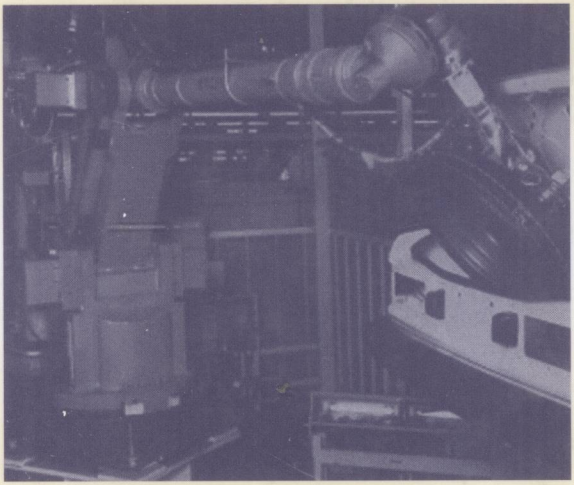
Control Engineering Series

Robot Manipulator Control

Theory and Practice

Second Edition, Revised and Expanded



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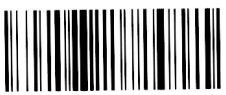

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Robot Manipulator Control

Theory and Practice

Second Edition, Revised and Expanded

CONTROL ENGINEERING

A Series of Reference Books and Textbooks

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Series Introduction

Many textbooks have been written on control engineering, describing new techniques for controlling systems, or new and better ways of mathematically formulating existing methods to solve the ever-increasing complex problems faced by practicing engineers. However, few of these books fully address the applications aspects of control engineering. It is the intention of this new series to redress this situation.

The series will stress applications issues, and not just the mathematics of control engineering. It will provide texts that present not only both new and well-established techniques, but also detailed examples of the application of these methods to the solution of real-world problems. The authors will be drawn from both the academic world and the relevant applications sectors.

There are already many exciting examples of the application of control techniques in the established fields of electrical, mechanical (including aerospace), and chemical engineering. We have only to look around in today's highly automated society to see the use of advanced robotics techniques in the manufacturing industries; the use of automated control and navigation systems in air and surface transport systems; the increasing use of intelligent control systems in the many artifacts available to the domestic consumer market; and the reliable supply of water, gas, and electrical power to the domestic consumer and to industry. However, there are currently many challenging problems that could benefit from wider exposure to the applicability of control methodologies, and the systematic systems-oriented basis inherent in the application of control techniques.

This series presents books that draw on expertise from both the academic world and the applications domains, and will be useful not only as academically recommended course texts but also as handbooks for practitioners in many applications domains. *Nonlinear Control Systems* is another outstanding entry in Dekker's Control Engineering series.

Preface

The word 'robot' was introduced by the Czech playwright Karel Capek 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 Switzerland 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, modern complex machines are not useful unless equipped with a suitable control system.

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 autonomous robotic automation in industry and unstructured environments 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. It is a revised and expended version of our 1993 book. Chapters have been added on commercial robot manipulators and devices, neural network intelligent control, and implementation of advanced controllers on actual robotic systems. Chapter 1 places this book in the context of existing commercial robotic systems by describing the robots that are available and their limitations and capabilities, sensors, and controllers.

We wanted this book to be suitable either for the controls engineer or the roboticist. Therefore, Appendix A provides a background in robot kine-

matics and Jacobians, and Chapter 2 a background in control theory and mathematical notions. The intent was to furnish a text for a second course in robotics at the graduate level, but given the background material it is used at UTA as a first year graduate course for electrical engineering students. This course was also listed as part of the undergraduate curriculum, and the undergraduate students quickly digested the material.

Chapter 3 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 4 covers the essential topic of computed-torque control, which gives important insight while also bringing together in a unified framework several sorts of classical and modern robot control schemes.

Robust and adaptive control are covered in Chapters 5 and 6 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 7 addresses some advanced techniques including learning control and arms with flexible joint coupling.

Modern intelligent control techniques based on biological systems have solved many problems in the control of complex systems, including unknown non-parametrizable dynamics and unknown disturbances, backlash, friction, and deadzone. Therefore, we have added a chapter on neural network control systems as Chapter 8. A robot is only useful if it comes in contact with its environment, so that force control issues are treated in Chapter 9.

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. Commercially available packages such as MATLAB make it very easy to simulate robot control systems.

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. In fact, Chapter 10 shows the techniques for implementing the advanced controllers developed in this book on actual robotics systems.

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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