
Robot Manipulator Control

Theory and Practice

Second Edition, Revised and Expanded

CONTROL ENGINEERING

A Series of Reference Books and Textbooks

Editors

NEIL MUNRO, PH.D., D.SC.

Professor

Applied Control Engineering

University of Manchester Institute of Science and Technology

Manchester, United Kingdom

FRANK L.LEWIS, PH.D.

Moncrief-O'Donnell Endowed Chair

and Associate Director of Research

Automation & Robotics Research Institute

University of Texas, Arlington

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Frank L. Lewis

*University of Texas at Arlington
Arlington, Texas, U.S.A.*

Darren M. Dawson

*Clemson University
Clemson, South Carolina, U.S.A.*

Chaouki T. Abdallah

*University of New Mexico
Albuquerque, New Mexico, U.S.A.*



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The publisher has gone to great lengths to ensure the quality of this reprint but points out that some imperfections in the original may be apparent

To My Sons Christopher and Roman
F.L.L.

To My Faithful Wife, Dr. Kim Dawson
D.M.D.

To My 3 C's
C.T.A.

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 fly ball 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 expanded 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 kinematics 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.

We thank Wei Cheng of Milagro Design for her L^AT_EXtypesetting and

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F.L.Lewis, Arlington, Texas

D.M.Dawson, Clemson, South Carolina

C.T.Abdallah, Albuquerque, New Mexico

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Chapter 1

Commercial Robot Manipulators

This chapter sets the stage for this book by providing an overview of commercially available robotic manipulators, sensors, and controllers. We make the point that if one desires high performance flexible robotic workcells, then it is necessary to design advanced control systems for robot manipulators such as are found in this book.

1.1 Introduction

When studying advanced techniques for robot control, planning, sensors, and human interfacing, it is important to be aware of the systems that are commercially available. This allows one to develop new technology in the context of existing technology, which allows one to implement the new techniques on existing robotic systems.

A National Association of Manufacturer's report [NAM 1998] states that the two most important drivers for US commercial business manufacturing success in the 1990's have been reconfigurable manufacturing workcells and local area networks in the factory. In this chapter we discuss flexible robotic workcells, commercial robot configurations, commercial robot controllers, information integration to the internet, and robot workcell sensors. More information on these topics can be found in the Mechanical Engineering Handbook [Lewis 1998] and the Computer Science Engineering Handbook [Lewis and Fitzgerald 1997].

Flexible Robotic Workcells

In factory automation and elsewhere it was once common to use fixed layouts built around conveyors or other transportation systems in which each robot performed a specific task. These assembly lines had distinct workstations, each performing a dedicated function. Robots have been used at the workstation level to perform operations such as assembly, drilling, surface finishing, welding, palletizing, and so on. In the assembly line, parts are routed sequentially to the workstations by the transport system. Such systems are very expensive to install, require a cadre of engineering experts to design and program, and are extremely difficult to modify or reprogram as needs change. In today's high-mix low-volume (HMLV) manufacturing scenario, these characteristics tolled the death knell for such rigid antiquated designs.

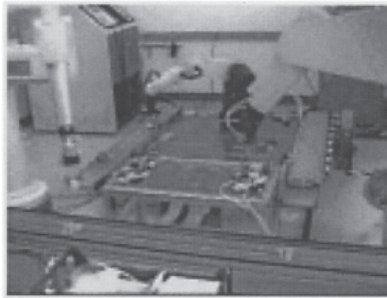


Figure 1.1.1: UTA's Automation and Robotics Test Cell.

In the assembly line, the robot is restricted by placing it into a rigid sequential system. Robots are versatile machines with many capabilities, and their potential can be significantly increased by using them as a basis for *flexible robotic workcells* [Decelle 1988], [Jamshidi et al. 1992], [Pugh 1983] such as the UTA Automation and Robotics Test Cell in Figure 1.1.1. In the flexible robotic workcell, robots are used for part handling, assembly, and other process operations. By reprogramming the robots one changes the entire functionality of the workcell. The workcell is designed to make full use of the workspace of the robots, and components such as milling machines, drilling machines, vibratory part feeders, and so on are placed within the robots' workspaces to allow servicing by the robots. Contrary to the assembly line, the physical layout does not impose a priori a fixed sequencing of the operations or jobs. Thus, as product requirements change, all that is required is to reprogram the workcell in software [Mireles and Lewis 2001]. The

workcell is ideally suited to emerging HMLV conditions in manufacturing and elsewhere.

The rising popularity of robotic workcells has taken emphasis away from hardware design and placed new emphasis on innovative software techniques and architectures that include planning, coordination, and control (PC&C) functions. A great deal of research into robot controllers has been required to give robots the flexibility, precision, and functionality needed in modern flexible workcells. The remainder of this book details such advanced control techniques.

1.2 Commercial Robot Configurations and Types

Much of the information in this section was prepared by Mick Fitzgerald, who was then Manager at UTA's Automation and Robotics Research Institute (ARRI).

Robots are highly reliable, dependable and technologically advanced factory equipment. The majority of the world's robots are supplied by established companies using reliable off-the-shelf component technologies. All commercial industrial robots have two physically separate basic elements—the manipulator arm and the controller. The basic architecture of most commercial robots is fundamentally the same, and consists of digital servocontrolled electrical motor drives on serial-link kinematic machines, usually with no more than six axes (degrees of freedom). All are supplied with a proprietary controller. Virtually all robot applications require significant design and implementation effort by engineers and technicians. What makes each robot unique is how the components are put together to achieve performance that yields a competitive product. The most important considerations in the application of an industrial robot center on two issues: manipulation and integration.

Manipulator Performance

The combined effects of kinematic structure, axis drive mechanism design, and real-time motion control determine the major manipulation performance characteristics: reach and dexterity, pay load, quickness, and precision. Caution must be used when making decisions and comparisons based on manufacturers' published performance specifications because the methods for measuring and reporting them are not standardized across the industry. Usually motion testing, simulations, or other analysis techniques are used to verify performance for each application.

Reach is characterized by measuring the extent of the *workspace* described by the robot motion and *dexterity* by the angular displacement of the

individual joints. Some robots will have unusable spaces such as dead zones, singular poses, and wrist-wrap poses inside of the boundaries of their reach.

Payload weight is specified by the manufacturers of all industrial robots. Some manufacturers also specify inertial loading for rotational wrist axes. It is common for the payload to be given for extreme velocity and reach conditions. Weight and inertia of all tooling, workpieces, cables and hoses must be included as part of the payload.

Quickness is critical in determining throughput but difficult to determine from published robot specifications. Most manufacturers will specify a maximum speed of either individual joints or for a specific kinematic tool point. However, *average speed* in a working cycle is the quickness characteristic of interest.

Precision is usually characterized by measuring *repeatability*. Virtually all robot manufacturers specify static position repeatability. *Accuracy* is rarely specified, but it is likely to be at least four times larger than repeatability. Dynamic precision, or the repeatability and accuracy in tracking position, velocity, and acceleration over a continuous path, is not usually specified.

Common Kinematic Configurations

All common commercial industrial robots are serial-link manipulators, usually with no more than six kinematically coupled axes of motion. By convention, the axes of motion are numbered in sequence as they are encountered from the base on out to the wrist. The first three axes account for the spatial positioning motion of the robot; their configuration determines the shape of the space through which the robot can be positioned. Any subsequent axes in the kinematic chain generally provide rotational motions to orient the end of the robot arm and are referred to as wrist axes. In a robotic wrist, three axes usually intersect to generate true independent positioning in terms of 3-D orientation. See [Appendix A](#) for a kinematic analysis of the spherical robot wrist mechanism. Note that in our 3-dimensional space, one requires three degrees of freedom for fully independent spatial positioning and three degrees of freedom for fully independent orientational positioning.

There are two primary types of motion that a robot axis can produce in its driven link- either *revolute* or *prismatic*. Revolute joints are anthropomorphic (e.g. like human joints) while prismatic joints are able to extend and retract like a car radio antenna. It is often useful to classify robots according to the orientation and type of their first three axes. There are four very common commercial robot configurations: Articulated, Type I SCARA, Type II SCARA, and Cartesian. Two other configurations, Cylindrical and Spherical, are now much less common.

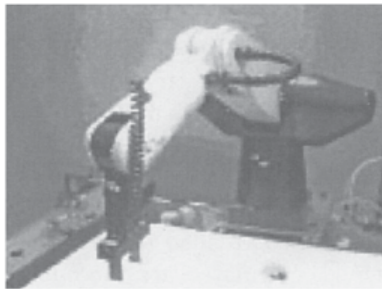


Figure 1.2.1: Articulated Arm. Six-axis CRS A465 arm (courtesy of CRS robotics).



Figure 1.2.2: Type I SCARA Arm. High precision, high speed midsize SCARA I. (courtesy of Adept Technologies, Inc.).

[Appendix C](#) contains the dynamics of some common robot manipulators for use in controls simulation in this book.

Articulated Arms. The variety of commercial articulated arms, most of which have six axes, is very large (Fig. 1.2.1). All of these robots' axes are revolute. The second and third axes are co-planar and work together to produce motion in a vertical plane. The first axis in the base is vertical and revolves the arm to sweep out a large work volume. Many different types of drive mechanisms have been devised to allow wrist and forearm drive motors and gearboxes to be mounted close to the first and second axis of rotation, thus minimizing the extended mass of the arm. The workspace efficiency of well designed articulated arms, which is the degree of quick dexterous reach with respect to arm size, is unsurpassed by other arm configurations when five or more degrees of freedom are needed. A major limiting factor in articulated arm performance is that the second axis has to work to lift both the subsequent arm structure and the payload. Historically, articulated arms have not been capable of achieving accuracy as high as other arm configurations, as all axes have joint angle position errors which are multiplied by link radius and accumulated for the entire arm.

Type I SCARA. The Type I SCARA (selectively compliant assembly robot arm) arm, Figure 1.2.2, uses two parallel revolute joints to produce motion in the horizontal plane. The arm structure is weight-bearing but the first and second axes do no lifting. The third axis of the Type I SCARA provides work volume by adding a vertical or z axis. A fourth revolute axis will add rotation about the z axis to control orientation in the horizontal plane. This type of robot is rarely found with more than four axes. The Type I SCARA is used extensively in the assembly of electronic components and devices, and it is used broadly for the assembly of small- and medium-sized mechanical assemblies.

Type II SCARA. The Type II SCARA, Figure 1.2.3, also a four axis configuration, differs from Type I in that the first axis is a long vertical prismatic z stroke which lifts the two parallel revolute axis and their links. For quickly moving heavier loads (over approximately 75 pounds) over longer distance (more than about three feet), the Type II SCARA configuration is more efficient than the Type I.

Cartesian Coordinate Robots. Cartesian coordinate robots use orthogonal prismatic axes, usually referred to as x , y , and z , to translate their end-effector or payload through their rectangular workspace. One, two, or three revolute wrist axes may be added for orientation. Commercial robot companies supply several types of Cartesian coordinate robots with workspace sizes ranging from a few cubic inches to tens of thousands of cubic feet, and payloads ranging to several hundred pounds. Gantry robots, which have an elevated bridge structure, are the most common Cartesian style and are well suited to

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