Preface

This book presents a comprehensive approach to the modeling and control of an advanced manipulator, the MIT Serial Link Direct Drive Arm (DDArm). Theoretical insights into position and force control are developed, and are experimentally demonstrated on the DDArm. Self-calibration procedures for link kinematic parameters, link inertial parameters, and load inertial parameters are presented, and the subsequent models are applied to improve control. The integrated presentation on modeling and control can be read as a prescription for robotics.

Our work in this area began in 1982, when Haruhiko Asada joined the MIT Mechanical Engineering Department and embarked on his second generation of direct drive arm designs. The key difference from the first generation design, executed while he was at Carnegie-Mellon University, was the use of brushless rare-earth motors built by the now-defunct ISI Corporation. Asada's second design is well known and is based on a parallel-drive configuration. At the same time as Asada embarked on his second design, he agreed to build for us another direct drive arm based on the ISI motors, but in a true direct drive configuration with the motors mounted at the joints.

The difference in structure of the two manipulators has led to distinct approaches. For the parallel-link direct drive arm, Asada and Kamal Youcef-Toumi thoroughly explored dynamics simplification through geometry and mass balancing to achieve a decoupled and invariant inertia matrix. For the serial link direct drive arm, we have accepted the full nonlinear dynamics of the manipulator, and have accommodated our modeling, algorithms, and control to these dynamics. We believe we have been successful in our approach, even as Asada and Youcef-Toumi have been successful in theirs.

The MIT Artificial Intelligence Laboratory has a long history of building robot devices, including the Minsky/Bennett Arm, the Silver Arm, the MIT Vicarm (designed by Victor Scheinman and after which the

PUMA is modeled), the Purbrick Arm, and the Utah/MIT Dextrous Hand (with Steve Jacobsen and the University of Utah). Although commercial robots have also been acquired, we have built our own robots to pursue planning and control strategies not implementable on commercial robots.

The impetus for direct drive arm technology in general and for our direct drive arm in particular is the elimination of gears, and the concomitant problems of friction, backlash, gear eccentricity, and joint compliance. The consequences of gears include an inability to control joint torque accurately, to specify a good dynamic model of the robot, and to control endpoint force quickly and accurately. By eliminating gears, it is possible to build an advanced manipulator for research that approaches ideal characteristics of high speed, load, and positional accuracy, and of force controllability.

With our DDArm, we have been able to test and develop advanced control strategies not possible on most other manipulators. Although a great many papers have been written on the theory of robot control, there have been almost no experimental results to validate these theories. Therefore our experimental results on model building, position control, and force control should be of great interest to the robot control community. Although it was an extremely time consuming process, conducting real experiments was important not only in verifying our algorithms but also in discovering unforeseen problems and gaining further insights.

Our general approach of building accurate robot models and then applying the models for high performance control is introduced in Chapter 1. This chapter is also somewhat tutorial, and describes the basics of position and force control. Chapter 2 begins with a general discussion of manipulators and their suitability for research, and then describes the properties of our DDArm. In particular, the control of joint torque is described.

The next three chapters then discuss how accurate kinematic and dynamic models of the robot can be estimated automatically. Chapter 3 discusses how the kinematic parameters, including link lengths and joint offsets, can be automatically calibrated using a motion tracking system. Chapter 4 describes how the inertial parameters of a load that a robot picks up can be identified using a wrist force/torque sensor. Chapter 5 describes a dynamic estimation procedure to obtain the mass, center of mass, and the moments of inertia of the rigid body inertial model of the robot links, based on joint torque sensing.

The models obtained in the earlier chapters 2-5 of this book are applied in the later chapters 6-9 for position and force control. It is shown that accurate models are important for all of those different control contexts. Chapter 6 compares the computed torque controller and the feedforward controller, which employ a dynamic model of the robot, to independent-joint PD controllers. Chapter 7 introduces single trajectory learning for position control, where a dynamic model is used in the learning operator to tune the motor commands through repetition to achieve ultra-high trajectory accuracy.

Force control is the subject of chapters 8 and 9. Dynamic instability, caused by hard contact with the environment, is explained in Chapter 8, and a solution based on open-loop joint torque control is presented. Kinematic instability is discussed in Chapter 9, and represents a new finding for certain hybrid position/force controllers. Resolved acceleration force control, equivalent to impedance control and the operational space method, is implemented and compared to other hybrid position/force controllers that do not use a dynamic model.

Notation

Throughout the book, we have used the following notation for mathematical formulas:

matrices ($\mathbf{B}$): uppercase bold font
vectors ($\mathbf{b}$): lowercase or greek bold font
scalar (b): italic font.

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