Introduction

The control and simulation of robots requires the development of different mathematical models. Several levels of modeling – geometric, kinematic and dynamic – are needed depending on the objectives, the constraints of the task and the desired performance.

Obtaining these models is not an easy task. The difficulty varies according to the complexity of the kinematics of the mechanical structure and its degrees of freedom. The mathematical tools presented in this book are based on a description of mechanisms allowing a unified approach whatever the type of structure: serial, tree structured, or containing closed loops.

Using these models in control and simulation requires efficient and easy-to-use algorithms to estimate the values of the geometric parameters and the dynamic parameters of the robot. Besides, the on-line implementation of a control law on a robot controller requires efficient models with a reduced number of operations. The techniques proposed in this book have been developed to meet these requirements.

This book is a revised and augmented edition of the French version "Modélisation, identification et commande des robots" published by Hermès in 1999, whose first edition "Modélisation et commande des robots" was published in 1988. We consider it to be the third edition as it contains substantial modification and updating. The content is the following:

- Chapter 1 gives an introduction to the terminology and general definitions for the concepts used in this book: kinematic chains, types of joints, configuration space, task space, redundancy, singular configurations, architectures of robot manipulators, robot characteristics;
- Chapter 2 sets out the basic mathematical tools used in robot modeling: homogeneous transformations, differential transformations, screws, twists and wrenches;
- Chapter 3 deals with the direct geometric modeling of simple open chain robots (also termed serial robots). The Khalil-Kleinfinger notation is used to describe the geometry of the mechanical structure. This notation, which is a variation of the Denavit-Hartenberg one, also handles the description of

complex chains with tree structures or closed loops (Chapters 7 and 10). The various methods of describing the orientation of a solid in space are covered at the end of the chapter;

- Chapter 4 treats the inverse geometric model. Three approaches are described: the Paul method, which can be used for most industrial robots, the Pieper method, which deals with six degree-of-freedom robots having three prismatic joints or a spherical joint, and the Raghavan-Roth method, which is suitable for six degree-of-freedom robots with general geometry;
- Chapter 5 addresses the direct kinematic model. After developing efficient methods for calculating the Jacobian matrix, we present several applications: analysis of the robot workspace, determination of the degrees of freedom of structure, velocity and force ellipsoids, twist-wrench duality;
- Chapter 6 covers inverse kinematics. The main topics are: inversion at regular configurations, inversion close to singularities, inversion for redundant robots, and minimal task description;
- Chapter 7 examines the geometric and kinematic models of complex chain robots with tree or closed chain structures. The problem of solving the constraint equations of closed loop robots is treated using both geometric constraint equations and kinematic constraint equations;
- Chapter 8 introduces the geometric and kinematic models of parallel robots. The main architectures and features of these structures are given;
- Chapters 9 and 10 deal with dynamic modeling: simple open chains are considered in Chapter 9, whereas complex kinematic chains are presented in Chapter 10. Lagrangian and Newton-Euler formulations, which are linear in the dynamic parameters, are presented. The determination of the minimum inertial parameters, also termed base inertial parameters, is carried out using a direct symbolic method and by a numerical method, which is based on a QR decomposition. The number of operations of the inverse dynamic model are minimized thanks to the use of the base parameters and customized symbolic programming techniques. The models obtained allow on-line implementation with today's personal computers. We also give different methods for the direct dynamic model computation, more especially a method avoiding the inversion of the inertia matrix;
- Chapters 11 and 12 are devoted to identification of the geometric and dynamic parameters respectively. In Chapter 11, we present various geometric calibration methods. Some of them need external sensors, the others being autonomous. The construction of the observation matrix and the solution of the calibration equation are detailed for all the methods. A short subsection introduces the active field of research into parallel robot calibration. In Chapter 12, which concerns the dynamic parameters, several identification

methods based on the dynamic model or energy model are introduced. All of them consist in solving a model that is linear in the dynamic parameters;

- Chapter 13 introduces the problem of trajectory generation. Beginning with point-to-point trajectories both in the joint space and in the task space, the chapter then examines the problem of adding intermediate points. At the end, the trajectory generation on a continuous path is briefly treated;
- Chapters 14 and 15 deal with motion control and force control. The motion control chapter specifically covers PID control, computed torque control, passive control and adaptive control while the force control chapter addresses passive control, impedance control, hybrid force-position control and hybrid external control.

At the end of the book the reader will find eleven appendices, which give either detailed computations of examples or introductions to relevant mathematical methods. An abundant bibliography of more than 400 references related to this fast-growing field of research is also included.

This book is intended for researchers, university lecturers, engineers and postgraduates in the fields of automatic control, robotics and mechanics. It provides the necessary tools to deal with the various problems that can be encountered in the design, the control synthesis and the exploitation of robot manipulators. It can also be recommended as a textbook for students. It constitutes a complete course of about 70 lecture hours on modeling, identification and control of robot manipulators for engineering schools or Master of Science classes. For an introduction course of about 25 hours, the content could be reduced to: geometric and kinematic models of serial structures, trajectory generation between two points, and PID control (Chapters 1, 2, 3, 4, 5 and 6; partially Chapters 13 and 14). For a course of about 50 lecture hours, one could treat further dynamic modeling, calibration of geometric parameters, identification of dynamic parameters, and trajectory generation as well as the methods of motion control (Chapters 9, 11, 12, 13 and 14).