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Advances in Control of Articulated and Mobile Robots

With 124 Figures and 15 Tables

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Foreword

At the dawn of the new millennium, robotics is undergoing a major transformation in scope and dimension. From a largely dominant industrial focus, robotics is rapidly expanding into the challenges of unstructured environments. Interacting with, assisting, serving, and exploring with humans, the emerging robots will increasingly touch people and their lives.

The goal of the new series of *Springer Tracts in Advanced Robotics (STAR)* is to bring, in a timely fashion, the latest advances and developments in robotics on the basis of their significance and quality. It is our hope that the greater dissemination of research developments will stimulate more exchanges and collaborations among the research community and contribute to further advancement of this rapidly growing field.

Advances in Control of Articulated and Mobile Robots edited by Bruno Siciliano, Alessandro De Luca, Claudio Melchiorri, and Giuseppe Casalino provides a unique collection of a sizable segment of the robotics research in Italy. It reports on contributions from ten academic institutions brought together within MISTRAL, an Italian project on robotics research.

This ten-chapter volume covers important research areas ranging from planning, control, and actuation of articulated mechanisms to sensing, perception, navigation, and real-time control architectures of mobile robots. The focus is on fundamental issues related to robots subjected to nonholonomic constraints, time delays, actuator saturation, or joint friction. The work also addresses other key issues concerned with the localization and mapping in unknown or partially known environments, the presence of moving objects, the use of multiple sensors, and the integration of mobility and manipulation.

The thorough discussion, rigorous treatment, and wide span of the work unfolding in these areas reveal the significant advances in the theoretical foundation and technology basis of the robotics field. MISTRAL culminates with this important reference to the world robotics community on the current developments and new directions undertaken by this project's Italian robotics team!

Stanford, California
November 2003

Oussama Khatib
STAR Editor

Preface

Since the development of robotics for industrial and manufacturing applications in structured environments, research in the field has been gradually seeking at providing robotic systems with enhanced autonomy for operation in unstructured environments. Significant examples include cooperating and assisting robots, haptic interfaces for virtual reality and remote operation in hostile environments, mobile robots and autonomous agent teams. The challenge presented by such themes demands advanced control techniques and architectures to perform robotic tasks such as manipulation, interaction, teleoperation, locomotion and cooperation.

This monograph stems from the research project MISTRAL (Methodologies and Integration of Subsystems and Technologies for Anthropic Robotics and Locomotion), funded in 2001–2002 by the Italian Ministry for Education, University and Research (MIUR), involving a significant portion of the national academic robot control community; namely, the research groups at: University of Bologna, University of Genoa, Polytechnical University of Marche, Polytechnic of Milan, University of Naples, University of Pisa, University of Rome "La Sapienza", University of Rome "Tor Vergata", Third University of Rome, Polytechnic of Turin. A complete description of the project is available at the web site *http://www-lar.deis.unibo.it/mistral*.

The aim of this monograph is to provide an updated source of information on the state of the art in advanced control of articulated and mobile robots, along with a taste of significance and impact of new research in the field. A number of relevant problems have been selected dealing with enhanced actuation, motion planning and control functions for articulated robots, as well as of sensory and autonomous decision capabilities for mobile robots.

The material has been organized as follows. The first two chapters are devoted to tutorial/survey presentations on two critical issues when controlling a robotic system: planning motion in the presence of differential constraints, and copying with time delay in remote operation, respectively. The remaining contents have been ordered in a progressive way; the next four chapters deal with control of articulated robots, whereas the final four chapters are focused on planning, localization and servoing of mobile robots. A reading track along the various contributions of the ten chapters of the volume is outlined in the following.

The volume starts with a comprehensive tutorial by *De Luca et al.* on motion planning for a class of *robotic systems subject to nonholonomic differential constraints*. Of special concern is the problem of planning point-to-point motion for systems subject to non-integrable first and second-order differential constraints. The solutions outlined for both non-flat nonholonomic kinematic systems and flat underactuated dynamic systems demonstrate the generality of the approach.

Teleoperation has historically been one of the pioneering areas in robotics. The key problem from a control viewpoint has been to cope with time delay. The chapter by *Arcara and Melchiorri* presents an extensive survey of the most adopted

techniques for telemanipulation. Control schemes are critically compared in terms of suitable criteria, and one type of passive controller is analyzed in detail for performance enhancement purposes.

As outlined above, the issue of performance plays a crucial role in robot control. The chapter by *Morabito et al.* concentrates on a specific phenomenon which may deteriorate performance in a robot manipulator undergoing actuator torque saturation. An effective *anti-windup control* law is proposed which is remarkably based on simple and intuitive parameter tuning.

The following two chapters are devoted to the problem of modelling and compensation of *nonlinear friction* in robot joint actuators, yet another effect which must be properly taken into account when designing advanced control systems. The chapter by *Ferretti, Magnani and Rocco* demonstrates how the use of high-resolution encoders allows an accurate analysis of the dynamic behavior of friction forces in the so-called presliding regime, and especially in the presence of hysteresis loops.

On the other hand, the treatment of nonlinear friction in the chapter by *Bona, Indri and Smaldone* is framed into the context of *rapid prototyping* of model-based robot controllers. General issues related to both hardware and software architectures are critically surveyed with the goal of achieving fast and systematic interaction between the algorithmic design phase and the experimental testing.

The use of visual sensors is argued to have high impact for operation in unstructured environments, especially if the robot is visually servoed in a closed-loop control fashion. The problem of *visual tracking* of 3D objects is treated in the chapter by *Caccavale et al.*, where a combined Extended Kalman Filter/Binary Space Partition tree technique is developed to achieve real-time estimation of the position and orientation of moving objects of known geometry using a fixed stereo camera system.

The remaining four chapters deal with issues concerning mobile robots. The development of a *real-time control architecture* for a prototype of differentially-driven wheeled mobile robot is discussed in the chapter by *Bellini et al.*. The solution resorts to RTLinux operating system which seems to gain increasing popularity within the research community; the software architecture includes low level motor feedback, high level trajectory loops, and communication protocols through an Ethernet radio link.

The chapter by *Casalino and Turetta* addresses the problem of coordinating the manoeuvring of a nonholonomic vehicle with the motion of a supported manipulation system, composed either by a single arm or by two arms. Kinematic redundancy is suitable exploited to optimize a number of constraints according to a systematic approach which ensures modularity and scalability within the overall *vehicle-manipulator robotic system*.

Sensory data fusion is covered in the chapter by *Bonci et al.*, where different methods and algorithms are introduced for the accurate localization of mobile robots on a given map, by integration of odometric, gyroscope, sonar and video camera measures using a Kalman filtering approach. On the other hand, different probabilistic methods are employed for the exploration of unknown environments.

The volume ends with the chapter by *Bicchi et al.* which considers three main problems arising in the navigation of autonomous vehicles in partially or totally unknown environments; namely, *map building, localization, and motion servoing*. The result is a generalization of SLAM, which allows the localization and mapping problems to be cast in a unified framework with the control problem.

The monograph is addressed to postgraduate students, researchers, scientists and scholars who wish to broaden and strengthen their knowledge in control of robotic systems.

Besides thanking all the Authors for their valuable contributions to this monograph, we wish to extend our appreciation to all the participants to the MISTRAL project who have produced significant research results during the latest two years. Warmest thanks are also for Thomas Ditzinger at Springer-Verlag in Heidelberg. A final word of thanks goes to Costanzo Manes for the pictorial illustration below.

Italy
October 2003

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