optimization, INFORMS 2006*, Pittsburgh, PA, Martin Zinkevich.

December 8, 2006, “What’s Wrong with Reinforcement Learning,” at the workshop: *Towards a New Reinforcement Learning at the Twentieth Annual Conference on Neural Information Processing Systems* (NIPS-2006), Richard Sutton.

December 8, 2006, “Grounding Artificial Cognition,” at the workshop: Grounding Perception, Knowledge and Cognition in Sensori-Motor Experience at the *Twentieth Annual Conference on Neural Information Processing Systems* (NIPS-2006).

December 8, 2006, “Bayesian Reinforcement Learning with Gaussian Processes,” at the workshop: *Towards a New Reinforcement Learning at the Twentieth Annual Conference on Neural Information Processing Systems* (NIPS-2006), Yakov Engel.

December 8, 2006, “Bayesian Policy Gradient Algorithms” at the workshop: *Towards a New Reinforcement Learning, at the Twentieth Annual Conference on Neural Information Processing Systems* (NIPS-2006), Mohammad Ghaamzadeh.

December 8, 2006, “Using Upper Confidence Bounds to Control Exploration and Exploitation,” at the workshop: On-line Trading of Exploration and Exploitation, at the *20th Annual Conference on Neural Information Processing Systems* (NIPS-2006), Csaba Szepesvari.

December 8, 2006, “Sample Complexity Results for Reinforcement Learning in Large State Spaces,” at the workshop: *Towards a New Reinforcement Learning at the Twentieth Annual Conference on Neural Information Processing Systems* (NIPS-2006), Csaba Szepesvari.

February 5, 2007, “A Reinforcement Learning Model of Response Timing in Classical Conditioning” part of Focus Session on “Modeling Data” at *Winter Conference on Animal Learning & Behavior*, Winter Park, Co, Elliot Ludvig.

AWARDS

The Alberta Ingenuity Center for Machine Learning, four of whose eight principal investigators are the four principal investigators of this RLAI project, received the Alberta Science and Technology Leadership Foundation (ASTech) 2006 award for Outstanding Leadership in Alberta Technology.

Michael Bowling was awarded an Alberta Ingenuity New Faculty grant to pursue “Subjective Models for Autonomous Robots.”

The following paper won the best student paper award at 2007 IEEE International Symposium on Approximate Dynamic Programming and Reinforcement Learning:

T. Wang, M. Bowling, and D. Schuurmans, “Dual Representations for Dynamic Programming and Reinforcement Learning.”

THESES

Alborz Geramifard, (MSc thesis), “iLSTD,” December 12, 2006.

Cosmin Paduraru, (MSc thesis), “Planning with Approximate and Learned MDP Models,” December 12, 2006.

Eddie Rafols, (MSc thesis), “Temporal Abstraction in Temporal-difference Networks,” September 29, 2006.

Adam White, (MSc thesis), “A Benchmarking System for Reinforcement Learning,” September, 2006.

Intelligent Sensing Systems

The past year in the NSERC/iCORE Syncrude/Matrikon Industrial Research Chair Intelligent Sensing Systems (ISS) research program has been one of consolidation.

As the team completes the third year and enters the fourth year of the Chair research, focus is shifting from the research of fundamental algorithms to the application of these algorithms in an attempt to demonstrate the value of this research.

The long-term direction of the Chair's research program is to push the scientific envelope of information and communication technologies and apply these technologies to the optimization of the performance of oil sands mining operations. The team studies sensor processing algorithms for monitoring the various stages of oil sands mining. This research will lead to objective performance models of the mining components as well as the entire mining process. These performance models will enable the industry to improve the performance of its mining process by maximizing the throughput, while minimizing the rejects and its environmental impact.

A key performance indicator of the mining process is the size of the oil sand ore as it progresses through the ore sizing and delivery pipeline. On that basis, the research addresses two areas that are fundamental for objectively evaluating a mining process focusing on ore size: reliable sensor processing algorithms for ore size measurement under variable environmental conditions and, statistical modeling of a system and its components with respect to the performance metrics.

The ISS team's approach to a comprehensive framework for the oil sand size analysis throughout the oil sand sizing process has been primarily based on the use of gray-scale intensity images, captured in the mine by existing video cameras and transmitted to the university laboratory. The gray-scale images can be analyzed as individual frames, a motion sequence or motion stereo pairs. The team's research was first developed with close interaction with the industry partner (Syncrude), and technology transfer partner (Matrikon).

The ISS's main achievements in the last year include

- Completion of an ore size measurement system for rejects processing,
- Evaluation of two competing algorithms for detecting large frozen lumps,
- Development of a prototype image editor for manually producing segmentation ground truth,
- Introduction of a new system for delivering live video from the mine in Fort McMurray to the university laboratory,
- Novel study of the screen performance with respect to the process variables, and
- Development of software for monitoring ore size in a pilot near-face slurry technology (INBIT).

Efforts, as thesis research, have also been made in:

- Investigation of a neural network based solution to the problem of automatic image feature selection for segmentation, and
- A biologically inspired approach to object detection using edge and motion, and its application to the detection of large frozen lumps.

This past year an addition of a junior faculty member, Prof Nilanjan Ray, an expert in image processing, also joined the ISS research team. The ISS team has expanded their collaborative research with other members of the Department of Computing Science and with Syncrude.

Research Program Overview

The primary challenge in the Chair's research has been the development of image processing algorithms for the analysis of ore size at various junctions of the mining process. These algorithms need to be reliable to work in an industrial setting and robust with respect to lighting and ore appearance changes, and they need to be developed in a way that can be easily integrated in the existing mining operations so that the research causes minimum interruption to mining operation in the technology integration process.

In the first three years of the ISS team's research, several application-driven algorithms have been developed, aiming at three parts of the mining process: crusher, conveyor belt, and rejects processing. The operating conditions are unique in each case, and they call for considerably different solutions. The ISS researchers' first target application – size measurement over a conveyor belt (conveyor OSA) - has matured to the point where the performance of the team's algorithm is state-of-the-art and delivers satisfactory performance, in spite of the fact that the noticeable differences still exist between the manually segmented ground truth images and automatically segmented images. However, in statistically terms, these differences may not be significant in most applications.

The ISS team has allocated considerable effort in developing competing solutions to the problem of detecting large frozen lumps when ore enters a crusher. It is an alarm system that alerts the crusher operators of impending large ore fragments that could potentially jam the crusher and cause production downtime. The team has developed two algorithms so far, one based on region segmentation of a static image and another based on background subtraction and a Markov Random Field (MRF) model. These algorithms have been thoroughly evaluated objectively against two image datasets, and a good understanding has been reached with regard to their performance. The plan with the large lump detection algorithms is to find an appropriate mechanism to implement the system, further improve the system's performance, and develop a third and possibly superior solution that is biologically inspired by human visual perception of objects in motion. These issues will be revisited during the winter months when large frozen lumps occur due to cold weather conditions.

Another research initiative that has been undertaken in the last year is the development of an image-editing tool designed specifically for manually segmenting ore images. The system, called OreTracer, has proved to be an extremely valuable tool in several areas. First, it has sped up the process of generating ground truth images, which are necessary in order to objectively and quantitatively evaluate various image segmentation algorithms. Second, it is being ported so that it can be used by Syncrude researchers to manually produce ore size measurements in situations where automated measurement is either unavailable or unreliable. Finally, it may serve as a front end of machine learning algorithms that use human editing sessions rules or patterns where humans segment images or revise machine-segmented images.

A developmental activity in the past year saw the reincarnation of Dirt-TV, the video link connecting Syncrude's North Mine to the University of Alberta (U of A) laboratory, moving towards transmitting images/video via the internet -- with respect to video feeds, reception and transmission options (rates, date and time, etc.) -- and less expensive than the predecessor. The new system is able to deliver live images to the Centre for Intelligent Mining Systems (CIMS) lab at a rate of one frame per second or in bursts of hundreds of consecutive images in a sequence, both of which adequately serve the purpose of gaining access to field data in real time.

In a secondary research priority area, the ISS research team has continued to work on mining equipment modeling. Specifically, a MSc thesis is being completed in the area of modeling the behavior of static sieving screens used by Syncrude to prevent over-size materials from entering the pumping and piping system. No such models exist for the set of operating conditions encountered in oil sand industry, and interesting observations have been collected in the study. The project on modeling the behavior of shovel cable with respect to its lifespan has not only shed light on relating operator practice variables to cable lifespan, but also provided Syncrude with a valuable case study for understanding how machine learning and data mining techniques can be used to interpret and analyze time-series telemetry data related to mining equipment.

Research Projects

This section of the report reviews research projects completed or mostly completed by the ISS team in the last year in both image segmentation algorithms and mining equipment models. On-going projects will be introduced in the next section.

Classification Driven Watershed Segmentation

The ISS team has developed a novel approach for creation of topographical function and object markers used within watershed image segmentation. Typically, marker-driven watershed segmentation extracts seeds indicating the presence of objects or background at specific image locations. The marker locations are then set to be regional minima within the topological surface (typically, the gradient of the original input image), and the watershed algorithm is applied. In contrast, The ISS team's approach uses two classifiers, one trained to produce markers, the other trained to produce object boundaries. As a result of using machine-learned pixel classification, the proposed algorithm is directly applicable to both single channel and multi-channel image data. Additionally, rather than flooding the gradient image, the team uses the inverted probability map produced by the second aforementioned classifier as input to the watershed algorithm. Experimental results demonstrate the superior performance of the classification-driven watershed segmentation algorithm for the tasks of image-based granulometry and remote sensing.

Image Segmentation via Multi-Slicing and Shape Learning

In this project, the team has developed an image segmentation system specifically targeted for oil sand ore size analysis. The segmentation scheme learns spectral and shape characteristics of training images of oil sand ore samples and builds a feature map via regression. The learning of spectral properties is successfully applied to enhance the image quality where significant contrast enhancement of the input image is achieved. To search an oil sand fragment, the shape of binary connected components, obtained through threshold decomposition of the enhanced image at every intensity level, is checked against likely oil sand shape features, such as area, shape solidity and eccentricity. Furthermore it is shown that the shape properties, which identify an oil sand fragment, can also be learned by the system enabling a practical system to contain a minimal number of tuning parameters. The efficacy of the system is demonstrated on real oil sand ore images and superior accuracy is achieved over the current state of the art systems. The team's integrated approach to image segmentation has the potential to be useful in a variety of other applications.

Large Lump Detection with Background Subtraction

Background subtraction is an effective technique for motion detection. Most traditional background subtraction algorithms assume a moving object (or objects) with respect to a static background, and segment the moving object(s) by classifying pixels into foreground and background with trained statistical models. Because classical background subtraction algorithms work with intensity images, they cannot handle situations in which all pixels are moving. To address this deficiency, the ISS team is presenting a novel background subtraction algorithm that is capable of detecting objects of interest while all pixels are in motion. The key idea behind this algorithm is to work with feature images, rather than the raw intensity images, in which foreground and background exhibit sufficiently different statistics. The team uses texture as the feature, extracted with circular Gabor filters at five different bands, to study the problem of detecting large objects (rocks) moving amid small fragments, in the application of detecting large frozen ore lumps traveling into a crusher. This is a problem of practical significance in order for a mining company to reduce the risk of the jamming of a crusher by detecting large lumps and taking preventive measures.

Local Adaptive Thresholding

The ISS researchers have investigated automated methods for gray-level image thresholding techniques toward producing segmentation. The team's proposed thresholding method is locally adaptive and can handle intensity variations to a good extent. Unlike other commonly available locally adaptive thresholding techniques, the team's proposed technique requires no tuning parameters. The absence of tuning parameters is particularly helpful as a preprocessing step in an automated segmentation system, because a practical system is anyways expected to have tuning parameters and finding the tuning parameter values is always a challenge. Thus the proposed thresholding method, being part of a segmentation system, will help ease the parameter tuning effort in a practical segmentation technique.

Segmentation Using Multiple Cues

Large lumps of oil sand may jam the crusher, especially in wintertime. Large lump removal, accompanied by plant's downtime, is very costly for the production process. Timely detection of large oil sand lumps would allow the plant operator to avoid such delay by having large lumps removed before it enters the crusher.

The ISS team attempts to use multiple cues of intensity, motion and shape to create a machine vision system for large lump detection. The usage of the cues is consistent with one of most prominent psychological theories of human perception called Gestalt theory. More specifically, Gestalt perceptual organization laws are used to explain the importance of each cue.

All cues are applied in succession. First, the edges are extracted using Canny edge detection at various smoothing levels of the images. Here the pixels are grouped according to the Gestalt laws of spatial proximity within the image and similarity of their intensity. Second, only moving edges are extracted and used for further processing. The second step is consistent with the grouping principle called "common fate", which states that parts that tend to move together are more prone to be a part of a single object. Third, regions are created closing the gaps between moving edges in accordance with the law of closure. Resulting regions are then filtered using the shape parameters, such as solidity, compactness and extent.

The proposed approach has not yet been quantitatively evaluated. The preliminary results show that edge-based information might be very important for large lump detection.

Performance Model of Screens

The performance model of screens research looks at modelling oil sand fixed screens that are used to prevent large particles from entering the oil sand slurry transportation system where they may cause significant damage. Alternatively, general screen models developed for the hard rock industry were examined to determine their applicability to oil sand ore.

Three types of screen modes were considered: empirical models, probability models, and kinetic models. The applicability of each model type depends on the assumptions made and the measurable variables. Due to current data measurement restrictions arising from modelling an operating plant, typical screening variables could not be used. Instead, geological and screen water usage variables collected by Syncrude during operation were considered. It was concluded that an empirical approach should be taken to developing a fixed screen model using linear regression techniques. Insight is gained into the operation of the fixed screens through the identification of important geological and water usage variables for both summer and winter operating conditions. Important variables for summer screening conditions were found to be primarily geological in nature, while winter screening conditions included water usage. The reason for this observation is being investigated to gain a greater understanding of screen performance during summer and winter conditions.

Prediction models using the significant geological and water usage variables were evaluated on data collected over a two year period using linear regression methods and cross-validation. Preliminary results show that the identified significant variables to model oil sand fixed screens perform significantly better than current performance modelling methods that consider only the material feed-rate presented to the screen. From this work, a preliminary fixed screen model was developed that explains a large portion of the previously unexplained variation in screen performance. Furthermore, the insight gained into the screening system from the geological and system water usage variables will aid operators make informed decisions during screen operation. The improved operation of the fixed screens will increase system efficiency allowing for the optimization of the overall process and a reduction in Syncrude's environmental footprint.

Prediction of Shovel Cable Lifespan

Shovels are a major piece of equipment in mining of mineral ore including oilsand. Shovel ropes are not meeting life expectations, lasting often a fraction of the design lifespan. Extending the average rope life will result in fewer ropes being used and have the side benefit of fewer unplanned shutdowns due to early rope failure. In this project, The ISS team uses the telemetry data from the motors of an electric shovel with the corresponding dispatch data, to either identify events that potentially reduce rope life or provide a predictor on rope life. The dataset includes approximately one year of eight shovels and the quantity of different materials (overburden and topsoil) dug in the corresponding period. A total of 70 complete rope histories have been extracted.

Previous studies show that, in heterogeneous materials rupture is the culmination of a self-organized damage. The precursors to rupture are useful to predict time to breakage. In the ISS team's project, the distributions of power values or products of these power values can be estimated from telemetry data. Some work has looked at these distributions and found that they are statistically different between the shovels, between the teams who jointly operate the same shovels, and between two materials (overburden and topsoil) of the same team or the same shovel. The team is investigating if and how these differences are related with the rope lifespan.

Objectives for Next Year

The ISS team's activities in the coming year consist of research in fundamental image segmentation algorithms and testing and porting of the technologies the team has developed for the end user. The algorithmic developments will focus on automatic feature extraction for image preprocessing using a layered neural network solution, semi-supervised segmentation in which humans are involved, at least initially, in the segmentation process, and an investigation of optimizing artificial lighting for image feature extraction. The transfer of technology will be mostly through participation in the INBIT project at Syncrude where ore size must be guaranteed in the screenless mining facility that is being tested, and in the team's continued effort at searching for users of the ore size measurement capabilities that have been developed within the CIMS.

The oil sand segmentation has proved to be an extremely challenging problem. In the early attempts, the ISS group examined and tried to adapt a large array of existing segmentation algorithms to this unique application domain. As a result, the ISS team has established a good mastery of the state-of-the-art image segmentation algorithms, which have been optimized for application domain. The performance of these algorithms is ultimately limited by the quality of the images that need to be processed. In order to improve the quality of the images, The researchers have worked on using artificial lighting and a major effort has been expended to design image pre-processing algorithms to enhance image quality. The team's approach has followed the direction in which a feature vector is defined for each image pixel, and that this feature vector is then used to train a classifier that computes the probability of that pixel being a member of the foreground (or background) class, with the result of being a probability map or image that has much improved quality and can make the job much easier for subsequent segmentation algorithms. While this effort continues, the team continues to study how to extract features automatically that can be used to optimize segmentation. This is in contrast to the current algorithm that involves manually defining a library of features and select through machine learning the most discriminating subset. Another technique to improve image quality is through the manipulation of artificial lighting. Study thus far has involved only empirical comparison between various lighting configurations. The optimal lighting configuration depends on the types of features to be exploited by the subsequent image segmentation algorithm.

Another new area of research will be directed toward semi-supervised segmentation. The challenge presented by oilsand ore images is that it is unlikely that an automated size measurement system will reach a level of performance approaching that of a human. As a result, manual intervention is expected to co-exist with the automatic segmentation algorithms, to create a combined, semi-supervised segmentation algorithm. Learning shape attributes that characterize good segmentation, parallel duplication of expert editing actions, and extracting image processing operator sequences and parameters that locally post-process and refine image segments are part of the ISS researcher's plans.

The team will actively participate in the pilot of near-face slurry technology, INBIT, by Syncrude. Near-face slurry removes the need for trucks and reduces the cost of mining oil sands as it places a greater demand on the crusher that it must guarantee ore size to be under a certain maximum dimension. At the testing stage, the optical size measurement is being deployed as a way to monitor ore size, and this is an excellent opportunity to demonstrate the value of the ISS team's research. INBIT images exhibit different characteristics and require an adaptation to the conveyor OSA. This is being done, and preliminary indications have demonstrated that the technology will provide reliable ore size measurement.

Preliminary examination of INBIT images shows ore fragments can be identified through a dark shadow around them. With this in mind, a promising segmentation algorithm can consist of the following three steps:

- finding candidate pixels via dimensional reduction techniques such as principal component analysis,
- treating these candidate points as seeds, applying snake/active contour based algorithm to segment the oil-sand particles, and
- eliminating false positives, by post-processing techniques.

The ISS group will explore shape as well as intensity based features for the oil-san particles to facilitate the aforementioned segmentation algorithm. Finally, temporal (image sequence) information will be used in the segmentation process.

The team has also planned other technology transfer projects, one related to exploiting opportunities, both within Syncrude and in other oil sand companies, of applying the ore size measurement software the group has developed, and the other to employing network video server as the front end for the video link between the oil sand mine and university laboratory. The second project makes use of a commercial technology that connects a video camera directly to the Internet and allows access to the video signal by any computer on the Internet. The technology will remove the need for a frame grabber and a local computer hosting the frame grabber, and is even more flexible than the current video link solution.

The coming year will be busy but exciting. It will be a critical year for the ISS researchers as they demonstrate the relevance of their research to the industrial users.

Research Team Members and Contributions

Team Leader
Professor Hong Zhang
CMS Director/Chair Holder

Faculty Team Members

Name	Role/Topic	Awards/Special Info
Melanie Calvert	Administrative Assistant	
Dr Ron Kube	CIMS co-director/industrial partner from Syncrude	
David Laing	Research Assistant	
Rajarshi Maiti	System Analyst	
Dr Mark Polak	Lab Manager	
Dr Nilanjan Ray	Assistant Professor	
Andrzej Zadorozny	System Analyst	

PostDoctoral Fellows

Name	Role/Topic	Awards/Special Info
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Dr Dongxiang Zhou		

PhD Candidates

Name	Role/Topic	Awards/Special Info
Ilya Levner		Alberta Ingenuity, iCORE
Baidya Saha		
Zhijie Wang		

MSc Candidates

Name	Role/Topic	Awards/Special Info
Maidong Hu		NSERC IPS
Yury Potapovich		
John Sheldon		NSERC IPS

Visiting Team Members

Name	Role/Topic	Awards/Special Info
Dr Dipti Mukherjee	Visiting Professor	
Lizhen Wang	Visiting Professor	

GRADUATES

Name	*Research Topic*	*Current Position*
PostDoctoral Graduates		
Dr Dongxiang Zhou	Motion Image Segmentation	National University of Defense, Technology, China
Name	*Research Topic*	*Current Position*
MSc Graduates		
Xiaoli Wang	Machine Learning for Image Segmentation	Working in US
Andrzej Zadorozny	Contrast Enhancement	5D Information Management, Edmonton

COLLABORATIONS

Participants	*Nature of Collaboration*
Provincial Collaborations	
University of Alberta Vadim Bulitko	Collaborative project
University of Alberta Joerg Sander	Joint student supervision
University of Alberta Russ Greiner	Joint student supervision
International Collaborations	
Northeast Univeristy, China Tianyou Chai	Research exchange
Syncrude CanadaRon Kube, Jim Kresta, Ian Parsons	Chair sponsor and technology user
Matrikon Mark Polak, David Shook	Chair sponsor and technology transfer

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