CONTROL OF ROBOT MANIPULATORS

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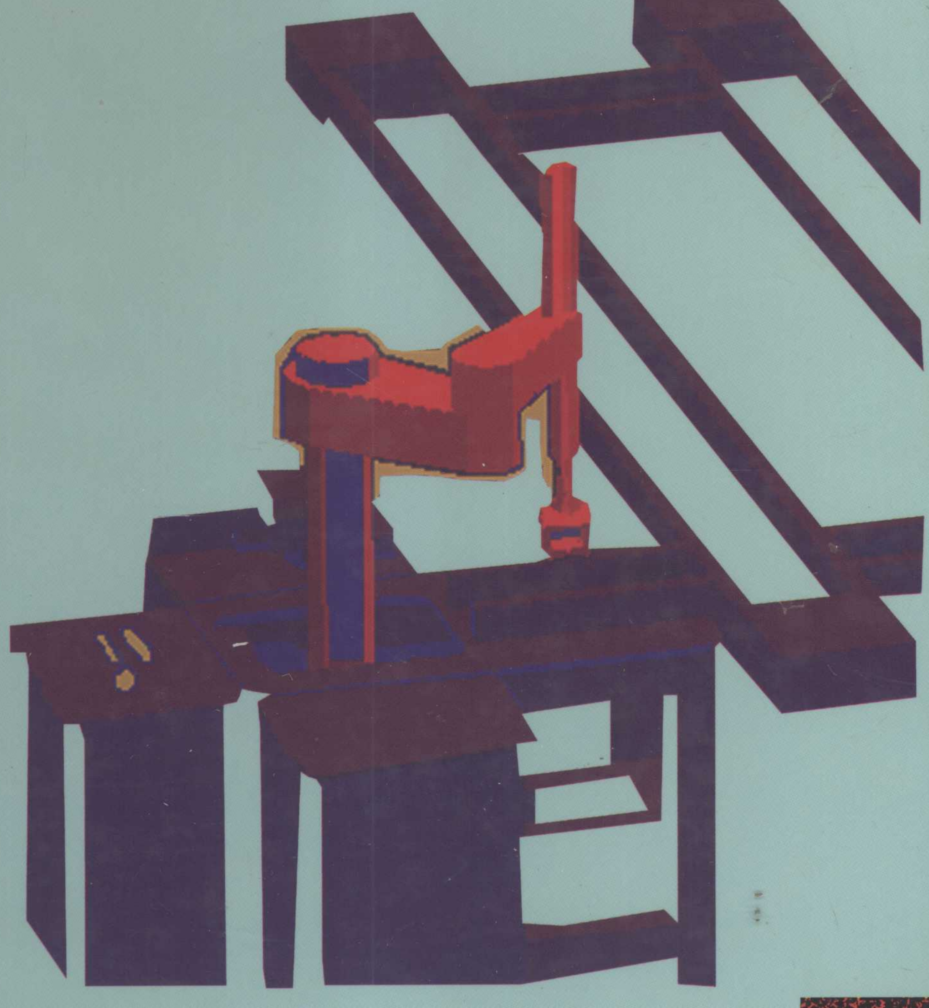

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MACMILLAN PUBLISHING COMPANY
New York

MAXWELL MACMILLAN CANADA
Toronto

MAXWELL MACMILLAN INTERNATIONAL
New York Oxford Singapore Sydney

Editor: John Griffin
Production Supervisor: John Travis
Production Manager: Roger Vergnes
Cover Designed by Mike Diver and Russ Maselli
Illustrations by Academy ArtWorks, Inc.

This book was set in Times Roman by Graphic Sciences Corporation, and printed and bound by Book Press. The cover was printed by Phoenix Color Corporation.

Printed in the United States of America

Macmillan Publishing Company
866 Third Avenue, New York, New York 10022

Macmillan Publishing Company is part of the Maxwell Communication Group of Companies.

Maxwell Macmillan Canada, Inc.
1200 Eglinton Avenue East
Suite 200
Don Mills, Ontario, M3C 3N1

Library of Congress Cataloging in Publication Data

Lewis, Frank L.
Control of robot manipulators / F.L. Lewis, C.T. Abdallah, D.M. Dawson.
p. cm.
Includes bibliographical references and index.
ISBN 0-02-370501-9
1. Robots—Control systems. 2. Manipulators (Mechanism)--Automatic control. I. Abdallah, Chaouki T. II. Dawson, D. M. III. Title.
TJ211.35.L48 1993 92-17922
629.8'92—dc20 CIP

Printing: 1 2 3 4 5 6 7 8 Year: 3 4 5 6 7 8 9 0 1 2

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To Christopher and Theresa
F. L. L.

To My Little Princess
C. T. A.

To My Wife Kim
D. M. D.

Preface

The word 'robot' was introduced by the Czech playwright Karel Čapek in his 1920 play *Rossum's Universal Robots.* The word 'robota' in Czech means simply 'work'. In spite of such practical beginnings, science fiction writers and early Hollywood movies have given us a romantic notion of robots. The anthropomorphic nature of these machines seems to have introduced into the notion of robot some element of man's search for his own identity.

The word 'automation' was introduced in the 1940's at the Ford Motor Company, a contraction for 'automatic motivation'. The single term 'automation' brings together two ideas: the notion of special purpose robotic machines designed to mechanically perform tasks, and the notion of an automatic control system to direct them.

The history of automatic control systems has deep roots. Most of the feedback controllers of the Greeks and Arabs regulated water clocks for the accurate telling of time; these were made obsolete by the invention of the mechanical clock in the fourteenth century. Automatic control systems only came into their own three hundred years later during the industrial revolution with the advent of *machines sophisticated enough* to require advanced controllers; we have in mind especially the windmill and the steam engine. On the other hand, though invented by others (e.g. T. Newcomen in 1712) the credit for the steam engine is usually assigned to James Watt, who in 1769 produced his engine which combined mechanical innovations with a control system that allowed automatic regulation. That is, machines are not useful unless suitably controlled.

Watt's centrifugal flyball governor in 1788 provided a constant speed controller, allowing efficient use of the steam engine in industry. The motion of the flyball governor is clearly visible even to the untrained eye, and its principle had an exotic flavor that seemed to many to embody the spirit of the new age. Consequently the governor quickly became a sensation throughout Europe.

Master-slave telerobotic mechanisms were used in the mid 1940's at Oak Ridge and Argonne National Laboratories for remote handling of radioactive material. The first commercially available robot was marketed in the late 1950's by Unimation (nearly coincidentally with Sputnik in 1957—thus the space age and the age of robots began simultaneously). Like the flyball governor, the motion of a robot manipulator is evident even for the untrained eye, so that the potential of robotic devices can capture the imagination. However, the high hopes of the 1960's for robotic automation in industry have generally failed to materialize. This is because robotics today is at the same stage as the steam engine was shortly after the work of Newcomen in 1712.

Robotics is an interdisciplinary field involving diverse disciplines such as physics, mechanical design, statics and dynamics, electronics, control theory, sensors, vision, signal processing, computer programming, artificial intelligence (AI), and manufacturing. Various specialists study various limited aspects of robotics, but few engineers are able to confront all these areas simultaneously. This further contributes to the romanticized nature of robotics, for the control theorist, for instance, has a quixotic and fanciful notion of AI.

We might break robotics into five major areas: motion control, sensors and vision, planning and coordination, AI and decision-making, and man–machine interface. Without a good control system, a robotic device is useless. The robot arm plus its control system can be encapsulated as a generalized data abstraction; that is, robot-plus-controller is considered a single entity, or 'agent', for interaction with the external world.

The capabilities of the robotic agent are determined by the mechanical precision of motion and force exertion capabilities, the number of degrees of freedom of the arm, the degree of manipulability of the gripper, the sensors, and the sophistication and reliability of the controller. The inputs for a robot arm are simply motor currents and voltages, or hydraulic or pneumatic pressures; however, the inputs for the robot-plus-controller agent can be desired trajectories of motion, or desired exerted forces. Thus, the control system lifts the robot up a level in a hierarchy of abstraction.

This book is intended to provide an in-depth study of control systems for serial-link robot arms. Appendix A provides a background in robot kinematics and Jacobians, Chapter 1 a background in control theory and mathematical notions. Thus, the book is suitable either for the controls engineer or the roboticist. The intent was to furnish a text for a second course in robotics at the graduate level. But given the background material it has been used as a first year graduate course for electrical engineering students.

Chapter 2 introduces the robot dynamical equations needed as the basis for controls design. In Appendix C and examples throughout the book are given the dynamics of some common arms. Chapter 3 covers the essential topic of computed-torque control, which gives important insight while also bringing together several sorts of classical and modern robot control schemes.

Robust and adaptive control are covered in Chapters 4 and 5 in a parallel fashion to bring out the similarities and the differences of these two approaches to control in the face of uncertainties and disturbances. Chapter 6 addresses some advanced techniques, including learning control and arms with flexible joint coupling. Finally, a robot is only useful if it comes in contact with its environment, so force control issues are treated in Chapter 7.

A key to the verification of successful controller design is computer simulation. Therefore, we address computer simulation of controlled nonlinear systems and illustrate the procedure in examples throughout the text. Simulation software is given in Appendix B. Having designed a robot control system it is necessary to implement it; given today's microprocessors and digital signal processors, it is a short step from computer simulation to implementation, since the controller subroutines needed for simulation, and contained in the book, are virtually identical to those needed in a microprocessor for implementation on an actual arm. That is, this book takes one from analysis through controller design and, through computer simulation, virtually to the point of actual implementation.

All essential information and controls design algorithms are displayed in tables in the book. This, along with the List of Examples and List of Tables at the beginning of the book, make for convenient reference by the student, the academician, or the practicing engineer.

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CHAPTER 1

Introduction to Control Theory

In this chapter we review the concepts of control theory that are important in robotics. We review the state-space formulation for linear and nonlinear systems and present the stability concepts needed in the sequel. The chapter is intended to introduce modern control concepts, but readers with a background in control theory may wish to consult it for notation and convenience.

1.1 Introduction

The control of robotic manipulators is a mature yet fruitful area for research, development, and manufacturing. Industrial robots are basically positioning and handling devices. Therefore, a useful robot is one that is able to control its movement and the forces it applies to its environment. This book is concerned with the control aspect of robotic manipulators. To control requires the knowledge of a mathematical model and of some sort of intelligence to act on the model. The mathematical model of a robot is obtained from the basic physical laws governing its movement. Intelligence, on the other hand, requires sensory capabilities and means for acting and reacting to the sensed variables. These actions and reactions of the robot are the result of controller design.

In this chapter we review the concepts of control theory that are needed in this book. All proofs are omitted, but references are made to more specialized books where proofs are provided. Once a satisfactory model of the robot dynamics is obtained as described in Chapter 2, automatic control theory as presented in this chapter may be used to modify the actions and reactions of the robot to different stimuli. Subsequent chapters will therefore deal with the application of control principles to the robot equations. The particular controller used will depend on the complexity of the mathematical model, the application at hand, the available resources, and a host of other criteria.

We begin the chapter with a review of the state-space description for linear, continuous, and discrete-time systems. A similar review of nonlinear systems is presented in Section 1.3. Stability theory is presented in Section 1.4, which constitutes the bulk of the chapter. In Section 1.5, advanced stability concepts are compiled to make later developments more concise. Finally, in Section 1.6 we review the basic linear controller designs from a state-space point of view, and the chapter is concluded in Section 1.7.