Robotics Research

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Robotics Research

The Seventh International Symposium

With 580 Figures

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Preface

The Seventh International Symposium of Robotics Research was held in Herrsching near Munich, Germany, from October 21 to 24, 1995, the first to be organized following the renewal undergone by the International Foundation of Robotics Research (IFRR) during the preceding Symposium (Hidden Valley, October 1993).

A board of eighteen officers was appointed:

Suguru Arimoto	(Tokyo University)
Ruzena Bajcsy	(University of Pennsylvania)
Robert Bolles	(SRI International)
Mike Brady	(Oxford University)
Paolo Dario	(Pisa University, Italy)
Joris De Schutter	(Katholieke Universiteit Leuven, Belgium)
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It was our commitment to bring together active, leading robotics researchers from academia, government, and industry, with the ambitious objective to assess the state of Advanced Robotics and to discuss future research directions.

Papers representing authoritative reviews of established research areas as well as papers reporting on new areas were sought for presentation. A number of leading researchers were asked to submit extended abstracts outlining papers representing their areas of research.

In addition to inviting participants, a call for papers was issued in order to include researchers who had made significant new contributions to robotics. All abstracts and submitted papers were reviewed by the eighteen IFRR officers acting as the Symposium Program Committee before final paper selection was made. Attendance at the Symposium, 63, was limited to presenters and invited participants.

It is worth noting that of the sixty three participants, only thirty were present at Hidden Valley in 1993.

The organization of the Proceedings follows that of the Symposium, with a chapter devoted to each session. Senior members of the robotics research community were asked to chair each session and to write a session summary which introduces the chapter.

During the four-days of sessions, fifty five papers were presented in a single track with emphasis being put in open discussion with a pro-active role of the chair.

We believe to express the general opinion of the attendees in writing that we had a most interesting four-days work with an outstanding set of original results as well as clean, enlightening new formulations of standing problems. Hence, the Symposium endeavoured to contribute with meaningful steps forward to build the emerging body of concepts, methods, scientific and technical knowledge and tools that shape Robotics.

Indeed, the papers cover not only a broad spectrum of subjects, but, most important, they range from pure exploratory research to application-oriented research work, sometimes even directly related to a real-world generic case.

Thus whichever viewpoint we stand for, Robotics revival, birth or just normal evolution and progress we hope to share with the readers what we experienced together : an already quite mature body of knowledge is fostered by novel cutting edge applications and shall respond to the two-folded challenge of scientific and technical soundness as well as economical and technical impact.

We would like to express, on behalf of IFRR our thanks to the following institutions that financially sponsored the 7th ISRR : the Bavarian Ministry of Economics, Traffic and Technology, DLR (German Aerospace Research Establishment), KUKA (German robot manufacturer), LAAS-CNRS (French Research Laboratory, and Secretariat of the International Foundation for Robotics Research), SIEMENS.

Our special thanks also go to the staff of DLR for a very efficient and most pleasant venue organisation, and to the IFRR Secretariat for the continuing logistic support.

Gerhard Hirzinger and Georges Giralt
Co-Chairs
The Seventh International Symposium of Robotics Research

List of Authors

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PART 1

MANIPULATION

SESSION SUMMARY

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The session on Manipulation contains four papers on dynamic interaction, design of dextrous hands, object reorientation using grasp gaits and palmar manipulation. The first two papers are review papers in their respective fields; the last two papers present pioneering work in the planning of manipulations. These last papers focus on different types of manipulative actions: the third paper deals with the planning of *prehensile* manipulation combined with a sequence of regrasps as in the case of a multifingered hand; the fourth paper deals with the planning of *nonprehensile* manipulation, such as sliding and dropping, as in the case of manipulation using multiple palms.

The first paper by E. Fasse and N. Hogan, *Control of physical contact and dynamic interaction*, reviews several different approaches to controlling mechanical interaction, including impedance and admittance control and compares them with hybrid force/position control. The problems of physical contact and the strengths and weaknesses of interaction control are considered in view of specification of a desired behavior and implementation.

The second paper by A. Bicchi, *Hands for dextrous manipulation and powerful grasping: a difficult road towards simplicity*, discusses the state of the art in the design of artificial hands, and comments about expected future developments. Bicchi favors a minimalistic attitude in the design of hands for practical applications; designing simple and effective devices for executing non-trivial devices is in fact much more difficult than contriving very complex systems for the same task. He distinguishes between dextrous hands and hands for grasping. Both have opposite requirements in some sense as dexterity means the ability to change the position and orientation of the manipulated object with respect to the hand, while grasping is intended to prevent motion relative to the hand.

The third paper by S. Leveroni and K. Salisbury, *Reorienting objects with a robot hand using grasp gaits*, addresses the planning of robot finger motions to enable continuous and stable reorientation of grasped objects. With a given grasp on an object, the range of reorientation through which the fingers may move the object is limited by the workspace of the fingers and grasp stability. If however the object can be properly regrasped without dropping it, further motion of the object in the desired direction may be possible. Such a sequence of finger/objects motions and regrasps is called a grasp gait. The paper develops tools and methods to find suitable grasp gaits that enable a robot hand to reorient convex objects in two dimensions.

The final paper by M. Erdmann, *An exploration of nonprehensile two-palm manipulation: planning and execution*, presents a system for orienting parts using two palms which consists of a planner and an executive. Based on a geometric description of a part, the coefficients of friction between the part and each of the palms, and a start and goal configuration of the part, the system plans and executes a sequence of nonprehensile palm motions (e.g. purposeful sliding and constrained dropping) which orient the part from the specified start to the specified goal configuration.

Hands for Dexterous Manipulation and Powerful Grasping: A Difficult Road Towards Simplicity

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Abstract

In this paper, an attempt at summarizing the evolution and the state-of-the-art in the field of robot hands is made. In such exposition, a critical evaluation of what in the author's view are the leading ideas and emerging trends, is privileged with respect to exhaustiveness of citations. A basic distinction is made between hands designed for mimicking the human anatomy and physiology, and hands designed to meet practical, if restricted, task requirements.

The fact that most of the sophisticated robot hands produced so far never found their way into real-world applications is a strong stimulus at re-thinking some of our approaches. In particular, arguments are presented in favour of a "minimalistic" attitude in the design of hands for practical applications, i.e., use the least number of actuators, the simplest set of sensors, etc., for a given task. To achieve this rather obvious engineering goal is a challenge to our community. The paper illustrates some of the new, sometimes difficult theoretical problems that are brought about by building and controlling simpler, practical devices.

1 Introduction

"*'Αναξαγόρας μὲν οὖν φησι διὰ τὸ χεῖρας έχειν φρονιμώτατον εἶναι τῶν ζώων άνθροπον : εύλογον δὲ διὰ τὸ φρονιμώτατον εἶναι χεῖρας λαμβάνειν*[1]". In one of his books on nature sciences [2], the greek philosopher Aristotle (384–322 BC) thus argued against the conceptions of his late colleague Anaxagoras (500?–428 BC) regarding the relationship between human hands and mind. As they appear to be the two most distinguished features of humans among animals, the two philosophers debated whether it was because humans had dextrous hands that they grew intelligent, or the other way around. It has been later on confirmed by several findings of paleoanthropologists that the mechanical dexterity of the human hand has been a major factor in allowing homo sapiens to develop a superior brain (a similar role played by the anatomical structure of the human larynx in relation with speech capabilities has been also recognized).

While the dexterity of the human hand has been admired since the oldest times, it still represents an unmatched standard for artificialists, and probably will for good. Nonetheless, there are theoretical and practical intermediate goals that are worth our best efforts to work towards dexterity. This paper discusses in what state the art of building artificial hands is at present times, and argue about possible directions it may take in the future. Excellent surveys are available on robot hand systems and components (see e.g. [44], [49], [111], [42], [100], [122], [53], and [95]), and the reader is referred there for other views on the state of the art.

In Section 2 the dualism between anthropomorphic and non-anthropomorphic design is considered, and issues raised by real-world applications of artificial hands are introduced. The strong need for simplicity in the design of practical robot hands is underscored. In Section 3 these themes are substantiated with examples of manipulation-oriented hands, while in Section 4 robustness of grasping is addressed. Throughout the paper, open problems of both theoretical and technological nature are presented.

[1] **"Anaxagoras says that because of having hands, man grew the most intelligent among animals. [I think] it is correct to say that because of his intelligence he has hands"**

2 Anthropomorphism in Design

Although stronger or faster artificial hands may be built, performance of human hands are unequalled if a sufficiently broad scope of manipulation tasks is considered. It is therefore natural for a roboticist to take inspiration from such a design success, and set forth for himself the goal of building hands that achieve, albeit partially, such capabilities. However, the toolbox nature can use is extremely different from what we have, in terms of actuators, sensors, and control means. Hence, the question whether artificial hands should *look like* those of humans, is not settled.

Good reasons for building anthropomorphic hands are found in applications where a *replacement* is needed. In other words, if the system is to use the same interface with the environment that was designed for the human hand (e.g. handles, consoles, tools etc.), then an anthropomorphic hand can save much effort in redesigning the interface. Such is typically the case with prosthetic devices (see e.g. [71], [139], [30], [58]). The same criteria apply in a closer field to robotics, i.e., telemanipulation (see e.g. [35], [8], [131], [37], [46], [130], [79], [62]), although there exist examples of non strictly anthropomorphic hands intended also for remote operation (see e.g. [21]). It should be noted that anthropomorphic design also makes it easier for the human operator to map his natural manipulation behaviours into commands for the device. Future robots for the domestic environment will probably have human-like hands, although at present it seems hard to reasonably forecast how close such future is.

On the other hand, if the control of the robot hand is realized by computer programs, and the environment is at least partially available for design decisions (as it happens in industrial parthandling, for instance), then several reasons may suggest that an anthropomorphic hand is not the best solution. Among the drawbacks of human-like hands, are the complex kinematic structure, the high number of actuators, and the sophistication of sensing systems. Cost-effectiveness and reliability are at a premium in factory applications of robot hands, and make the simplest grippers an optimal solution for most trivial grasping tasks. Manufacture of large enough batches of products justifies the development of specialized grippers for the task (Kato [70] reviewed a very large number of such devices). However, as the life cycle of products decreases in the technological competition, the need for flexibility in parthandling devices becomes more and more important.

In between the completely unstructured world and the perfectly defined environments, there is a whole gray scale of applications where the familiar flexibility/efficiency tradeoffs have to be seeked for actively. This concept is well radicated in the robotics community, see for instance [151] and [25]. Design of devices for this class of problems usually obey the good old engineering principle of minimalism: choose the simplest mechanical structure, the minimum number of actuators, the simplest set of sensors, etc., that will do the job (or class of jobs).

Complexity reduction is especially important in terms of hardware components of the system, as they often make for most of the cost, weight, and failures of robots. On the other hand, it often turns out that sophisticated design, analysis, programming, and control are required to perform difficult tasks by means of simple devices. Designing simple and effective devices for executing non-trivial tasks is actually much more difficult than contriving very complex systems for the same job. This is true both in a technological and theoretical sense, as this paper attempts at illustrating.

3 Design of dextrous hands

"Dexterity" is a rather broad concept in common language, that involves aspects of ability and stability in peforming motions of the manipulated object by means of the hand. We will restrict here to the notion, widely accepted in the robotics manipulation literature, that dexterity means the capability of changing the position and orientation of the manipulated object from a given reference configuration to a different one, arbitrarily chosen within the hand workspace. In this section, we examine several attempts at achieving dexterity by robot hands.

Robot hands are systems comprised of two or more fingers that act on a manipulated object via contacts. The presence of contact phenomena in manipulation makes for the most of the peculiarity of manipulation among other robotic systems. and clearly contact models deeply affect the analysis of manipulation systems. A standard classification of contact models introduced in robotics ([126] [31]) distinguishes point-contact-with-friction (or "hard-finger"), "soft-finger", and complete-constraint contacts (or "very-soft-finger"). Other important aspects of contact modeling regard the visco–elastic behavior (rigid, isotropically elastic, etc.) and the behavior in sliding and rolling conditions, namely, the static and kinetic coefficients of friction, and whether the contact point moves on the contacting surfaces as they rotate with respect to each other ("rolling contact"), or not. The latter case corresponds to an idealized situation of contact between surfaces with infinite relative curvature.

Salisbury ([83]) showed first that the minimum theoretical number of d.o.f.'s to achieve dexterity in a hand with rigid, hard-finger, non–rolling and non–sliding contacts, is 9. As a simple explanation of this fact, consider that at least three hard-fingers are necessary to completely restrain an object. On the other hand, as no rolling nor sliding is allowed, fingers must move so as to track with the contact point on their fingertip the trajectory generated by the corresponding contact point on the object, while this moves in 3D space. Hence, 3 d.o.f. per finger are strictly necessary. The Salisbury Hand ([124]) was accordingly designed to have nine joints, distributed in each finger so as to optimize a measure of individual "manipulability" of the finger ([125]).

Several other hands developed in University or Government research centers have adopted design schemes similar to Salisbury's under this regard, as e.g. the University of Karlsruhe Hand ([Wöhlke, 1990]), the hand developed at the Technical University of Darmstadt ([105], [150]), and that of Delft University ([64]). Hands of this type are not usually strictly anthropomorphic.

Some researchers preferred to introduce redundant degrees of freedom in their hands to achieve more flexibility of use. In one of the earliest successful hand designs, Okada employed two four–joint fingers and one three–joint thumb (see [101]). In the design of the hand of the Technical University of München ([87]), the three–joint three–finger design has been modified by introducing one more joint per finger, the motions of which are however mechanically coupled so that a total of nine d.o.f.'s is maintained. Coupling some of the joints in the hand allows to mechanically introduce grasping behaviors by curling the fingers to wrap the object, which is a feature of the human hand and of some prosthesis–oriented hands ([139]). Other authors introduced more than three fingers in their robot hands, with a basically twofold motivation: four– and five–fingered hands are closer to the anthropomorphic model, and allow to alternate the fingers in contact with the object so as to achieve richer manipulation patterns. Typical examples of anthropomorphic hands are the Utah/MIT Hand ([59]) and the Anthrobot Hand ([1]).

Actuation means are another active area of research. While shape memory alloys once used in the Hitachi hand do not seem to have found their way into practical applications, the hand developed at the New York University by Ebner and Wallace [34] has 15 joints actuated by direct–drive magnetic actuators. A two fingered hand with 12 d.o.f. for miniaturized object handling has been presented by Tanikawa *et al.* [137] that is actuated by piezoelectric motors. Hayakawa and Kawamura [47] presented a pneumatic bellows system realizing a soft gripper.

Notwithstanding the great effort spent, and the impressing technological and theoretical results achieved by the robotics community in building and controlling dextrous robot hands, the number of applications in the real–world and the performance of such devices in operative conditions should be frankly acknowledged as not yet satisfactory. In particular, the high degree of sophistication in the mechanical design prevented dextrous robotics hand to succeed in applications where factors such as reliability, weight, small size, or cost, were at a premium. One figure partially representing such complicacy is the number of actuators, that ranges between 9 and 32 for hands considered above. Further reduction of hardware complexity, even below the theoretically minimum number of 9, is certainly one of the avenues for overcoming this impasse.

It should be recalled at this point that Salisbury's analysis of minimal design requirements for dexterity was based on a particular definition of dexterity and a set of assumptions on the contact model. Thus, for instance, it can be easily shown that if soft–finger contacts are considered, fingers with at least four d.o.f.'s are needed to achieve dexterity in the sense above defined. Even the human hand can not be considerd dextrous if soft–finger contacts are enforced at the fingertips.

Other means of achieving dexterity can be devised if we allow some modifications of the concept of dexterity, and of the assumptions on contact models. In most applications, for instance, it is not necessary that the manipulated object can track a given trajectory in position and ori-