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Lorenzo Sciavicco and Bruno Siciliano

Modelling and Control of Robot Manipulators

Second Edition

With 190 Figures

Springer

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To our families

Series Editors' Foreword

The topics of control engineering and signal processing continue to flourish and develop. In common with general scientific investigation, new ideas, concepts and interpretations emerge quite spontaneously and these are then discussed, used, discarded or subsumed into the prevailing subject paradigm. Sometimes these innovative concepts coalesce into a new sub-discipline within the broad subject tapestry of control and signal processing. This preliminary battle between old and new usually takes place at conferences, through the Internet and in the journals of the discipline. After a little more maturity has been acquired by the new concepts then archival publication as a scientific or engineering monograph may occur.

A new concept in control and signal processing is known to have arrived when sufficient material has developed for the topic to be taught as a specialised tutorial workshop or as a course to undergraduates, graduates or industrial engineers. The *Advanced Textbooks in Control and Signal Processing Series* is designed as a vehicle for the systematic presentation of course material for both popular and innovative topics in the discipline. It is hoped that prospective authors will welcome the opportunity to publish a structured presentation of either existing subject areas or some of the newer emerging control and signal processing technologies.

The authors Lorenzo Sciavicco and Bruno Siciliano declare that robotics is more than fifteen years old and is a young subject! Yet, this textbook shows that a well-established paradigm of classical robotics exists and the book provides an invaluable presentation of the subject. The Series is fortunate in being able to welcome this text as a second edition. Thus it is an updated text which has benefited from the authors' teaching practice and an awareness of very recent developments in the field. Notable in this sense is the inclusion of material on vision sensors and trajectory planning.

As a course textbook, the authors have explained how various chapters may be drawn together to form a course. Further, the book is supported by a Solutions Manual. Last, but not least we ought to mention three very substantial Appendices giving useful supplementary material on the necessary mathematics, rigid body dynamics and feedback control. A fine new addition to the Series!

M.J. Grimble and M.A. Johnson
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December 1999

About the Authors

Lorenzo Sciavicco was born in Rome, Italy, on December 8, 1938. He received the *Laurea* degree in Electronic Engineering from the University of Rome in 1963. From 1968 to 1995 he was with the University of Naples, where he served as Head of the Department of Computer and Systems Engineering from 1992 to 1995. He is currently *Professor* in the Department of Computer Engineering and Automation of the Third University of Rome. His research interests include automatic control theory and applications, inverse kinematics, redundant manipulator control, force/motion control and cooperative robots. He is co-author of more than 80 journal and conference papers, and he is co-author of the book *Modeling and Control of Robot Manipulators* (McGraw-Hill 1996). Professor Sciavicco has been one of the pioneers of robot control research in Italy, and has been awarded numerous grants for his robotics group. He has served as a referee for industrial and academic research projects on robotics and automation in Italy.
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Bruno Siciliano was born in Naples, Italy, on October 27, 1959. He received the *Laurea* degree and the *Research Doctorate* degree in Electronic Engineering from the University of Naples in 1982 and 1987, respectively. From 1983 to 2000 he was with the Department of Computer and Systems Engineering of the University of Naples. Since November 2000 he is *Professor* in the Department of Information and Electrical Engineering of the University of Salerno. From September 1985 to June 1986 he was a Visiting Scholar at the School of Mechanical Engineering of the Georgia Institute of Technology. His research interests include inverse kinematics, redundant manipulator control, modelling and control of flexible arms, force/motion and vision-based control, and cooperative robots. He is co-author of more than 180 journal and conference papers, and he is co-author of the books: *Modeling and Control of Robot Manipulators* with *Solutions Manual* (McGraw-Hill 1996), *Theory of Robot Control* (Springer 1996), *Robot Force Control* (Kluwer 1999). He is co-editor of 4 journal special issues, and he is co-editor of the books: *Control Problems in Robotics and Automation* (Springer 1998), *RAMSETE* (Springer 2001), *Experimental Robotics VIII* (Springer 2002). He has delivered more than 70 invited seminars abroad. Professor Siciliano has served as an *Associate Editor* of the *IEEE Transactions on Robotics and Automation* from 1991 to 1994, and of the *ASME Journal of Dynamic Systems, Measurement, and Control* from 1994 to 1998. He is co-editor of the *Advanced Robotics Series* (Springer), and he is on the Editorial Boards of *Robotica*, the *Journal of Robotic Systems* and

the *JSME International Journal*. He is an *IEEE Fellow* and an ASME Member. He has held representative positions within the *IEEE Robotics and Automation Society*: *Administrative Committee Member* from 1996 to 1999, *Vice-President for Publications* in 1999, and *Vice-President for Technical Activities* since 2000. From 1996 to 1999 he has been *Chair* of the *Technical Committee on Manufacturing and Automation Robotic Control* of the *IEEE Control Systems Society*. He is *Co-Chair for Conferences and Publications* of the undergoing *European Robotics Research Network*. He has served as chair or co-chair for numerous international conferences. He has been awarded numerous grants for his robotics group.
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Preface to the Second Edition

The subject matter of this textbook is to be considered well assessed in the classical robotics literature, in spite of the fact that robotics is generally regarded as a young science.

A key feature of the First Edition was recognized to be the blend of technological and innovative aspects with the foundations of modelling and control of robot manipulators. The purpose of this Second Edition with the new Publisher is to add some material that was not covered before as well as to streamline and improve some of the previous material.

The major additions regard Chapter 2 on kinematics; namely, the use of the unit quaternion to describe manipulator's end-effector orientation as an effective alternative to Euler angles or angle and axis representations (Section 2.6), and the adoption of a closed chain in the design of manipulator structures (Sections 2.8.3 and 2.9.2). Not only are these topics analyzed in the framework of kinematics, but also their impact on differential kinematics, statics, dynamics and control is illustrated. In particular, different types of orientation error are discussed for inverse kinematics algorithms (Section 3.7.3), and the concept of kineto-statics duality is extended to manipulators having a closed chain (Section 3.8.3). Yet, the dynamic model of a parallelogram arm (Section 4.3.3) clearly shows the potential of such design over the kinematically equivalent two-link planar arm. Further, the problem of planning a trajectory in the operational space is expanded to encompass the different descriptions of end-effector orientation (Section 5.3.3), and the implications for operational space control are briefly discussed (Section 6.6.3).

Another addition regards the presentation of the main features of vision sensors (Section 8.3.4) which have lately been receiving quite a deal of attention not only in research but also in the industrial community.

Finally, the bibliography has been updated with more reference texts in the introduction (Chapter 1) as well as with those references that have been used in the preparation of the new material (Chapters 2 to 8). New problems have been proposed and the Solutions Manual accompanying the book has been integrated accordingly.

Naples, December 1999 *Lorenzo Sciavicco and Bruno Siciliano*[◇]

[◇] The authors have contributed equally to the work, and thus they are merely listed in alphabetical order.

The **Solutions Manual for Modelling and Control of Robot Manipulators, Second Edition** (ISBN 1-85233-221-2S) by Bruno Siciliano and Luigi Villani can be requested by textbook adopters from

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Preface to the First Edition

In the last fifteen years, the field of robotics has stimulated an increasing interest in a wide number of scholars, and thus literature has been conspicuous both in terms of textbooks and monographs and in terms of specialized journals dedicated to robotics. This strong interest is also to be attributed to the interdisciplinary character of robotics, which is a science having roots in different areas. Cybernetics, mechanics, bioengineering, electronics, information science, and automatic control science—to mention the most important ones—are all cultural domains which undoubtedly have boosted the development of robotics. This science, however, is to be considered quite young yet.

Nowadays, writing a robotics book brings up a number of issues concerning the choice of topics and style of presentation. Current literature features many texts which can be grouped in scientific monographs on research themes, application-oriented handbooks, and textbooks. As for the last, there are wide-ranging textbooks covering a variety of topics with unavoidably limited depth and textbooks instead covering in detail a reduced number of topics believed to be basic for robotics study. Among these, mechanics and control are recognized to play a fundamental role, since these disciplines regard the preliminary know-how required to realize robot manipulators for industrial applications, *i.e.*, the only domain so far where robotics has expressed its level of a mature technology.

The goal of this work is to present the foundations of modelling and control of robot manipulators where the fundamental, technological and innovative aspects are merged on a uniform track in respect of a rigorous formalism.

Fundamental aspects are covered which regard kinematics, statics and dynamics of manipulators, trajectory planning and motion control in free space. Technological aspects include actuators, proprioceptive sensors, hardware/software control architectures and industrial robot control algorithms. Established research results with a potential for application are presented, such as kinematic redundancy and singularities, dynamic parameter identification, robust and adaptive control and interaction control. These last aspects are not systematically developed in other textbooks, even though they are recognized to be useful for applications. In the choice of the topics treated and the relative weight between them, the authors hope not to have been biased by their own research interests.

The book contents are organized into 9 chapters and 3 appendices.

In Chapter 1, the problems concerning the use of *industrial robots* are focused in the general framework of *robotics*. The most common manipulation mechanical structures are presented. *Modelling and control* topics are also introduced which are developed in the subsequent chapters.

In Chapter 2 *kinematics* is presented with a systematic and general approach which refers to Denavit-Hartenberg convention. The *direct kinematics equation* is formulated which relates joint space variables to operational space variables. This equation is utilized to find manipulator workspace as well as to derive a kinematic calibration technique. The *inverse kinematics problem* is also analyzed and closed-form solutions are found for typical manipulation structures.

Differential kinematics is presented in Chapter 3. The relationship between joint velocities and end-effector linear and angular velocities is described by the geometric *Jacobian*. The difference between geometric Jacobian and analytical Jacobian is pointed out. The Jacobian constitutes a fundamental tool to characterize a manipulator, since it allows finding singular configurations, analyzing redundancy and expressing the relationship between forces and moments applied to the end effector and the resulting joint torques at equilibrium configurations (*statics*). Moreover, the Jacobian allows formulating inverse kinematics algorithms that solve the inverse kinematics problem even for manipulators not having a closed-form solution.

Chapter 4 deals with derivation of manipulator *dynamics*, which plays a fundamental role for motion simulation, manipulation structure analysis and control algorithm synthesis. The dynamic model is obtained by explicitly taking into account the presence of actuators. Two approaches are considered; namely, one based on *Lagrange* formulation, and the other based on *Newton-Euler* formulation. The former is conceptually simpler and systematic, whereas the latter allows computation of dynamic model in a recursive form. Notable properties of the dynamic model are presented, including linearity in the parameters which is utilized to develop a model identification technique. Finally, the transformations needed to express the dynamic model in the operational space are illustrated.

As a premise to the motion control problem, in Chapter 5, *trajectory planning* techniques are illustrated which regard the computation of interpolating polynomials through a sequence of desired points. Both the case of *point-to-point motion* and that of *path motion* are treated. Techniques are developed for generating trajectories both in the joint and in the operational space, with a special concern to orientation for the latter. Finally, a trajectory dynamic scaling technique is presented to keep the joint torques within the maximum available limits at the actuators.

In Chapter 6 the problem of *motion control* in free space is treated. The distinction between joint space *decentralized* and *centralized* control strategies is pointed out. With reference to the former, the independent joint control technique is presented which is typically used for industrial robot control. As a premise to centralized control, the computed torque feedforward control technique is introduced. Advanced schemes are then introduced including PD control with gravity compensation, inverse dynamics control, robust control, and adaptive control. Centralized techniques are extended to operational space control.

Interaction control of a manipulator in contact with the working environment is tackled in Chapter 7. The concepts of mechanical *compliance* and *impedance* are defined as a natural extension of operational space control schemes to the constrained motion case. *Force control* schemes are then presented which are obtained by the addition of an outer force feedback loop to a motion control scheme. The hybrid force/position control strategy is finally presented with reference to the formulation of natural and artificial constraints describing an interaction task.

Chapter 8 is devoted to the presentation of *actuators* and *sensors*. After an illustration of the general features of an actuating system, methods to control electric and hydraulic servomotors are presented. A few proprioceptive sensors are then described, including encoders, resolvers, tachometers, and force sensors.

In Chapter 9, the functional *architecture* of a robot *control* system is illustrated. The characteristics of programming environments are presented with an emphasis on teaching-by-showing and robot-oriented programming. A general model for the hardware architecture of an industrial robot control system is finally discussed.

Appendix A is devoted to *linear algebra* and presents the fundamental notions on matrices, vectors and related operations.

Appendix B recalls those basic concepts of *rigid body mechanics* which are preliminary to the study of manipulator kinematics, statics and dynamics.

Finally, Appendix C illustrates the principles of *feedback control* of linear systems and presents a general method based on Lyapunov theory for control of nonlinear systems.

The book is the evolution of the lecture notes prepared for the course "Industrial Robotics" taught by the first author in 1990 and 1991 and by the second author since 1992 at the University of Naples. The course is offered to Computer, Electronic and Mechanical Engineering graduate students and is developed with a teaching commitment of about 90 hours.

By a proper selection of topics, the book may be utilized to teach a course on robotics fundamentals at a senior undergraduate level. The advised selection foresees coverage of the following parts*: Chapter 1, Chapter 2, Chapter 4 (Sections 4.1 and 4.3), Chapter 5, Chapter 6 (Sections 6.1, 6.2, 6.3, and 6.4), Chapter 8, and Chapter 9. The teaching commitment is of about 50 hours. In this case, the availability of an industrial robot in the laboratory is strongly recommended to accompany class work with training work.

From a pedagogical viewpoint, the various topics are presented in an instrumental manner and are developed with a gradually increasing level of difficulty. Problems are raised and proper tools are established to find engineering-oriented solutions. Each chapter is introduced by a brief preamble providing the rationale and the objectives of the subject matter. The topics needed for a proficient study of the text are presented into three considerable appendices, whose purpose is to provide students of different extraction with a homogeneous background. Mechanical Engineering students will benefit from reading of the appendices on linear algebra and feedback control, whereas Computer and Electronic Engineering students are advised to study the appendix on rigid body mechanics.

The book contains more than 170 illustrations and more than 50 worked-out examples and case studies throughout the text with frequent resort to simulation.

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* Those parts that shall be covered only at a graduate level are marked with an asterisk in the table of contents.

The results of computer implementations of inverse kinematics algorithms, inverse dynamics computation, trajectory planning techniques, motion and interaction control algorithms are presented in much detail in order to facilitate the comprehension of the theoretical development as well as to increase sensitivity to application in practical problems. More than 80 problems are proposed and the book is accompanied by a Solutions Manual that comes with a toolbox created in MATLAB® with Simulink® to solve those problems requiring computer simulation. Special care has been devoted to the selection of bibliographical references (more than 200) which are collected at the end of each chapter.

Naples, July 1995 *LS & BS*

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Particular thanks go to Pasquale Chiacchio and Stefano Chiaverini, with whom the authors have been collaborating on robotics research activities for several years; the discussions and exchange of viewpoints with them in the planning stage of the text have been stimulating. Significant have been Pasquale Chiacchio's contribution to the writing of Chapter 5 on trajectory planning and Stefano Chiaverini's contribution to the writing of Chapter 7 on interaction control.

The valuable engagement of Luigi Villani, first as a graduate student of the course and then as a doctorate student, is acknowledged. He has substantially contributed to the writing of Appendix B on rigid body mechanics as well as of the final version of Chapter 4 on dynamics. His careful reading of the entire manuscript has allowed for an improvement of a few topics. He has provided relevant support in the development of those examples requiring computer simulation. The educational potential of the text is certainly increased by the availability of a solutions manual which features Luigi Villani as a co-author.

A special note of thanks goes to the colleagues Wayne Book, Alessandro De Luca, Gianantonio Magnani, Claudio Melchiorri and Deirdre Meldrum for having provided constructive criticisms on the contents of the book, which they have adopted in the form of lecture notes for university courses they have taught. A number of useful suggestions have also come from the colleagues Olav Egeland, Mark Spong and Antonio Tornambè, to whom the authors' sincere thanks are to be presented.

Students' participation in the refinement of the various versions of the lecture notes has been active with their requests of clarification and pointing out of numerous imprecisions.

Fabrizio Caccavale and Ciro Natale have been precious in the revision of the material for the second edition of the book. The latter is to be acknowledged also for his contribution to the writing of Section 8.3.4 on vision sensors. The second edition has also benefited from the comments on the first edition by the colleagues Thomas Alberts, Jon Kieffer, George Lee, Carlos Lück, Norberto Pires and Juris Vagners.

Finally, the authors wish to thank Nicholas Pinfield, Engineering Editor of Springer-Verlag, London, for his great enthusiasm in the project and for bringing the second edition of the book to fruition. His assistant, Oliver Jackson, also deserves a warm note of mention for his precious collaboration and patience during the preparation of the manuscript.

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