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Experimental Robotics I

The First International Symposium
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About the Editors

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Preface

Experimental Robotics 1 — The First International Symposium is the first attempt at collecting works in Robotics from the point of view of experimental research. The meeting at which these contributions were presented took place in Montréal in June 1989. It is the first of a series to be organized in a circular fashion around North America, Europe, and Asia.

The series of events that led to this meeting can be traced back to Spring 1987 in Albany, New York. Several members of the organizing committee, who were attending a SIAM conference on Applied Geometry, began to discuss the major trends that would underly Robotics Research toward the rapidly looming end of this Century. We all agreed that experiments were called to play a larger role in the very way Robotics Research will be approached. Of course we did not mean that theoretical developments are not important, we simply felt that their importance can only be assessed through experimentation, that is, synthesis.

We proposed that the presentations be centered on theories and principles, as applied to robotics, that are validated by experiments. One of the conclusions of the meeting was thus to draw a clear distinction between "demonstrations" and "experiments". An increasing amount of researchers in the field of robotics no longer feel satisfied with hypothetical developments. They strive to distinguish what *can* be done from what *could* be done, and are willing to submit their theories to the test of physical implementation. The content of this collection of contributions reflects a cross-section of the current state of robotic research from one particular aspect: experimental work, and how it affects the theoretical basis of subsequent developments.

Of course, the selection of topics: the study of friction, calibration issues, and design of manipulators, for example, reflects this theme. Some of these problems may have been considered in the past as secondary ones, but they are now revealed as being critical, and we conjecture that progress toward their solution will have a significant impact on most aspects of robotics research. A cursory examination of the contents of the papers shows that, in Robotics, once again, practice is sometimes ahead of theory: successes and failures are rarely fully explained by the theory and investigators are left with conjectures. This is a further justification for the choice of the experimental theme.

The international program committee was composed of the following individuals: V. Hayward, *McGill University*, Canada; O. Khatib, *Stanford University*, USA; J. Angeles, *McGill University*, Canada; R. Chatila, LAAS/CNRS, France; J. Craig, *Silma*, USA; P. Dario, *University of Pisa*, Italy; B. Espiau, IRISA/INRIA, France; G. Hirzinger, DFVLR, FRG; K. Salisbury, MIT, USA; and T. Yoshikawa, *Kyoto University*, Japan. A total of 35 papers have been included in the program, representing Australia, Belgium, Canada, England, France, Germany, Italy, Japan, USA, and Yugoslavia. A keynote lecture given by Prof. Lozano-Perez from MIT on the topic "Tasks, Experiments, and Strategies" kicked off the meeting with the delivery of numerous inspiring ideas. Due to the small size of this meeting and the quality of the attendees, a large amount of interaction took place during the three days of this meeting.

The international committee has proposed that the next meeting should take place in Toulouse, France, in the Spring 1991. The committee has asked Dr. Raja Chatilla from LAAS-CNRS, Toulouse, France, and Dr. Gerd Hirzinger from from DLR, German Aerospace Research Establishment, Institute for Flight Systems, to co-chair the next meeting.

The McGill Research Center for Intelligent Machines (McRCIM) hosted this meeting on the McGill University campus. All the persons involved in this center must be thanked for helping to make this event possible. In particular, Prof. Martin Levine, director of McRCIM, gave a warm welcome address which created an informal, yet productive atmosphere. Dean Bélanger, forefather of McRCIM, then discussed the important connection between theory and experiments in Robotics. He must be thanked for his contribution and support. Prof. Lozano-Perez's keynote lecture alone made the effort of putting this meeting together worthwhile. The members of the program committee must be gratefully acknowledged for accepting to shoulder the difficult task of selecting the papers.

This meeting could not have taken place without the backing of many individuals, institutions and companies: Norman Kaplan from the National Science Foundation, Washington D.C.; Christine Quérido from "Les Fonds pour la Formation des Chercheurs et l'Aide à la Recherche (FCAR), Sainte Foy, Québec"; Pierre Girard and René Blais from "L'Institut de Recherche d'Hydro-Québec (IREQ), Varennes, Québec"; Fred Christie and Pierre Maltais from The Canadian Space Agency, Ottawa, Ontario; Len Allen and Roy Hoffman from CAE Electronics Limited, Saint Laurent, Québec; Samad Hayati from the Jet Propulsion Laboratory, Pasadena, California; Ian Rowe and Ravi Ravindran from SPAR Aerospace Limited, Weston, Ontario.

In the end, the credits must go to the authors for the quality of their contributions and their availability during the conference. The final kudos go to Margaret Dalziel, Manager of McRCIM, who skillfully engineered the organization of this meeting and whose talent was very much appreciated.

Finally, we hope that the video document which accompanies this collection of contributions will prove to be a useful illustration of the reported research.

Montréal, November 1989

Vincent Hayward (McGill University)
Oussama Khatib (Stanford University)

Introduction

The classification adopted in this collection of contributions proceeds along the lines of a nearly traditional division of topics in robotics. The reader will notice numerous cross-correlations between sections. As with most classifications, it is perhaps artificial and somewhat unsatisfactory.

Section 1 covers the control of flexible limbs, intermittent tasks, the control of cooperating robots, force control, and adaptive control. The second section deals with design issues: control of friction at low velocities, actuators, joints, and manipulators. Section 3 investigates questions in perception in terms of model construction, task guidance, visual servoing, and tactile feedback. Section 4 tackles kinematic problems such as inversion and calibration. Finally, section 5 deals with problems in motion planning.

Most of the papers share three overridding concerns that we might wish to use as guidelines for future work in Experimental Robotics.

Dealing with uncertainty, is one of these concerns. It is certainly not a new issue in engineering, but it is treated in various and particular ways by the robotics approach. Experimental robotics research suggests that there might be dual perspectives to reducing uncertainty. Conventional wisdom tells us that we need to "see to act" (as in control), whereas the dialectic reversal of this proposition requires us to "act to see" (as in perception). Dealing with uncertainty is an attribute of intelligence and autonomy. Whether it lies in the effectors, the sensors or elsewhere is still an open question; what is sure is that robots need a lot of it.

The second general theme which stems from these contributions is the *extension of the task repertoire.* This certainly indicates a major trend in robotics research. Clearly, no systematic methodology is proposed; however, biological systems seem to provide the largest source of inspiration (*i.e.* running, juggling, etc...). It is of course an exercise in synthesis, for which the tools are difficult to find, whereas analytical tools are already abundantly available.

The third general direction suggested by the reading of the papers is *redundancy and cooperation.* Advanced robots will undoubtly be endowed with large amount of redundancy from the viewpoints of action and perception. This redundancy must be orchestrated to achieve cooperation. This is the running theme of a large amount of current research. The necessity of multi-sensory perception systems is generaly agreed upon. Similarly, multi-actuator action systems are also coming into focus. Cooperative action, for lack of a better word, should become the center of focus for understanding advanced robotic systems.

Each of these three themes encompasses the others and it can be observed that most of the papers incorporate elements of all three.

Section 1
Control

This first set of papers is concerned with feedback control of manipulators. The papers by Oakley and Cannon and by Sweevers, Adams, De Schutter, Van Brussel, and Thielemans are concerned with the accurate control of manipulators with flexible links. Both papers insist on the importance of accurate structural modeling to achieve the control of manipulators with flexible links. Modeling goes hand-in-hand with identification. This issue is treated in depth by Sweevers and co-workers.

In the past few years, researchers have become increasingly interested in augmenting the vocabulary of tasks performed by manipulators. The class of "intermittent tasks" should obviously belong to the vocabulary of advanced manipulators. Useful intermittent tasks are observed frequently in everyday life: walking, tossing, tapping, and so-on. The papers by Bühler, Koditschek and Kindlmann and by Thompson and Raibert treat this question from radically different viewpoints. Bühler and co-workers offer an in depth analysis of a very simple task: "the vertical juggle," and propose a non-linear control approach to regulate it. Thompson and Raibert consider the inherently complex task of running and explore the structure of a passive mechanical system to accomplish it without explicit feedback or supply of energy.

It has been often observed that the cooperation of multiple manipulators could also significantly augment the class of achievable tasks, for example in grasping and sharing loads. The paper by Miyazaki, Sonoyama, Manabe, and Manabe explores the issue of cooperation through a series of examples: antagonist "muscle-like" pneumatic actuators and a multiple finger hand. A collection of task-dependent control strategies are evaluated for these examples. An adaptive load-sharing algorithm detailed by Uchiyama and Yamashita is demonstrated to provide the basis of a remarkable collection of dual-arm cooperative tasks.

The control of forces applied by manipulators to their environment has been for a long time a central problem in robotics. The paper by Yoshikawa and Sudou sets the problem in a larger framework than that usually encountered in the literature. The constraints dictated by the manipulator (dynamics) and by the task (shape and surface orientation estimation) are included in the problem framework. Hannaford and Lee propose a stochastic model of force histories recorded during the successful execution of tasks performed under telemanipulation. This model can be utilized to reliably segment tasks into distinct phases.

The paper by Daneshmend, Hayward and Pelletier reports on an adaptive algorithm applied to stabilize damping control (a form of force control) in the presence of uncertainty about the knowledge of environmental stiffness properties. Niemeyer and Slotine apply adaptive control theory to combine high-speed and high-precision robotic "whole-arm" manipulation.

Section 2
Design

The underlying properties of manipulator mechanisms have a major impact on the performance of the control strategies that are applied to them. Hence, a greater emphasis has been recently placed on the design of manipulators.

Papers on the analysis and control of friction have been included in the design section because the control of friction disturbances has a major impact on the design of manipulators. The paper by Armstrong is concerned with the modeling and control of Stribeck friction which is at the root of the stick-slip behavior of machines. The paper by Canudas de Wit tackles a similar problem and proposes an adaptive control algorithm.

The design of actuators is currently undergoing a tremendous evolution as testified by the two contributions in this area. The first paper by Bobrow and Desai describes a hybrid actuator design in which an electric source of energy powers a joint via hydraulic velocity reduction, thereby optimizing a number of design parameters. A second paper by Tsuda, Higuchi and Nakamura describes the high-speed digital control of a magnetically levitated robot wrist.

The design of a passive poly-articulated joint is tackled by Xu, Paul and Corke. They propose an instrumented six d-o-f compliant wrist assembly to implement a robust hybrid position/force control law. Vischer and Khatib present the development and testing of a low-geared torque-controlled joint and describe a new design for an inductive contactless transducer torque sensor. The performance of this joint, optimized for the ARTISAN manipulator, is checked against an earlier design implemented on one joint of a PUMA manipulator.

The section on design concludes with two papers on manipulators. Manipulators mounted on a compliant base, such as in the cases of vehicle support or outer space, are investigated by West, Hootsmans, Dubowsky, and Stelman. A "vehicle emulator" has been designed and built to carry out experiments regarding the control of manipulators placed under such conditions. Dietrich, Hirzinger, Gombert, and Schott discuss several concepts oriented towards the development of light-weight manipulators. The use of advanced materials such as carbon fibers is discussed, as well as issues in sensor integration.

Section 3
Perception

The issue of perception overshadows many advanced robotic application. The paper by Moutarlier and Chatila deals with combined sensing and motion inaccuracies in the context of mobile robots. They propose two approaches. The first one is based on the estimation of the robot state. The second approach relies on actively re-positioning the robot to reduce uncertainty before fusing sensory information into a global environmental model. The problems discussed in the paper by Even, Marcé, Morillon and Fournier differ from those of the previous paper because the presence of a human operator is assumed and the goal is to provide an accurate synthetic feedback.

The paper by Steer focuses on the issue of autonomously navigating a mobile robot with multi-sensory feedback given a known environment. Thus, it differs fundamentally from the two previous papers. The paper by Ijel, Laugier and Troccaz considers the problem of automatically grasping polyhedral objects, given a partial knowledge of the geometry of the environment. Their method relies on a local model refinement method combined with automatic sensor placement, thus combining problems addressed in the three previous papers.

The ability of to use visual perception at high rates is an exciting prospect for a truly sensor based robot. Rives, Chaumette, and Espiau suggest the possibility of closing the loop directly in the sensor frame, thus offering the ability for a manipulator equipped with a wrist mounted camera to overcome problems in sensor and kinematic calibration. Robust control theory is then used as a theoretical framework. Corke and Paul discuss the design of a robot position control loop via visual feedback at video-rate.

Tactile sensing is addressed by Sabatini, Dario, and Bergamasco in the context of tactile contact with soft material. Once again, their work is carried out with a view to extending the task repertoire of robots toward advanced applications such as automated palpation in medicine and other fields, agriculture for example. Eberman and Salisbury address the problem of minimizing the number of sensors to resolve contact information. They show under which conditions contact information can be resolved solely from joint torque measurements. Berger and Khosla discuss the application of tactile sensing to edge tracking, as part of a dynamic exploratory procedure.

Section 4
Kinematics

The efficient kinematic inversion of manipulators with arbitrary architectures still remains an open problem. Lenarčič and Košutnik consider in their paper the intriguing idea of deriving approximate solutions of the inverse kinematic problem, having observed that in many situations an exact solution is, in fact, not necessary. They propose a collection of methods to efficiently compute reliable approximate solutions, particularly when the accuracy of the end-effector orientation is of lesser importance than its position. Charentus and Renaud discuss the kinematic modeling of a modular redundant manipulator (up to 24 actuators) in view of its control. The control of a manipulator with an architecture which is both serial and parallel, as well as heavily redundant is thus discussed.

Khalil, Caenen, and Enguehard present a method to identify the Denavit-Hartenberg parameters of serial manipulators from theodolite measurements. Their method is based on the identification of differential changes of the geometric parameters. Bennett and Hollerbach propose to sweep the kinematic null-space of a redundant closed kinematic chain to sufficiently over-constrain the problem for self-calibration, thus eliminating the need for external instrumentation. They apply this method to pairs of fingers of a mechanical hand. Ioannides, Angeles, Flanagan, and Ostry suggest the use of polar-decomposition filtering to improve the performance of a least-square estimation procedure in the presence of noisy sensor data.

Section 5
Motion Planning

Mason discusses manipulation strategies arising in the context of sliding blocks along walls which suggest a possible unification of the methods available for the analysis of fine motions and those available for synthesis.

Bodduluri, McCarthy and Bobrow investigate motion planning for two manipulators sharing a common load. A general path-planning algorithm developed for multi-dimensional chains produces collision-free motions for two cooperating arms with astonishing ease. Finally, Flanagan and Ostry investigate the properties of multi-joint human motions and propose a model combining staggered joint interpolation and minimum jerk joint trajectories.

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