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Control Problems in Robotics and Automation

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Foreword

It is rather evident that if we are to address successfully the control needs of our society in the 21st century, we need to develop new methods to meet the new challenges, as these needs are imposing ever increasing demands for better, faster, cheaper and more reliable control systems. There are challenging control needs all around us, in manufacturing and process industries, in transportation and in communications, to mention but a few of the application areas. Advanced sensors, actuators, computers, and communication networks offer unprecedented opportunities to implement highly ambitious control and decision strategies. There are many interesting control problems out there which urgently need good solutions. These are exciting times for control, full of opportunities. We should identify these new problems and challenges and help the development and publication of fundamental results in new areas, areas that show early promise that will be able to help address the control needs of industry and society well into the next century. We need to enhance our traditional control methods, we need new ideas, new concepts, new methodologies and new results to address the new problems. Can we do this? This is the challenge and the opportunity.

Among the technology areas which demand new and creative approaches are complex control problems in robotics and automation. As automation becomes more prevalent in industry and traditional slow robot manipulators are replaced by new systems which are smaller, faster, more flexible, and more intelligent, it is also evident that the traditional PID controller is no longer a satisfactory method of control in many situations. Optimum performance of industrial automation systems, especially if they include robots, will demand the use of such approaches as adaptive control methods, intelligent control, "soft computing" methods (involving neural networks, fuzzy logic and evolutionary algorithms). New control systems will also require the ability to handle uncertainty in models and parameters and to control lightweight, highly flexible structures. We believe complex problems such as these, which are facing us today, can only be solved by cooperation among groups across traditional disciplines and over international borders, exchanging ideas and sharing their particular points of view.

In order to address some of the needs outlined above, the IEEE Control Systems Society (CSS) and the IEEE Robotics and Automation Society (RAS) sponsored an *International Workshop on Control Problems in Robotics and Automation: Future Directions* to help identify problems and promising solutions in that area. The CSS and the RAS are leading the effort to identify future and challenging control problems that must be addressed to meet future needs and demands, as well as the effort to provide solutions to these problems. The Workshop marks ten years of fruitful collaboration between the sponsoring Societies.

On behalf of the CSS and RAS, we would like to express our sincere thanks to Kimon Valavanis and Bruno Siciliano, the General and Program Chairs of the Workshop for their dedication, ideas and hard work. They have brought together a truly distinguished group of robotics, automation, and control experts and have made this meeting certainly memorable and we hope also useful, with the ideas that have been brought forward being influential and direction setting for years to come. Thank you.

We would like also to thank the past CSS President Mike Masten and the past RAS President T.-J.Tarn for actively supporting this Workshop in the spirit of cooperation among the societies. It all started as an idea at an IEEE meeting, also in San Diego, in early 1996. We hope that it will lead to future workshops and other forms of cooperation between our societies.

Panos J. Antsaklis
President, IEEE Control Systems Society

George A. Bekey
President, IEEE Robotics and Automation Society

Preface

The purpose of the book is to focus on the state-of-the-art of control problems in robotics and automation. Beyond its tutorial value, the book aims at identifying challenging control problems that must be addressed to meet future needs and demands, as well as at providing solutions to the identified problems.

The book contains a selection of invited and submitted papers presented at the *International Workshop on Control Problems in Robotics and Automation: Future Directions*, held in San Diego, California, on December 9, 1997, in conjunction with the 36th IEEE Conference on Decision and Control. The Workshop has been jointly sponsored by the IEEE Control Systems Society and the IEEE Robotics and Automation Society.

The key feature of the book is its wide coverage of relevant problems in the field, discussed by world-recognized leading experts, who contributed chapters for the book. From the vast majority of control aspects related to robotics and automation, the Editors have tried to opt for those "hot" topics which are expected to lead to significant achievements and breakthroughs in the years to come.

The sequence of the topics (corresponding to the chapters in the book) has been arranged in a progressive way, starting from the closest issues related to industrial robotics, such as force control, multirobots and dexterous hands, to the farthest advanced issues related to underactuated and nonholonomic systems, as well as to sensors and fusion. An important part of the book has been dedicated to automation by focusing on interesting issues ranging from the classical area of flexible manufacturing systems to the emerging area of distributed multi-agent control systems.

A reading track along the various contributions of the sixteen chapters of the book is outlined in the following.

Robotic systems have captured the attention of control researchers since the early 70's. In this respect, it can be said that the motion control problem for rigid robot manipulators is now completely understood and solved. Nonetheless, practical robotic tasks often require interaction between the manipulator and the environment, and thus a *force control* problem arises. The chapter by *De Schutter et al.* provides a comprehensive classification of different approaches where force control is broadened to a differential-geometric context.

Whenever a manipulation task exceeds the capability of a single robot, a *multirobot cooperative system* is needed. A number of issues concerning the modelling and control of such a kind of system are surveyed in the chapter by *Uchiyama*, where the problem of robust holding of the manipulated object is emphasized.

Multifingered *robot hands* can be regarded as a special class of multirobot systems. The chapter by *Bicchi et al.* supports a minimalist approach to design of *dexterous* end effectors, where nonholonomy plays a key role.

Force feedback becomes an essential requirement for *teleoperation* of robot manipulators, and *haptic interfaces* have been devised to alleviate the task of remote system operation by a computer user. The chapter by *Salcudean* points out those control features that need to be addressed for the manipulation of virtual environments.

A radically different approach to the design control problem for complex systems is offered by *fuzzy control*. The potential of such approach is discussed in the chapter by *Hsu and Fu*, in the light of a performance enhancement obtained by either a learning or a suitable approximation procedure. The application to mechanical systems, including robot manipulators, is developed.

Modelling robot manipulators as rigid mechanical systems is an idealization that becomes unrealistic when higher performance is sought. *Flexible manipulators* are covered in the chapter by *De Luca*, where both joint elasticity and link flexibility are considered with special regard to the demanding problem of trajectory control.

Another interesting type of mechanical systems is represented by walking machines. The chapter by *Hurmuzlu* concentrates on the locomotion of *bipedal robots*. Active vs. passive control strategies are discussed where the goal is to generate stable gait patterns.

Unlike the typical applications on ground, *free-floating robotic systems* do not have a fixed base, e.g. in the space or undersea environment. The derivation of effective models becomes more involved, as treated in the chapter by *Egeland and Pettersen*. Control aspects related to motion coordination of vehicle and manipulator, or else to system underactuation, are brought up.

The more general class of *underactuated mechanical systems* is surveyed in the chapter by *Spong*. These include flexible manipulators, walking robots, space and undersea robots. The dynamics of such systems place them at the forefront of research in advanced control. Geometric nonlinear control and passivity-based control methods are invoked for stabilization and tracking control purposes.

The chapter by *Canudas de Wit* concerns the problem of controlling mobile robots and multibody vehicles. An application-oriented overview of some actual trends in control design for these systems is presented which also touches on the realization of transportation systems and intelligent highways.

Control techniques for mechanical systems such as robots typically rely on the feedback information provided by proprioceptive sensors, e.g. position, velocity, force. On the other hand, heteroceptive sensors, e.g. tactile, proximity, range, provide a useful tool to enrich the knowledge about the operational environment. In this respect, vision-based robotic systems have represented a source of active research in the field. The fundamentals of the various proposed approaches are described in the chapter by *Corke and Hager*, where

the interdependence of vision and control is emphasized and the closure of a visual-feedback control loop (*visual servoing*) is shown as a powerful means to ensure better accuracy.

The employment of multiple sensors in a control system calls for effective techniques to handle disparate and redundant sensory data. In this respect, *sensor fusion* plays a crucial role as evidenced in the chapter by *Henderson et al.*, where architectural techniques for developing wide area sensor network systems are described.

Articulated robot control tasks, e.g. assembly, navigation, perception, human-robot shared control, can be effectively abstracted by resorting to the theory of *discrete event systems*. This is the subject of the chapter by *McCarragher*, where constrained motion systems are examined to demonstrate the advantages of discrete event theory in regarding robots as part of a complete automation system. Process monitoring techniques based on the detection and identification of discrete events are also dealt with.

Flexible manufacturing systems have traditionally constituted the ultimate challenge for automation in industry. The chapter by *Luh* is aimed at presenting the basic job scheduling problem formulation and a relevant solution methodology. A practical case study is taken to discuss the resolution and the implications of the scheduling problem.

Integration of sensing, planning and control in a manufacturing work-cell represents an attractive problem in intelligent control. A unified framework for *task synchronization* based on a Max-Plus algebra model is proposed in the chapter by *Tarn et al.* where the interaction between discrete and continuous events is treated in a systematic fashion.

The final chapter by *Sastry et al.* is devoted to a different type of automation other than the industrial scenario; namely, air traffic management. This is an important example of control of *distributed multi-agent systems*. Owing to technological advances, new levels of system efficiency and safety can be reached. A decentralized architecture is proposed where air traffic control functionality is moved on board aircraft. Conflict resolution strategies are illustrated along with verification methods based on Hamilton-Jacobi, automata, and game theories.

The book is intended for graduate students, researchers, scientists and scholars who wish to broaden and strengthen their knowledge in robotics and automation and prepare themselves to address and solve control problems in the next century.

We hope that this Workshop may serve as a milestone for closer collaboration between the IEEE Control Systems Society and the IEEE Robotics and Automation Society, and that many more will follow in the years to come.

We wish to thank the Presidents Panos Antsaklis and George Bekey, the Executive and Administrative Committees of the Control Systems Society and Robotics and Automation Society for their support and encouragement, the Members of the International Steering Committee for their

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