

Robots are now widely used in factories, and applications of robots in space, the oceans, nuclear industries, and other fields are being actively developed. Also, for the future, the use of robots in every facet of society, including the home, is being seriously considered. To support the development of these broad applications, robotics has evolved into a systematic approach to the engineering of robots.

This book has been written with the objective of presenting some fundamental concepts and methodologies for the analysis, design, and control of robot manipulators in an easily understandable way. I believe that this knowledge is useful not only in robotics but also in the analysis and control of other types of mechanical systems.

The book is based on class notes used at Kyoto University. It is intended as a text or reference book on robotics, mainly for graduate students in engineering. Junior and senior undergraduate students, however, should also be able to understand the material without much difficulty. The physical meanings of the concepts and equations used in the book are explained as fully as possible, and the required background in kinetics, linear algebra, and control theory is presented in an intuitively clear way to spare the reader from having to refer to texts in those other fields.

The book is organized as follows. After an overview in chapter 1, chapters 2 through 4 cover the analysis of robot manipulator mechanisms. Based on this analysis, chapters 5 through 7 discuss the control of robot manipulators.

Chapter 1 introduces several typical robot manipulator mechanisms and their controllers, in order to acquaint the reader with the kind of hardware that will be dealt with. Chapter 2 covers the kinematics of robot manipulators, studying geometrically the motion of manipulator links and objects related to the manipulation task in terms of position, velocity, and acceleration. Chapter 3 deals with the dynamics of robot manipulators, looking at how the manipulator's motion is affected by its mass distribution and applied forces. This chapter includes the derivation of the dynamic equations of motion, their use for control and simulation, and the identification of inertial parameters. Chapter 4 develops the concept of manipulability to analyze and evaluate quantitatively the manipulation ability of manipulators. This concept is examined first from the viewpoint of kinematics and then from the viewpoint of dynamics.

Chapter 5 covers various position-control algorithms that make the end effector of a manipulator follow a desired position trajectory. Chapter 6

discusses two typical force-control methods. These make the contact force between the end effector and its environment follow a desired force trajectory. Chapter 7 discusses, for manipulators with redundant degrees of freedom, a way to develop control algorithms for active utilization of the redundancy. The appendixes give compact reviews of the function atan2 , pseudo-inverses, singular-value decomposition, and Lyapunov stability theory.

When writing a textbook in a changing field like robotics in which many new achievements are being unveiled day by day, one usually has a difficult time deciding what to include. I have attempted to include as many important results as possible. At the same time, I have tried to present them plainly with the help of many illustrative examples.

It is my pleasure to thank several people who have contributed in various ways to the completion of this book. The content and the form of this book are much influenced by Richard P. Paul's pioneering book *Robot Manipulators* (MIT Press, 1981), which I translated into Japanese in 1984. I wish to thank Yoshihiko Nakamura and Toshiharu Sugie, with whom I have worked on research projects that some parts of this book are based on. Yasuyoshi Yokokohji read the manuscript and provided many useful comments. Discussions with Junichi Imura and Kiyoshi Maekawa proved valuable in the writing of the section on adaptive control (section 5.6). Mike Lipsett, who happened to be with me at Kyoto University at a critical stage in the writing of the English version, contributed many improvements. Takashi Hosoda, Jun Koreishi, Junichi Imura, and Osamu Suzuki helped me with revisions and corrections. Masako Awakura performed the magic of turning all my vague scribbling into a finely typed manuscript.

This book is mostly a translation of my Japanese book *Robotto Seigyo Kisoron (Foundations of Robot Control)*, published in Tokyo by Corona Publishing Co. Ltd. in 1988. I am grateful to Corona for its cooperation and support in publishing this English version. I also wish to thank Frank P. Satlow and Teresa Ehling of The MIT Press for patiently awaiting my manuscript. My wife, Sanae, supported and encouraged me at home during the writing of this book.