Centre for Intelligent Machines
Annual Report 1999

June 1998 – May 1999

McGill University
Montréal, Québec, Canada

Postal Address: 3480 University Street, Montréal, Québec, Canada H3A 2A7
Telephone: (514) 398-6319 FAX: (514) 398-7348
Network Address: cim@cim.mcgill.ca

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CIM Profile

1 Preface

1.1 Introduction

The mission statement of the Centre expresses our goals of excellence in research and graduate student education:

> *Intelligent machines are capable of adapting their goal-oriented behaviour by sensing and interpreting their environment, making decisions and plans, and then carrying out those plans using physical actions. The mission of CIM is to excel in the field of intelligent machines, stressing basic research, technology development, and education. CIM seeks to advance the state of knowledge in such domains as robotics, automation, artificial intelligence, computer vision, and systems and control theory.*

More and more this is being achieved by collaborative efforts involving researchers with very different interests. Therefore we see that the original objective of forming the Centre – to encourage interdisciplinary activities which transcend traditional departmental boundaries – is being attained.

Essential to the Centre's ability to achieve its goals and objectives is the funding provided by FCAR (Québec's Fonds pour la Formation de Chercheurs et l'Aide à la recherche), under the Programme Centres de recherche. The importance of this support can never be overstated, as it remains key to the Centre's ability to function with optimal efficiency, thus assuring that the needs of the Centre, vis à vis its faculty, students, and industrial partners, are effectively met.

NSERC, through its NCE/IRIS, research and strategic grants, continues to provide the Centre's faculty members with the valuable support necessary to maintain the highest standards of research possible. It is also a positive influence in the Centre's ability to attract and retain a highly competitive pool of talented students.

CIM fulfills its mission as a research centre with dedication and integrity. Over the years, the people of CIM have proudly assumed the role of ambassadors and mentors to multitudes of visiting scholars, international delegations, politicians, business leaders, government officials, youngsters and high school students.

The graduate students of CIM benefit profoundly by the culture of the Centre, which emphasizes teamwork and collaboration and an extraordinary willingness to share knowledge, equipment and space. Equally important, through interaction with industry, they develop a keen awareness of business issues and concerns. Thus, the spirit of entrepreneurship is alive and well at the Centre, as evidenced by the many spin-off companies that have been born of CIM graduates.

Below are some of the highlights of 1998-99.

1.2 Personnel Changes

New Members

We have been joined by three new members, *Dr. Benoit Boulet*, in Systems and Control, *Dr. Kaleem Siddiqi* in Artificial Perception, and *Dr. Venkat Krovi* in Robotics.

- Dr. Boulet, a graduate of the University of Toronto, brings with him expertise in the area of H^∞ control and several years of industry experience designing advanced control systems. One of his roles in the Centre will be to investigate applications of advanced control in the process industries which are highly critical to the Québec economy, complementing a group that is world renowned for its theoretical contributions.
- Dr. Siddiqi, a recent postdoctoral fellow from Yale University, is considered to be one of the most promising new young scientists in the field of computer vision and a leading expert in the area of shape analysis. With the arrival of Dr. Siddiqi, along with Clark and Cooperstock in 1997, the expertise of the Centre in Artificial Perception is unsurpassed by any institution in Canada.
- Dr. Krovi, a recent graduate from the University of Pennsylvania, is a leading expert in the design and analysis of mechanical systems, strongly complementing the internationally renowned program lead by Dr. Jorge Angeles.

New Director

After nearly fourteen years of helping to make CIM one of the leading robotics research institute in the world, *Professor Martin Levine* stepped down as the Director of the Centre to devote his full time to teaching, research, and continuing the tradition of successful CIM spin-off companies. On September 1, *Professor Frank Ferrie* became the new Director and thus postponed his sabbatical leave until January.

1.3 Awards and Honourable Mentions

- Recipient AIRTC'98 Best Paper Award: *Prof. Peter Caines, T. Mackling, C. Martinez-Mascarua*, "COCOLOG Logic Control for Hierarchical and Hybrid Systems", Presented at the 7th IFAC International Symposium on Artificial Intelligence in Real Time Control, Grand Canyon, AZ. USA, October 5 - 8, 1998.
- *Prof. Peter Caines:* Visiting Professor: The Chinese University of Hong Kong, Department of Mechanical and Automation Engineering, August 1997 - June 1998.

1.4 New Research Projects

- The establishment of the Human Computer Interface (HCI) theme is a reflection of the changing role of information technology in the mission of the Centre. Although information technologies are revolutionizing society, real breakthroughs will be dependent on the ability of information systems to interact on human terms, i.e. to perceive, reason, and act in response to a given task. The latter characteristics are precisely the definition of an intelligent machine. HCI research leverages our expertise in artificial perception, robotics, and systems and control in an entirely new direction to create intelligent information systems. Working with our colleagues at Université de Montréal, Concordia, and Université de Québec Montréal, we have already begun to investigate the application of our work in artificial perception to the problem of database retrieval. Thanks to new funding by the Canadian Foundation for Innovation, a new initiative in shared reality environments (in collaboration with the McGill Faculty of Music) headed by Clark and Cooperstock will take our expertise into an entirely new domain - at the leading edge of the information revolution. Bolstered by a cadre of enthusiastic new young scientists and building on the strengths developed during its first decade, the Centre is now ready to face the challenges of the millennium.

- *Prof. Frank Ferrie* is a Principal Investigator in the new GEOID (Geomatics and Informed Decisions) NCE, research programme. The new networks are not only a key source of funding for CIM but also a critical link for the Centre into some of the most important collaborative research projects in the country.
- Shared Reality Environment, *(Profs. Cooperstock and Clark),* funded by a New Opportunities grant from the Canadian Foundation for Innovation.
- Tactile Display Based on Lateral Skin Stretch Stimulation, *(Prof. Vincent Hayward)* NCE funded (in collaboration with Queen's University, Psych., Prof. Lederman).
- Haptically Assisted Manipulation of Medical Images, *(Prof. Vincent Hayward)* NCE funded (in collaboration with Robarts Institute, Ont., Dr. Peters).
- Synthesis of Haptic Signals in Virtual Environments, *(Prof. Vincent Hayward)* NCE funded (in collaboration with UBC, CS, Prof. Pai).
- In collaboration with *Prof. C.D. Charalambous, Prof. Peter Caines* is now a Network Investigator of the MITACS (Mathematics of Information Technology and Complex Systems), NCE, research programme. This is a three to four year research programme on information technology and complex systems and spans researchers in institutions across Canada.
- *Prof. Jorge Angeles* and Prof. Patel (Concordia), Bombardier and Canadian Space Agency Strategic Project Title: A Framework for the Design and Control of a Macro-Micro Manipulator System (M3).

1.5 Conferences Attended and Visits Hosted

- CIM has had the pleasure of hosting several long-term visitors this year. Among them were: *Prof. Michel Taix* from l'Université Paul Sabatier, Toulouse, France is collaborating with Prof. Gregory Dudek until August 1999. Prof. Jorge Angeles hosted *Prof. Giorgio Figliolini* from the University of Cassino, Italy as well as *Prof. Marek Kujath* from Dalhousie University, NS from September 98 to February 99. *Kamal Bouyoucef* from the University of Algeria spent the fall semester working with Prof. Vincent Hayward.
- CIM organizes three series of lectures on a regular basis throughout the year: seminars in Computer Vision, in Systems and Control and in Robotic Mechanical Systems. The latter is supported by a Seminar Grant from the Faculty of Graduate Studies and Research.
- The Centre welcomes many young visitors on an ongoing basis. During 1998-99 various students from local summer camps and high schools such as Reach Summer Camp and Jewish Vocational Services were given tours and demos of the labs and an opportunity to ask about careers in engineering.
- This year again CIM faculty and students presented papers and seminars at conferences around the world. Some of the major ones attended were:
  - June 1998: IRIS/PRECARN Conference, Vancouver, B.C.;
  - May 27-29: 2nd International Conference on Integrated Design and Manufacturing in Mechanical Engineering, at Université de Technologie de Compiegne, FR;
  - June 29-Jul 4:6th International Symposium on Advances in Robot Kinematics, Strobl/Salzburg, Austria;
  - July 6-9:Twelfth CISM-IFToMM Symposium on the Theory and Practice of Robots and Manipulators – Ro.Man.Sy. 98. Paris;
  - Sept. 28 -29: Symposium on "El Papel Que Juega la Investigacin en la Formacin de Alumnos y Profesores de Ingeniera," Universidad de Guanajuato, MX;

  - Nov. 9-13: Workshop on the Occasion of the 60th Anniversary of the Moscow Institute of Machines, Moscow;
  - May 1998: IEEE International Conference on Robotics and Automation (ICRA) Leuven, Belgium;
  - June 1998:Conference on Computer Vision and Pattern Recognition (CVPR) Santa Barbara, CA;
  - June 1998: Workshop on Perception for Mobile Agents, Santa Barbara, CA; July 1998: Telluride Workshop on Neuromorphic Engineering, Telluride, CO;
  - March 1999; 6th Int. Symp. on Experimental Robotics, Sidney, AU; May 1999: IEEE Int. Conf. on Robotics and Automation, Detroit;
  - Dec. 1998: Int. Conf. on Decision and Control,. San Diego, CA;
  - Nov. 1998: Innovation in Industrial Actuator Design, Int. Mechanical Engineering Congress and Exposition, Anaheim, CA;
  - April 13-15, 1998: First International Workshop on Hybrid Systems: Computation and Control, HSCC '98, U. C. Berkeley, CA;
  - Dec. 1998: 37th IEEE Conference on Decision and Control, Tampa, FL;
  - Oct. 5 - 8, 1998: 7th IFAC International Symposium on Artificial Intelligence in Real Time Control, AZ;
  - August 1998: IEE International Workshop on Discrete Event Systems.

- During his leave of absence, for the academic year 1997-1998, at the Chinese University of Hong Kong, *Professor Peter Caines* presented research seminars at several institutions. In particular, he gave talks at Hong Kong University, The City University of Hong Kong, The Hong Kong Baptist University, and the Hong Kong University of Science and Technology, as well as at the New Delhi Institute of Technology, the NASA-Ames Research Center, CA, and at the Brockettfest, Harvard University.

1.6 Public Relations

- January 1999, The McGill Reporter featured Professor Jeremy Cooperstock, *"Putting Technology in it's Place"*.
- April 25, 1999, The Montreal Gazette featured Professor Gregory Dudek in an article on robots: *"In Reality, Robots are Still Dunces"*.
- On February 17, 1999, at The Study School Science Fair, 3233 The Boulevard, Westmount, the following CIMites acted as judges: Gilbert Soucy, Tal Arbel, Richard Unger, Eric Bourque, Alain Domerq, Diana Hernandez.
- Discovery Channel (Cable 37) visited the Centre on September 16th to meet with several members of CIM and film many of our robots in action. Cameras were set up in the various labs and interviews were conducted throughout the course of the day. Under the bright lights, Professors Levine, Hayward, Buehler and Dudek, and students from the ARL, MRL, and Haptic Lab answered questions relating generally to robotics in space, orbital medicine, space stress and art in space. The episode, called *"Robots in Space"* was aired in March 1999.
- The CIM logo will hang on the wall of the next Space Shuttle as it takes off with our Astronaut Julie Payette on May 27, 1999.

Frank Ferrie
Director
McGill Centre for Intelligent Machines (CIM)

2 Overview of CIM

2.1 History

Research in intelligent machines involves the study of the complexities of human processes – thinking, feeling, seeing, moving, making decisions and carrying out specific tasks. The Centre for Intelligent Machines was founded in 1985 to provide researchers in robotics, computer vision, speech recognition and systems and control with a context in which to pursue a common goal: the understanding and creation of systems which exhibit intelligent behaviour.

At the peak of its first decade, CIM (then known as the McGill Research Centre for Intelligent Machines, or McRCIM), was home to 16 academic members working across many disciplines – the Departments of Electrical, Mechanical, Biomedical and Mining and Metallurgical Engineering and the School of Computer Science. The Centre reports to the Faculty of Engineering and the Faculty of Graduate Studies and Research of McGill University.

2.2 Funding

- Direct Sources:
- MESS - 1985 - 1989 - Ministère de l'Enseignement supérieur et de la science du Québec
- FCAR - 1989 - present - Fonds pour la Formation de chercheurs et l'aide à la recherche
- Indirect Sources:
- NCE/IRIS - 1989 - present - The federal government's Networks of Centres of Excellence program (NCE) established 15 networks in which the Institute of Robotics and Intelligent Systems (IRIS) is one. CIM researchers lead several IRIS projects, and provided CIM with valuable indirect support to increase its number of research engineers and technical staff, to augment its experimental research and to substantially upgrade its computer network.
- CIAR - 1984 - 1995 - Canadian Institute of Advanced Research represented by five key members of CIM.

2.3 Facilities

Since its inception, the Centre for Intelligent Machines has functioned primarily on the 4th floor of the McConnell and Macdonald Engineering Buildings. Today, this area houses 35 offices, nine labs, a computer machine room and a video editing room. Main laboratories include the Ambulatory Robotics Lab, the Artificial Perception Lab, the Haptics Lab, the Mobile Robotics Lab and the Robotic Mechanical Systems Lab.

2.4 Research Today

Presently, CIM is comprised of 17 faculty members spanning the Faculty of Engineering and the Faculty of Science, and drawing from the Departments of Electrical and Computer Engineering, Mechanical Engineering, and the School of Computer Science.

Although the core focus of the Centre has remained consistent since its formation in 1985 - robotics and intelligent machines - CIM's research is continuously evolving. Research within the Centre continues to span a broad spectrum, ranging from computational neuroscience to the design of advanced sensors and actuators. The explosion of growth within the information technology sector has spawned new and exciting initiatives within the Centre.

2.5 Students

Originating from engineering and computer science, students of CIM are enrolled in post-graduate studies related to his or her supervisor's area of expertise. In 1998-99, the student population was 83, of which 47 were PhD's and 36 were Masters. The breakdown is as follows:

- Electrical and Computer Engineering: 19 Masters, 30 Ph.D.
- Mechanical Engineering: 11 Masters, 10 Ph.D.
- School of Computer Science: 6 Master's, 7 Ph.D. and 1 Postdoc.

2.6 Contribution to Graduate Training

CIM's "culture" provides many benefits to its graduate students. Because of the emphasis on teamwork, the Centre's students develop a multi-faceted and creative approach to project management. They gain hands-on experience in giving presentations and popular lab "demos" to a diverse and challenging audience ranging from renowned scientists and high ranking executives to university graduates and grade school students, thus refining their leadership and interpersonal skills. They participate in an environment where, on a day-to-day basis, considerable attention is paid to coaching by supervisors and senior research engineers alike. Equally important, through interaction with industry, the students develop a keen awareness of business issues and concerns. One consequence to this environment has been the generation of a considerable number of spin-off companies over the past decade. These companies are largely creations of former graduate students and represent measurable success in the transfer of CIM technologies.

Additionally, CIM faculty and students contribute original research work at local, national and international forums. Needless to say, the training aspect of this participation is key in the teaching of our graduate students, who are thus encouraged to face a community of international scholars early in their research careers.

2.7 Contribution to Undergraduate Training

While CIM's role in graduate training is well recognized both within and outside the university, it is important to note that, at the undergraduate level, CIM contributes substantially in various ways. In addition to the approximately 15 undergraduate courses taught by CIM faculty members, the Centre makes a valuable contribution to undergraduate training (1) by making its research facilities available to CIM research personnel for purposes of developing courses, whereby our rich stock of hardware and software is second to none; (2) by providing the academic departments with excellent teaching assistants drawn from a talented pool of graduate students; and (3) by providing a continuous source of undergraduate projects, and the facilities in which to conduct them, to the various departments.

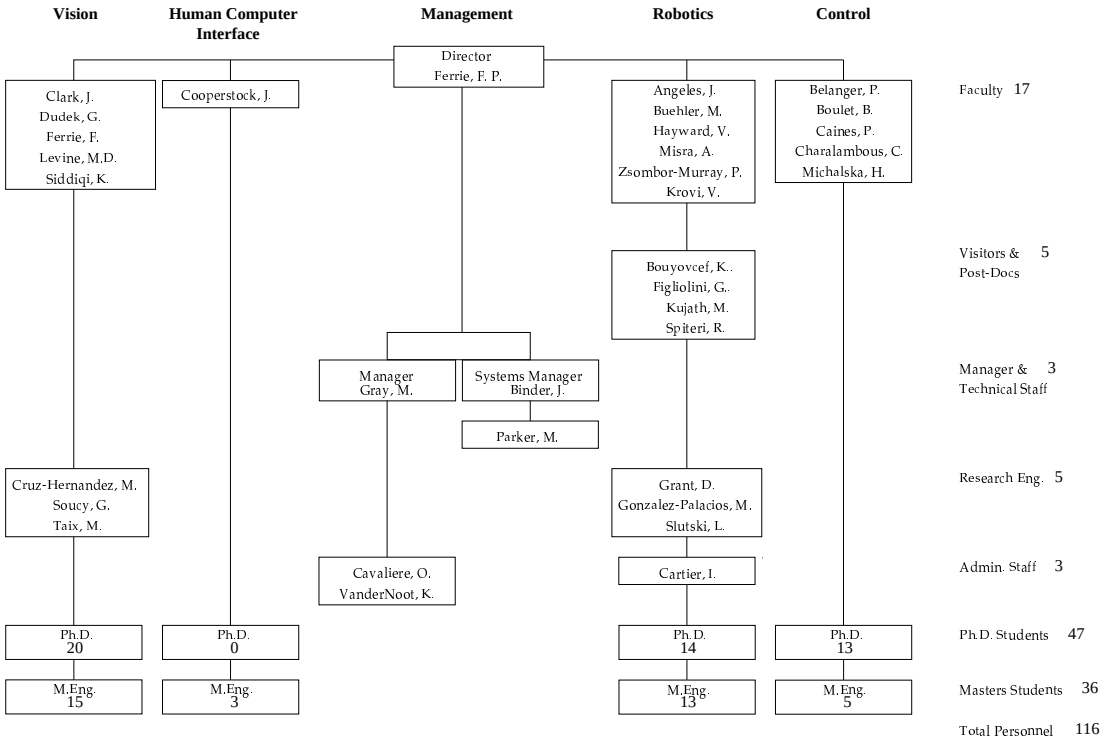


Figure 2.1: CIM Chart

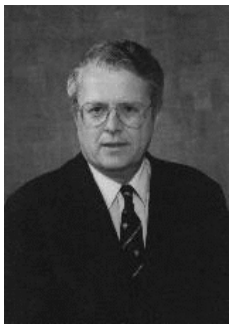
3 People

3.1 Faculty

Angeles, Jorge *514-398-6313* angeles@cim.mcgill.ca

Analysis, synthesis, and optimization of mechanical systems
- CAD/CAM integration
- Geometric modelling
- Multibody dynamics
- Robot design and control
- Theory of kinematic chains

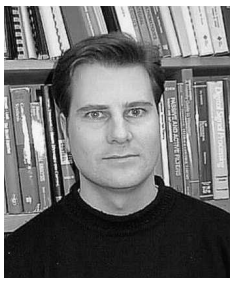
Bélanger, Pierre *514-398-5113* belanger@cim.mcgill.ca



Control systems
- Industrial process control
- Parameter identification
- Robotics

Adaptive systems
- Multivariable feedback design
- Application of adaptive/feedback control to industrial processes
- Robotic manipulator control
- Large scale and nonlinear systems
- Stochastic filtering, identification and control

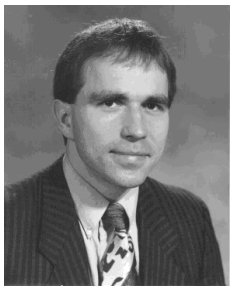
Boulet, Benoit *514-398-1478* boulet@cim.mcgill.ca



Robust control systems
- Industrial process control
- Tunable multivariable control
- Model validation
- Robotics and space structures

H-infinity control
- Fuzzy logic control
- Manufacturing execution systems

Buehler, Martin *514-398-8985* buehler@cim.mcgill.ca



Robot locomotion
- Dynamically stable legged locomotion
- Design and control of walking, climbing and running robots
- Teleoperation and autonomous operation of remote systems
- Control of direct drive mototrs and robots

Caines, Peter *514-398-7129* peterc@cim.mcgill.ca

Systems and control theory
- Hybrid and nonlinear systems
- Hierarchical control and large scale systems
- Logic control systems
- Adaptive control
- Stochastic filtering, identification and control
- Applications to robotics, air traffic control
- Industrial processes, manufacturing, communication networks

Charalambous, C. *514-398-8348* chadcha@cim.mcgill.ca

Stochastic systems and systems and control theory
- Optimal filtering
- Optimal control, decision and identification
- H∞ - optimization
- Applications of theory of large deviations
- Applications in engineering and mathematical finance

Communications systems
- Digital communications
- Wireless networks
- CDMA spread spectrum

Clark, James *514-398-2654* clark@cim.mcgill.ca

Analog VLSI smart sensors, active vision
- Visual-motor systems
- View-based recognition, attention
- Mobile robot collaboration

Computer vision
- Robotics
- Analog VLSI
- Cognitive neuroscience
- Sigal processing

Cooperstock, Jeremy *514-398-5992* jer@cim.mcgill.ca

Intelligent environments
- Ubiquitous computing
- Multimodal interfaces
- Adaptive and learning systems
- Media spaces
- Videoconference technology

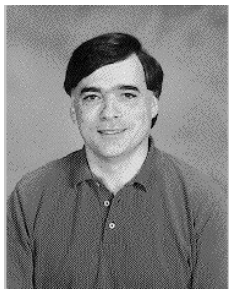
Human-computer interaction
- Artifical intelligence
- Multi-agent systems

Dudek, Gregory *514-398-4325* dudek@cim.mcgill.ca

Navigation
- Shape recognition
- Mobile robotics, telerobotics, teleoperation
- Vision and visualization, graphics, artificial intelligence

Robot mapping
- Map making, localization, pose estimation, landmark learning
- Virtual environment creation
- Object recognition
- Scene modelling

Ferrie, Frank *514-398-6042* ferrie@cim.mcgill.ca



Computer vision and artificial perception
- Active vision
- Sensors
- Environment modelling
- Shape representation
- Visual reconstruction, recognition and visualization
- Robotics
- Artificial intelligence

Hayward, Vincent *514-398-5006* hayward@cim.mcgill.ca

Robotics
- Actuators: design and control

Haptic interfaces
- Device design and control
- Rendering and simulation computational techniques
- Applications to medicine, rehabilitation and music

Krovi, Venkat *514-398-2777* venkat@cim.mcgill.ca

Mechanical, mechatronic and robotic systems
- Design for manipulation, motion and force guidance
- Design for extended human interaction
- User and task-specific customization by design
- Modular/interchangeable electronic and mechanical functionality
- Nonlinear & geometric control of constrained mechanical systems
- Rapid product realization - virtual and physical prototyping

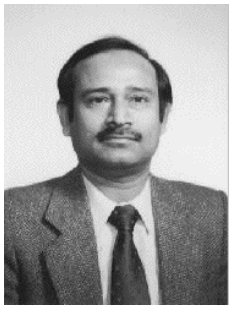
Levine, Martin *514-398-7115* levine@cim.mcgill.ca

Computer vision
- Robotics
- Image processing
- Artifical intelligence
- Graphics
- Computer vision

Michalska, Hannah *514-398-3053* michalsk@cim.mcgill.ca

Control theory
- Nonlinear systems
- Stabilization
- Optimal control
- Nonlinear feedback control design
- Application of feedback control to industrial processes
- Robotic manipulator control
- Large-scale and nonlinear systems
- Stochastic filtering, identification and control
- Control of non-holonomic systems

Misra, Arun *514-398-6288* misra@cim.mcgill.ca



Dynamics and control of space systems
- Multibody dynamics
- Space robotics
- Tethered space systems
- Space structures
- Fluid-structure interaction

Siddiqi, Kaleem *514-398-3371* siddiqi@cim.mcgill.ca

Computer vision
- Shape representation and recognition
- Efficient indexing and matching

Computer graphics and image processing
- Shape segmentation
- Image smoothing and enhancement

Psychophysics
- Shape perception
- Visual search

Zsombor-Murray, Paul *514-398-6311* paul@cim.mcgill.ca

Kinematic geometry
- Design and analysis of motion of articulated multi-rigid-body mechanisms and manipulators
- Parallel mechanisms
- Theoretical kinematics
- Computational kinematic geometry

3.2 Students

Student	Degree	Supervisor
Arbel, Taly	Ph.D	Prof. F. FERRIE
Arseneau, Shawn	M.Eng	Prof. J. COOPERSTOCK
Astley, Oliver	Ph.D	Prof. V. HAYWARD
Audette, Michel	Ph.D	Profs. K. SIDDIQI and PETERS
Battaglia, Robert	M.Eng	Prof. M. BUEHLER
Begin, Isabelle	Ph.D	Prof. F. FERRIE
Bélair, François	M.Sc.	Prof. G. DUDEK
Benoit, Stephen	Ph.D	Prof. F. FERRIE
Benzacar, Eric	M.Eng	Prof. F. FERRIE
Bérubé-Lauzière, Yves	Ph.D	Prof. F. FERRIE
Bilodeau, Glen	Ph.D	Prof. E. PAPADOPOULOS
Bouix, Sylvain	Ph.D	Prof. K. SIDDIQI
Bourque, Eric	Ph.D	Prof. G.DUDEK
Burlington, Scott	M.Eng	Prof. G. DUDEK
Cebula, Andrzej	Ph.D	Prof. P. ZSOMBOR-MURRAY
Cocosco, Anca	M.Eng	Prof. M. BUEHLER
Cruz-Hernandez, Manuel	Ph.D	Prof. V. HAYWARD
Daum, Michael	M.Sc.	Prof. G. DUDEK
de Lasa, Martin	M.Eng	Prof. M. BUEHLER
Deng, Suet Yan	M.Eng	Prof. B. BOULET
Dionne, Dany	Ph.D	Prof. H. MICHALSKA
Domercq, Alain	M.Eng	Prof. J.J. CLARK
Doutriaux, Stephane	M.Eng	Prof. J. COOPERSTOCK
Drissi-Smaïli, Fatima	Ph.D	Prof. J.J. CLARK
Dupuis, Erick	Ph.D	Profs. V. HAYWARD and E. PAPADOPOULOS
Ehtiati, Tina	Ph.D	Prof. M. LEVINE
Freguin, Jerome	M. Eng	Prof. H. MICHALSKA
Glaum, Michael	Ph.D	Profs. G. ZAMES* and C. CHARALAMBOUS
Grant, Danny	Ph.D	Prof. V. HAYWARD
Greenish, Stephanie	M.Eng	Prof. V. HAYWARD
Guenov, Valentin	Ph.D	Prof. P. ZSOMBOR-MURRAY
Hafed, Ziad	Ph.D	Prof. J.J. CLARK
Haurani, Ammar	Ph.D	Prof. H. MICHALSKA
Hawker, Geoff	M.Eng	Prof. M. BUEHLER

*Prof. Zames passed away on August 10, 1997

Student	Degree	Supervisor
Hayes, John	Ph.D	Prof. P. ZSOMBOR-MURRAY
Hernandez-Alonso, Diana	Ph.D	Prof. M. LEVINE
Huang, Minyi	Ph.D	Prof. P. CAINES
Hubbard, Paul	Ph.D	Prof. P. CAINES
Ignatova, Maria	M.Sc.	Prof. M. LEVINE
Jarry, Benoit	M.Eng	Prof. H. MICHALSKA
Jelonek, Thomas	Ph.D	Prof. F. FERRIE
Jugessur, Deeptiman	M.Sc.	Prof. G. DUDEK
Lau, Hang Fai (Anthony)	M.Eng	Prof. M. LEVINE
Lemch, Ekaterina	Ph.D	Prof. P. CAINES
Lu, Mu-Chiao	M.Eng	Prof. H. MICHALSKA
Mackling, Thomas	Ph.D	Prof. P. CAINES
Mahvash, Mohsen	Ph.D	Prof. V. HAYWARD
Menemenlis, Nickie	Ph.D	Prof. C. CHARALAMBOUS
Min, Byung No	Ph.D	Prof. A. MISRA
Mitran, Marcel	M.Eng	Prof. F. FERRIE
Montagnier, Pierre	Ph.D	Prof. J. ANGELES
Navarro-Martinez, Oscar	M.Eng	Prof. J. ANGELES
Ng, Romney Ka-Ho	M.Eng	Prof. M. LEVINE
Nguyen, Huy Binh	M.Eng	Prof. H. MICHALSKA
Obaid, Sami	M.Eng	Prof. M. BUEHLER
Ostrovskaya, Svetlana	Ph.D	Prof. J. ANGELES
Papadopoulos, Didier	M.Eng	Prof. M. BUEHLER
Parsa, Kourosh	Ph.D	Profs. J. ANGELES and A. MISRA
Polifroni, Sandra	M.Sc.	Profs. G. DUDEK and F. FERRIE
Qumsieh, Ala	M.Eng	Prof. J.J. CLARK
Rekleitis, Ioannis	Ph.D	Prof. G. DUDEK
Rey, Daniel	Ph.D	Prof. E. PAPADOPOULOS
Romanovski, Iakov	Ph.D	Prof. E. CAINES
Sarkis, Joseph	M.Eng	Prof. M. BUEHLER
Shaikh, Mohammad Shahid	Ph.D	Prof. P.BÉLANGER
Shen, Gang	Ph.D	Prof. P. CAINES
Shum, Jonathan	M.Eng	Prof. P. ZSOMBOR-MURRAY
Sim, Robert	Ph.D	Prof. G. DUDEK
Simard, Philippe	Ph.D	Prof. F. FERRIE
Simhon, Saul	Ph.D	Prof. G. DUDEK
Sun, Wei (Victoria)	Ph.D	Prof. M. LEVINE
Talebinejad, Shervin	M.Eng	Profs. M. BUEHLER and E. PAPADOPOULOS
Teng, Chin-Pun (Amy)	Ph.D	Prof. J. ANGELES
Torres-Mendez, Luz A.	Ph.D	Prof. G. DUDEK
Torres-Torriti, Miguel	Ph.D	Prof. H. MICHALSKA
Tremblay, Pierre-Jules	M.Eng	Prof. F. FERRIE
Unger, Richard	M.Sc.	Prof. G. DUDEK
Valois, Jean-Sebastien	M.Eng	Prof. F. FERRIE
Wang, Qing Yuan (Cathy)	M.Eng	Prof. V. HAYWARD
Wei, Haiqing	Ph.D	Prof. C. CHARALAMBOUS
Xu, Aoxiang	M.Eng	Prof. J. COOPERSTOCK
Yamazaki, Kenneth	M.Eng	Prof. M. BUEHLER
Yi, Dingrong	Ph.D	Prof. V. HAYWARD

Part II

Research Profile

4 Communication Systems

4.1 Wireless Fading Channels

Stochastic Models for Multipath Fading Channels in Wireless Communications

This project introduces stochastic differential equations in order to model the long-term and short-term effects of electromagnetic waves transmitted over wireless multipath fading channels. For long-term signal transmission it is shown that the instantaneous power of the multipath components follow a mean reverting log-normal stochastic differential equation. For short-term signal transmission it is shown that the instantaneous power of the multipath components follow a mean reverting square-root diffusion process. In both cases the probability distributions are derived and the second-order statistics are computed. The ergodic properties of the instantaneous power are also investigated. These models give rise to probability distributions which are generalizations of Rayleigh, Rician, Nagakami and Log-Normal distributions.

Authors: *C.D. Charalambous, N. Menemenlis*

Statistical Analysis of Multipath Fading Channels in Wireless Communications

This project is concerned with the statistical analysis of multipath fading channels, when the envelope and phase distributions are arbitrary, the number of paths over a signalling interval is a counting process, and the times of arrival of the paths are the points of the counting process. The analysis includes conclusions on the second-order statistics of the channel, the Gaussianity of the received signal through central-limit theorems, and power delay profile and Doppler spread of the channel.

Authors: *C.D. Charalambous, N. Menemenlis*

5 Perception

5.1 Active Perception

FPGA-Based Spiking Neural Networks

The bulk of digital neural network implementations utilize digital words which encode or represent the average firing rate of the neurons that are being modeled. There is a growing awareness, however, that there is significant information encoded in the relative timing between pulses in a true neural network, and this information is eliminated by the averaging process inherent in computing firing rates. Nerve pulses are perfectly suited to implementation in digital logic, as they are inherently binary. We have been investigating the design of digital circuits that implement various models of spiking neurons, and applying these circuits to the implementation of sensorimotor systems modeled after the human oculomotor system. We have been using the Altera FLEX programmable gate arrays for our implementations. The advantages of using these FPGAs is that it is quick and easy to test and implement in hardware a prototype neural network circuit. Powerful design tools are also readily available for these gate array devices.

Authors: *J.J. Clark, T.T. Hung*

Attention and View-Based Object Recognition

This project involves the application of attentional processes to the implementation of view-based object recognition schemes. In this approach, objects are recognized by comparing their appearance from a given viewpoint to (interpolated) views which have been previously recorded. Attention promises to improve this process by minimizing irrelevant inputs and by increasing viewpoint invariance. In such an active view-based object recognition technique, hypotheses as to an object's identity alter the way in which further information regarding the object is gathered. Previously, we had implemented the low level attentional shift algorithms based on hard-wired measures of saliency (colour and saturation), and have used these to guide the motion of a video camera via a Directed Perception Pan-Tilt unit. In the last year, we have developed an object representation that can be used to integrate and learn the association between observed views and object identities. We are currently testing our algorithms in a demonstration environment.

Authors: *A. Domercq, J.J. Clark*

View-Based Route-Learning

This project is concerned with the development of a neural network, based on the Kohonen Self-Organizing-Map, that will permit a mobile robot to navigate from one place to another. The navigation process is that of route following, where stimulus-response pairs are learned by the network. The network learns to associate the motor acts required to execute the route instructions with visual information (views) obtained along the route.

Authors: *F. Hamze, J.J. Clark*

Visual Modeling for CAD/CAM and Autonomous Systems

Much of the research structured under this Project focuses on the intermediate level of visual sensing as it relates to applications in advanced manufacturing and mobile robotics. Funded as part of the Institute for Robotics and Intelligent Systems (a network of centers of excellence), specific topics include the inference of piecewise-continuous surfaces from discrete data sets, theories and representations for 3D shape, recovery of shape from motion and stereo, data and sensor fusion, object and scene modeling, strategies for autonomous exploration, and the recognition of known objects in unstructured environments. A key objective consists of achieving an automatic transformation of sets of unconnected points in 3D space into surface mesh representations which are properly formatted for interfacing with commercial CAD/CAM systems. The Project also targets the development of tools for reliably inferring scene models from sensor data. While the CAD application seeks object descriptions with an accuracy of a metrological-like quality, the processing

strategies are equally applicable to the fusion of sparse data from multiple low cost sensors into a virtual sensing device well suited for mobile robotics. (Figure 5.1).

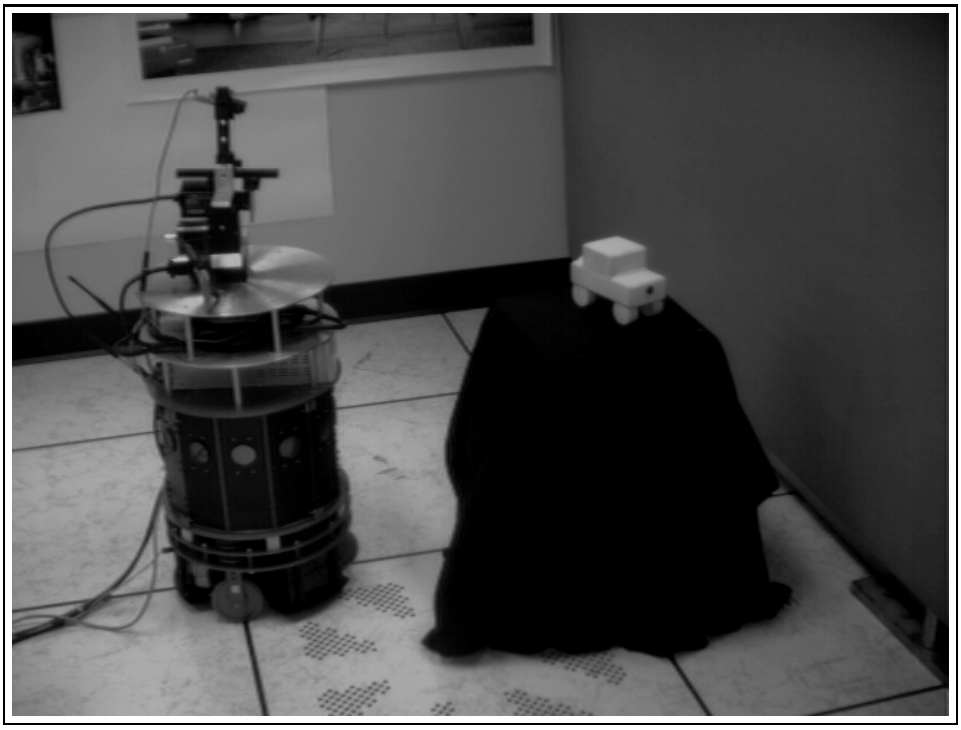


Figure 5.1: The Autonomous Explorer

Authors: *F. Ferrie (Project leader), G. Dudek, M.D. Levine, S.W. Zucker (McGill), P. Cohen (Polytechnique), D. Laurendeau (Laval)*

Computer Vision Using Streaming Video

The purpose of this project is to develop a framework for performing distributed computer vision tasks over the web, using streaming video interconnects. To date, we have constructed a number of DirectX *ActiveMovie* plug-in filters which perform various image process operations such as edge detection, motion detection and coloured region extraction. We are currently in the process of developing the software neccessary to publish and access video streams to and from the web and interface these streams to our plug-in filters.

Authors: *P.O. Laprise, M. Sidloi, J.J. Clark*

5.2 Active Vision

Attention and Eye Movements

Following the *premotor* theory of attention, we take the view that attention and eye movements are inextricably linked, so that every shift in attention gives rise to a plan to make a saccadic eye movement. This movement is often suppressed, however, by a fixation system. This project has the goal of deriving and using models of the link between attention and eye movements to allow the *tracking* of attention. To date, we have constructed, using Matlab, a detailed neural network model of the human Superior Colliculus, a structure in the brain which controls the generation of saccadic eye movements. This model allows us to explore the

interaction between fixation and attention in the generation of saccadic eye movements. We have begun preliminary studies of some hypotheses regarding observable correlates of attention shifts in motor activities of subjects viewing computer displays.

Authors: *Z. Hafed, J.J. Clark*

Optimal Spiral Search

This work involves the use of spiral search techniques as applied to mobile robot navigation, and multi-agent coordination. The work follows for theoretical results on the optimal strategies for finding an object, or accomplishing specific objectives with minimum travel time. For example, if an object is to be found in a planar environment, what is the most efficient way to explore? Standard spiral search provides algorithms with good competitive ratios for simple geometries (line finding an object on a line). This project aims to extend those results to complex real-world domains.

Authors: *S. Burlington, G. Dudek*

PCA Background Invariance

This project deals with appearance based recognition using Principal Components Analysis with the added ability to account for varying backgrounds and non-rigid deformation. This is done using an attention operator to focus on the object to be recognised and performing PCA only on the sub-windows within the object. This allows an object to be recognized as a collection of familiar fragments that "vote" for it's identity. Each voting patch has a strong association with the particular object being recognized, and hence only a small number of these need be determined. This work is also being examined in the context of place recognition, for navigation.

Authors: *D. Jugessur, G. Dudek*

Distributed Robot Control Software Environment

A distributed, device independent mobile robot controller and simulator is being developed. It supports distributed computation and visualization and can control one or more real Nomad or RWI robots. A beta version and some additional details are available.

Authors: *G. Dudek, R. Sim*

Multi-Robot Exploration and Rendezvous

This project deals with the exploration of an unknown environment using two or more robots working together. Key aspects of the problems are coordination, and particularly rendezvous, between the robots, and efficient decomposition of the exploration task.

Authors: *N. Roy (Ph.D. Carnegie Mellon University), I. Rekleitis, G. Dudek*

Virtual Environment Construction

We are examining techniques for the creation and management of virtual reality analogues for the real world. This includes the automatic acquisition of image-based VR images, as well as the automated selection of viewpoints and scenes of interest. The selection of a set of representative pictures is referred to as the "vacation snapshot problem". In addition, selecting views of interest depends of the estimation of statistical properties of the environment. As a result, efficient exploration strategies to permit these statistics to be computed are very important, leading to a strategy we refer to as alpha-backtracking.

Authors: *E. Bourque, P. Ciaravola, G. Dudek*

Accurate Position Estimation from Learned Visual Landmarks

This method is applied for learning, encoding, detecting, and using visual landmarks for mobile robot pose estimation. The work deals primarily with landmarks from monocular video cameras and can be used to learn a small set of robust landmarks to localize a robot (or other device) in an almost-arbitrary environment.

Authors: *R. Sim, G. Dudek*

Multi-Robot Collaboration

We are interested in elaborating a taxonomy for systems of multiple mobile robots. The specific issues we are focussing on are the relationships between inter-robot communication, sensing, and coordination of behaviour in the context of position estimation and exploration.

Authors: *G. Dudek in collaboration with Professors E. Milios and M. Jenkin of York University and D. Wilkes at Ontario Hydro.*

Pose Estimation From Image Data Without Explicit Object Models

We consider the problem of locating a robot in an initially-unfamiliar environment from visual input. The robot is not given a map of the environment, but it does have access to a limited set of training examples each of which specifies the video image observed when the robot is at a particular location and orientation. Such data might be acquired using dead reckoning the first time the robot entered an unfamiliar region (using some simple mechanism such as sonar to avoid collisions). In this paper, we address a specific variant of this problem for experimental and expository purposes: how to estimate a robot's orientation(pan and tilt) from sensor data.

Performing the requisite scene reconstruction needed to construct a metric map of the environment using only video images is difficult. We avoid this by using an approach in which the robot learns to convert a set of image measurements into a representation of its pose (position and orientation). This provides a *local* metric description of the robot's relationship to a portion of a larger environment. A large-scale map might then be constructed from a collection of such local maps. In the case of our experiment, these maps express the statistical relationship between the image measurements and camera pose. The conversion from visual data to camera pose is implemented using multi-layer neural network that is trained using backpropagation. For extended environments, a separate network can be trained for each local region. The experimental data reported in this paper for orientation information (pan and tilt) suggests the accuracy of the technique is good while the on-line computational cost is very low.

Related work is taking place in the context of the IRIS project (below). A recent article appears in Neural Computation.

Authors: *G. Dudek, C. Zhang*

Spatial Abstraction and Mapping

This project involves the development of a formalism and methodology for making the transition from raw noisy sensor data collected by a roving robot to a map composed of object models and finally to a simple abstract map described in terms of discrete places of interest. An important early stage of such processing is the ability to select, represent and find a discrete set of places of interest or landmarks that will make up a map. Associated problems are those of using a map to accurately localize a mobile robot and generating intelligent exploration plans to verify and elaborate the map.A compressed postscript copy of a paper of this work can be downloaded here:
ftp://ftp.cim.mcgill/pub/mobile-robot/paper:RA94-model-based-localization.pz.Z

Authors: *G. Dudek, P. Mackenzie (CRIM).*

Spatial Mapping with Uncertain Data

As a sensor-based mobile robot explores an unknown environment it collects percepts about the world it is in. These percepts may be ambiguous individually but as a collection they provide strong constraints on the topology of the environment. Appropriate exploration strategies and representations allow a limited set of possible world models to be considered as maps of the environment. The structure of the real world and the exploration method used specify the reliability of the final map and the computational and perceptual complexity of constructing it. Computational tools being used range from graph-theoretic to connectionist.

Author: *G. Dudek*

Optimal Sampling for Metrological Applications

Digitizing a physical object in order to obtain a CAD description (often referred to as "reverse engineering") is required for a wide variety of applications. Even though the technology of measuring devices has advanced to a high level of maturity (e.g. reliable laser scanners), the task of automating the whole process of digitizing an object still remains unsolved. At every step in the process, from data acquisition to model fitting, human intervention is often required, slowing down the process considerably.

In this project, we concentrate on a very specific part of the reverse engineering process, the automation of the data acquisition stage. The problem is as follows: given a measuring instrument, e.g. a laser rangefinder, determine a trajectory in 3-D that will result in an optimal sampling of the object being scanned. What makes this particular problem interesting is that the object is not known a priori, so the system must simultaneously optimize measurement parameters (e.g. maintain a prescribed sampling density) while discovering the object's surfaces.

Borrowing from differential geometry and topology, we have developed a solution to this problem that has thus far shown excellent promise in laboratory experiments. Briefly, one can define a space of local covers in terms of an atlas of charts derived from sensor measurements. The sensor itself is parameterized, e.g. position and orientation, so that different instances give rise to different local covers. Globally we seek a sensor trajectory that generates a complete surface covering subject to prescribed sampling requirements, local sensor optimization (e.g. constraints on field of view), and kinematic limits on sensor positioning. Even with these constraints the solution space is still intractable. However, by exploiting the further constraint that surface shape and sensor trajectory are locally coupled, we show that it is possible to automatically generate a suitable trajectory.

Authors: *F. Callari, G. Soucy, F.P. Ferrie (McGill), D. Baird, D. Lamb (Hymarc Ltd.)*

5.3 Computer Vision

Presenter Tracking in a Classroom Environment

As intelligent environments become more focused on supporting human activity, we see a growing need for the computer to ascertain users, location and activity, be it for face detection, gesture recognition, or even simple tracking. To support such applications, a robust tracking algorithm is required. A camera tracking algorithm for a pan and tilt camera is proposed that is robust to moderately dynamic backgrounds and varying lighting conditions, while requiring only modest computational resources. The algorithm is based on pre-filtering as well as temporal differencing, and achieves impressive results in the real-world setting of a university classroom.

Authors: *S. Arseneau, J. Cooperstock*

Real-Time Image Segmentation for Action Recognition

In order to recognize actions of a human properly, an algorithm must be able to detect a person accurately in any given image. This data will be used to ascertain what action the user is performing. Many methods have been proposed that use a temporal differencing technique in which the image of the user is subtracted

from a previously known image with the same background, without the user. These methods, however, are plagued with problems of noise and "ghosting," the undesirable introduction of image fragments as a result of changes in light intensity and moving objects in the background. The proposed algorithm combines several image processing methods in order to produce a clean difference image, while being far more robust to changes in light intensities and in the background scene.

Authors: *S. Arseneau, J. Cooperstock*

Virtualizing Reality

The concept of virtualized reality relates to the problem of transcribing the form of the real world into representations from which synthetic views and/or behaviours can be generated. Much of our work to date has focused on the representation and recovery of 3D shape using a variety of sensor modalities (laser rangefinding systems, stereo imaging, shading analysis) and representations (parametric surfaces, articulated solid geometry, triangulations). Applications have included automatic CAD/CAM model generation from metrological data, environmental modeling for autonomous robotics, morphological characterization of skeletal components for the construction of medical prostheses, and the automatic generation of virtual reality models from sensor-equipped mobile robots.

As part of the VERTEX Centre of Excellence (Institute for Robotics and Intelligent Systems), our current work is focused on both the creation and augmentation of virtual reality from on-line measurements. For example in the VERTEX scenario we are using live data (television + structured light) from an underwater submersible to localize the vehicle within a known environment and to build task-specific descriptions of the surrounding vicinity. Although current work deals primarily with visual models, a long term objective of this research is to incorporate qualitative physical reasoning in order to predict behaviours in response to applied forces and disturbances.

Authors: *T. Arbel, S. Benoit, P. Simard, G. Soucy, and F.P. Ferrie*

Synthetic Vision System for Search and Rescue Helicopters

Certain tasks, such as flying a helicopter in proximity to the ground, are difficult to automate due to the complex interaction between the operator and the machine. For example, a pilot needs a clear view of the surrounding terrain in order to avoid obstacles, plan escape routes or to maintain the aircraft in a precise hover relative to the ground. Low to zero visibility conditions make it difficult if not impossible to fly, and are particularly problematic for search and rescue missions which often take place during less than ideal weather conditions.

One approach to solving this problem is to provide the pilot with a synthetic view of the ground by means of a helmet mounted display (immersive virtual reality). In the CAE SVS, position and heading provided by the aircraft navigation system are used to index a database of digital elevation maps from which a synthetic view of the ground is generated. This view is augmented by a live feed from an infrared scanner mounted on an external gimbal, which servos according to the pilot's direction of gaze. As of this writing we have recently completed the evaluation of different methods of fusing live + synthetic data in order to maximize the information content of the synthetic view with respect to flight control and mission task requirements. These will shortly be incorporated into the flight test platform.

The next phase of this research will involve incorporation of radar or lidar sensors, with the aim of automatically detecting potential obstacles and augmenting the display with suitable markers. Much of this will be based on our prior research in active vision and gaze planning in order to develop suitable algorithms to steer the sensors and extract the relevant information within time constraints.

Authors: *P. Simard, F.P. Ferrie, N.K. Link (CAE), R. Kruk (CAE)*

Extraction of Features from Remote-Sensed Imagery for a Search and Rescue Synthetic Vision Database

The generation of synthetic displays for the SVS application described above relies to a large extent on the availability of annotated remote sensing databases for the regions over which the aircraft will fly. Correct localization of features, e.g., location of hydro pylons, transmission lines, height of tree canopies, mountains, etc., translates directly into higher degrees of certainty in the planning of flight paths and escape routes. The sheer volume of data arising from both geographic scale and the need for timely updates poses a considerable challenge.

This project, part of the GEOID national centre of excellence, is aimed at the development of new algorithms capable of extracting these features automatically and to higher degrees of accuracy by exploiting new developments in image analysis and understanding. We are currently investigating the use of sequential estimation techniques developed earlier for object recognition as a basis for recognizing terrestrial features, given registered images at different wavelengths and from potentially multiple sources. Another part of this project deals with the problem of actually generating the synthetic view from the data available in the remote sensing database.

Authors: *P. Simard, F.P. Ferrie, D, Clausi (Waterloo), J. Elder (York), P. Sheppard (CRESTech)*

Recognizing Objects by Accumulating Evidence over Time

This project is a direct outgrowth of our earlier work in recognizing parametric models using probabilistic inverse theory [1]. The general idea is that uncertain interpretations can be regularized by accumulating evidence over time in situations where multiple observations are available (e.g. a stationary observer in a mobile environment or vice-versa). As with our earlier work, a probabilistic identification framework is used to represent beliefs in different object hypotheses by conditional probability density functions. What is new is the use of Bayesian chaining rules to update the beliefs as new data are acquired. In this way decisions can be postponed until evidence for a clear winner emerges.

We continue to investiage the application of our sequentual recogition strategy to the appearance-based recognition problem of identifying objects on the basis of signatures from optical flow. Detailed empirical studies conducted in the past year suggest that the strategy can solve the interpretation problem (confounding of structure, motion, and imaging geometry) under suitable constraints (curvalinear motion). Further work will be aimed at putting these empirical observations on a more solid analytical footing, leading to a better understanding of how optical flow can be used in more general settings.

1. Tarantola, Albert, *Inverse Problem Theory: Methods for Data Fitting and Model Parameter Estimation*, Elsevier Science Publishing Company, Inc., New York, 1987.

Authors: *T. Arbel and F.P. Ferrie*

Viewpoint Selection by Navigation through Entropy Maps

This project combines our work in sequential object recognition with active vision to create a process which can unambiguously recognize an object in a minimum number of views. Applications of this research include navigation systems that determine their positions relative to fixed landmarks in the environment and machine vision systems that must determine the position and orientation of known objects in potentially unstructured environments. The latter application is characteristic of work we have done with Hymarc Ltd. for the Canadian Space Agency. Our approach is based on a sequential recognition strategy in which object hypotheses are represented as conditional probability density functions. A Bayesian accumulation (chaining) method is used to accumulate evidence for the different hypotheses as new data are gathered on line. Selection of viewpoints is accomplished using an active vision approach that selects on the basis of minimizing ambiguity of recognition. The same off-line training process that is used to determine the prior conditional probability density functions used for recognition is also used to construct entropy maps relating ambiguity

as a function of viewing position. These are effectively used by the active vision process to plan gaze. Experiments have shown that the combined use of sequential recognition and gaze planning greatly enhance the robustness of appearance-based methods. We are now investigating applications of object recognition using optical flow measurements as the basic input to the system.

Authors: *T. Arbel and F.P. Ferrie*

Autonomous Physics-Based Colour Learning under Daylight

This research is centered around the problem of identifying objects illuminated by daylight using the color information in digital images. The main difficulty lies in the wide illumination variations, which depend on weather conditions and time of day, and significantly alter the color response of the camera for a given single object. This poses a serious problem if color is to be used as a consistent means of identification independent of these variations. This is the well-known color constancy problem. Physics-based vision approaches have been applied with some success to solving this problem, but generally in the context of controlled or known illumination. As for daylight, learning approaches have by far been preferred, and so far no systematic attempt has been made to develop a physics-based method relying on the color formation equations. Obviously, outdoor illumination varies, but the question as to whether or not this can be modelled appears to have been overlooked in the computer vision literature. This does not do justice to the considerable amount of work done to characterize daylight, culminating in the semi-empirical model developed by Judd et al. [1].

This project consists of two parts. The first is a model used to predict an object's color under daylight based on the color formation equations and the empirical model of Judd et al. Using the model one can predict regions in color space corresponding to measurements made by a specific television camera. The second part consists of a learning component that refines these initial predictions on the basis of a model determined by a training procedure. The main contributions of this work are first to provide a solid theoretical understanding of colour formation under daylight, and second to use this to arrive at a hybrid method conciliating the strengths of both learning and modelling. Finally, the fact that the method can be made autonomous constitutes a definite advantage over other learning approaches found in the literature.

1. Judd, D.B., MacAdam, D.L., and Wyszecki, G., *Spectral Distribution of Typical Daylight as a Function of Correlated Color Temperature*, JOSA 54, pp. 1031-1040, 1964.

Authors: *Yves Bérubé-Lauzière, Denis Gingras (Institut National Optique), and F.P. Ferrie*

Interactive Model Recognition from Optical Flow

Optical flow is the velocity field induced on the retina by the relative motion between a viewer and an object in its visual field. As such it encodes important perceptual cues with respect to the motion and structure of objects in a scene. The advent of low-cost sensors coupled with high-performance computing power has re-kindled interest in both the determination of the optical flow field and its interpretation in terms of scene structure. The context of this research is the characterization of three-dimensional shape given prior knowledge in the form of a parametric model. In this scenario an operator presents a target object to a video camera and moves it according to the computer's suggestions for new viewpoints (using a strategy derived from the autonomous explorer). Our goal is to correctly recover the 3-D motion and structure of the object from the resulting flow and to minimize the ambiguity of this interpretation by using constraints derived from the recovered flow field, the structure of the model, and feedback provided to the operator.

In our laboratory set-up, an optical flow field is generated in real time from a sequence of gray-scale images. Velocities are computed by matching "tiles" of pixels in sequential frames, and not from differential relations of light intensity. This way, displacements much greater that one pixel can be found as easily as subpixel displacement. A coarse (40x30) optical flow field is computed for a sequence of video images at a real-time rate of 3 frames/second on a Silicon Graphics Indy workstation. From these estimates a discrete range map is computed from the discrete optical flow using the projection equations and rigid-body constraints. Together, the range and flow are used to produce a pose estimate, and the pose and range

are finally used to fit a superellipsoid model to the data. With a 3D physical model, the translational and rotational dynamics of the object can be predicted within a Kalman filter. The optical flow for the next iteration is refined by feeding the expected projection of the object's surface back into the image plane. This strategy thus uses a combination of bottom-up measurements and top-down feedback. The laboratory implementation currently displays a 3D frame superimposed on a live video image showing the target object's pose and position. A color-coded image of the object will show the surface uncertainty on the object, allowing the user to manipulate the object intelligently, e.g. moving the object so as to bring less certain regions of the surface into view. (Figure 5.2).

Figure 5.2: Laboratory set-up for building object models from optical flow measurements

Authors: *S. Benoit, F.P. Ferrie*

Pose Estimation: Known Objects in Unstructured Environments

This project focuses on investigating methods for pose and point estimation (PPE) on complex, rigid, known, non-cooperative 3-D objects from range images. The "point" estimation issue is remarked and studied alongside the "pose" estimation one (in itself a classic problem of computer vision), in that it is the goal of the project to build a system able to make confident assertions about the position in 3-D space of particular "relevant" points on the objects at hand. This goal stems from one possible application of this research, namely manipulation and docking operations of space station structures in space.

Our proposed solution is a Bayesian inference scheme, based on several layers of information processing. Starting from range images of the objects, a chain of shape analysis processes produces first a segmentation of large, reliable features on the objects, whose shape is modelled by geometric primitives (superellipsoids in the proposed test-bed solution). The shape parameters are used for part recognition (via a Bayesian discriminative classifier) and for placing "landmark" points upon the parts themselves. Eventually, the landmarks are used to estimate the target point position. Uncertainty in the modelization process is carried along, and expressed in the form of posterior probability distributions about the target. This effectively quantifies the confidence degree in the estimation.

Extensive tests of the above technique on test objects have given promising results about the practical feasibility of the proposed methodology. More details are available on line:
http://www.cim.mcgill.ca/~apl/Papers/callari-landmark-identification.ps.gz

Authors: *F. Callari, G. Soucy, F.P. Ferrie (McGill), D. Baird, D. Lamb (Hymarc Ltd.)*

Integrating Descriptions from Multiple Views

The primary intent of this work is to present a method for sequentially associating three-dimensional surface measurements acquired by an autonomous exploration agent with models that describe those surfaces. Traditional multiple-viewpoint registration approaches are concerned only with finding the transformation that maps data points to a chosen global frame. Given a parts-based object representation, and assuming that the view correspondence can be found, the problem of associating the registered data with the correct part models still needs to be solved. While traditional approaches are content to group segmented data sets that geometrically overlap one another with the same part, there are cases where this causes ambiguous situations.

This research project addresses the model-data association problem as it applies to three-dimensional dynamic object modeling. By tracking the state of part models across subsequent views, we wish to identify possible events that explain model-data association ambiguities and represent them in a Bayesian framework. The model-data association problem is therefore relaxed to allow multiple interpretations of the object's structure, each being assigned a probability. Rather than making a decision at every iteration about an ambiguous mapping, we look to the future for the information needed to disambiguate it. An algorithm based on this research has been successfully tested and integrated into our autonomous exploration testbed. Experimental results demonstrate that the approach is highly successful in solving the model-data association problem and is well-suited to applications in reverse engineering.

Authors: *P. Tremblay, F.P. Ferrie*

Matching Hierarchical Structures Using Association Graphs

It is well known that the problem of matching two relational structures can be posed as an equivalent problem of finding a maximal clique in a (derived) "association graph." However, it is not clear how to apply this approach to computer vision problems where the graphs are hierarchically organized, i.e., are trees, since maximal cliques are not constrained to preserve the partial order. We have provided a solution to the problem of matching two trees by constructing the association graph using the graph-theoretic concept of connectivity. We prove that in the new formulation there is a one-to-one correspondence between maximal cliques and maximal subtree isomorphisms. This allows us to cast the tree matching problem as an indefinite quadratic program using the Motzkin-Straus theorem, and we use "replicator" dynamical systems developed in theoretical biology to solve it. Such continuous solutions to discrete problems are attractive because they can motivate analog and biological implementations. The framework is also extended to the matching of attributed trees by using weighted association graphs. We illustrate the power of the approach by matching articulated and deformed shapes described by shock trees.

Authors: *M. Pelillo (University of Venice), K. Siddiqi, S. W. Zucker (Yale University)*

5.4 Content Based Image Retrieval

An Improved Appearance-based Approach to Image Retrieval and Classification

A content-based image retrieval system operates by matching indices that are based on the contents or structure of an image as opposed to annotations included as part of the database representation. As part of the Digital Library Project, a collaborative effort among researchers from Concordia University, McGill University, Université de Montréal, and Université du Québec à Montréal, the goal of this work is to investigate how content-based retrieval can be integrated into existing standards for digital libraries. The idea

is to complement traditional annotations with indices generated from scene content in a *query by example* context.

We are currently investigating a two-step hierarchical approach that first attempts to assign a query image to a restricted set of classes within the database, and then returns the best matches to each of the selected classes. Each class has associated with it specialized pre-filtering intended to enhance the selectivity of its associated pattern classifier. Since appearance-based methods are used for classification, this pre-filtering also serves to reduce the sensitivity of the classifier to features that are not used for indexing. The database organization also helps to speed up retrieval since only a subset of the database need be considered once the applicable classes have been determined. Preliminary experiments indicate that this approach appears to be well-suited for query by example applications. We are currently investigating the relationship between different pre-filtering approaches and scene categories. Trials will then be performed on larger scale image databases and our work integrated with that of the rest of the consortium.

Authors: *F. Beyrouti, F.P. Ferrie*

Hidden Markov Models for Scene Analysis

Users of image databases are often interested in finding a set of images that belong to a single identifiable linguistic class. An example of this is a search for so-called "scapes", such as landscapes, urban scenes, beach scenes, mountain scenes, seascapes, etc. We are employing Hidden Markov Models(HMM), which have been used very successfully in speech recognition but scarcely in computer vision, to analyze and interpret an image. An existing linguistic classification will be used, and learning methods will be employed to learn the probabilities associated with all nodes and transitions in the HMM.

Authors: *D. Hernández, M.D. Levine*

5.5 Face Recognition

Face Recognition and Aging

Suppose we wish to search an image database to answer such questions as "Find all pictures of Frank Sinatra in the database". A major issue has to do with recognizing individual faces as the same, notwithstanding the normal aging process. We will study the modeling of the aging process and include it in a face recognition program. One major issue is the collection of data. We intend to first obtain it from other sources and later to develop our own graphics aging software. We will then test the developed theories and methods on a series of images of actors who have had long film or television careers.

Authors: *W. Sun, M.D. Levine*

The Smart Door Project

The objective of this project is to use face recognition to automatically open doors based on a stored database of facial codes. A significant problem in this regard is to make the recognition independent of 3D head rotation. This has been known for a long time to corrupt recognition results and no satisfactory solution exists. We are investigating both hardware and software solutions to this problem.

Authors: *W. Pereira, W.-J. Chang, M.D. Levine*

Finding Faces in Color Images Just Using Hue

The detection, localization and extraction of faces from images is a challenging problem in computer vision. Its applications include criminology, security systems, content-based image retrieval etc. Faces of subjects with different racial characteristics, in arbitrary size, position and orientation, under varying illumination conditions or partially occluded have to be detected and localized. This project is a study of how well human faces can be detected and localized in color images by using color information alone, hue in particular.

The typical way of using color for face localization is simple thresholding. In contrast to this, this work explores the color histogram intersection method. Simple thresholding processes color information pixel by pixel, whereas histogram intersection operates on groups of pixels. It thus captures more information. We investigate the possibility to localize faces based only on the use of color, as opposed to the post-processing of the thresholding image, usually required with simple thresholding.

A color space is sought that minimizes the variations in facial color due to races and illumination conditions. We take advantage of the CIE XYZ color space because of both its perceptual superiority to the RGB space, and because a normalization of the space takes place prior to computing hue. Normalization of color space with respect to intensity is shown to minimize the variations of facial color. We choose to specify facial color using just hue and we further model it through 1D hue histogram. We compute a generalized facial color model by accumulating facial color histograms across many images. Testing was accomplished on a database of 200 color images downloaded from the Internet. We have observed that the generalized facial color models we compute are largely independent of the racial characteristics of the subjects. To accommodate the specificity of working with accumulation histograms instead of with histograms of just one object, we propose modifications to the color histogram intersection measure.

An iterative algorithm scanning the image at multiple scales is proposed. At each scanning position the algorithm computes a histogram intersection measure to evaluate the color similarity between the sub-image at this position and the generalized facial color model. The algorithm produces a list of locations that have high similarity with the generalized facial model. A threshold value on the similarity value is used to separate the locations containing faces. The algorithm is invariant to different facial orientation, partial occlusion, and to translation and rotation about an axis perpendicular to the image plane, due to the use of integral image characteristics such as a histogram. Multi scaling enables the algorithm to detect faces of different size.

Authors: *M.V. Ignatova, M.D. Levine*

5.6 Focus of Attention

Color, Texture, and Symmetry for Focus of Attention in Images

It is well known that object symmetry is an important component in determining human focus of attention. Earlier, we have proposed a new method, based on symmetry in gray level images, for object isolation and segmentation in complex images and a real-time implementation has also been developed and tested.

We have added to this analysis the two additional features of color and texture. Both region and edge analysis are used to compute a graph description of the important and salient objects in the scene. The user is able to interactively select a desired combination of perceptual variables to control which salient objects will be retrieved.

Authors: *A.H.F. Lau, M.D. Levine*

5.7 Haptic Human-Computer Interaction

Haptic Percetual effects Investigation and Harnessing

The object of haptic interfaces is to associate voluntary motions with mechanical perception in a controlled and programmable manner. These two sides of interaction can hardly be dissociated. A number of perceptual effects have been described in this context, and some newer ones have been discovered by the investigators. It is key to the development of haptic interfaces to be sensitive to the existence of these effects, during the design of devices, of rendering techniques, and of applications. We endavor to quantify a selected subset of these effects on the basis of their potential to facilitate the engineering of haptic interfaces.

Authors: *G. Robles, V. Hayward*

3D Medical Image vizualizaion

A new technique to assist medical staff visualize and exploit large data sets produced by medical imaging techniques is being developed. It is based on haptic feedback, a recently developed technology which takes advantage of the kinesthetic and tactile channels of human operators. A system is being developed that will allow better interrogation of 3-D volumic medical image, aimed at a significant reduction of errors in interpretation and manipulation in three dimensions. This will apply both in situations where the "operator" is a radiologist interpreting the data or a surgeon being guided by the images. Effectiveness of associating mechanical and textural properties to medical images will be determined for specific tasks, using performance measures obtained from populations of trained and untrained subjects.

Authors: *D. Yi, V. Hayward*

5.8 Human-Computer Interaction

Reactive House

The *Reactive House* is a two-room interactive exhibit designed and built for the Ontario Science Center's *Millennium Exhibit*. The exhibit consists of a dining room and living room scenario. Each room reacts to user activity, utilizing information from video cameras, voice recognition, and various low-level sensors.

In the dining room, a ceiling-mounted camera detects the arrival of visitors near the table. A computer-synthesized voice then instructs the visitors to be seated in order to begin the meal selection process. From there, a video is displayed, presenting the fridge contents, and a number of meal choices are offered. Each visitor is asked to make a meal selection using a panel of buttons. Each selection serves as a vote for a particular meal, and the *room* then decides on an overall top choice. Pre-dinner music is played while a light in the oven is turned on, indicating that the meal is being prepared.

In the living room, a microswitch mounted in an office chair indicates that someone is sitting down, while a rotary encoder provides the angle to which the chair is facing. This information is used to activate either a television or stereo, depending on which device is being faced. The occupant of the chair is prompted to utter appropriate keywords in order to change TV channels (e.g. "sports" or "drama") or make musical selections (e.g., "soft rock," or "jazz"). Voice recognition is used to interpret the corresponding selection, and an associated video or audio clip is then played back.

The exhibit features a playful sense of humour, warning visitors who straggle at the dining table after the meal has ended, "if you don't leave soon, you'll have to stay and help clean the dishes." Another example of this interaction is in response to the stereo volume being raised too high. A distant voice can be heard to shout, "Hey kids! Keep it down!" followed by the *room* informing visitors that someone has complained, so the music volume will now be lowered.

Authors: *S. Lau, M. Leong, W. Tsai, P. Tjhin, S. Doutriaux, J. Cooperstock*

UbiComp VCR

The UbiVCR introduces a "buttonless interface" approach to remote control of consumer electronics appliances. Exploiting contextual knowledge concerning the user's viewing habits, the current program being viewed, and database information, the system responds to voice commands in order to facilitate time-consuming tasks such as VCR record timer programming and tape searching.

Building on an earlier, multi-program, two-computer prototype, a PC-based system was developed that offers similar functionality within a single program. This simpler platform will serve as the basis for further experiments comparing ease-of-use and efficiency of speech controlled interfaces versus their button-based remote-control counterparts.

Authors: *G. Gagnon, H. Tam, J. Cooperstock*

Automated Door Attendant

The Automated Door Attendant serves the role of a simplified secretary. Its physical components include a video monitor, speaker, microphone, and camera, which serve as the physical embodiment of an artificial agent, displayed as an animated character (the IBM ViaVoice agent). The agent utilizes speech recognition and synthesis to support verbal interaction, in addition to a video-based motion detector to *wake up* when someone is standing in front of the door. Using the attendant, visitors may leave video messages, schedule appointments, or review web-based documents and demos.

The purpose of the door attendant is to study the possibilities and limitations of artificial agents deployed in roles typically assigned to humans. An earlier prototype, developed in 1998, exhibited some of the core functionality, but was insufficiently developed nor robust for actual deployment. The present system has been operational since May 1999 and its basic secretarial functions will be put to real use and monitored starting in September.

Authors: *S. Djihanian, K. Moussaoui, Y. Dib, Z. Klinger, J. Cooperstock*

Intelligent Classroom

The objectives of this project are to overcome the complexity facing users of electronic classrooms while allowing instructors to benefit from the available functionality of the presentation technology. This is attained through reactive control of the technology and automatic capture of lecture material. The former improves teacher-student interaction and quality of learning, while the latter facilitates the production of on-line pedagogical material for later review by students and/or instructors.

Many components are integrated to perform control of the classroom, including programmed sensors for the VCR, document camera, digital tablet, and electronic whiteboard. A central program receives messages from the various sensors and in response, configures the equipment appropriately. For example, when a document is placed under the document camera, the room lights are adjusted, the projector turned on with the document camera input made active, and the screen lowered. In addition, the room responds to and learns from simple manual override commands and provides feedback as to which devices are currently active.

Automatic capture of lecture material is performed through the Classroom 2000 system, in conjunction with a presenter tracking camera and an audience member localizing system, currently under development. The result is a web-based version of the class, in which the entire set of written notes and slides is accompanied by an audiovisual stream of the lecture, along with student questions.

Authors: *Y. Liao, S. Hooshangi, S. Doutriaux, J. Cooperstock*

Improved Web-based Pedagogical Tools

In a preliminary evaluation of the Classroom 2000 lecture-capture tools at McGill, several shortcomings were identified. These included (a) inability to annotate and record a lecture delivered using the full capabilities of a PowerPoint presentation, (b) lack of post-lecture interaction between students and instructor, and (c) inflexibility of the system to support student use for recording and delivering mini-presentations.

Identification of these issues led to the implementation of a number of additional tools. First, the *Transparent ZenPad* interface for annotating a PowerPoint presentation within the Classroom 2000 system, was developed. This tool obtains slide number information from PowerPoint and allows the user to write directly overtop of any slide. All inkstrokes are then saved with the lecture.

Second, an interactive *Previously Asked Questions* interface, embedded within each lecture, was developed. While reviewing a lecture on-line, students may peruse questions pertaining to any slide, or submit new questions of their own at the click of a mouse button. Instructors or TAs can respond to these questions, with the question and answer then forming an integrated component of the lecture.

Third, a modified version of the standard ZenPad interface was devised, tailored to the needs of a student mini-presentation. This system includes a timebar, indicating the amount of time remaining, and permits multiple recordings and reviews of the presentation until the student is satisfied with the result.

Authors: *J. Yeong, H. Agha, J. Luo, H. Nasseridin, O. El-Sharif, J. Cooperstock*

Graffiti Board

The GraffitiBoard is a wall-sized computer display that tracks the position of a pointer (such as a user's finger) and displays the resulting penstrokes as if the user were writing on the wall. A video projector produces the displayed image while a video camera captures the users' actions.

By applying a simple colour tracking algorithm or a more complex cross-correlation technique, it is possible to recognize certain actions and respond accordingly. For example, if the user's hand is placed on the wall, a palette with various painting options can be generated at that location. For our demonstration program, we use both colour tracking and correlation techniques to track the movement of user's finger and draw pictures and letters.

Authors: *W. Lim, J. Cooperstock*

Haptic Rendering of Images

This research aims at providing a technique to assist users to interactively segment images. For example, a trained professional will have no difficulty segmenting structures in a noisy ultrasonic medical image. The activity of specifying the contours of a structure from visual data, using currently available computer input devices, is nevertheless time-consuming and error prone.

Using a haptic device, a combination of edge information contained in the image and information derived from the user's volontary motion is used to generate forces which assist motor control. This can be shown to improve the accuracy/speed tradeoff during performance of that task as compared to conventional input devices.

Authors: *Q. Wang, V. Hayward*

Tactile Display Device

Many devices and systems have been built in the past to display distributed tactile information to the skin. Although applications of such devices are extremely promising, none of the existing tactile displays has succeeded in creating the sensations of 2-D fine textures. We are researching a radically new way of producing artificial and computer-controlled stimuli to the skin. Our design is simple to manufacture, and does not require great integration density. Such devices may also be used to augment or possibly replace visual clues, a capability that existing haptic devices have only to a certain degree. This is applicable to radically new interfaces for use in a number of areas of human activity, including medicine, design, etc...(Figure 5.3)

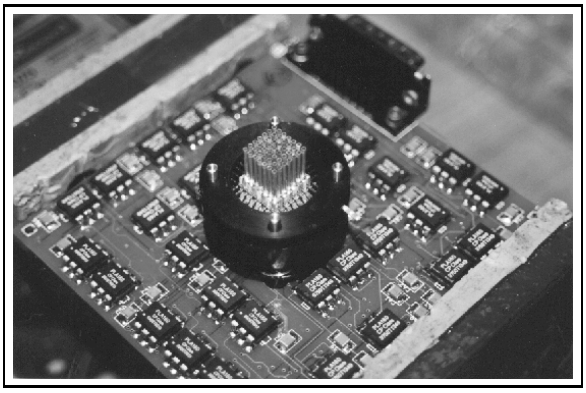


Figure 5.3: 2-D Tactile Display

Authors: *M. Cruz-Hernandez, V. Hayward*

5.9 Medical Imaging

Level-Set Surface Segmentation and Fast Cortical Range Image Tracking for Computing Intra-surgical Deformations

We have proposed a method for estimating intra-surgical brain shift for image-guided surgery, which consists of five stages: 1) the identification of relevant anatomical surfaces within the MRI/CT volume, 2) range-sensing of the skin and cortex in the OR (operating room), 3) rigid registration of the skin range image with its MRI/CT homologue, 4) non-rigid motion tracking over time of cortical range images, and 5) interpolation of this surface displacement information over the whole brain volume via a realistically valued finite element model of the head. The surface identification scheme implements 3D surface segmentation as the level-set of a 4D moving front. A by-product of this stage is a Euclidean distance and closest point map, which is later exploited to speed up the rigid and non-rigid registration. The method has been validated with a novel deformable brain-shaped phantom, made of Polyvinyl Alcohol Cryogel.

Authors: *M. A. Audette (Montreal Neurological Institute, McGill University), K. Siddiqi, T. M. Peters (Robarts Research Institute)*

5.10 Mobile Robotics

Multi-Agent Tracking and Estimation

In this work we are using groups of robots working semi-autonomously to accomplish a joint mapping or tracking task. Each robot can independently make visual measurements of the environment and from this can both contribute to a shared world-model, as well as refine the position estimates of itself and the other robots in the ensemble. This combines aspects of Kalman filtering for pose estimation, image mosaic generation for appearance modeling, motion stereo for local pose estimates and image segmentation.

Authors: *G. Dudek, M. Jenkin (York U.), R. Unger*

Defining Islands of Reliability for Exploration and Hybrid Topological-Metric

This project involves the development of a formalism and methodology for making the transition from raw noisy sensor data collected by a roving robot to a map composed of object models and finally to a simple abstract map described in terms of discrete places of interest.

We are interested in the definition and detection of landmarks and local reference frames in a large-scale environment. We are examining automatic methods for generating coupled navigation and sensing algorithms that are generalized across specific sensing technologies such as vision and sonar. These landmarks and reference frames are used to construct a hybrid topological metric map. The representation consists of local metric maps connected together to form a graph. Each local map is considered a node in the graph and the edges of the graph qualitatively describe the hierarchy and relationship of neighbouring nodes. The work is inspired by biological environment perception.

Authors: *S. Simhon, G. Dudek*

Real-time Vision-Based Collision Avoidance from Ego-Motion

This work involves the use of real-time motion estimation for collision avoidance. The primary emphasis is on the rapid computation of optical flow, combined with the segmentation and mapping to provide a real time estimate of 3-dimensional occupancy. The noisy and occasionally bumpy character of robot motion even in an office environment introduces a variety of artefacts whose removal is critical to the success of the methodology.

Authors: *F. Belair, G. Dudek*

5.11 Network Communication

Video Transport for Low-latency Human-Human Collaboration

Anyone who has used videoconferencing tools, ranging from simple desktop applications such as CU-SeeMe or Netmeeting, to high fidelity professional systems, quickly realizes that videoconferencing is not the same as physical presence, nor even to a telephone call. While the conversants can see video images of each other, these are often of limited quality. Worse, the latency in the audio signal results in an unnatural "turn-taking" style of conversation that diminishes the quality of interaction and exaggerates the sense of distance.

In order to overcome these problems, we are developing a new research facility known as the Shared Reality Environment. The primary goal of this environment is to support the exchange of low-latency, high-fidelity audio and video streams between multiple users in different locations. Satisfying this goal for the video stream presents a number of difficulties.

A first approach is to make use of M-JPEG or MPEG encoded video. The problems here are cost and latency. MPEG hardware tends to be expensive, and while this is less of an issue for M-JPEG, with current technology, either method introduces a minimum of 50 ms latency for compression and decompression, on top of the image acquisition time. Avoiding compression presents the option of transmitting raw data. For high resolution, 30 fps video, this requires massive amounts of bandwidth. Even on a 100 Mbps ethernet, transmission of a single frame of 640x480 at 24 bits takes approximately 100 ms.

The fact that much of the data in a video frame is redundant forms the basis of compression techniques. For example, a static background in a sequence of images may constitute the majority of each frame. Since our goal is to allow users to interact, we may simply remove the background in its entiretiy, and thus reduce encoding and decoding time. The remaining image components, if sufficiently small, may be transmitted as raw data without compression, thereby reducing overall latency. Key to this work is the ability to locate, quickly, an approximate bounding box of a person in a scene.

Authors: *A. Xu, J. Cooperstock*

High-fidelity Audio Transport over Internet

Real-time transmission of audio data over the internet has become relatively commonplace, but the quality and number of channels has so far been limited due to bandwidth constraints. With the ongoing growth of new, high speed networks, comes the potential of high-fidelity, multi-channel audio distribution.

In cooperation with the AES Technical Committee for Networked Audio Systems (TCNAS), we are developing the protocols for two demonstrations of this technology. The first consists of an AC3 (encoded Dolby 5.1) audio stream at 448 kbps while the second consists of a 6-channel, 96kHz, 24 bits per sample, uncompressed stream, requiring approximately 13 Mbs. In both cases, the audio transmission is synchronized to a simultaneous video transmission, using MPEG-1 technology.

Such high bandwidth transmissions fare well provided that the intervening network does not become congested. However, in the present case of IPv4, quality of service cannot be guaranteed. Hence, our protocol must incorporate buffering and adapt dynamically to network load so as to sustain an uninterrupted playback.

Authors: *A. Xu, J. Cooperstock*

5.12 Shape Analysis

Shock Graphs and Shape Matching

We have been developing a theory for the generic representation of 2-D shape, where structural descriptions are derived from the shocks (singularities) of a curve evolution process, acting on bounding contours. We have now begun to apply the theory to the problem of shape matching. The shocks are organized into a directed, acyclic *shock graph*, and complexity is managed by attending to the most significant (central) shape components first. The space of all such graphs is highly structured and can be characterized by the rules of a *shock graph grammar*. The grammar permits the reduction of a shock graph to a unique rooted shock

tree. We have introduced a novel tree matching algorithm which finds the best set of corresponding nodes between two shock trees in polynomial time. Using a diverse database of shapes, we have demonstrated our system's performance under articulation, occlusion, and moderate changes in viewpoint. Representative results are shown in Fig. 5.4.

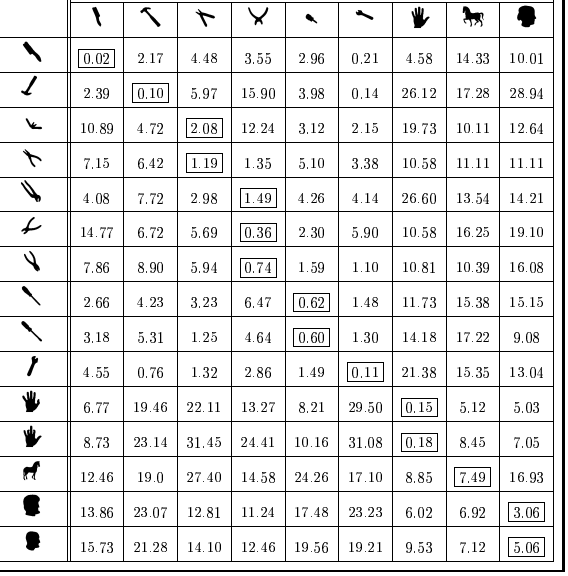
Instance	Distance to Class Prototype								
									
	[0.02]	2.17	4.48	3.55	2.96	0.21	4.58	14.33	10.01
	2.39	[0.10]	5.97	15.90	3.98	0.14	26.12	17.28	28.94
	10.89	4.72	[2.08]	12.24	3.12	2.15	19.73	10.11	12.64
	7.15	6.42	[1.19]	1.35	5.10	3.38	10.58	11.11	11.11
	4.08	7.72	2.98	[1.49]	4.26	4.14	26.60	13.54	14.21
	14.77	6.72	5.69	[0.36]	2.30	5.90	10.58	16.25	19.10
	7.86	8.90	5.94	[0.74]	1.59	1.10	10.81	10.39	16.08
	2.66	4.23	3.23	6.47	[0.62]	1.48	11.73	15.38	15.15
	3.18	5.31	1.25	4.64	[0.60]	1.30	14.18	17.22	9.08
	4.55	0.76	1.32	2.86	1.49	[0.11]	21.38	15.35	13.04
	6.77	19.46	22.11	13.27	8.21	29.50	[0.15]	5.12	5.03
	8.73	23.14	31.45	24.41	10.16	31.08	[0.18]	8.45	7.05
	12.46	19.0	27.40	14.58	24.26	17.10	8.85	[7.49]	16.93
	13.86	23.07	12.81	11.24	17.48	23.23	6.02	6.92	[3.06]
	15.73	21.28	14.10	12.46	19.56	19.21	9.53	7.12	[5.06]

Figure 5.4: Similarity between database shapes and class prototypes. In each row, a box is drawn around the most similar shape.

Authors: *K. Siddiqi, A. Shokoufandeh (Rutgers University), S. J. Dickinson (Rutgers University), S. W. Zucker (Yale University)*

Geometric Flows for Shape Segmentation

A number of active contour models have recently been proposed in the literature, which unify the curve evolution framework with classical energy minimization techniques for segmentation, such as snakes. The essential idea is to evolve a curve (in 2D) or a surface (in 3D) under constraints from image forces so that it clings to features of interest in an intensity image. Recently, the evolution equation has been derived from first principles as the gradient flow that minimizes a modified length functional, tailored to features such as edges. However, because the flow may be slow to converge in practice, a constant (hyperbolic) term is added to keep the curve/surface moving in the desired direction. We have derived a modification of this term based on the gradient flow derived from a weighted area functional, with image dependent weighting factor. When combined with the earlier modified length gradient flow, we obtain a PDE (partial differential equation) which offers a number of advantages, as illustrated by several examples of shape segmentation on medical images. In many cases the weighted area flow may be used on its own, with significant computational savings. A representative example is shown in Fig. 5.5.

Authors: *K. Siddiqi, A. Tannenbaum (University of Minnesota), S. W. Zucker (Yale University)*

Hamilton-Jacobi Skeletons

The eikonal equation and variants of it are of significant interest for problems in computer vision and image processing. It is the basis for continuous versions of mathematical morphology, stereo, shape-from-shading

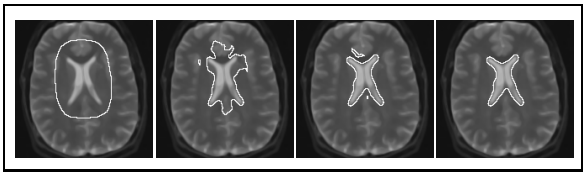


Figure 5.5: The evolving front, overlayed in white, converges on the outline of the brain ventricle in an MR image.

and for recent dynamic theories of shape. Its numerical simulation can be delicate, owing to the formation of singularities in the evolving front, and is typically based on level set methods. However, there are more classical approaches rooted in Hamiltonian physics, which have received little consideration in computer vision. We have introduced a new algorithm for simulating the eikonal equation, which offers a number of computational and conceptual advantages over the earlier methods when it comes to shock tracking. In parallel we have developed a very efficient algorithm for shock detection, where the key idea is to measure the net outward flux of a vector field per unit volume, and to detect locations where a conservation of energy principle is violated. A representative example of a 3D skeleton obtained from this framework is shown in Fig. 5.6.

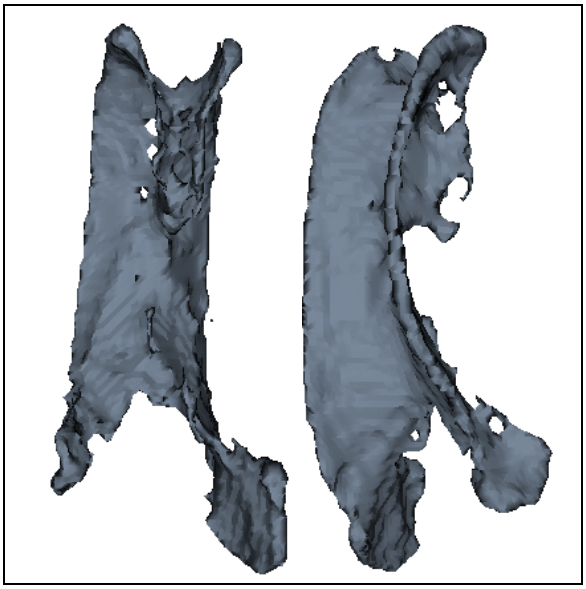


Figure 5.6: Two views of a (3D) divergence-based skeleton of brain ventricles, segmented from a 3D MR image.

Authors: *K. Siddiqi, S. Bouix, A. Tannenbaum (University of Minnesota)*

6 Robotics

6.1 Ambulatory Robotics

Control of Running in Quadruped Robots

In order to minimize cost and complexity of legged robots, we investigate the design and control of simple mechanical designs for quadruped robots which feature only one actuated degree of freedom per leg. This project explores modeling and control of a bounding gait for our Scout II quadruped robot.

Early results have shown that stable bounding is possible with minimal closed loop feedback, yet achieving stable running at speeds up to 1.2 m/s. Ongoing research pursues robust velocity control, gait transitions, turning, power minimization and teleoperation interfaces.

Authors: *D. Papadopoulos, M. Buehler*

Control of Quadruped Walking with Passive Knees

Much of the lower leg motion during the swing phase in human walking is passive. We have followed a similar approach by designing a passive revolute knee joint for our Scout II quadruped robot. This permits new gaits, like trotting, keeps the design simple (in comparison with actively powered knee joints), and promises reduced power consumption - a critical challenge for autonomous robots.

The goal of this project is to develop compact designs for passive, but lockable joints, and control algorithms for trotting with passive knees.

Authors: *G. Hawker, M. Buehler*

Control of Compliant Walking in Quadruped Robots

Based on earlier encouraging results with stiff-legged walking with the Scout I quadruped robot, we are now investigating controllers for compliant walking in the larger Scout II robot. Simple loss-less models are used as a basis for developing explicit periodic forcing controllers, which excite the body pitching dynamics for a compliant bounding-type walk. This approach is compared with others based on neural oscillators and central pattern generators.

Authors: *M. de Lasa, M. Buehler*

Control of Step and Stair Climbing in Quadruped Robots

The justification for the complexity and cost of legged robots lies in their ability to negotiate rough terrain, overcome obstacles, and climb stairs. In this project, we develop controllers which permit the Scout II quadruped to dynamically negotiate obstacles.

Authors: *S. Talebinejad, M. Buehler, E. Papadopoulos (U. Athens, Greece)*

Design and Control of an Autonomous Hexaped Runner

Stable and robust autonomous dynamic locomotion is investigated in a six-legged robot. The RHex 0 hexapod runs dynamically in a tripod gait over flat and badly broken terrain. Like Scout II, RHex 0 has a very simple mechanical structure with only one actuator per leg, and compliant legs.

Its design and control is motivated by a collaboration of roboticists, biologists, and mathematicians, in an attempt to capture specific biomechanical locomotion principles. RHex 0 operating principles are similar to those observed in cockroaches, despite the vastly different morphologies.

This 'functional biomimesis' approach attempts to capture some of the animals' agility without having to copy each detail of their morphology.

Authors: *E. Z. Moore, D. McMordie, M. Buehler, U. Saranli (U. Michigan), D. E. Koditschek (U. Michigan), R. J. Full (UCB)*

Walking Controllers for the SONY Robot Dog

We are developing integrated intelligent behaviors for a commercial entertainment robotic device - the SONY robot dog. The application domain is soccer playing and the results are demonstrated annually in the international RoboCup competition, where teams of robot dogs face off in soccer games. The focus of this particular locomotion sub-project is to develop advanced locomotion controllers for basic quadrupedal locomotion, robust mobility, error recovery, as well as soccer specific behaviors such as goal keeping, scoring, blocking, and kicking. An important aspect is the tight integration of the locomotion behaviors with perception and planning.

Authors: *Tariq Gunheim, L. Mitrea, M. Buehler, J. Cooperstock, G. Dudek*

Mobile Platforms Designs for Outdoor Locomotion

The focus of this project is the study of the rough terrain locomotion and obstacle-crossing behaviour of two alternative mobile platforms: a wheeled-tracked vehicle and a four-legged robot, the Scout II. Part of this project involves the development of realistic models of the mobile platforms including their motion controllers. We are also developing rough terrain models, motion control algorithms for rough terrain, and algorithms for obstacle-crossing.

Simulations are carried out within the Working Model simulation environment (dynamical simulator package). The behaviour of the mobile platforms will be evaluated via the use of a number of performance indices, such as stability, power consumption, manoeuvrability, and so on.

Authors: *S. Talebinejad, E. Papadopoulos, M. Buehler*

6.2 Dynamics and Control

Control of a Boom-Mounted Robot Arm (COBRA)-Phase II

This project is a joint effort of McGill University, the University of Western Ontario, the Canadian Space Agency, Bombardier Services, and Fredericton, N.B.-based Measurand Inc. Phase II of this project, financed with a contract from Bombardier Services, in the framework of the STEAR-Quebec Program, comprises the modelling, simulation and control of an industrial manipulator mounted on a flexible boom for long-reach capabilities. The project aims at the proof of concept of the control of the manipulator in the presence of motions of the base, occurring by virtue of the flexibility of the boom, when excited by the motion of the manipulator. Envisioned applications comprise aircraft maintenance and servicing, in operations such as shot-peening, stripping, painting, and deicing. In addition, all these operations include inspection. (Figure 6.1).

Authors: *J. Angeles, A. K. Misra, A. Hemami, K. Parsa, R. V. Patel (U. of Western Ontario), A. Robins (Bombardier Services), L. Cléroux (Bombardier Services), C. Perron (Bombardier Services), L. A. Danisch (Measurand Inc.)*

6.3 Geometry and Kinematics

Parallel Manipulators with Higher Pair Joints

A novel class of parallel manipulator, where one joint in each leg consists of a holonomic, higher kinematic pair, is dealt with herein. The joint in question achieves a one degree of freedom relative motion between two links where one rolls, without slip, on the other, like a rack and pinion or a pair of meshing, but not necessarily circular, gears. Such systems have been rarely investigated in the past and have received only incomplete attention in the context of poorly conceived attempts to model planar grasping. It is believed that our work represents the first instance where algorithms based on the kinematics mapping methods of Grünwald and Study(GSM's) have been successfully applied to the analysis of closed chains containing higher pairs. This has led to recent, successful application of GSM's to both workspace and singularity analysis of parallel manipulators in general.

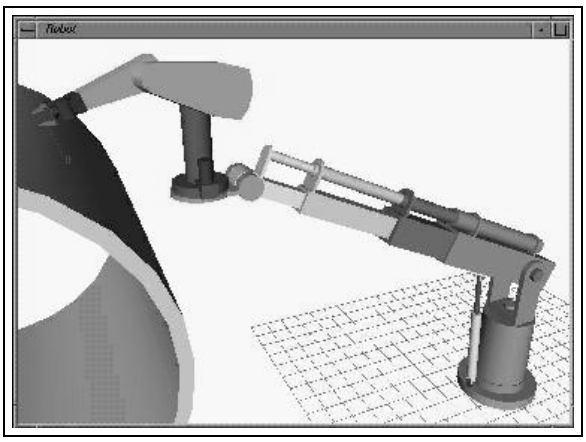


Figure 6.1: Boom-mounted robot

Authors: *M.J.D. Hayes (MU-Leoben), M. Husty (Univ. Innsbruck), P.J. Zombor-Murray*

Three and Six Degree of Freedom Double Triangular Manipulators

The advantages of greater speed, rigidity and payload-to-mass ratio, peculiar to parallel manipulators with respect to their serial counterparts, are well known and have been often stated. However it is usually difficult to analyze the forward kinematics and dynamics of six degree of freedom parallel architectures. Recently we have resumed the investigation of a class platform manipulators, called double triangular and based on the results of H.R.M. Daniali (Ph.D. '95). Of particular interest is the simplest, planar version(PDTM) which is being constructed as a machine tool platform. This architecture should lead to superior machine tool designs. Consider that the usual x-y-z milling table, with three orthogonal, serial slide-ways, lacks rotational capacity and the drives are serially mounted. The PDTM has full planar mobility, and the three lead-screws are base-driven and constitute the structural support as well. Coupled with a PR machining head, a full five DOF milling machine may be thus realized. This is believed to be a better design than the new, radically unconventional inverted Stewart-Gough platform milling machines which have enjoyed limited success but have also been prone to singularities which lead to destructive failures. It is also felt that the PDTM architecture will provide greater dexterity than existing millers and will, like x-y-z positioners, be singularity-free within their substantial workspace.

Authors: *J.C.F. Shum, N. Tilson, P.J. Zsombor-Murray*

Parallelotriangular Mechanisms and Line Contact Constraint

The pair of tetrahedra that move with intersecting edges is a parallel mechanism with six line contact constraints; the six R-P-R-P-R joints. It is also a six legged platform that moves, albeit with legs of zero length. Such five degree of freedom joints or, conversely, ones that inhibit only one degree of freedom, are conveniently studied with simple double triangular mechanisms, of planar, spherical and spatial variety, which use them. Forward kinematics, singularity and isotropy of all three types have been obtained. However, much remains to be done concerning analysis of the spatial variety(RDTM). Of particular interest are recent results which indicate that the forward kinematics RDTM's are dual to the inverse kinematics of 6R wrist partitioned serial chains, i.e., solvable is closed form. Though some controversy surrounds this claim, confirmation (or otherwise, alas) is imminent.

Authors: *V. Karakusevič, V.Krovi, P.J. Zsombor-Murray*

6.4 Haptic Device

In Situ Measurements of Cutting Forces During Surgery

Several experiments were completed in conjunction with a surgical doctor to acquire force data during cutting surgical acts for analysis. The force-position relationship, the frequency components present in the signal and the significance of the cutting rate, as well as any invariant properties are investigated. A database of the collected data has been created and preliminary analysis performed. (Figure 6.2)

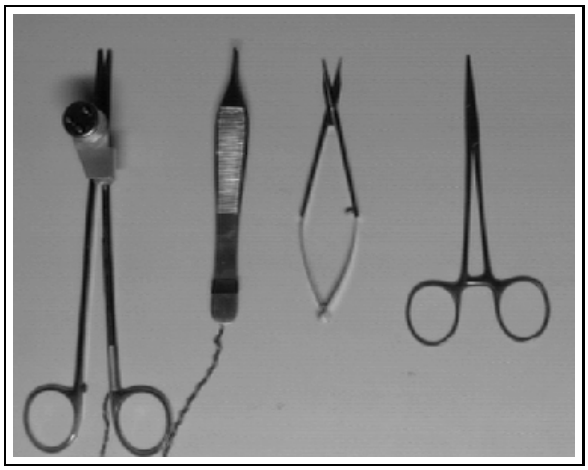


Figure 6.2: Instrumented surgical instruments used in the experiment

Authors: *S. Greenish, V. Hayward and T. Steffen*

Haptic Rendering of Viscoelastic Properties of Tissues

We are investigating a computational method to render in real-time the 3-D viscoelastic properties of tissues, so that a user may experience a mechanical interaction with these tissues, provided that a haptic device of sufficient fidelity is available. Drastic computational reduction is accomplished by implementing a multi-layer finite element mesh. The top layer, or parent, consists of a coarse mesh of the entire body; child meshes represent sub-regions of the coarse mesh, but have a much finer resolution. By using equivalent impedances to relate the two meshes, it is possible to decouple the coarse and fine regions; this enables the system to not only have different resolutions in difierent regions, but also allows the parent and child meshes to be updated at different frequencies. The multi-layer mesh also addresses numerical integration issues.

Authors: *O. Astley, V. Hayward*

A Six/Seven DOF Haptic Interface

This device is intented to be operated with a multi-digit precision grasp (like a pen) which makes it suitable for a large number of applications. It is electrically actuated, and motion is transmitted to the distal joints by stiff polymeric tendons. A second generation device, which has the characteristic of being statically and dynamically balanced, has been developed by MPBT Inc., Montréal, in collaboration with McGill University (Fig. 6.3).

The design also has provision for a scissor-like distal axis making for the 7th degree of freedom. While a comprehensive set of performance figures is being measured for future reference in improved versions, the following figures stand for the current prototype. Workvolume: 120X180X160mm; Orientation: 90X100X120 degrees; Peak Force and Torque 5N and 300 Nmm; Displacements resolution: 0.02 mm, angular resolution:

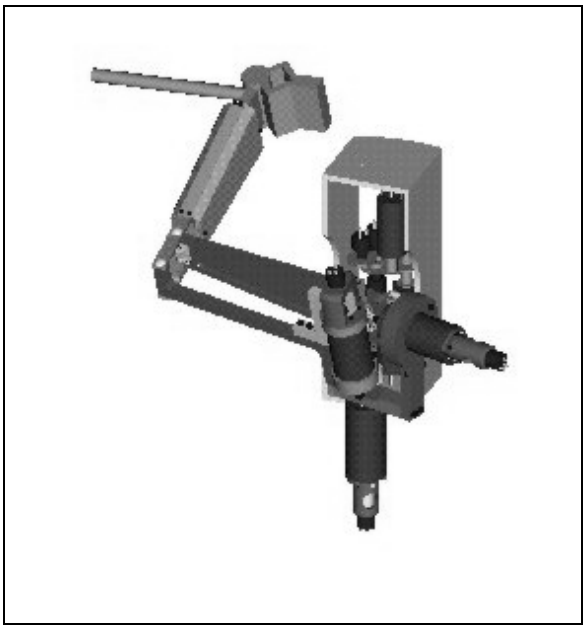


Figure 6.3: Freedom-7 Haptic Interface

20 seconds of degrees; Resolvable forces and torques at the handle: 0.01 N and 0.7 mNm; Electromechanical bandwidth: 200 Hz in all directions; Inertia perceived by the user: less than 100g. The use of advanced composite is also being researched by Prof. Lessard (Mech. Eng.) for increased performance and manufacturability. A commercial version is now marketed by MPB Technologies, Montréal (Fig. 6.4)

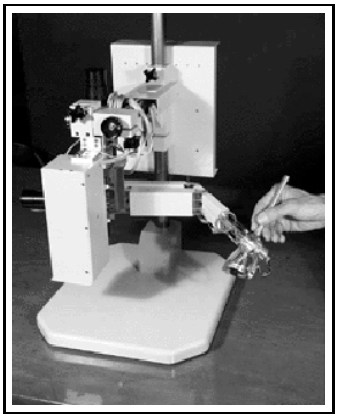


Figure 6.4: Commercial Version of Freedom-6

Authors: *V. Hayward, P. Gregorio, X. Chen*

A Two DOF Planar Haptic Interface: The Pantograph

We have designed a desktop haptic interface (a programmable force feedback mouse so-to-speak). Several prototypes have been constructed to date. Prominent features of this device include a large workspace,

low friction, low inertia, high rigidity and a minimal intrusion in the work area. Programmed mechanical models are used to kinesthetically describe the features of an interface. These models are analogous to iconic representations in conventional graphic interfaces. Users, acting and perceiving through the haptic channel, simultaneously perceive simulated objects through the visual and auditory channels (Fig. 6.5). Although this design is now five years old, it still supports a number of experiments.

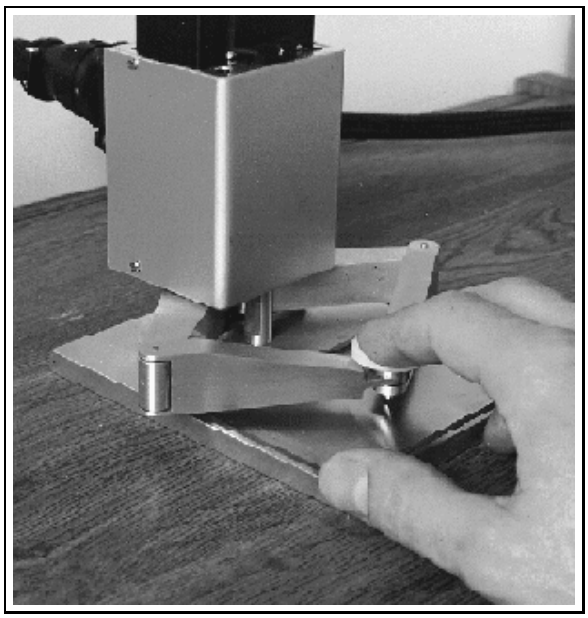


Figure 6.5: The Pantograph

Many versions have been produced and experimented with. Presently, Haptic Technologies Inc., Montréal is marketing one version equiped with an embedded processor. A newer product has evolved from the original design named the PenCat/Pro. (Figures 6.6 and 6.7).

Authors: *V. Hayward, C. Ramstein (Haptic Technologies Inc.)*

Haptic Device Evaluation in Microgravity

Haptic interfaces can create under computer control tactile and kinesthesic sensations. One application is to allow operators to touch virtual objects, for example, icons of graphical displays. An experiment has been designed at the Canadian Astronaut Program to evaluate a haptic device (see "A Two DOF Planar Haptic Interface: The Pantograph") in microgravity and compare it to a coventional trackball device. Microgravity flight experiments were performed. A new generation device is being designed and constructed with a view to a Shuttle experiment.

Authors: *J. Payette, V. Hayward, C. Ramstein*

6.5 Identification and Control

Torque Control Using a Harmonic Drive

A nonlinear dynamic model was derived for the torque generated by a harmonic drive. Measurements were taken in two cases: locked-load, to approximate low-speed operation, and free-load. Frequency response measurements, with variable amplitudes, were taken as a means of approximating the uncertainty model, and H-infinity controllers were subsequently designed. These proved to be reliable and performed well. The

Figure 6.6: Commercial version of the Pantograph

models were also used to "clean up" torque signals corrupted with periodic noise signals related in frequency to some of the gear-related signals.

Authors: *H. Dokht-Taghirad, P.R. Bélanger*

Adaptive Algorithm with Short Adaptation Time

The traditional delay-plus-first-order model from process control was used as the basis for a new adaptive control algorithm. Model poles were assumed known, but zeros were allowed to vary. The special features of the model were used to devise a rapid algorithm, whose convergence was studied not asymptotically, but in finite time. The effects of noise and of deviations from model structure were studied. This algorithm, which was originally developed from ad-hoc principles, has proved to be quite reliable in actual applications.

Authors: *S. Gendron, P.R. Bélanger*

Hysteresis Compensation in Smart Materials

Most available actuators and transmissions exhibit nonlinear characteristics which impair precision and speed of response. This research addresses the problem of reducing the hysteresis found in the actuation of most smart materials. The concept of phaser is introduced, an operator which shifts the phase of a periodic signal but keeps its magnitude unchanged. Since it is possible to approximate phasers with linear filters, it is possible to design practical compensators. The design requires the knowledge of one parameter, easily identified from experimental transfer function estimates. For the system with saturating hysteresis, two phasers are used in a tandem connection. This compensation reduces the hysteresis to a memoryless single saturation. The method is applied to an SMA and piezo actuators. (Figure 6.8).

Authors: *M. Cruz-Hernandez, V. Hayward*

Adaptive Velocity Estimation

A method is investigated to estimate velocity from discrete and quantized position measurements. The method is optimal in the sense that it minimizes the velocity error variance while maximizing the accuracy

Figure 6.7: The PenCat/Pro

of the estimate. The design of the estimator requires only one parameter.

Authors: *F. Janabi-Sharifi, V. Hayward, C-S. J. Chen*

Modelling and Force Control of the SARCOS Arm

This project focuses on the modelling, identification, and control of the SARCOS arm. Applying forces with robots or teleoperated manipulators is a very complex task due to the interactions with an unknown environment, and to the high bandwidth loops involved. To simplify the problem, linear system analysis is used, and actuator dynamics are ignored. However, nonlinear actuator dynamics can result in unstable behavior during force controlled tasks. In this research study accurate models of the SARCOS manipulator hydraulic joints are derived to be used in control design. Robust model-based joint controllers will be developed aiming at masking nonlinear and undesirable joint dynamics, and in pushing the limits of bandwidth performance.

Authors: *G. Bilodeau, E. Papadopoulos*

6.6 Manipulators and Actuators

High-Performance Mechanical Transmissions

We are currently developing a new generation of mechanical transmissions, intended to replace gears in applications where backlash, friction, and flexibility cannot be tolerated. **Speed-o-Cam** is a speed-reduction mechanism based on cams and pure-rolling contact, that is capable of producing, in one single stage, a reduction of $N:1$, where N is an integer that can be as high as 8 for planar mechanisms, and 12 for spherical mechanisms. The limit here is imposed by the maximum pressure-angle value, which is commonly accepted as around 30°. We have produced one prototype that is intended for the coupling of parallel shafts; a second prototype, in its final stages of production, is aimed at coupling shafts with intersecting axes. Although the prototype of the latter was designed for shafts intersecting at right angles, virtually any angle can be accommodated, from 0° to 180°. In the extreme cases, an angle of 0° produces an external plate cam; an angle of 180° - an internal plate cam. Planar **Speed-o-Cam** is intended to replace spur and helical gears, while its spherical counterpart is targeted at bevel gears. One more transmission under development, **Slide-o-Cam**, is aimed at replacing rack-and-pinion mechanisms, and follows the same principle of power transmission under pure-rolling conditions for minimum friction losses, high stiffness and zero backlash. (Figures 6.9 and 6.10).

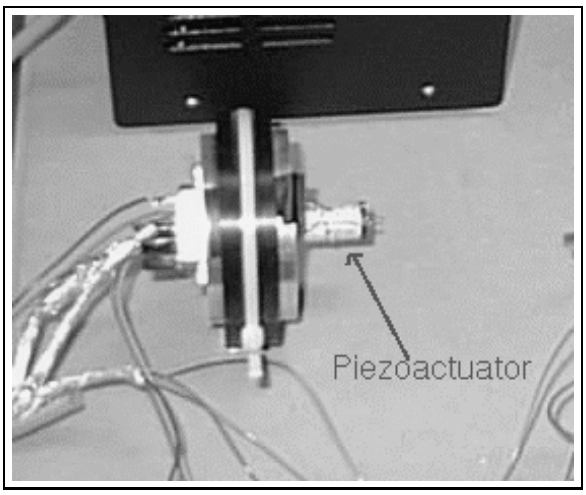


Figure 6.8: Piezo actuation test bed with optical microdisplacement measurements

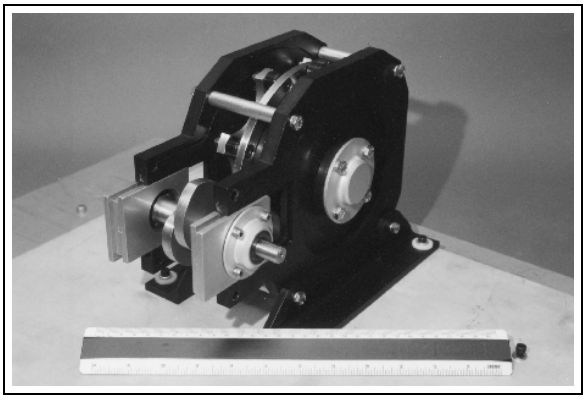


Figure 6.9: Planar **Speed-o-Cam** prototype

One more task in this project is the structural optimization of the transmissions. The major issue here is that cam mechanisms are subject to periodically-varying loads. Results available for structural optimization concern mostly the case in which the structure is optimum for one single given load. Within the framework of this project, we are developing novel structural optimization criteria and techniques to meet them. The purpose is to obtain mechanisms that are both light and structurally robust.

As mentioned above, cam transmissions induce periodically-varying loads, which, under steady-state conditions and small perturbations, lead to linear dynamical systems with periodically-varying coefficients. Results from classical control theory for time-invariant systems cannot directly be extended to this kind of systems. Using Floquet-Lyapunov theory, we are developing novel techniques for the stability analysis and the feedback control of these systems.

Authors: *J. Angeles, L. Slutski, M. A. González-Palacios, R. Spiteri, P. Montagnier, C. Teng, O. Navarro, C. J. Wu, D. Wang, S. Asamoah*

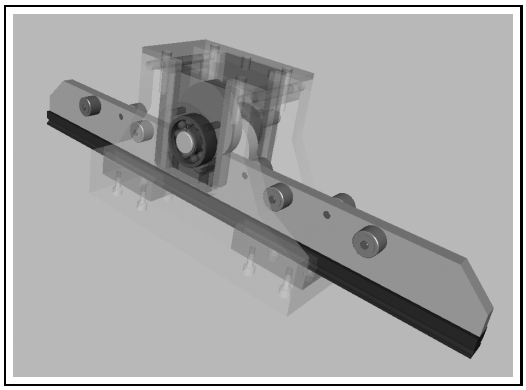


Figure 6.10: Virtual prototype of **Slide-o-Cam**

Design and Manufacturing of an 11-DOF Macro-Micro-Manipulator (M^3) System

The need to service and maintain aircraft has called for a new generation of manipulators that are characterized by a long reach and a highly redundant kinematic architecture. The challenge to robot designers here is to produce a mechanical system capable of accurate tasks in the presence of a flexible structure. Current designs of such robots exist, but they are limited to tasks that are quite error-tolerant, e.g., cleaning. In these tasks the end-effector is supplied with a highly compliant tool, namely, a cylindrical brush rotating about its axis that does the cleaning, the inherent compliance being thus capable of compensating positioning errors. Besides, these tasks are quite tolerant in terms of speed accuracy.

Other tasks required in the servicing and maintenance of aircrafts are more demanding in terms of accuracy, e.g., stripping, deicing, and painting. Stripping requires more accuracy in the execution of the task, in that the tool is rigid and sharp, positioning errors thus becoming dangerous, for they can lead to damage of the fuselage. Deicing requires a uniform application of the solvent, which calls for moderately accurate positioning but highly accurate velocity control. Painting, in turn, is the most demanding of these tasks, for it requires an accurate velocity control of the painting nozzle with the purpose of guaranteeing a uniform application of the painting, while concurrently requiring a highly accurate positioning control. This requirement becomes critical when the painting involves the tracing of regular geometric shapes on the fuselage, like curves that appear projected either as straight lines or as circles. These requirements motivated the need for a light, and hence, flexible structure, while at the same time capable of executing accurate positioning and velocity control.

In this project a modular approach to the design of the mechanical structure of an 11-axis robot to accomplish accurate positioning and velocity-controlled tasks in the presence of a flexible substructure is currently being explored. The manipulator is designed as a cascade of three modules, the proximal one being termed the macromanipulator, and comprising four revolute axes aimed at realizing four-dof positioning tasks proper of what are called SCARA—Selective-Compliance Assembly Robot Arm. The macromanipulator is responsible for a long reach and a high flexibility. The two other modules, comprising the seven-axis micromanipulator, are responsible for the accurate positioning and orientation of the tool attached to the end-effector. Of these, the intermediate module, the *Cuatro Arm*, developed during Phase I of IRIS, a Canadian network of centres of excellence, is a four-dof architecture responsible for the positioning of a point of its terminal link, which plays the role of the centre of the three-dof spherical wrist. Both the intermediate module and the spherical wrist were designed with an isotropic architecture for highest positioning accuracy. The spherical wrist, that we term the *Agile Wrist*, owes its name to the architecture adopted, namely, that of the *Agile Eye* developed by Prof. Clément Gosselin and his team at Université Laval, in Ste.-Foy, Quebec. (Figure 6.11).

Authors: *A. Morozov, O. Navarro, J. Angeles, R. V. Patel (U. of Western Ontario)*

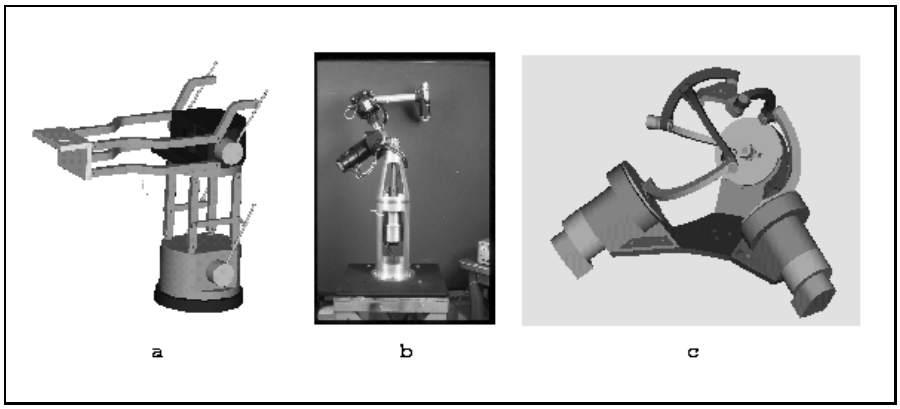


Figure 6.11: The three modules of the M^3 System: (a) the 4-dof macro-manipulator; (b) the intermediate 4-dof Cuatro Arm; and (c) the 3-dof Agile Wrist

Robot Calibration

The calibration of redundant robots poses challenges to the roboticist that are not present in the calibration of their nonredundant counterparts. A motivation for this project is space applications, mainly in light of the imminent commissioning of the International Space Station. In these applications, the robot must be calibrated without external sensors, for a fixed base is not readily available.

One basic item to identify in the context of robot calibration is the offsets in the joint-angle dials, whose zero does not always coincide with their nominal locations. However, when attempting to identify the joint offsets with the aid of the robot's own encoders, using self-motions, it turns out that, upon fixing the end-effector (EE) to the robot base, the offsets of the end joints cannot be identified. A set of measurements is needed in a different EE pose—position and orientation. We have established identifiability conditions and developed an identification algorithm that has undergone satisfactory tests in a dual-arm robotic workcell that is under development, as outlined in this same issue. (Figure 6.12).

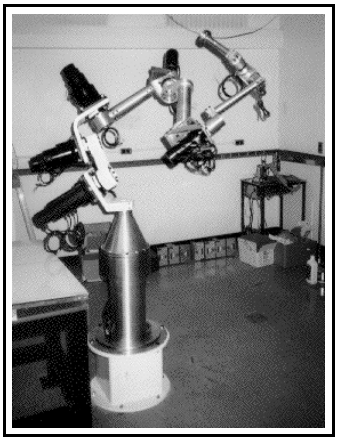


Figure 6.12: REDIESTRO 1

Authors: *Y. Gonthier, G. Bilodeau, F. Ranjbaran, J. Angeles, A. Robins (Bombardier Services)*

Dual-Arm Robotic Workcell

Two seven-axis, redundant manipulators were designed from scratch at CIM, with an architecture optimized to provide them with the highest accuracy, which led to what we have termed *kinetostatic isotropy*. This feature gives the manipulator the highest accuracy for positioning and force-sensing, which makes it ideal for hybrid force-and-positioning control. The manipulators, REDIESTRO 1 and REDIESTRO 2, are supplied with a six-axis force sensor at their end-effector, the latter being supplied, additionally, with torque sensors at its joints. These manipulators are the major components of a dual-arm workcell that is being developed in conjunction with the Canadian Space Agency and Bombardier Services. The workcell is used for the development of algorithms for object-avoidance and force control, which will be used on the International Space Station, since this robot has many features of the Space Station Remote Manipulator System. This project is financed by a contract with Bombardier Services in the framework of the Strategic Technologies for Autonomous Robotics (STEAR) Program. (Figure 6.13).

Figure 6.13: Dual-arm robotic workcell

Authors: *J. Angeles, R. V. Patel (U. of Western Ontario), A. Robins (Bombardier Services), F. Shadpey (Bombardier Services)*

Sensitivity Analysis and Control of High Performance Electromechanical Transmissions

In a number of applications, high performance transmissions are needed. They have high power density, low friction and high frequency response. In the design of such transmissions, a number of parameters must be traded-off. Sensitivity analysis allows us to systematically select such parameters and design controllers to guarantee robustness and rejection of disturbances such as friction.

Authors: *E. Cruz-Hernandez, V. Hayward*

High Strain Shape Memory Alloy Actuators and their Control

The actuators consist of fibers woven in a specific pattern which achieves a large amount of displacement amplification with very small losses. In one prototype, twelve fibers are run in parallel resulting in a 16 mm diameter package weighing 6 grams and capable of pulling 4 N. In this configuration, the strain is about 20% and the rise time shorter than 100 ms for an antagonist set-up in ambient air. A model of these actuators, which is relevant to control design, has been developed. The model is sufficiently accurate to allow controllers designed in simulation to be applied in practice without tuning. Variable structure controllers have been investigated with the purpose of achieving the control of position, force, and acceleration. Experimental performance results in the time domain demonstrate that this control can achieve very fast rise time, high

rejection of disturbance, small tracking and steady state error, and quenching of limit cycles, despite their numerous nonlinear properties. Patent granted. (Figure 6.14).

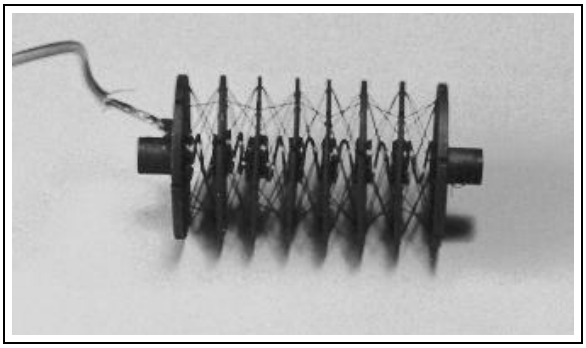


Figure 6.14: A single NiTi actuator package, 16 mm accross.

Authors: *D. Grant, V. Hayward*

Acoustical Stimulus System for Measurement of the Auditory Motion Aftereffect (aMAE)

A device was designed, constructed and used to measure the auditory motion aftereffect aMAE. It is capable of moving a sound source smoothly, quietly and swiftly on a spherical workregion centered around a subject's head. Due to its high speed of motion safety considerations have been taken into account in addition to basic performance requirements in terms of workspace, speed, low noise, and low visual intrusion. The basic structure consists of a spherical closed-loop five-bar linkage of 0.8 m operating radius, specifically optimized for this purpose. This device is presently in operation at the University of British Columbia, see Figure 6.15.

Figure 6.15: The STAS

Authors: *V. Hayward, E. De Silva, P. Zakarauskas, M. Cynader*

Minimal Complexity Manipulation Assistive Devices

Robotic serial chain mechanisms offer considerable flexibility in accomplishing a wide variety of mechanical manipulations within their workspace. However, in many cases, the multiple degrees of freedom of the robotic serial chain tend to be excessive for specialized and repetitive tasks. Hence we are investigating the development and use of a novel class of minimal-complexity manipulator assistive devices called Coupled Serial Chain mechanisms for such tasks. Such Coupled Serial Chain (CSC) mechanisms can be realized by coupling the rotational joints of a serial chain linkage with cable-pulley or geared transmissions. The resulting multi-link articulated mechanisms resemble robotic serial chains in terms of their workspace and their anthropomorphic geometry. However, unlike their robotic counterparts, they require fewer actuators, are simpler to control and can be manufactured inexpensively.

The greatest advantage lies in the ability to customize these mechanisms to perform specific manipulation tasks with complex trajectories and force interactions with the environment, which makes them attractive for use in tasks like assembly plant automation. In this research, we are investigating the use of Fourier methods to customize such CSC mechanisms for desired path following tasks. In conjunction with optimization, this enables the creation of a powerful tool for the mechanism designer by helping in the identification of many alternative feasible solutions and permitting a more complete and rapid exploration of the design space.

Authors: *Y-W. Pang, V. Krovi*

6.7 Modelling, Simulation, and Control

Dynamics of Nonholonomic Mechanical Systems

Nonholonomic mechanical systems pose a challenge to roboticists. Indeed, different from holonomic systems, a paradigm of which is the standard industrial manipulator, their nonholonomic counterparts require, for the description of their configurations, a number of variables greater than their mobility. As a consequence, some of the state variables of these systems are neither controllable nor observable. This kind of systems is studied here with the purpose of devising novel mechanical designs and control strategies that will make the operation of rolling robots more reliable and efficient. In the process of this study, we came across a new class of nonholonomic mechanical systems that leads to mathematical models resembling holonomic systems because of their simplicity. We term these systems *quasiholonomic*. In order to fully characterize quasiholonomic systems, we undertook an in-depth review of nonholonomic systems that led to the concept of *holonomy matrix*, to supplement the classical results based on the Frobenius Theorem.

Currently we are investigating mechanical design criteria under which a given robotic topology can lead to a quasiholonomic system. Our aim in this project is to design rolling robots with omnidirectional wheels that will be capable of either quasiholonomic or fully holonomic motions with suitable control schemes. A major issue in this investigation is the loss of holonomy, or quasiholonomy, due to disturbances from the environment. We will thus have a plant to control which is capable of undergoing topological changes, when switching from holonomic mode to nonholonomic (or quasiholonomic) mode, and vice versa. (Figure 6.16).

Authors: *S. Ostrovskaya, J. Angeles*

Computational Models of Friction

Friction occurs almost everywhere and many things, including human acts, depend on it. The model we are developing can be used to synthesize it, so it can be presented under computer control to a subject using a haptic device. The model is also a possible contribution to the existing model-based compensation techniques. It has the following properties: It is time free (autonomous), only displacements enter in the formulation; it does not drift; it is robust to noise, input is not assumed to be noise-free; a discrete formulation exists which is online and computationally efficient; it accounts for vector motions and forces (2 or 3D); and its parameters have a simple physical interpretation.

Authors: *V. Hayward, B. R. Armstrong, P. Dupont*

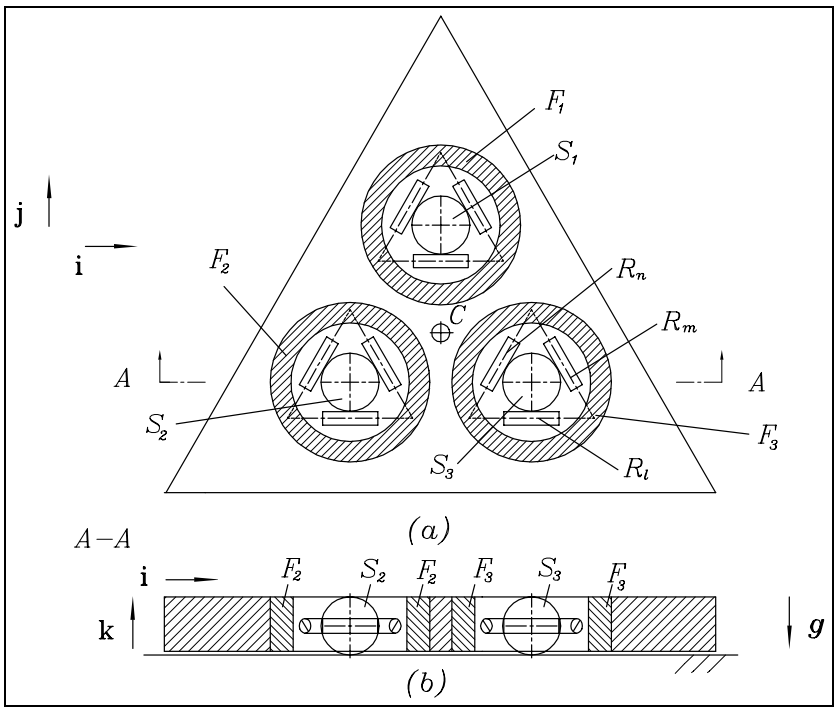


Figure 6.16: Rolling robot with three ball-wheels: (a) top view; (b) cross section AA

Modelling the Dynamics of Flexible Multibody systems

The goal of this project is to develop a dynamics formalism for flexible multibody systems by adopting the object-oriented concept. A multibody system can be regarded as a combination of bodies and kinematic constraints which can be treated as elementary "object". Each of these objects is being cast into a module equipped with characteristic parameters and operations. The *system* object is being designed to organize the topological structure of the multibody system and generate the global equations of motion. The object-oriented approach makes it easier to upgrade or modify already designed systems by simply adding or replacing objects. This is a collaborative project with CAE.

Authors: *A. K. Misra, B. N. Min*

Dynamics and Control of Mobile Manipulators

Mobile platforms equipped with manipulator systems have been proposed to perform important missions in the construction, field, and space environments. Their missions will include such diverse tasks as earth removal operations, tree harvesting, handling of toxic and radioactive waste, and planetary exploration. In this research study we focus on dynamics, planning and control problems found in mobile manipulator systems and aim to better understand some of the fundamental problems introduced by the use of such systems.

Authors: *D. Rey, E. Papadopoulos*

"Follow-the-Leader"

This idea is to have a train of off-rail vehicles follow the path, taken by the leader, as precisely as required. Such a system is of use as an automated mining excavator followed by a train of ore pass-back units,

supporting, say, a conveyor belt. Each element is connected to the one in front with an instrumented articulated drawbar. The motion of a neighbouring follower is dictated by the inverse kinematics of the drawback displacements, in a backward sense, that occured in the forward sense when the leader made a previous move. No known vehicle system exists which uses this sort of autosurveying. Furthermore the drawbar need not be a mechanical connection. It is virtually "there" as long as the follower can reliably measure the leader's trajectory, by remote sensing or other means. As long as at least one train element is "belayed" the others can compute their absolute position, not withstanding ground instability or slip at the contact of tracks, wheels, legs or whatever supports and/or propels a vehicle.

Authors: *V. Guenov, V. Krovi, P. O'Leary (MU-Leoben), P.J. Zsombor-Murray*

6.8 Planning

Visualization of RoboCup Soccer Agents using Swarm

This project has the goal of developing a visualization system that will aid in the programming of collaborative behavior in teams of mobile robots. We are building this visualization system using the *Swarm* framework from the Santa Fe Institute. Swarm is a framework, written in Objective-C, for constructing simulations of complex multi-agent systems. We have applied the visualization system to visualizing the overt behaviour and covert planning processes, expressed by multiple Soccer agents in the RoboCup domain. Using this visualization system, developers of RoboCup soccer teams will be able to more fully simulate and understand the behaviours of their software agents. It is our ultimate goal to use such a visualization tool to develop and test collaboration strategies to be used in actual mobile robots.

Authors: *S. Lerner, L. Hochstein, J. Cooperstock, J.J. Clark*

Trajectory Generation at or Near Singularities

A method has been devised for controlling the trajectories defined in Cartesian coordinates near or through the kinematic singularities of robot manipulators admitting a closed form kinematic solution. Our work considers a global approach based on "path energy functions" which in the regions of singularities reduce the path velocity in such a way that both joint velocities and accelerations remains bounded without incurring any deviation from the desired path. The existence proof of such path velocity schedules has been established for a large class of manipulators and desired trajectories. An algorithm has been found to construct these velocity schedules in the discrete case.

Authors: *J.E. Lloyd, V. Hayward*

Computer Aided Design of Robot Motion

Methods of computer aided geometric design have been used recently to effectively design smooth rigid body motions that interpolate through a given, discrete pose sequence. In this project we aim to use these methods to smoothly control the motion of a system of rigid bodies, i.e., the chains of jointed links in a manipulator system, so as to ultimately enhance the dynamic performance of any given robot. The challenge, here, lies in the treatment of intermediate links, which, unlike the end effector and the workpiece, are kinematically constrained by the joints connecting them to their neighbours. To the best of our knowledge, this has never been attempted, previous work having been restricted to a) splining of individual joint variable rate and B-spline and NURBS pose interpolation of what is essentially unconstrained motion of a rigid body in b) the plane and c) in space.

Authors: *A. Cebula, P.J. Zsombor-Murray, M.L Husty*

6.9 Sensors

On-Line Hand-Eye Calibration

The *hand-eye calibration problem* consists of:

> *Given two frames, $\mathcal{G}$ and $\mathcal{H}$, attached to the gripper of a robotic end-effector (EE) and to a sensor rigidly mounted on the EE, respectively, find the relative* pose*—position and orientation—of the two frames, from measurements of the EE pose by means of sensor and joint-encoder readouts.*

Algebraically, the problem is known to lead to a quadratic homogeneous equation in the unknown pose matrix, which prevents any direct solution. The solution first proposed in the literature exploited the properties of proper orthogonal matrices, while decoupling the orientation problem from the position problem. This solution, relying on perfect measurements, led, for two sets of measurements, to a system of nine linear equations in four unknowns. This procedure was later on streamlined by means of quaternions, but these required the introduction of an iterative procedure relying on the singular-value decomposition of a matrix at each iteration. If we consider that the singular-value decomposition is itself iterative, the new procedure did not lead to a computational gain. Moreover, this procedure neither considered measurement noise.

The issue of noisy measurements was addressed for the first time as recently as 1995. The solutions proposed so far, however, are not yet implementable online. In this project we developed an algorithm to solve the hand-eye problem that relies on recursive linear least squares and is, hence, applicable online. To this end, we resort to the invariant formulation of rotations developed at CIM's Robotic Mechanical Systems Laboratory. (Figure 6.17).

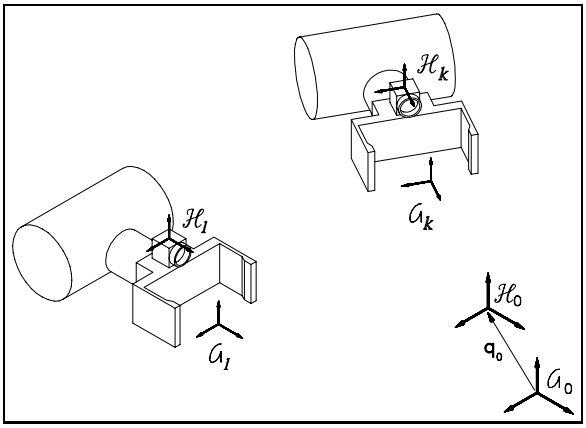


Figure 6.17: Layout of the hand-eye calibration problem

The solution that we propose is based on two nested recursive least-square processes, the external one, for the estimation of the the relative orientation, the internal one, depending on the former, for the estimation of the relative position of the origins of the two frames $\mathcal{G}$ and $\mathcal{H}$. Each process is based on the standard recursive least-square algorithm.

Upon convergence, the external process yields a rotation matrix that is not necessarily proper orthogonal, and hence, not acceptable. However, the proper-orthogonal component of this matrix is computed by post-processing, using polar-decomposition filtering. The latter is based on Higham's algorithm.

Tests run so far on a laser range finder mounted on a six-axis robot in the Computer Vision Laboratory have been successful in the implementation of the algorithm developed here.

Authors: *J. Angeles, G. Soucy, F. Ferrie*

6.10 Space Robotics

Contact Dynamics Associated with Space Manipulator Systems

For manipulator-assisted satellite capture, docking/berthing or space structure assembly operation, the end-effector ideally should make contact with the target grapple point with zero relative velocity. This of course is not possible in practice and leads to an impact. The nature of this impact and the contact deformations and forces induced affect the subsequent dynamics and control of the system. There can also be undesirable attitude drift of the mother spacecraft. The details of the contact dynamics are being studied using a finite element formulation that has been coupled to a flexible multibody dynamics code. Various scenarios including multi-impact cases are being studied.

Authors: *A. K. Misra, S. W. Kim*

6.11 Telerobotics

Control of Direct Drive Robots

Direct drive motors simplify greatly the mechanical complexity of actuated joints by eliminating the transmission systems required with traditional electric actuators. In addition, they permit accurate torque control at each joint, through eliminating backlash, compliance, and much of the friction incurred with gear transmissions. Based on experiments with the McGill/MIT Direct Drive Motor, this project develops new optimal commutation laws for torque control of synchronous motors, and improves the control of Direct-Drive Robots with positive joint torque feedback.

Authors: *F. Aghili, M. Buehler, J. M. Hollerbach (U. Utah)*

Operation of Redundant Telemanipulators

Redundant manipulators are increasingly used for their greater capabilities but entail greater complexity in their control since the end effector trajectory must be controlled together with their self motions. In direct teleoperation an operator cannot control simultaneously all the degrees of freedom. The traditional approach is to solve a redundancy resolution problem autonomously. For applications such as space robotics or other unstructured environments, this approach is not suitable due to the multiplicity of constraints. A generalized framework for the operation of manipulators with more degrees of freedom than an operator can control simultaneously is being developed.

Authors: *E. Dupuis, V. Hayward, E. G. Papadopoulos*

7 Systems and Control

7.1 Discrete and Hybrid Systems

Hierarchically Accelerated Dynamic Programming

The HADP methodology is based on the theory of state aggregation (or abstraction) originally developed by Y.J. Wei, P.E. Caines and associates in CIM. This technique aggregates the states of a controlled system by use of the so-called dynamical consistency relation between blocks of states in a partition of the state space. The DC relation defines high level controlled events in such a way that all high level plans conceived in terms of the DC events (on the resulting so-called high level partition machine) must necessarily be realizable in the low level base machine. By using hierarchical systems whose successive layers are related in this manner, efficient dynamic programming (DP) algorithms have been designed called Hierarchically Accelerated Dynamic Programming (HADP) algorithms. At the cost of a degree of sub-optimality (which may be estimated by application of the developing HADP theory), these algorithms show very significant acceleration with respect to any conventional method. It is to be noted that any advances in DP methodology for single layer systems may be incorporated into the single layer subalgorthims of the HADP technique; hence the HADP methodology is able to profitably exploit progress in conventional optimization techniques. Current research is focusing on the algorithmic generation of the aggregates constituting the states of the partition machines at successive hierarchical layers.

Authors: *G. Shen, P.E. Caines*

Hierarchical Supervisory Control Theory

In this work we present a hierarchical control theory for supervisory automata based on state aggregation. Conditions are determined on state partitions which ensure that the control of transitions between blocks in a high-level (i.e. aggregated) model, combined with local state - dependent controls, is effective in the sense of achieving specifications given either for the high-level model or for the low-level system. A design methodology is proposed for the construction of the necessary partitions. We show this formulation of hierarchical supervision satisfies the consistency conditions in the existing language-based hierarchical supervisory control theory. Examples are presented including a material transfer line with re-entrant flow and a double queue.

Authors: *P. Hubbard, P.E. Caines*

Hierarchical Hybrid Control Systems

Many complex control systems in engineering, such as air traffic management systems, complex robotic systems, and intelligent highway systems, have a hierarchical-hybrid nature in the sense that at a low level they can be characterized by systems with discrete and continuous states, and at a high level they are organized as a discrete supervisory system. In this work a hybrid (base) system is modelled via a state space which is the direct product of a discrete state space and a continuous state space, together with continuous and discrete dynamics and controls. Based upon previous work of Y-J. Wei and P.E. Caines the notion of dynamical consistency is extended to hybrid systems so as to define the hybrid partition machines associated with a system $\mathcal{S}$. This then permits the development of a control theory and associated algorithms for the design and operation of hierarchical control systems for complex hybrid systems. Recent work has extended this work to the case of systems subject to disturbances.

Authors: *E. Lemch, P.E. Caines*

Feedback Control of Nonholonomic Systems

Nonlinear systems with nonholonomic constraints are encountered quite frequently in practice but are known to be particularly difficult to control. The difficulty in steering such systems is caused by the fact that their linearization is uncontrollable and fully linearizing state-feedback transformations cannot be constructed.

Author: *H. Michalska*

7.2 Industrial Process Control

Design, Simulation and Implementation of Decentralized Controllers for a Multivariable Feed Blending System

This industrial control research project was concerned with the applicability of decentralized PI control to a nonlinear multivariable feed blending process at the Falconbridge nickel smelter near Sudbury, Ontario.

Falconbridge's new Raglan mine located in Northern Québec started to ship its nickel concentrate to the Sudbury smelter in the spring of 1998. A new continuous feed blending process design allowed the existing concentrate slurry from the Strathcona mine to be blended with the Raglan concentrate before being roasted and fed into the electric smelting furnace.

The basic idea behind the process was to mix dry Raglan concentrate with Strathcona slurry and process water in a repulper tank to maintain both a concentrate dry mass ratio setpoint, and a density setpoint at the output of the repulper tank. The most important controlled variables to achieve efficient roaster and furnace operation were the pulp density, followed by the Raglan to Strathcona dry mass ratio. The repulper tank level also had to be regulated.

Following the development of a nonlinear multivariable model of the feed blending process, we obtained a linearized model to design linear decentralized PI controllers. The design was carried out in the frequency domain. Robustness of the controllers was checked through extensive simulation studies with the full nonlinear process model. The feed blending control system was successfully commissioned in the spring of 1998 and has been reported to perform well since then.

Authors: *B. Boulet, L. Ryan, C. Graves, B. MacKay*

7.3 Logic Control

Macro-COCOLOG

The issues of efficiency, transparency and implementability of COCOLOG logic control systems are treated in this work via the creation of the following entities:

(i) Syntactic hierarchies of COCOLOG languages called *Macro COCOLOG languages* wherein iterated axiomatic definitions of new terms and predicates are adjoined to the basic COCOLOG language so as to give compact expression to complex concepts defined at earlier iterations (while preserving consistency and completeness).

(ii) The languages of (i) are employed in the construction of the (finitely) nested *Macro (COCOLOG) CCRs* generalizing the IF..THEN.. rules appearing in standard COCOLOG Conditional Control Rules (CCRs). The enhancement of the basic COCOLOG system, involving first, Macro (COCOLOG) Languages and, second, Macro (COCOLOG) Actions (taken together with the associated execution model) is called *Macro COCOLOG*. The resulting system is such that base level (i.e. standard) COCOLOG controllers realizing complex control specifications for systems with complex dynamics may be designed by tractable and comprehensible procedures.

(iii) Variable Macro Actions, which are mechanisms for the re-utilization of Macro actions via the manoeuvre of parametrizing them by state dependent quantities permitting them to be directly invoked during the evolution of the controlled system.

Current work involves the incorporation of the IF..THEN.. COCOLOG CCRs directly into the axiomatic basis of the COCOLOG to give a system called $COCO_{DEF}$.

Authors: *C. Martinez-Mascarua, P.E. Caines*

Automated Theorem Proving and Formal Methods in System Theory

It is shown that the standard notions of tautology and subsumption can be naturally generalized within the context of modified deduction rules for binary clausal resolution-refutation algorithms. Furthermore, this may be carried out in such a way that refutation completeness is preserved. The modified deduction rules build-in the reflexivity, symmetry, transitivity and predicate substitutivity axioms for equality. Primitives for the analysis and control specification of non-deterministic finite state machines analogous to reachability and current state estimation are introduced in COCOLOG. A hierarchical control theory has been developed in this framework which generalizes the results of Caines and Wei in the deterministic setting.

Authors: *T. Mackling, P. E. Caines*

7.4 Nonlinear Control

Global Controllability of Hamiltonian and Other Nonlinear Systems: Fountains and Recurrence

A form of local accessibility for nonlinear control systems is introduced called the continuous fountain condition. Subject to the condition that (i) the states of a system are continuous fountains and (ii) one of various recurrence conditions holds it is shown that the systems state space is (globally) controllable. These results are then applied to certain subsets of the state space of controlled Hamiltonian systems called energy slices in order to establish their controllability. These results have application to hybrid hierarchical control in that they give conditions for a finite analytic partition to satisfy the in-block controllability condition.

Authors: *E. S. Lemch, P.E. Caines*

Control of Limit Cycles in Nonlinear Systems

This new project is concerned with the design of feedback laws which make the closed loop system have a globally attractive limit cycle of a prespecified size. The solution of this theoretical problem finds many applications. Feedback control of a hopping mobile robot is one example. The control objective is to stabilize the hopping height of the robot to a reference value. The project is carried out in collaboration with the experimental laboratory of Professor Martin Buehler.

Authors: *H. Michalska, M. Buehler*

Moving Horizon Control of Nonlinear Systems

Very few control design techniques can handle constraints imposed, a priori, on the system. One of the most powerful design techniques which can handle constraints easily and is applicable to systems in general form is referred to as 'model predictive control' or 'moving horizon control'. Previous work in this area is concerned with construction of stabilizing 'moving horizon' control laws and design of 'moving horizon' observers.

Author: *H. Michalska*

Moving Horizon Control Without Constraint on the Terminal State

Previous moving horizon controllers were based on the solution of a family of open-loop optimal control problems with an equality constraint on the terminal state (the state of the system at the end of the optimization horizon was required to be zero).

A new class of moving horizon controllers is investigated which does not require the satisfaction of this constraint. It is important for applications since optimal control problems with equality constraints are hard to solve.

Author: *H. Michalska*

Optimization-Based Tracking of Nonlinear Systems

A moving horizon type of algorithm is investigated to achieve tracking of reference trajectories in the output space. The algorithm is to be tested on an aircraft model. The control objective is to generate an on line feedback law which allows for asymptotic tracking of a reference trajectory despite disturbances such as head-winds etc. and model-system errors (for example, inaccurate actuator dynamics).

Author: *H. Michalska*

Switching Control of Drift-Free Systems

The project is concerned with the design of discontinuous feedback controls which involves control elements such as relay, time-delay and zero hold, to stabilize systems of the form $\dot{x} = \sum_{i=1}^{i=m} g_i u_i$. The resulting control law is discontinuous but the discontinuities occur in well specified, isolated moments of time, so the resulting closed-loop system does not exhibit chattering. An additional advantage of the designed feedback is that a priori constraints on the controls can be incorporated easily.

Author: *H. Michalska*

Guiding Function Approach to Stabilization of Nonholonomic Systems

A new method is proposed for the design of piece-wise continuous stabilizing feedback for such systems. The method is based on introducing a set of guiding functions (which are not Lyapunov functions) which help in the computation of feedback.

Author: *H. Michalska*

Hierarchical Set Point Control of Chained Systems

Set point feedback control for systems in chained form can be designed by dividing the overall system into subsystems which are then stabilized independently. A supervisory controller synchronizes the action of the controllers at the subsystem level so that the overall system asymptotically achieves a reference set point.

Author: *H. Michalska*

7.5 Robust Control

Robust $\mathcal{H}_\infty$ Flight Control

A gust load alleviation system uses motion sensor feedback to drive the aircraft's control surfaces in order to attenuate aerodynamic loads induced by wind gusts. An $\mathcal{H}_\infty$-optimal gust load alleviation system is designed to control the vertical acceleration of a B-52 aircraft model with flexibilities. The aircraft is assumed to be subjected to severe wind gusts causing undesirable vertical motion. The purpose of our controller design is to reduce the transient peak loads caused by the gusts. Our design takes the flexible modes of the aircraft model into account. We use the Dryden gust power spectral density model to guide our performance specification and control design, as well as for time-domain simulations. The $\mathcal{H}_\infty$-optimal controller is shown to reduce dramatically the effect of wind gust on the aircraft's vertical acceleration.

Authors: *N. Aouf, B. Boulet*

Consistency of Open-Loop Experimental Frequency-Response Data with Coprime Factor Plant Models

The model/data consistency problem for coprime factorizations considered in this research is the following: Given some possibly noisy frequency-response data obtained by running open-loop experiments on a system, show that these data are consistent with a given family of perturbed coprime factor models and a time-domain $\mathcal{L}_\infty$ noise model. In the noise-free open-loop case, the model/data consistency problem boils down to the existence of an interpolating function in $\mathcal{RH}_\infty$ that evaluates to a finite number of complex matrices at a finite number of points on the imaginary axis. A theorem on boundary interpolation in $\mathcal{RH}_\infty$ is a building block that allows us to devise computationally simple, necessary and sufficient tests to check if the perturbed coprime factorization is consistent with the data. For standard coprime factorizations, the test involves the computation of minimum-norm solutions to overdetermined complex matrix equations. The Schmidt-Mirsky Theorem is used in the case of special factorizations of flexible systems. For $\mathcal{L}_\infty$ noise corrupting the frequency-response measurements, a complete solution to the open-loop noisy SISO problem using the structured singular value μ is given.

Authors: *B. Boulet, B. A. Francis*

7.6 Stochastic Estimation and Control

Stochastic Control with Randomly Intermittent State Observation

This project involves the formulation and explicit solution of stochastic control problems for linear systems where complete state observations are only permitted at random times. In this novel but practically important class of problems the optimal control with respect to quadratic criteria depends upon state predictions between the random sampling instants. General and Poisson distributed observation point processes have been considered.

Authors: *M. Ades, R. Malhame, P.E. Caines*

Relations Between Optimal Risk-Sensitive Stochastic Control/Filtering and Robust Control/ Filtering

In this work, the connection between robust deterministic filtering and control with respect to external disturbances, also known as state space H^∞ robust control and filtering, and stochastic optimal control and filtering is introduced by invoking large deviations theoretic concepts. This link is of particular interest in mathematical models in which the disturbances are inherently random but robust filters and controller are preferable.

Author: *C.D. Charalambous*

Maximum Likelihood Parameter Estimation for Systems with Noisy Dynamics and Observations

his project is concerned with estimating unknown parameters for nonlinear systems which are subject to noisy dynamics and observations. The parameters are computed using Maximum-Likelihood techniques via the Expectation-Maximization (EM) algorithm. The methodology is based on computing the unnormalized conditional density of the nonlinear filtering problem, followed by computing the parameters via the EM algorithm. In the special case of Gauss-Markov models, the parameters entering the Kalman-Filter are obtained in closed-form, while for general nonlinear models a Galerkin's approximation scheme is introduced which computes the conditional density. The ML parameter estimates are expressed in terms of the coefficients of the Galerkin scheme.

Authors: *C.D. Charalambous, M. Demetriou*

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