Centre for Intelligent Machines
Annual Report 1998

June 1997 – May 1998

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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 1997-98.

1.2 Personnel Changes

- On May 31, CIM bid farewell to *Professor Evangelos Papadopoulos* who, after several years in Canada, decided to return to his homeland Greece with his family. He is now with the Department of Mechanical Engineering at the National Technical University of Athens but retains links with McGill as an Adjunct Professor and with CIM as supervisor of his three remaining students.

- After a brief illness, *Professor George Zames* passed away on August 10, 1997. Born in Poland in 1934 he came to McGill as an undergraduate at the age of 15 in Engineering Physics. After studying at MIT where he achieved his first breakthrough with the now classic Small Gain Theorem, Professor Zames returned to McGill in 1974. Several years later he produced his second breakthrough, the H-infinity theory with which he gained world-wide recognition and awards in the field of Control and Systems Theory. Professor Zames was a founding member of CIM. He will always be fondly remembered as a mentor, colleague and valued friend.

- On the positive side, in January, *Professor Jeremy Cooperstock* joined the Centre as an Assistant Professor in Electrical and Computer Engineering. He completed his M.Sc. and Ph.D. at the University of Toronto, and came to Montreal via Japan as a researcher at the Sony Computer Science Laboratory.

- During the 1997 - 98 year, three of CIM's members have been pursuing their research in various parts of the world. *Professor Vincent Hayward* is spending a sabbatical year at IRCAM in Paris, France. *Professor Paul Zsombor-Murray* is at the Technical University of Graz, Austria, and *Professor Peter Caines* is on leave of absence at the University of Hong Kong.

- *Francesco Callari*, a postdoctoral fellow at CIM for the past three years, was appointed Lecturer for the Faculty of ECE. *Paul Fisette* returned to the Department of Mechanical Engineering at l'Université Catholique de Louvain-la-Neuve, Belgium, after ten months as a postdoctoral fellow at the Centre. In August, *Raymond Spiteri* joined the Centre

for a year as a postdoctoral fellow under the supervision of Professor Jorge Angeles, with the support of the Centre de Recherches Mathematiques and the Institut des Sciences Mathématiques.

- Three new Research Associates are collaborating with Prof. Jorge Angeles: *Dr. Yao Jin*, from China; *Dr. Leonid Slutski*, from Ben-Gurion University of the Negev in Israel; and *Oswaldo Lozano* from Peru.

1.3 Awards and Honourable Mentions

- At the Canadian Image Processing and Pattern Recognition Meeting held in Kelowna, BC, in May 1997, *Professor Martin Levine* was awarded the 1997 CIPRS Service Award for his outstanding contribution to research and education in Computer Vision.

- At the IRIS/Precarn Conference held in Ottawa on June 8-10, 1997, *Ioannis Rekleitis* (Ph.D. candidate supervised by Prof. Gregory Dudek) won a Best Poster Award for his submission entitled "Multirobot Exploration of an Unknown World: Efficiently Reducing Odometry Error". The criteria were scientific merit and originality, quality of presentation, and relevance.

- In July 1997, McGill/CIM's Martian Explorer, "Invader", won an impressive first place at the Mobile Robot Competition of the American Association for Artificial Intelligence held in Providence Rhode Island. The team consisted of *Francois Bélair, Eric Bourque, Deep Jugessur and Robert Sim* under the supervision of *Professor Gregory Dudek* and the help and support of all the members of the Mobile Robotics Lab.

- *Michael Glaum* (Ph.D. candidate), was awarded the 1998 O. Hugo Schuck Best Paper Award of the American Automatic Control Council for the paper which he co-authored with his supervisor G. Zames, "A Function Calculus for Identification and System Analysis" published in the Proceedings of the 1997 American Control Conference, Albuquerque, NM, June 1997.

1.4 New Research Projects

- With the beginning of the IRIS Phase 3 in April 1998, several members have embarked on new research projects in collaboration with colleagues across the country. "Virtual Environments", "Computer-Assisted Machine Operation", "Robot Partners: Collaborative Perceptual Robotic Systems", "Haptic Interfaces", "Attention in Virtual Reality", "Intelligent Tools for Diagnosis and Surgery" and "Reality-Based Modelling in Virtual Environments" are the new projects being investigated by Profs. Buehler, Clark, Dudek, Ferrie and Hayward.

- Prof. Jeremy Cooperstock will be constructing a Reactive Environment here at CIM, utilizing speech, gesture, and video as interaction methods, and applying these tech-

niques to an Intelligent Hospital scenario. A specialist in human-computer interaction, Professor Cooperstock's primary research interest is making technology more usable.

1.5 Conferences and Visits Hosted

- On April 30, 1998, CIM hosted the first meeting of it's Advisory Board. Members of the Board in attendance were *Prof. John Dealy*, Dean of the Faculty of Engineering at McGill; *Ms. Carol Ann Davidson*, Senior Program Manager, Discovery Channel; *Dr. Toby Gilsig*, Consulting Partner of Secor Inc. and co-founder and CEO of M3i; and *Dr. Albert Aguayo*, Director of the Centre for Research in Neuroscience at the Montreal General Hospital.

CIM had the pleasure of hosting several long-term visitors this year. Among them were:

- Dr. Yao Jin, Researcher at Sechuan Union University, is spending 12 months at the Centre as a Research Associate with Prof. Jorge Angeles.

- Two students spent their final semesters here at CIM under the supervision of Prof. Jorge Angeles: Gerhard Grabner from the University of Graz in Austria and Jordi Daban from the Universidad Polytechnica de Catalunya, Barcelona, Spain.

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.

- Visiting lectures for the Systems and Control series included: Dr. Marios Polykarpou, University of Cincinnati; Dr. Bassam Bamieh, University of Illinois, Urbana.

- The Robotic series hosted, among others: Dr. Vladimir Brodsky, Technion-Israel Institute of Technology, Israel; Prof. Ahmad Hemami, École Polytechnique de Montréal; Prof. Alec Zahavi, Ben-Gourion University of Negev, Beer-Sheva, Israel; Prof. Leonard Maunder, University of Newcastle upon Tyne, UK; Prof. Monique Teillaud, INRIA Sophia Antipolis, France.

The Centre welcomes many visitors on an ongoing basis. Some of the visits hosted during 1997-98 were:

- Throughout the summer, as of June 26, 1997, CIM gave tours and demonstrations to science students at the Reach Summer Camp.

- Career Day Visits were organized for high school students from Explorations '97 Montreal Area High School Program; from the Jewish Vocational Services on November 18, 1997; from the Protestant School Board of Greater Montreal on May 6 and from the West Island College on May 12, 1998.

While shifting its objectives to include greater interaction with industry, CIM intends to continue to build on its strengths. The Centre remains unwavering in its commitment to both applied and curiosity-driven research, as well as in its pursuit of excellence in teaching of graduate students. Thus, CIM's goal is an ambitious one – to continue to respond to the demands of a global marketplace without compromising its scientific and educational integrity.

Martin D. Levine
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

Presently, CIM is comprised of 15 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 1997-98, the student population was 86, of which 39 were PhD's and 47 were Masters. The breakdown is as follows:

- Electrical Engineering: 18 Masters, 21 Ph.D.'s and 1 Postdoc
- Mechanical Engineering: 17 Masters, 16 Ph.D.'s and 1 Postdoc
- School of Computer Science: 12 Master's, 2 Ph.D.'s 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.

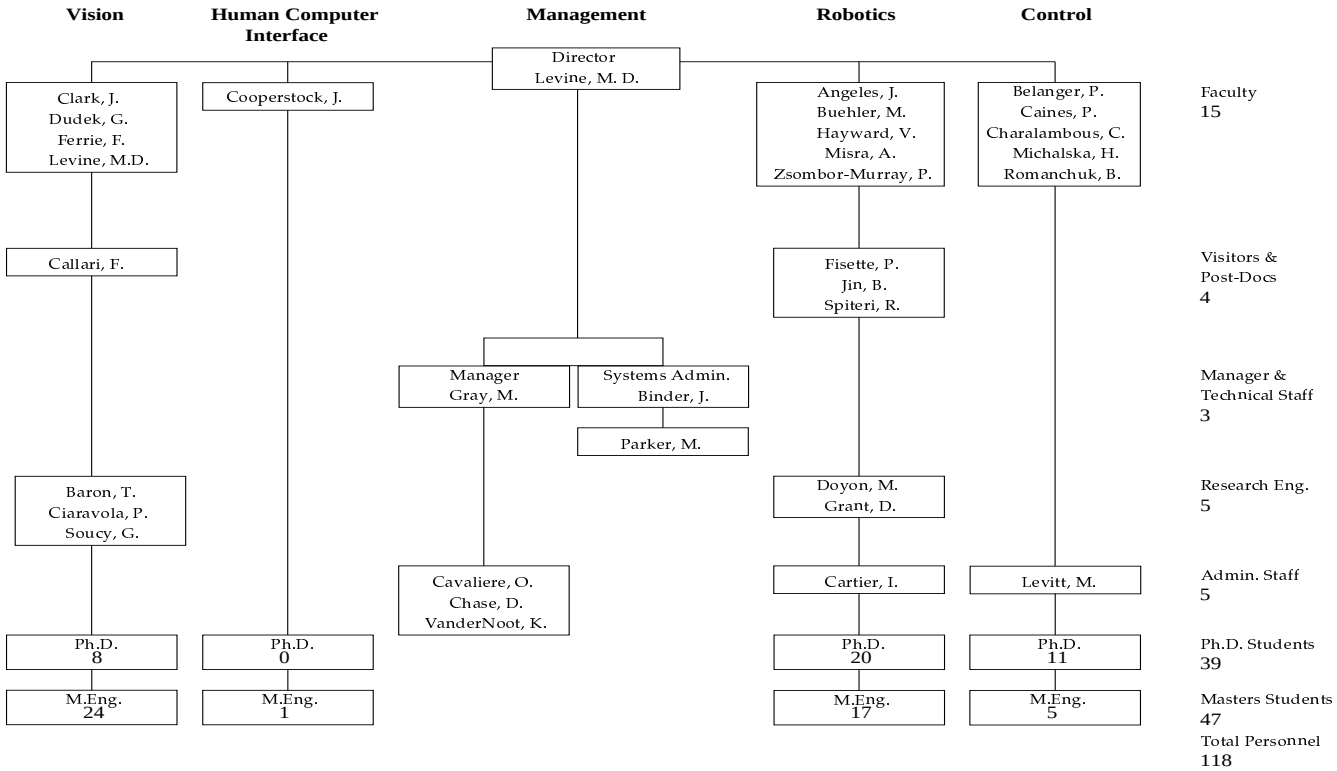

Figure 1: CIM Chart

3 Active Perception

3.1 Visual-motor Systems

VLSI Smart Sensors

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

In robotic applications real-time response to sensory input is a must. Video cameras are typically used to provide visual input for robotic systems, but these produce massive quantities of information which must be processed. Much of this information is irrelevant for the robot's purposes, however. Thus, it is better that robotic sensing devices (such as cameras) provide refined, object oriented, signals for action rather than raw sense data. As different actions are required in different applications, these sensing devices should be flexible, or programmable, much in the same way that gate arrays are a flexible way to provide functionality in a standard integrated circuit. Using architectures based on object-oriented data structures will permit many different types of data and data processing to coexist in a single standardized system. Combined with the application of active sensing principles such as attentional selection and control optimization, such systems will provide a viable path towards achieving the goals of machine vision researchers. We have developed a CMOS analog VLSI smart sensor which incorporates an "attentional" mechanism, which determines the location in the sensed image which is most "salient" and outputs the coordinates of this location. This sensor chip is based on a model of the way visual attention acts to control the generation of eye movements in the human brain. To date, we have simulated the activity of such a device and verified its operation. We have fabricated, through the Canadian Microelectronics Centre, a set of test chips which contain the building blocks as well as a preliminary prototype of the complete sensor (see Fig. 2). These are currently undergoing testing. We are investigating the application for such a chip to visually acquire a salient target and direct a point-wise laser based 3-D scanner towards the target for further processing. Such a system could be used in surveillance applications, such as for watching over warehouses or large fields.

Attention and View-Based Object Recognition

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

Our main goal in this project is to understand the process of visual attention, which is the process by which the human brain selects information to be analyzed further. In particular, we are interested in 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 active view-based object recognition techniques, hypotheses as to an object's identity alter the way in which further information regarding the object is gathered. Such approaches to object recognition hold the promise of real-time

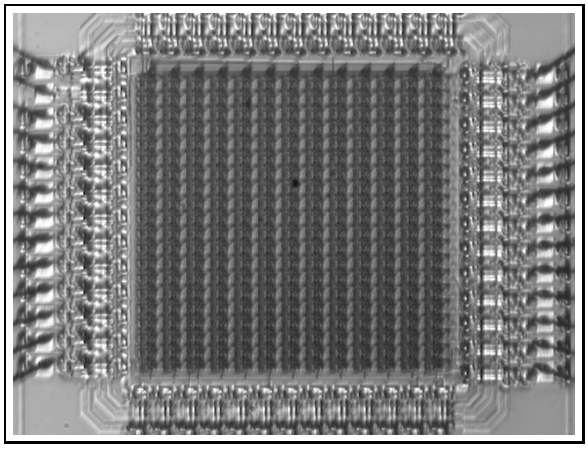

Figure 2: A micro-photograph of the prototype attention/saccade generation VLSI integrated circuit.

performance, due to their directed nature which reduces the amount of information that needs to be processed. Another advantage of active view-based recognition schemes is that of robustness to variations in the scene, due to the fixation of attention on only relevant scene information. At the moment, we have 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.

Attention and Change Detection

Authors: *R. Rensink (Nissan CBR), J.K. O'Regan (Université René Descartes), J.J. Clark*

In this project we are investigating the processes by which humans visually detect changes in their environment and how to apply this knowledge to building robot vision systems. Psychophysical experiments done with collaborators at the Nissan Cambridge Basic Research Center have shown that people can only detect changes in their visual field if they have allocated visual attention to the aspect of the scene that is changing. If this attentional allocation is disrupted, by a flash of light or a blanking of the image, then otherwise easily seen changes become very difficult to detect. Changes to items in the visual scene which are not attended to cannot be detected. These experiments lead to a model of the human visual system wherein very little direct information about the environment is stored at any given time. This suggests that real-time robot vision systems may be achieved by likewise retaining only sparse descriptions, and updating these descriptions only when scene changes are detected. We are currently implementing such a system in our lab at CIM.

Active Differential Photometric Stereo

Authors: *H. Pekau, J.J. Clark*

In previous research our group, in conjunction with Prof. Iwahori of the Nagoya Technical Institute, had developed a method for obtaining the shape and absolute depth to a surface having an arbitrary reflectance map. This algorithm utilized the 3-D controlled motion of a point light source near to the object. This algorithm, however, required the computation of the gradient of the image intensity with respect to the light source position. As such, the solution provided by the algorithm will be extremely sensitive to noise in the image measurements and errors in the positioning of the light source. In our current work, we have found that the Clark-Iwahori differential algorithm can be transformed, via application of the divergence theorem, into an algorithm that requires only knowledge of the integral of image intensity over various surfaces and volumes in the light source position space. No derivatives need be computed. This integral algorithm promises to be much more robust in the face of image noise and position errors. We have implemented this new algorithm using the facilities of the CIM Artificial Perception Lab. For the purposes of this experiment we constructed a prototype of a planar distributed illumination source, shown in Fig. 3.

Figure 3: The prototype of the planar extended light source used in the active differential shape from shading experiment.

4 Active Vision

4.1 Visual-motor Systems

Modeling of the Saccade Generation Process

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

Saccades are the rapid movements which direct the gaze from one point to another. We are interested in the role that spatial attention plays in the targeting and triggering of such movements. Following the *premotor* theory of attention, it is our belief 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. Thus, part of our investigation lies in determining how attention interacts with the fixation system. Currently, we are constructing, 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 will allow us to explore the interaction between fixation and attention in the generation of saccadic eye movements.

5 Perception

5.1 Active Perception

Active Vision Using Optimal Control

Authors: *K. Benameur, P.R. Bélanger*

In this project, we used Optimal Control Theory to calculate trajectories that are best from an estimation point of view. We start from a dynamic model of an object whose position and velocity coordinates are to be estimated. Camera observations are seen to be 2D projections of a number of object feature points on a plane; the image points are dependent in a known manner on object and camera locations, i.e. are related to these by known equations. These observation equations, and the observation noise, depend on such variables as zoom and position. It is possible to formulate an optimization problem where the control variables are the forces acting on the cameras, and the performance index is a function of the covariance of the errors in the estimates generated by a Kalman filter. The outcome is a trajectory designed for optimum estimation of object position and velocity. We have used the results also to study the grasping of a moving object, where a compromise is needed between control and estimation.

Recognizing Volumetric Models in the Presence of Uncertainty

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

Classically, the problem of object recognition has long been formulated as that of recognizing the instance of some object in a scene through information acquired from an image. This has motivated such questions as how to compute stable and effective representations for objects from image data and how to correctly identify an unknown object from its representation. Our interest, and the primary focus of this research, is how such decisions can be made in the presence of uncertainty and how one can explicitly represent and reason about the uncertainty. We have proposed a framework for parametric shape recognition based on a probabilistic model of inverse theory first introduced by Tarantola in [Tarantola:87]. The key result is a method for generating classifiers in the form of conditional probability densities in order to recognize an unknown from a set of reference models. Our procedure is automatic. Off-line, it invokes an autonomous process to estimate reference model parameters and their statistics. On-line, during measurement, it combines these with a priori context-dependent information, as well as the parameters and statistics estimated for an unknown object, into a single description. That description, a conditional probability density function, represents the likelihood of correspondence between the unknown and a particular reference model. The original context of this work was three-dimensional object recognition in which objects were represented by parametric shape descriptors and their uncertainties. Since then we have extended the approach to include parametric representations computed from other imaging modalities. Generally the process is the same. Object models are computed from a bottom-up analysis leading to a set of descriptors which form the basis for recognition.

An experimental system has been implemented in which objects are represented by either single or multiple parametric models. These experiments have indicated that recognition performance is near perfect for cases in which most of the object is visible to the observer, and falls off gracefully (minimal false-positive response) when only partial information is available.

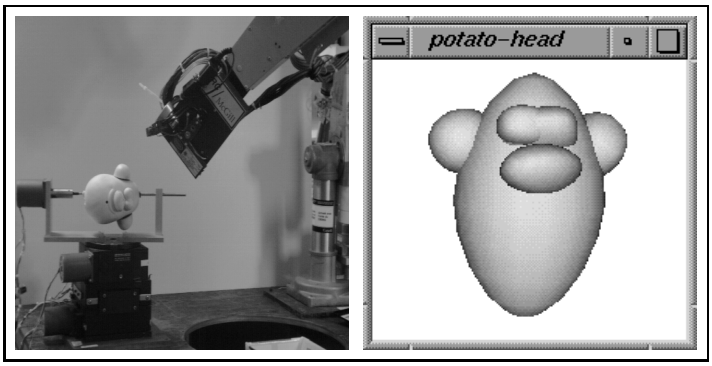

Figure 4: Scene and Composite Model

Optimal Sampling for Metrological Applications

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

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.

Active Object Recognition

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

In a typical scenario, an autonomous agent, capable of sensing visual information about its environment, is faced with the problem of recognizing objects from (geometrical) models of them. The sensors are affected by noise, the models are only approximate representations of the surrounding real scene, and both these sources of error cause uncertainty in the recovered models. Since the recognition of the objects is model-based, uncertainty in the models translates into ambiguity in the recognition: different objects may be equally likely to have produced the sensed data, given the available uncertain information. Yet a decision must be made about which objects are present in the scene and/or what further action must be taken. Building on previous results in the related field of active modeling, we propose a unified Bayesian methodology for actively inferring the objects from the data, and in so doing

- Account for the sources of uncertain information in a principled and consistent manner;
- Optimally gather new data by incorporating in the agent the use of feedback from the current state of information.

We have shown that

- Optimal active recognition strategies are inherently different from active modeling ones, even when the recognition is entirely based on models. Indeed, the partitioning of the space of models in classes of objects introduces an additional information structure which is relevant to the recognition process alone.
- An optimal criterion for gathering new data in order to disambiguate object models is to maximize the ratio of the predictive correlation of model and object data sensitivities to the predicted variance of the model alone. This optimality has been proved in the special binary classification case, and work is under way to extend the result.

Extensive experiments performed have produced encouraging results, showing that the new active recognition technique outperforms a model-only based one, as well as simple "random walk" approaches.

Visual Modeling for CAD/CAM and Autonomous Systems

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

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: The Autonomous Explorer

Building Volumetric Models from Sensor Data

Authors: *F.P. Ferrie, G. Soucy, P. Whaite*

In order to perform tasks such as describing, manipulating, and avoiding collisions with objects, one needs to be able to extract basic information about their three-dimensional size and shape from available sensor data. But these data provide only indirect information about 3-D shape, e.g. how surfaces reflect light or estimated point samples from a surface. Our related work in visual reconstruction deals explicitly with the problem of inferring 3-D surfaces from data provided by television cameras and laser rangefinders. The emphasis of this research, on the other hand, is the problem of *interpreting* the shape of an object that is represented by a particular surface. For the purposes of our work the shape of an object is represented by a collection of volumetric primitives, where each describes the coarse geometric characteristics of a particular part. The intent is to be able to generate a unique description of an object in a bottom-up fashion using only general constraints about a particular domain of objects. This kind of description is in itself adequate for many tasks involving object manipulation in a robotics environment. However, a longer term interest is to investigate how such descriptions can lead to generic forms of object recognition. The formal basis of this work is differential geometry, which contributes to the modeling problem in two related ways. First it provides a mathematical basis for characterizing surface features related to object/ground separation and parts decomposition. In another related project we are investigating the structure of these local features or "trace points", particularly how they give rise to contours that separate a surface into different parts. Second, concepts from differential geometry *in the large* are used to infer the geometric structure of surfaces corresponding to parts, or equivalently, to choose a volumetric primitive that best describes a surface from a finite repertoire. We have developed algorithms for parts decomposition and the inference of volumetric primitives from surface data. These have been successfully applied to objects whose parts decomposition can be characterized by a dense covering of trace points. However, the general case is more complex and involves cues that must themselves be inferred (similar to the case of subjective contours). We are continuing in this direction, but are also looking at applications in machine vision to gain insight into the general problem.

On Integrating Local and Regional Form and Modeling Empty and Occupied Space

Authors: *T. Jelonek, F.P. Ferrie*

This research is concerned with answering two questions: how can one robustly infer the boundaries of grouped data sets and how can one characterize the relationships between the subsequently inferred models? A robust model inference is achieved by an aggregation of data (range measurements) into shape models (or parts) that considers both local and regional geometric information. That is, robustness is achieved by the design of a cooperative process that integrates local shape cues (negative minima of curvature) and the consistency of the region with its associated representation (superellipsoids). Part boundaries are determined

by integrating model parameter estimation with curvature extrema detection. To completely characterize the significance of the scene via a part representation one must explicitly represent both the intrusions and extrusions (the convexities and concavities - the figure and ground) that determine form. That is, our shape primitive will model not only the solid shape itself but also the environment surrounding the form. The research has investigated how one can describe a scene of multiple objects and their constituent parts by examining the relationships between the properties (for example, orientation, size, curvature, etc.) of the inferred models.

Multiple View Integration

Authors: *G. Soucy, F.P. Ferrie*

Problems in robot vision such as object manipulation and trajectory planning require that multiple views of data (e.g. time series, multiple sensor, etc.) be integrated into a consistent interpretation of the scene. Our approach to this problem is based on a surface reconstruction algorithm that combines information from different viewpoints. It does so without explicitly computing correspondence and without invoking a global rigidity assumption. Motion parameters (rotations and translations) are recovered locally under the assumption that the curvature structure at a point on a surface varies slowly under transformation. The recovery problem can thus be posed as finding the set of motion parameters that preserves curvature across adjacent views. This might be viewed as a temporal form of the curvature consistency constraint used in image and surface reconstruction. To reconstruct a 3-D surface from a sequence of overlapping range images, one can attempt to apply local motion estimates to successive pairs of images in pointwise fashion. However this approach does not work well in practice because estimates computed *locally* are subject to the effects of noise and quantization error. This problem is addressed by invoking a second constraint that concerns the properties of physical surfaces. The motions of adjacent points are coupled through the surface, where the degree of coupling is proportional to surface rigidity. We interpret this constraint to mean that motion varies smoothly from point to point and attempt to regularize local estimates by enforcing smooth variation of the motion parameters. This is accomplished by applying a regularizing filter to the local estimates as a second stage of processing. By combining curvature and motion consistency constraints we have been able to derive a multiple view reconstruction algorithm that can accurately reconstruct three-dimensional surfaces from a sequence of range images. Because of the importance of such algorithms to our research in visual modeling and reverse engineering, work continues on improvement and refinement.

Integrating Descriptions from Multiple Views

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

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.

Volumetric Uniqueness and Gaze Control

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

The bottom-up strategy often employed in building volumetric models of objects proceeds from the inference of parts to the estimation of part shape using an appropriate parametric model to describe each part. A principal weakness of this approach is that the resulting models are of limited stability, i.e. a small perturbation in the data can lead to large changes in the resulting model. We argue that this approach is inappropriate because the process of inference is inherently non-unique, i.e. the data cannot support the selection of one interpretation over another. It is therefore misleading to select an interpretation based on some ad-hoc criterion of "perceptual acceptability", but it is necessary to communicate the nature of the non-uniqueness to the processes that make use of the fitted models. The problem then is to devise the means by which to communicate the non-uniqueness. One possibility is to exploit the matrix of covariances produced as a by-product of the iterative fitting procedure. The covariance matrix describes an ellipsoid of confidence in parameter space, and the pose and shape of the ellipsoid captures the interdependencies of the parameter uncertainties. One way in which this measure of non-uniqueness can be exploited is in the selection of gaze positions for a mobile scanner. The idea is that the additional data obtained at the new position should maximize an improvement in the uniqueness of the volumetric interpretation. As part of our earlier research we implemented this gaze control strategy in our autonomous exploration system and demonstrated that it could incrementally plan a path such that data collected along the way resulted in a unique model in a time significantly faster than random probing. Current research is investigating different metrics for quantifying non-uniqueness and extending the paradigm beyond volumetric modeling to other forms of visual modeling such as appearance manifolds generated from image sequences.

5.2 Active Vision

Enhanced 3D Representation using Multiple Models

Authors: *N. Ayoung-Chee, G. Dudek, F. Ferrie*

The choice of the most suitable generic shape model is an open problem in computer vision. Modeling provides a compact description of the raw data and provides parameters that allow tasks such as recognition and pose estimation to be performed. However most model driven methods are based on knowledge or expectations on how the data is structured. Such approaches do not fare well in unstructured environments since no a priori assumptions can be made of the environment. The approach presented here attempts to address this problem by building complementary descriptions of the data using both global and local models. Superquadrics and surface patches were chosen as the local modeling primitives. They respectively allow a model to express both gross qualitative shape and fine structural details. This approach to modeling is illustrated experimentally using laser range data. A superquadric is fitted to this data using a nonlinear least squares minimization (Levenberg-Marquardt) of the superquadric inside-outside function. The superquadric that results in the best possible fit is expressed in terms of its position, size, shape and pose parameters. The residual of the fit is then modeled at several scales using multiple surface patches with uniform mean and Gaussian curvature. A hierarchical ranking of these patches is used to describe the residual based on geometric properties. These geometric properties are ranked according to criteria expressing their stability and utility. The most stable patches are selected as the description of the residual. Using these two models, a composite representation in terms of a superquadric augmented with multiscale patches is generated. This is illustrated experimentally. This representation can then be used for both pose estimation and object recognition.

Optimal Spiral Search

Authors: *S. Burlington, G. Dudek*

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.

PCA Background Invariance

Authors: *D. Jugessur, G. Dudek*

This project deals with appearance based recognition using Principal Components Analysis with the added ability to account for varying backgrounds. 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.

Real-time Recognition and Collision Avoidance.

Authors: *F. Belair, E. Bourque, R. Sim, I. Rekleitis, G. Dudek*

Several members of the mobile robotics group are assembling components of our software infrastructure into a real-time mobile robotics testbed.

Distributed Robot Control Software Environment

Authors: *G. Dudek, R. Sim*

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.

Environment Shape and Layout from Active Shadows

Authors: *M. Langer (NEC), M. Daum, G. Dudek, S. W. Zucker*

This project deals with the inference of environmental structure from shadow information. An abstract can be found at: http://www.cim.mcgill.ca/~dudek/mobile/shadows.html

Multi-Robot Exploration and Rendezvous

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

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.

Object Description and Recognition

Authors: *G. Dudek, N. Ayoung-Chee, F. Ferrie*

This project involves shape modeling based on a combination of local curvature information at multiple scale, and global superquadric surface fitting.

Mobile Robot Exploration using Fused Data from Two Sensors

Authors: *I. Rekleitis, G. Dudek, P. Freedman*

This research investigates the combined use of a sonar range finder and a laser range finder (QUADRIS or BIRIS) for exploring a structured indoor environment. This methodology is called "just-in-time" sensing.

Virtual Environment Construction

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

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.

Accurate Position Estimation from Learned Visual Landmarks

Authors: *R. Sim, G. Dudek*

This method 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.

Multi-Robot Collaboration

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

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.

Pose Estimation From Image Data Without Explicit Object Models

Authors: *G. Dudek, C. Zhang*

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.

Spatial Abstraction and Mapping

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

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

Spatial Mapping with Uncertain Data

Author: *G. Dudek*

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.

5.3 Computer Vision

Recognizing Objects by Accumulating Evidence over Time

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

This project is a direct outgrowth of our 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 are currently investigating the application of the recognition strategy to an appearance-based recognition problem, whereby optical flow fields, resulting from movements between camera and object, are used

to obtain signatures related to object structure. Preliminary results indicate that despite the ambiguity inherent in the interpretation of optical flow (i.e. the confounding of structure, motion, and imaging geometry), the sequential approach can be used to successfully recognize objects provided that reasonable constraints are applied movement.

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

Viewpoint Selection by Navigation through Entropy Maps

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

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. Preliminary 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.

Autonomous Physics-Based Colour Learning under Daylight

Authors: *Y. Bérubé-Lauzière, D. Gingras (Institut National Optique), F.P. Ferrie*

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 modeling. 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.

An Improved Appearance-based Approach to Image Retrieval and Classification

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

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.

Interactive Model Recognition from Optical Flow

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

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.

Pose Estimation: Known Objects in Unstructured Environments

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

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

Figure 6: Laboratory set-up for building object models from optical flow measurements

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 sketched 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

5.4 Content-based Image Retrieval

Hidden Markov Models for Scene Analysis

Authors: *D. Hernández, M.D. Levine*

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.

5.5 Face Recognition

Face Recognition and Aging

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

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.

The Smart Door Project

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

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.

Finding Faces in Color Images Just Using Hue

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

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.

5.6 Focus of Attention

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

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

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.

5.7 Human-computer Interaction

Shared Reality Environment for Human-Human Collaboration

Authors: *A. Xu, J. Cooperstock*

In the camera-monitor mediated world of videoconferencing, the limitations of communications bandwidth and equipment capability tend to place a severe handicap on the senses of sight and sound and eliminate the sense of touch. As a result, even in state of the art videoconference rooms using the highest quality equipment, the sense of co-presence enjoyed

by individuals in the same room is never fully achieved. Gaze awareness, recognition of facial gestures, social cues through peripheral or background awareness, and sound spatialization through binaural audio, all important characteristics of multi-party interaction, are often lost in a videoconference. Our objective is to introduce the computer as an intermediary in the communications. At the same time, it is necessary to move from the restricted videoconference environments of television monitors and stereo speakers to immersive spaces in which video fills the participant's visual field and is reinforced by spatialized audio cues. Haptic feedback should be exploited to help bridge the physical separation of remote individuals. This feedback could range from reproducing the floor vibrations in response to a user walking about to the tactile response of a surgeon's instrument as it moves through different tissue. Our testbed, currently in development, consists of a number of audio-insulated rooms, each equipped with high resolution video projectors, cameras, microphones, and multi-channel audio, interconnected by an ATM switch. The video is rear-projected to cover three walls of each room, thereby encompassing the users' visual field and creating the illusion of a larger shared space. Multi-channel audio is used to produce effective spatialization of sound sources, enhancing the sense of co-presence. While 3D rendering will be explored, our emphasis lies in effective use of scaling, perspective transformations, and image blending techniques, to achieve a reasonable sense of co-presence in 2D without the physical constraints of special viewing equipment.

Automated Door Attendant

Authors: *B.C. Nguyen, J. Pollack, J. Cooperstock*

An electronic kiosk provides an interactive environment wherein visitors may obtain desired information. In general, these spaces make use of limited, unimodal interaction methods (i.e., text and graphics for output and touch-screen selections for input). Our objective is to augment such interaction with higher level modalities of video and speech. The purpose is to mask the fact that an individual is dealing with a computer rather than another person. The more human-like the computer is made to appear, the more natural and less intimidating the interaction becomes, regardless of one's computer expertise. Simply put, it is easier to ask for information than to search for it by pressing buttons. In order to evaluate such a system outside of a laboratory context, we have prototyped an automated door attendant, which functions as a "secretary in a door," tailored for the needs of a professor's office. The technology includes a video monitor, speaker, microphone, and camera, and uses speech recognition and speech synthesis to support interaction through speech. The attendant greets visitors who stop in front of the office, allows them to leave messages, schedule appointments, and review pertinent documents through a Web browser.

5.8 Mobile Robotics

Mapping Using Non-metric Information

Authors: *G. Dudek, E. Milios, M. Jenkin (York U.), D. Wilkes (U. of Toronto)*

Autonomous navigation using sensory information often depends on a usable map of the environment. This work deals with the automatic creation of such a map by one or more autonomous agents and the minimal requirements such a map must satisfy in order to be useful. Recent emphasis is on collections of robots that are loosely coupled. One aspect of this work is the analysis of how uncertainty either in the map or in sensing devices relates to the reliability and cost of navigation and path planning. Another aspect is the development of sensing strategies and behaviours that facilitate reliable self-location and map construction.

Defining Islands of Reliability for Exploration and Hybrid Topological-Metric

Authors: *S. Simhon, G. Dudek*

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.

Geon Recognition using a Mobile Robot Vision System

Authors: *R.K.H. Ng, M.D. Levine*

Geons are simple 3-D geometric primitives proposed by Biederman for object representation. The idea is to segment objects into an arrangement of simple geometric shapes. Objects represented by geons can be identified more easily since the many-to-one mapping of object recognition is reduced to the recognition of a small number of geons. In this project, a vision system is implemented for the search and recognition of geons. The vision system is composed of a color camera and a laser range finder, and it is mounted on a pan-tilt unit. The entire setup is mounted on a mobile robot. The task of the system can be divided into two phases: the first phase is focus of attention. Our focus of attention algorithm is based on color, and the color camera searches for objects with that color. Upon detection of a geon, the mobile robot moves towards it in preparation for the next phase. The second phase is object recognition. With the robot in the proximity of the geon, the laser range

finder is used to obtain range data of the geon for recognition. Since only a small number of geons ($N = 7$) is considered in this project, very sparse range data is sufficient for successful recognition.

ORB: Object Recognition for Real-time Autonomous Mobile Robot Navigation

Authors: *D.T. Bui, M.D. Levine*

An object recognition system called ORB[1] is proposed and implemented for use on a mobile robot. ORB utilizes the QUADRIS sensor platform developed at CIM (Center for Intelligent Machines) at McGill University, which is composed of two BIRIS[2] laser range finders. ORB performs a series of sensory and perceptual tasks in conjunction with a mobile robot control architecture called SPOTT. ORB's main task is to sense the mobile robot's surroundings and provide laser range data, in the form of line segments, for SPOTT's map database. In an office environment, ORB also identifies and labels the *structural objects* (i.e., walls, doors) in this map. While navigating through an office space, the mobile robot may be required to search for certain objects in the area. In this scenario, ORB is used to recognize the *movable objects* (i.e., chairs, tables and desks). ORB is able to perform its tasks in a fast and efficient manner by using simple models to represent the *structural* and *movable* objects in the database. ORB's recognition procedures only require sparse sets of range scans to identify aforementioned objects. The *structural object* models are built from prior knowledge of the office environment. For example, the doorway model would consist of the known doorway widths found on the experimental office floor. ORB has been tested extensively in the CIM environment, but it can also be applied to any office space provided the structural dimensions are known a priori. ORB's models for the *movable objects* are idealized descriptions with the object's surfaces represented by planes. The physical dimensions of the *movable object* models are defined by *Architectural Standards*, as office furniture is built to conform to these standards.

[1] **O**bject **R**ecognition and map **B**uilding using the QUADRIS sensor platform on a mobile robot.
[2] Official trademark of the National Research Council of Canada.

6 Robotics

6.1 Ambulatory Robotics

Control of Passive Dynamics

Authors: *K. Yamazaki, M. Ahmadi, M. Buehler*

Design for passive dynamics appears to be necessary on the path towards energy efficient practical legged robots. However, robots with proper passive dynamics are either unstable or if there is a stable limit cycle, its domain of attraction is typically small. Interpreting locomotion as a periodically forced limit cycle oscillation of a highly nonlinear dynamical system, control forcing functions are developed which stabilize the limit cycle over a large region of phase space, consume minimal energy, and provide strong robustness to modeling errors, noise and external disturbances. In addition, we develop controllers for negotiating obstacles while running in the passive dynamic regime. In the absence of accurate models of contact, material deformation, noise and actuator dynamics, physical experimentation is mandatory. Based on encouraging simulation results we are implementing our passive dynamic design and control ideas on the ARL Monopod II.

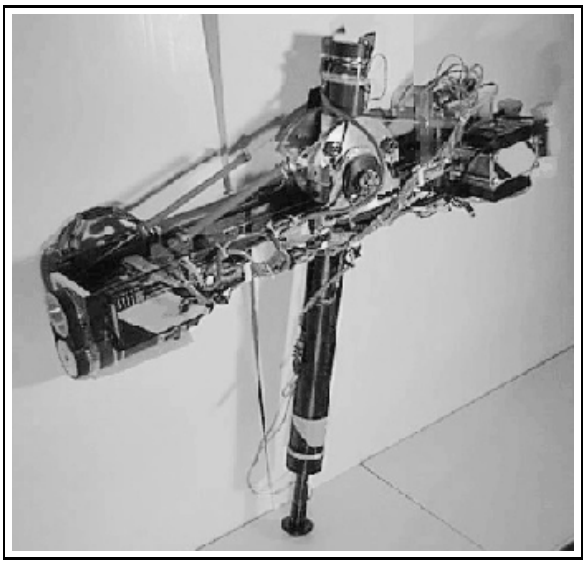

Figure 7: ARL Monopod

Control of Complex Dynamical Systems

Authors: *A. Cocosco, M. Buehler*

Legged robots are highly complicated, nonlinear dynamical systems with many actuated and non-actuated degrees of freedom. Since linearization can rarely be justified as a means to simplify those dynamics, synthesizing stable and robust controllers is challenging. With the advent of fast and inexpensive computing power, it becomes possible to synthesize controllers using computational methods, like adaptive simulated annealing or genetic programming. So far we have succeeded in developing stable controllers for one legged running robots, and our goal is to develop the framework for synthesizing controllers for quadruped locomotion in unstructured environments, as well as other complex systems.

Design and Control of Quadruped Robots

Authors: *K. Yamazaki, R. Battaglia, M. Buehler*

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. Two protoypes of such robots, SCOUT I and SCOUT II have been built and have demonstrated experimentally to be capable of walking, turning, and climbing over a step, despite their mechanical simplicity. The underlying principle is dynamic operation, based on controlled momentum transfer. When the legs are made compliant, running (bounding) is achievable as well.

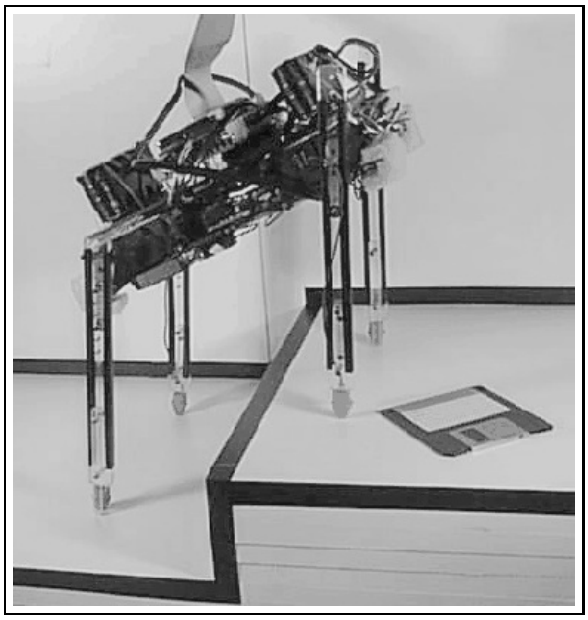

Figure 8: ARL Scout I

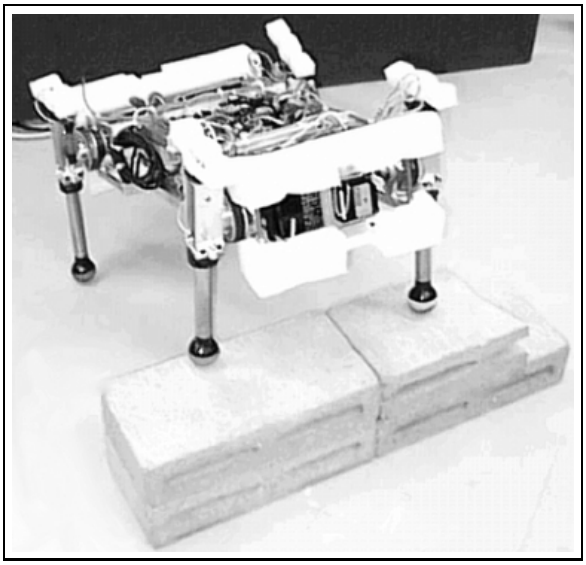

Figure 9: ARL Scout II

6.2 Dynamics and Control

COBRA-Phase I

Authors: *J. Angeles, S. Ostrovskaya, P. Montagnier*

This project, whose acronym stands for *Control of a Boom-Mounted Robot Arm*, is a joint effort of McGill University, Concordia University, the Canadian Space Agency, and Bombardier Services. Phase I of this project, financed with a contract from Bombardier Services, in the framework of the STEAR-Quebec Program, comprises a feasibility study of the dynamics and control of long-reach manipulators mounted on a boom with important structural flexibility, that can hamper the execution of the task. Envisioned applications are aimed at aircraft maintenance and servicing, in operations such as shot-peening, stripping, painting, and deicing. All these operations include, additionally, inspection.

6.3 Geometry and Kinematics

Parallel Manipulators with Higher Pair Joints

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

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

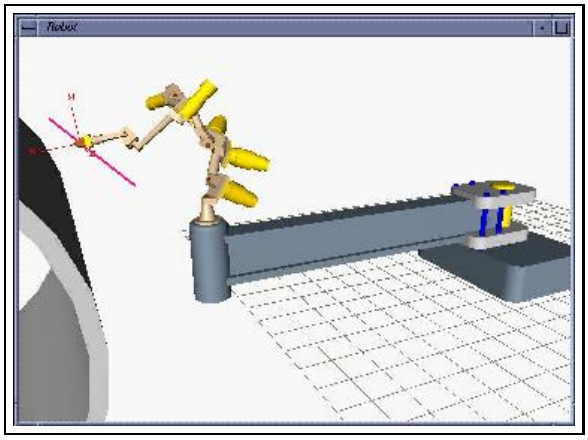

Figure 10: Boom-mounted robot

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 have been successfully applied to the analysis of closed chains containing higher pairs.

Three Degree of Freedom, Two Loop Spatial Manipulators

Authors: *P. Gervasi, M. Husty (MU-Leoben), P.J. Zsombor-Murray*

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 begun to investigate a class of three degree of freedom platform manipulators with three R*-S-R legs in roughly octahedral configuration with (*) indicating the actuated, basal joint. This manipulator offers an attractive solution for tasks requiring reduced mobility. Furthermore, their kinematic analysis is quite simple and by adding a second actuated joint near the base in each leg, say R*-P*-S-R, a six degree of freedom platform, whose direct kinematic equations are identical to those formulated for the three legged, three degree of freedom, R*-S-R variety, is obtained. This architecture should lead to more economical and easily controllable vehicle simulator designs than existing ones based on the conventional six U-P*-S legged Stewart-Gough platform.

Parallelotriangular Mechanisms and Line Contact Constraint

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

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. Of particular interest is an analytical approach based on the observation that each edge of the movable triangle occupies a line complex whose axis is a circle and whose axis, in turn, is an edge of the fixed triangle. Furthermore, one observes that in the case of intersecting tetrahedral edges this complex degenerates to a congruence of lines in the point of intersection as the circle assumes zero radius. In fact the double tetrahedron may be thought of as a Siamese, antisymmetric pair of special spatial triangles with only one dual angle vertex.

6.4 Haptic Device

In Situ Measurements of Cutting Forces During Surgery

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

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.

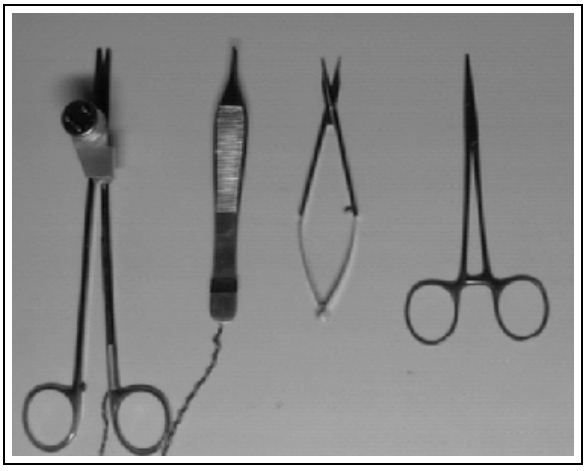

Figure 11: Instrumented surgical instruments used in the experiment

Haptic Rendering of Viscoelastic Properties of Tissues

Authors: *O. Astley, V. Hayward*

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 different regions, but also allows the parent and child meshes to be updated at different frequencies. The multi-layer mesh also addresses numerical integration issues.

A Six/Seven DOF Haptic Interface

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

This device is intended 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 MPB Technologies Inc., Montréal, in collaboration with McGill University.

The design also provides for a scissor-like distal axis acting as 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: 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 for increased performance and manufacturability. A commercial version is now marketed by MPB Technologies, Montréal (Fig. 13)

A Two DOF Planar Haptic Interface: The Pantograph

Authors: *V. Hayward, C. Ramstein (CiTi)*

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

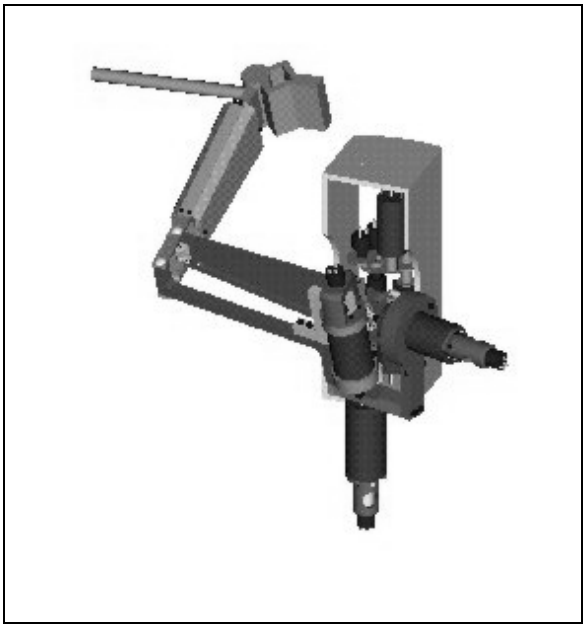

Figure 12: Freedom-7 Haptic Interface

perceive simulated objects through the visual and auditory channels, see Figure 14. Many versions have been produced and used for experimental purposes. Presently, Haptic Technologies Inc., Montréal is marketing one version equipped with an embedded processor.

Haptic Device Evaluation in Microgravity

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

Under computer control, haptic interfaces can create tactile and kinesthesic sensations. One application allows 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.

6.5 Identification and Control

Torque Control Using a Harmonic Drive

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

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

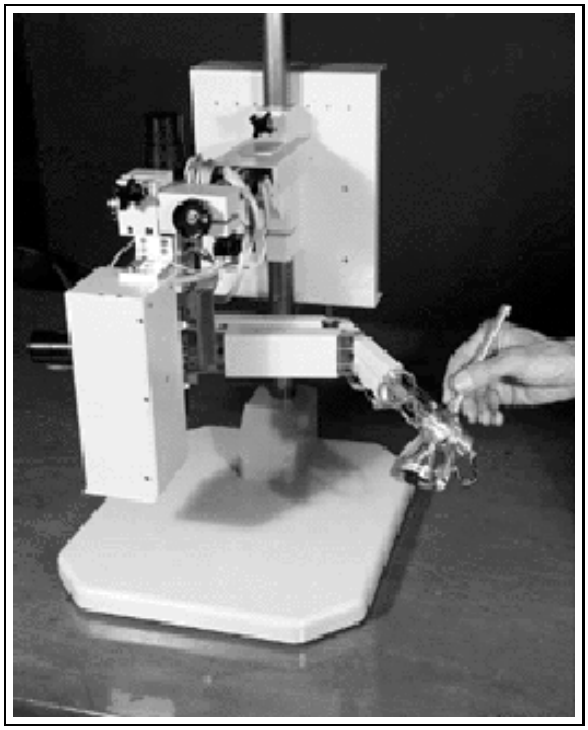

Figure 13: Commercial Version of Freedom-6

means of approximating the uncertainty model, and H-infinity controllers were subsequently designed. These proved to be reliable and performed well. The models were also used to "clean up" torque signals corrupted with periodic noise signals related in frequency to some of the gear-related signals.

Adaptive Algorithm with Short Adaptation Time

Authors: *S. Gendron, P.R. Bélanger*

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.

Control Algorithm Design for Flight Simulators

Authors: *C.J. Wu, E. Papadopoulos*

Large aircraft flight simulators consist of a Stewart platform mechanism powered by six hydraulic cylinders. The cylinders are commanded to move so that the platform base

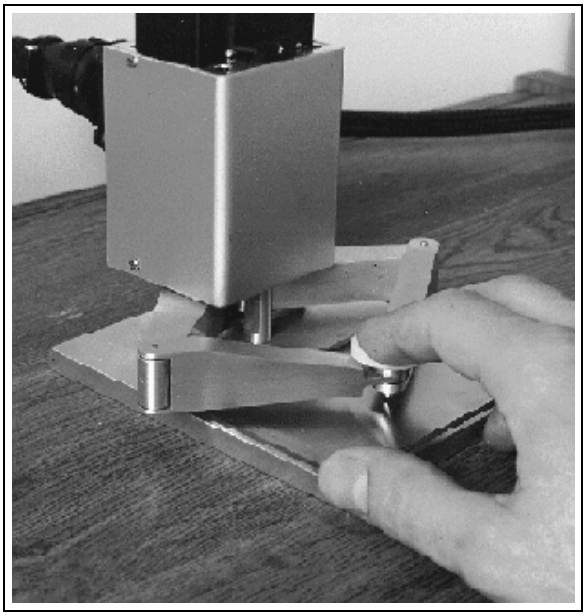

Figure 14: The Pantograph

(cockpit) emulates the motion of a true aircraft under pilot commands. However, current control systems do not take into account inertia forces and hydraulic actuation dynamics, thus reducing system capabilities. In this project, we aim to redesign cylinder controllers so that the working envelope of such a simulator is extended.

Dynamic Modeling, Identification and Control of Forestry Machines

Authors: *Y. Gonthier, E. Papadopoulos*

Forestry machines typically include a mobile base equipped with a manipulator arm and a specialized end-effector, see Figure 16. Such systems are designed empirically, and are controlled at the joint level by experienced operators, using visual feedback. In this project we develop kinematical and dynamical models for forestry machines, including the effects of actively actuated bases. Also, the hydraulic system of an experimental machine is being modeled to include its pumps, transmission lines, valves, and hydraulic actuators. Identification techniques will be used to obtain the machine's parameters. The currently developed models are designed to drive a realistic real-time machine simulator, as well as to provide the basis for designing task space model based controllers.

Modeling and Force Control of the SARCOS Arm

Authors: *G. Bilodeau, E. Papadopoulos*

This project focuses on the modeling, identification, and control of the SARCOS arm. Applying forces with robots or teleoperated manipulators is a very complex task due to

Figure 15: Commercial version of the Pantograph

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.

Actuator Compensation

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

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.

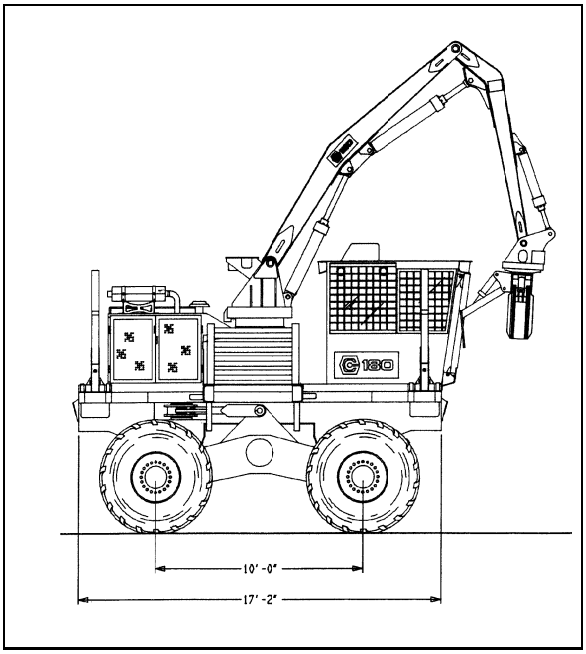

Figure 16: Side view of the FERIC experimental forestry machine. The machine's articulated arm is actuated hydraulically, and mounted on a mobile base that can be tilted independently.

Adaptive Velocity Estimation

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

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

6.6 Manipulators and Actuators

High-Performance Mechanical Transmissions

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

We are currently developing a new generation of mechanical transmissions, intended to replace gears in applications where backlash, friction, and flexibility cannot be tolerated. We have thus produced two prototypes of **Speed-o-Cam**, 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 depends on the type of mechanism. 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

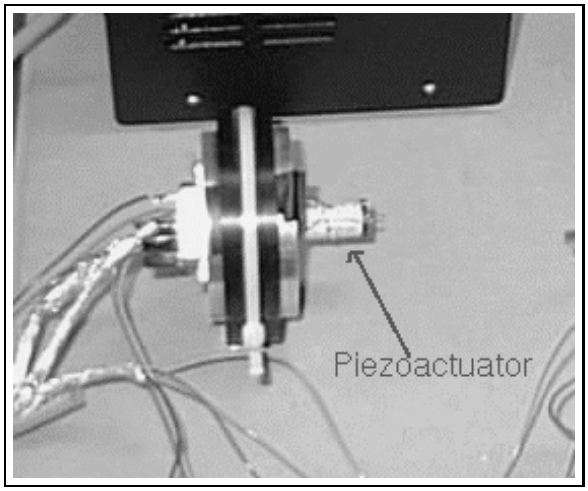

Figure 17: Piezo actuation test bed with optical microdisplacement measurements

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.

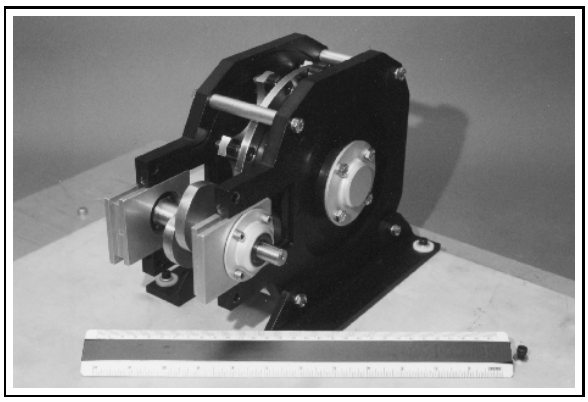

Figure 18: Assembled planar **Speed-o-Cam** prototype

The limiting factor in N is the pressure angle: for the planar mechanism, intended to couple parallel shafts, a value of N up to 8 is possible within a maximum pressure angle of 30°; for spherical mechanisms, the corresponding value of N is 12. In each case, the low-speed shaft carries two cams located in different planes or, correspondingly, different concentric spheres, with the purpose of guaranteeing positive action for every mechanism

configuration, without the need to add springs to maintain contact. The high-speed shaft is rigidly attached to a roller-carrying plate, with uniformly-distributed rollers on each side of the plate. The cams are close to cardioid, with the spherical ones of convex shape; the planar ones bear a small region where the profile becomes concave, but this element is essentially convex as well. For this reason, the load-carrying capacity of **Speed-o-Cam** is substantially higher than that of its gear-train counterpart for the same size and same speed-reduction ratio. Additionally, design provisions have been taken to allow for a preloading of the mechanism so that backlash will be eliminated.

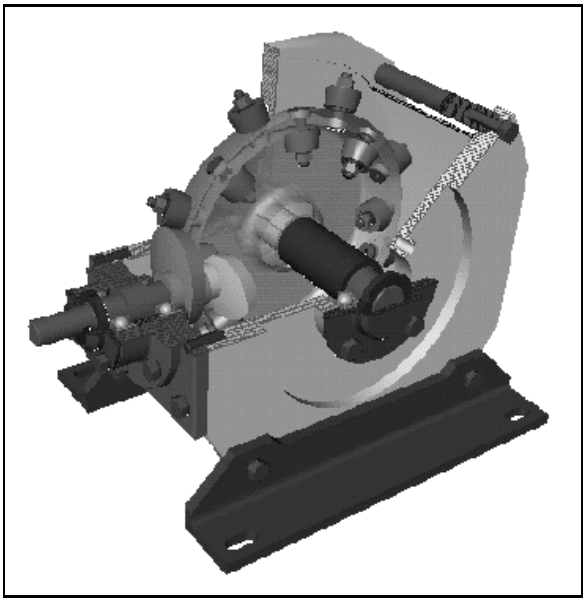

Figure 19: A rendering of the spherical **Speed-o-Cam**

Other mechanical transmissions are also envisaged for the near future, in applications that require to replace rack-and-pinion transmissions or to rectify a nonuniform speed ratio or of a nonuniform torque-transmission ratio.

REDIESTRO 2

Authors: *N. Arenson, M. Arenson, R. Ranjbaran, J. Angeles, R. V. Patel (Concordia), A. Robins (Bombardier Services)*

This manipulator is to be regarded as the left hand of a dual-arm workcell, the right hand being REDIESTRO 1, its 1993 predecessor. Thus, REDIESTRO 2 is the mirror-image of REDIESTRO 1; however, different from REDIESTRO 1, REDIESTRO 2 was designed with one torque encoder at every joint and a six-axis force sensor at the end-effector. The prototype of this manipulator was designed, manufactured and assembled in a record twelve

months. Not a minor achievement if we consider that the blueprints of REDIESTRO 1 turned out to be of little use to design its successor, because the presence of the torque encoders at the joints called for a design from scratch of the latter. This project is a joint effort of NSERC, the Canadian Space Agency, Bombardier Services, McGill University and Concordia University.

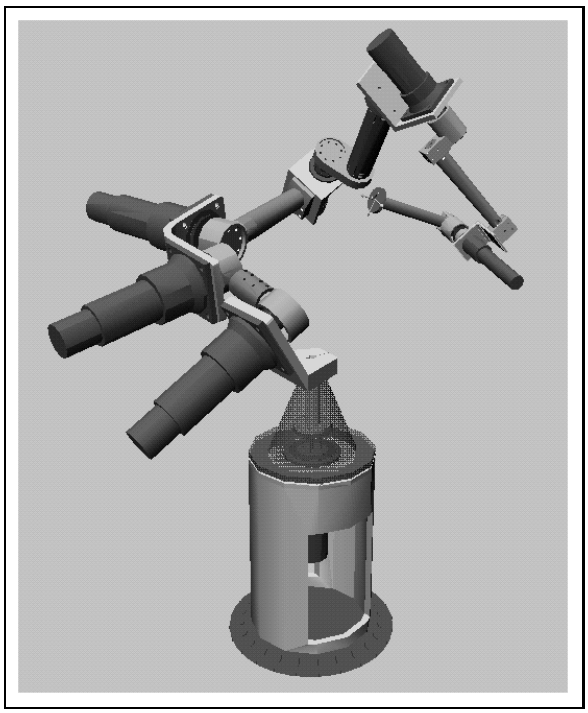

Figure 20: REDIESTRO 2, a highly dextrous redundant manipulator

Robot Calibration

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

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 its nominal location. However, when attempting to identify the joint offsets with the aid of the own robot 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 identifiable 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.

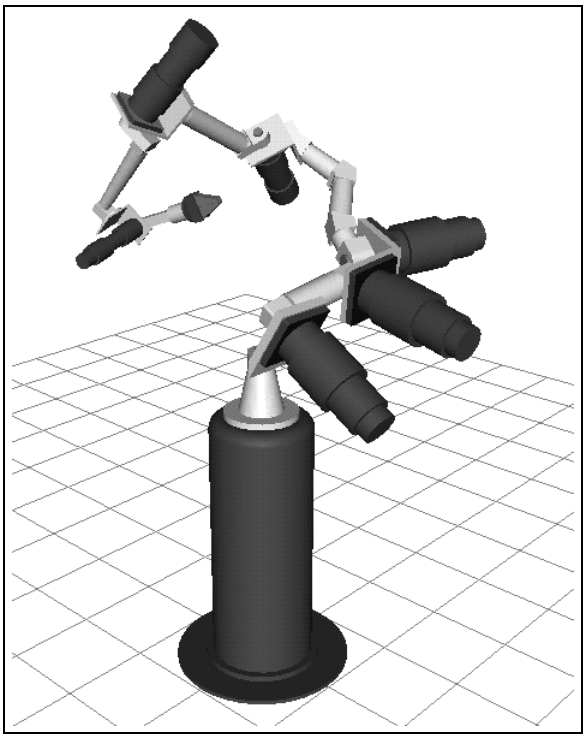

Figure 21: Graphics rendering of REDIESTRO 1

Dual-Arm Robotic Workcell

Authors: *J. Angeles, R. V. Patel, A. Robins (Bombardier Services), F. Ranjbaran (Bombardier Services), F. Shadpey (Bombardier Services)*

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 *kinetostic isotropy*. This feature gives the manipulator the highest accuracy for positioning and force-sensing, which makes it ideal for the 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.

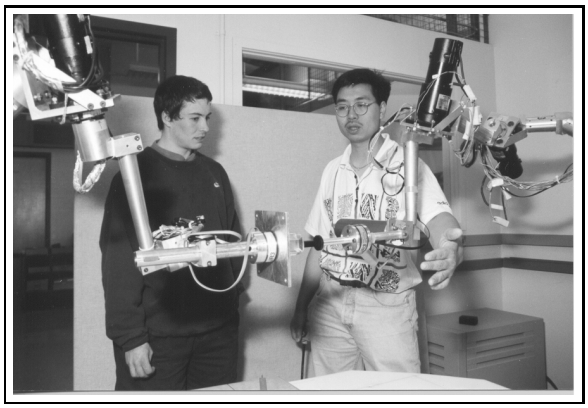

Figure 22: Dual-arm robotic workcell

Sensitivity Analysis and Control of High Performance Electromechanical Transmissions

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

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 paramaters and design controllers to guarantee robustness and rejection of disturbances such as friction.

Systems Approach to Modeling Shape Memory Actuators

Authors: *X. Lu, V. Hayward, D. Grant*

A mathematical model for shape memory actuators has been developed. It accounts for thermal, material (chemical and mechanical), and kinematic properties as separate attributes, which once interconnected account for the input-output properties of this type of actuator. A software package has been written which is sufficiently flexible to be used as (a) a simulator to study controllers, (b) a design tool to find the dimensions of a given actuator with given constraints. Work is in progress to develop an engineering model suitable for control design.

High Strain Shape Memory Alloy Actuators and their Control

Authors: *D. Grant, V. Hayward*

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 ambiant air. Variable structure controllers are being investigated with the purpose of achieving the control of position, velocity, force, and combinations of these variables. 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 Pending.

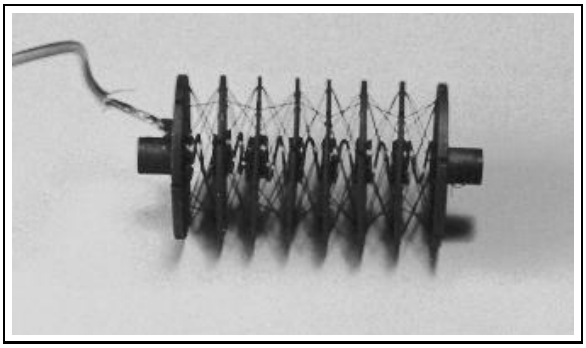

Figure 23: A single NiTi actuator package, 16 mm across.

Hydraulic Manipulator Shoulder Module

Author: *V. Hayward*

Parallel mechanisms may provide for structural rigidity and good dynamic performance; however, their utility is generally limited by an inherently small workspace. The use of actuator redundancy can simultaneously increase the workspace and remove singularities. A novel method to perform multi-goal optimization has been devised to determine the set of optimal and realizable designs. Following this principle, a prototype of a 3 DOF spherical joint module, the "shoulder" for a light-weight robotic arm has been built. (See Figure 24). It is powered by four high-performance hydraulic actuators. The joint develops 200 Nm of torque around any direction with a supply pressure of 4 MPa and has a moving mass of less than 1 Kg. The torque control bandwidth exceeds 50Hz. Patent pending.

This joint has been redesigned for optimal structural properties by Prof. L. Lessard and

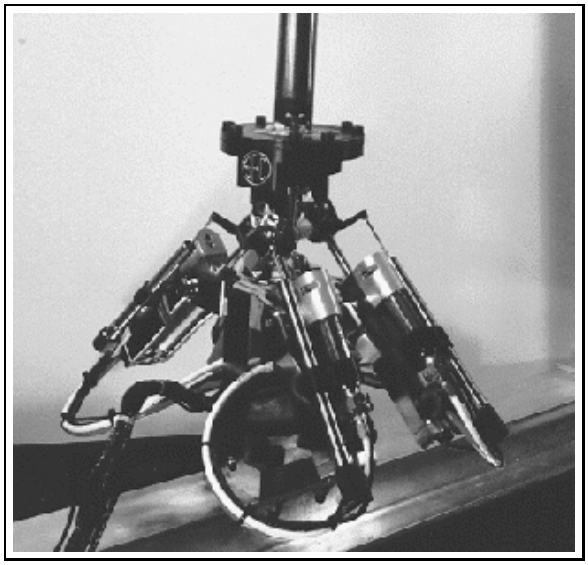

Figure 24: High Performance Hydraulic Manipulator Shoulder Module

his co-workers (Department of Mechanical Engineering, McGill University). An elbow joint with two actuators is also being designed and constructed, taking advantage of advanced composite materials.

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

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

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 25.

Highly Parallel Mechanisms

Authors: *F. Bulca, M. Husty, J. Angeles, P.J. Zsombor-Murray*

The kinematic analyses of the double tetrahedral mechanism as a paradigm of highly constrained parallel mechanisms is the starting point for this project. In this regard we apply the *functional matrix* concept to the degree of freedom analysis of this and other highly constrained mechanisms. Husty's example, in the use of kinematic mapping techniques

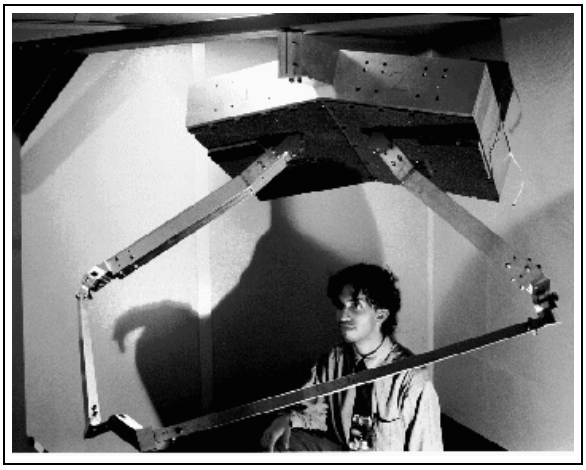

Figure 25: The STAS

to characterize the dextrous as well as entire workspace of a planar three legged R-R-R manipulator, is extended to treat spherical and spatial mechanisms of similar type so as to develop a systematic way to find the workspaces of platform mechanisms, in general. The Bennett, and other overconstrained 5R and 6R mechanisms as well as the double tetrahedron will be dealt with as specific instances of special cases.

6.7 Modeling, Simulation, and Control

Dynamics of Nonholonomic Mechanical Systems

Authors: *S. Ostrovskaya, J. Angeles*

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 degree of freedom. 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 lead 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 intense review of the Frobenius Theorem, that led to the concept of *holonomy matrix*. 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 that is capable to undergo topological changes, when switching from holonomic (or quasiholonomic) mode to nonholonomic mode, and vice versa.

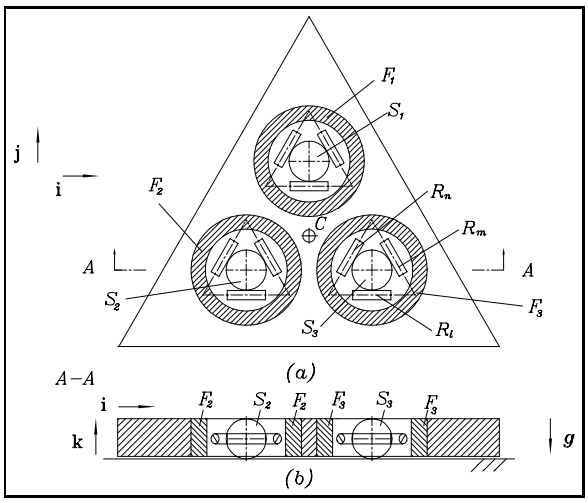

Figure 26: Rolling robot with three ball-wheels: (a) top view; (b) cross section AA.

6.8 Modeling and Simulation

Dynamics and Control of Mobile Manipulators

Authors: *D. Rey, E. Papadopoulos*

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.

Artificial Skeletal Muscle (ASM)

Authors: *F.R. Bubic, J. Angeles, P.J. Zsombor-Murray*

A rod-less, dynamic, seal-less, elasto-hydro-pneumatic cylinder pair to actuate a plano-revolute arm was built. This novel robotic actuator, which is based on conventional macro-technology exhibits constitutive characteristics similar to those of vertebrate limbs. A new device with a serial chain of six triple ASM units, each capable of continuous curvature and torsion, like an elephant's trunk, has been built and tested. US patent, "Flexible Robotic Links & Manipulator Trunks Made Therefrom", No. 5 080 000 (92-01-14), has been awarded

in this regard. A controller based on a principle similar to muscle fibre recruitment in the living organism has been devised.

6.9 Planning

Trajectory Generation at or Near Singularities

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

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.

Computer Aided Design of Robot Motion

Authors: *A. Čebula, P.J. Zsombor-Murray*

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.

6.10 Space Robotics

Payload-Attitude Controller Interaction in Space Robotic Systems

Authors: *E. Martin, E. Papadopoulos, J. Angeles*

Thruster-based spacecraft attitude control systems are inherently on-off, and hence, their operation produces a rather broad frequency spectrum that can excite manipulator sensitive modes due to flexible links or joints, see Figure 27. This problem is likely to appear especially when the manipulator is moving a big payload. The excitation of these modes can introduce further disturbances to the attitude control system, and therefore, undesirable fuel replenishing limit cycles may develop. In this work, such dynamic interactions are modeled, and analysis methods to predict their occurrence are employed. Control methods that can

reduce these undesirable effects are being subsequently developed.

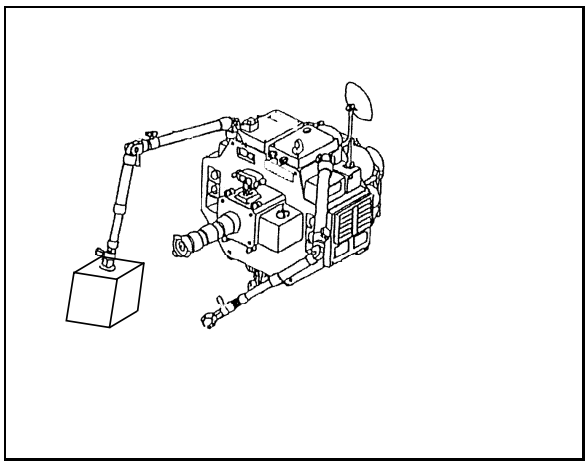

Figure 27: Concept of a thruster-controlled space robot manipulating a payload in orbit.

6.11 Telerobotics

Control of Direct Drive Robots

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

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.

Synthesis of Compliant Motions in Moving Environments

Authors: *M. Pelletier (IREQ), P. O'Reilly, M. Buehler*

This project is led by M. Pelletier at the robotics division of IREQ (Hydro Quebec). The goal is to develop methodologies for synthesizing compliant robot motions in environments that can move or oscillate due to random disturbances. The motion of the environment is taken into account in the task frame position, which is considered unknown and time-varying, but bounded. The position, velocity and force responses of the coupled robot/environment system are determined and tasks are formulated as inequality constraints on these expressions. The planning and control strategies are experimentally tested with realistic tasks

from the automated maintenance of electric power lines, which is currently done manually by Hydro Quebec.

Autonomous Dynamical Manipulation

Authors: *I. Abdul-Baki, G. Petryk, M. Buehler*

Teleoperation dexterity can be enhanced by incorporating full or partial autonomous execution of subtasks. We focus on tasks with dynamic robot-environment interactions which require velocity matching contacts with, and grasping of, moving objects. Such tasks present difficulties for full teleoperation due to obstruction of visual feedback to the operator, requirements for high master-slave bandwidth, or the need for excessive amount of sensory feedback to the master. New sensor-based geometric control algorithms are developed on a three DOF planar testbed and subsequently implemented on a SARCOS seven DOF robot arm with a three finger hand. The controller relies on data from a finger embedded Proximity Sensor Network, processed by a nonlinear recursive algorithm for filtering, data fusion and object localization.

Operation of Redundant Telemanipulators

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

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. This approach is not suitable for applications such as space robotics or other unstructured environments 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.

Virtual Mechanism Concepts in Advanced Teleoperation

Authors: *L. Joly, C. Andriot, V. Hayward*

This project is a collaboration between CIM and the Robotics and Teleoperation Department of the French Commission on Atomic Energy (CEA). New control algorithms for computer-aided teleoperation have been developed at CEA. Assistance is given to the operator by introducing "virtual mechanisms" between the master and the slave arms. They act as programmable jigs which guide the operator along desired task features. Automatic position and/or force control can also be added in user-specified directions. These algorithms have been successfully implemented at CEA on an electrically driven non-redundant system. The project aims at adapting and expanding this technique to a hydraulic and redundant dextrous bilateral teleoperation system manufactured by Sarcos Research.

7 Systems and Control Theory

7.1 Discrete and Hybrid Systems

Feedback Control of Nonholonomic Systems

Author: *H. Michalska*

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.

Hierarchically Accelerated Dynamic Programming

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

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 (see caineshhc). 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 theory of HADP), these algorithms show very significant speed-up with respect to any conventional method. (This is a property which cannot be eroded by progress in the development of conventional single layer methods, since HADP uses such methods as its building blocks.)

Hierarchical Supervisory Control Theory

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

In this work a hierarchical control theory for supervisory automata based on state aggregation has been developed. We give definitions for the partitions and high-level dynamics for hierarchical supervisory control automata. Our primary interest is the problem of ensuring (non-blocking) accessibility of the goal states and we can show this may be decomposed and solved in a hierarchical fashion with local control in conjunction with control at the aggregated level. These results are consistent with those obtained in the existing language-based hierarchical supervisory control theory. The theory has been applied to transfer line models of physical plants with material feedback.

Hierarchical Hybrid Control Systems

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

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.

7.2 Logic Control

Macro-COCOLOG

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

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.

Automated Theorem Proving and Formal Methods in System Theory

Author: *T. Mackling*

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.

7.3 Maximum Likelihood Parameter Estimation

Maximum Likelihood Parameter Estimation for Systems with Noisy Dynamics and Observations

Authors: *C.D. Charalambous, R.J. Elliott, V. Krishnamurthy*

This project is concerned with estimating unknown parameters for continuous-times systems which are subject to noisy dynamics and observations. In the special case of Gauss-Markov systems, the parameters entering the Kalman-Filter are estimated via Maximum-Likelihood techniques using the Expectation-Maximization algorithm.

7.4 Nonlinear Control Systems

Nonlinear H-infinity Analysis of Saturating Systems

Author: *B.G. Romanchuk*

In this work, we examine the extension of the H-infinity approach to control design (pioneered by Professor George Zames) to nonlinear systems. More specifically, systems in which the control action is limited, an important practical consideration. What is studied is the theoretical background to such an extension, as well as qualitative studies of the answers that will in fact occur once numerical algorithms are implemented.

Control of Limit Cycles in Nonlinear Systems

Authors: *H. Michalska, M. Buehler*

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.

Moving Horizon Control of Nonlinear Systems

Author: *H. Michalska*

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.

Moving Horizon Control Without Constraint on the Terminal State

Author: *H. Michalska*

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.

Optimization-Based Tracking of Nonlinear Systems

Author: *H. Michalska*

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).

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

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

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. The results in this paper have application to hybrid hierarchical control in that they give conditions for a finite analytic partition to satisfy the in-block controllability condition.

7.5 Optimal Control

Switching Control of Drift-Free Systems

Author: *H. Michalska*

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.

Guiding Function Approach to Stabilization of Nonholonomic Systems

Author: *H. Michalska*

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.

Hierarchical Set Point Control of Chained Systems

Author: *H. Michalska*

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.

7.6 Stochastic Optimal Control

Separation Principle for Nonlinear Partially Observed Stochastic Systems

Authors: *C.D. Charalambous, R.J. Elliott*

This project is concerned with optimal control of nonlinear stochastic systems with noisy dynamics and observations. The pay-off function is of an exponential-of-integral form which leads to robust controllers with respect to unknown noise statistics. This type of pay-off function minimizes in addition to the average value of the integral sample cost, its standard deviation. A series of results are introduced concerning the explicit computation of optimal control laws, for systems with nonlinear dynamics and observations. The result extends the separation theorem of Linear-Gaussian Systems to nonlinear systems. Lie algebraic methods are also introduced to decide a priori whether there exists finite-dimensional optimal control laws. In addition, connections to deterministic disturbance attenuation problems are delineated.

The Relation Between Deterministic Disturbance Attenuation Design and Stochastic Control Design

Author: *C.D. Charalambous*

In this work, the connection between deterministic disturbance attenuation problems, also known as state space H^∞ robust control problems, and stochastic optimal control problems, 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.

Stochastic Control with Randomly Intermittent State Observation

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

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.

8 People

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	M. Buehler	CIAR Scholar
	P.E. Caines	CIAR Fellow
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	J. Cooperstock	
	G. Dudek	
	F. Ferrie	
	V. Hayward	
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Ahmadi, Mojtaba	Ph.D	Prof. M. Buehler
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Benzacar, Eric	M.Eng	Prof. F. Ferrie
Berube-Lauziere, Yves	Ph.D	Prof. F. Ferrie
Beyrouti, Fadi	M.Eng	Prof. F. Ferrie
Bhanji, Altaz	M.Eng	Prof. M. Levine
Bilodeau, Glen	Ph.D	Prof. E. Papadopoulos
Bitton, Michel	M.Eng	Prof. H. Michalska
Bourque, Eric	M.Sc	Prof. G. Dudek
Bui, Don	M.Eng	Prof. M. Levine
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Hayes, John	Ph.D	Prof. P. Zsombor-Murray
Hernandez-Alonso, Diana	Ph.D	Prof. M. Levine

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Mackling, Thomas	Ph.D	Prof. P. Caines
Martin, Eric	Ph.D	Profs. J. Angeles and E. Papadopoulos
Martinez-Mascarua, Carlos	Ph.D	Prof. P. Caines
Menemenlis, Nickie	Ph.D	Prof. C. Charalambous
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Montagnier, Pierre	Ph.D	Prof. J. Angeles
Navarro-Martinez, Oscar	M.Eng	Prof. J. Angeles
Ng, Romney Ka-Ho	M.Eng	Prof. M. Levine
O'Reilly, Philippe	M.Eng	Prof. M. Buehler
Obaid, Sami	M.Eng	Prof. M. Buehler
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Parsa, Kourosh	Ph.D	Profs. J. Angeles and A. Misra
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Roy, Nicholas	M.Sc.	Prof. G. Dudek
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Wu, Chu-Jen	M.Eng	Prof. E. Papadopoulos

Xu, Aoxiang	M.Eng	Prof. J. Cooperstock
Yamazaki, Kenneth	M.Eng	Prof. M. Buehler
Zhang, Chi	Ph.D	Prof. G. Dudek
Zia, Lilian	M.Eng	Prof. H. Michalska

9 Publications

Jorge Angeles

Angeles J. A fin-de-siècle view of TMM. In *Proc. International Conference on Mechanical Transmissions and Mechanisms*, pages 13–16, Tianjin, China, July 1997.

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