Chapter 1

Introduction

Robot manipulators have been widely used in the industrial applications in the past decades. Most of these applications are restricted to slow-motion operations without interactions with the environment. This is mainly due to limited performance of the available controllers in the market that are based on simplified system models. To increase the operation speed with more servo accuracy, advanced control strategies are needed. Consideration of the actuator dynamics in the controller design is one of the possible ways to improve system performance. Although some of the industrial robots are driven by hydraulic or pneumatic actuators, most of them are still activated by motors. Therefore, similar to majority of the related literature, we are only going to consider electrically driven (ED) robot manipulators in this book. On the other hand, explicit inclusion of the joint flexibility into the system dynamics can also improve the control performance. Since the robot dynamics is highly nonlinear, consideration of these effects will largely increase the difficulty in the controller design. Besides, the robot model inevitably contains uncertainties and disturbances; this makes the control problem extremely difficult.

In this book, we would like to consider the control problem of robot manipulators with consideration of actuator dynamics, joint flexibility and various system uncertainties. These uncertainties are assumed to be time-varying but their variation bounds are not available. Due to their time-varying nature, most traditional adaptive designs are not feasible. Because their variation bounds are not known, most conventional robust schemes are not applicable. The main strategy we employed in this book to deal with the uncertainties is based on the function approximation techniques (FAT). The basic idea of FAT is to represent the uncertain term as a finite combination of known basis functions so that proper update laws can be derived based on the Lyapunov-like design to give good performance. Since the FAT-based adaptive design does not need to represent the system dynamics into a regressor form, it is free from computation of the regressor matrix. Derivation of the regressor matrix is well-known to be very tedious for a robot manipulator with more than four joints. The regressor-free strategy greatly simplified the controller design process. Because, for the traditional robot adaptive control, the complex regressor matrix has to be updated in every control cycle in the real-time implementation, the regressor-free algorithm also effectively simplified the programming complexity.

When the robot end-effector contacts with the environment, the controllers designed for performing the free space tracking tasks cannot provide appropriate control performance. In this book, the renowned impedance control strategy will be incorporated into the FAT-based design so that some regressor-free adaptive controllers with consideration of the actuator dynamics for the robot manipulators can be obtained.

To have a better understanding of the problems we are going to deal with, Table 1.1 presents the systems considered in this book. The abbreviations listed will be used throughout this book to simplify the presentation.

Table 1.1 Systems considered in this book

	Systems	Abbreviation
1	Rigid robot in the free space	RR
2	Rigid robot interacting with the environment	RRE
3	Electrically-driven rigid robot in the free space	EDRR
4	Electrically-driven rigid robot interacting with the environment	EDRRE
5	Flexible-joint robot in the free space	FJR
6	Flexible-joint robot interacting with the environment	FJRE
7	Electrically-driven flexible-joint robot in the free space	EDFJR
8	Electrically-driven flexible-joint robot interacting with environment	EDFJRE

Free space tracking of a rigid robot

It can be seen that systems from 1 to 7 are all special cases of 8. However, it is not appropriate to derive a controller for the system in 8 directly, because starting from the simple ones can give us more insight into the unified approach to be introduced. Let us consider the tracking problem of a rigid robot in the free space first. It is the simplest case in this book and several control strategies can also be found in robotics textbooks under various conditions. We will start with the case when all system parameters are precisely known, and a feedback linearization based controller is constructed to give proper performance. Afterwards, we assume that most parameters in the robot model are not known but a regressor can be derived such that all uncertain parameters are collected into an unknown vector. Conventional adaptive strategies can thus be applied to give update laws to this unknown parameter vector, and closed loop stability can also be proved easily. However, implementation of this scheme requires the information of joint accelerations which is impractical in most industrial applications. What is worse is that the estimation in the inertia matrix might suffer the singularity problem. A well-known design proposed by Slotine and Li is then reviewed to get rid of the need for joint acceleration feedback and avoid the singularity problem. In the above designs, the robot dynamics should be linearly parameterized into a known regressor matrix multiplied by an unknown parameter vector. The regressor matrix is known to be tedious in its derivation for a robot with degree of freedom more than 4. The regressor matrix is not unique for a given robot, but depending on the selection of the parameter vector. The entries of this vector should be constants that are combinations of unknown system parameters. However, these parameters are mostly easier to be found than the derivation of the regressor matrix. For example, the weight, length, moment of inertia and gravity center of a link are frequently seen in the parameter vector and their values are very easy to measure in practice. It is not reasonable to construct a controller whose design needs to know an extremely complex regressor matrix but to update an easy-to-obtain parameter vector. Motivated by this reasoning, the regressor-free adaptive control approach is developed. The uncertain matrices and vectors in the robot model will be represented as finite combinations of basis functions. Update laws for the weighting matrices can be obtained by the Lyapunov-like design. The effect of the approximation error is investigated with rigorous mathematical justifications. The output error can thus be proved to be uniformly ultimately bounded. Finally, the trajectory of the output error is bounded by a weighted exponential function plus some constant. With proper adjustment of controller parameters, both the transient performance and the steady state error can be modified.

Compliant motion control of a rigid robot

Item 2, 4, 6 and 8 in Table 1.1 relate to the compliant motion control of robot manipulators whose dynamic model include the effect of the external force vector exerted by the environment. Many control strategies are available for rigid robots to give closed loop stability in the compliant motion applications. Among them, the impedance control employed in this book is the most widely used one which is a unified approach for controlling robot manipulators in both free space tracking and compliant motion phases. The impedance controller makes the robot system behave like a target impedance in the Cartesian space, and the target impedance is specified as a mass-spring-damper system. For rigid robots, we start with the case when the robot system and the environment are known and the impedance controller is designed. The regressor-based adaptive impedance controller is then derived for robot systems containing uncertainties. To avoid derivation of the regressor matrix, the regressor-free adaptive impedance controller using function approximation techniques is introduced. For the impedance controller of EDRRE, FJRE and EDFJRE, much more complex derivations will be involved due to the complexity in the system model. Unlike the rigid robots, the regressor-based designs of these robots need additional information such as the derivative of the regressor matrix, the joint accelerations and derivative of the external force. All of these are not generally available, and hence regressor-free designs are introduced to get rid of their necessity. The unified approach in the FAT-based regressor-free adaptive impedance controller designs for RRE, EDRRE, FJRE and EDFJRE can all give uniformly ultimately bounded performance to the output error and the transient performance can also be evaluated by using the bound for the output error signal.

Consideration of the actuator dynamics

The control problem of rigid robot manipulators has been well developed under the assumption that all actuator dynamics are neglected. However, it had been reported that the robot control problem should carefully consider the actuator dynamics to have good tracking performance, especially in the cases of high-velocity movement and highly varying loads. Therefore, in item 3, 4, 7 and 8 of Table 1.1, we include considerations of actuator dynamics in the system equations to investigate their effects in performance improvement. The input vector to a robot without consideration of the actuator dynamics contains torques to the joints, while the input vector to electrically-driven robots is with signals in voltages. This special cascade structure connecting the actuator and the robot dynamics enables us to employ backstepping-like designs to eliminate uncertainties entering the system in a mismatched fashion. The regressor-based adaptive designs are introduced first for items 3, 4, 7 and 8 followed by their regressor-free counterparts. Implementations of most regressor-based methods introduced here need the information of the derivative of the regressor matrix and joint accelerations, but the regressor-free designs do not. Besides, the uniformly ultimately bounded performance can be proved to be maintained when considering the actuator dynamics by using the regressor-free approach. Simulation cases for justifying performance improvements are designed with high speed tracking problems. All of these regressor-free schemes give good performance regardless of various system uncertainties.

Consideration of the joint flexibility

Many industrial robots use harmonic drives to reduce speed and amplify output torque. A cup-shape component in the harmonic drive provides elastic deformation to enable large speed reduction. Therefore, it is known that harmonic drives introduce significant torsional flexibility into the robot joints. To have a high performance robot control system, elastic coupling between actuators and links cannot be neglected. Modeling of these effects, however, produces an enormously complicated model. For simplicity, most researches regard the flexibility as an effect of the linear torsional spring connecting the shaft of the motor and the end about which the link is rotating. Two second-order differential equations should be used to describe the dynamic of a flexible joint: one for the motor shaft and one for the link. This implies that the number of degree-of-freedom is twice the number for a rigid robot, since the motion of the motor shaft is no longer simply related to the link angle by the gear ratio. The high system order and highly nonlinear coupling in the dynamics equation result in difficulties in the controller design. If the system model contains inaccuracies and uncertainties, the controller design problem becomes extremely difficult. In this book, we are going to design conventional regressor-based adaptive controllers for this system first and followed by a regressor-free control strategy. In addition, adaptive controllers for impedance control of flexible joint robot will also be derived. Furthermore, the actuator dynamics are to be considered so that in the most complex case a regressor-free adaptive impedance controller will be designed for an EDFJRE. When considering the joint flexibility, the realization of the regressor-based adaptive controller requires the knowledge of joint accelerations, the regressor matrix, and their derivatives. The regressor-free designs, however, do not need these additional information.

The regressor-free adaptive controller design

Calculation of the regressor matrix is a must in the traditional adaptive control of robot manipulators which is because the update laws are able to be designed only when the parameter vectors are unknown constants. Parameterization of the uncertainties into multiplications of the regressor matrix with the unknown parameter vector need to be done based on the system model. With proper definitions of the entries in the parameter vector, the regressor matrix can then be determined. Since these definitions are not unique, the regressor matrix for a given robot is not unique either. Some definitions will give relatively simple forms for the regressor matrix, while some will become very complex. When the degree of freedom of the robot is more than four, the derivation of the regressor matrix becomes very tedious. In general, the entries in the parameter vector are combinations of the quantities such as the link masses, dimensions of the links, and moments of inertia. These quantities are relatively easier to measure compared with the derivation of the regressor matrix. However, the traditional adaptive designs are only capable of updating these easy-to-measure parameters, but require the complex regressor matrix to be known. In addition, in every control cycle of the real-time implementation, the calculation of the regressor matrix is also time consuming which largely limits the computation hardware selections, especially in the embedded applications. In this book, a unified approach for the design of regressor-free adaptive controllers for robot manipulators is introduced which is feasible for robots with considerations of the actuator dynamics, joint flexibilities as well as the interaction with the environment. All of these designs will end up with the uniformly ultimately bounded closed loop performance via the proofs using the Lyapunov-like techniques.

The FAT-based design

Two main approaches are available for dealing with uncertainties in control systems. The robust strategies need to know the worst case of the system so that a fixed controller is able to be constructed to cover the uncertainties. In most cases, the worst case of the system is evaluated by proper modeling of the uncertainties either in the time domain or frequency domain. The variation bounds estimated from the uncertainty model are then used to design the robust terms in the controller. In some practical cases, however, these variation bounds are not available, and hence most robust strategies are infeasible. The other approach for dealing with system uncertainties is the adaptive method. Although intuitively we think that an adaptive controller should be able to give good performance to a system with time-varying uncertainties, conventional adaptive designs can actually be useful to systems with constant uncertainties. Therefore, to be feasible for the adaptive designs all time-varying parts in the system dynamics should be collected into a known regressor matrix, while the unknown constant parameters are put into a parameter vector. This process is called the linear parameterization of the uncertainties which is almost a must for adaptive designs. After the parameterization, proper update laws can then be derived to provide sufficient information to the certainty equivalence based adaptive controller such that the closed loop system can give good performance. However, there are some practical cases whose uncertainties are not able to be linearly parameterized (e.g., various friction effects), and some others are linearly parameterizable but the regressor matrices are too complex to derive (e.g., robot manipulators).

Now let us consider a case when the uncertainties are time-varying and their variation bounds are not available. Since they are time-varying, most traditional robust designs fail. Because their variation bounds are unknown, most conventional adaptive strategies are infeasible. In this book, we are going to call this kind of uncertainties the *general uncertainties*. For a system with general uncertainties, few control schemes are available to stabilize the closed loop system. Because the regressor-free adaptive controller design for robot manipulators should avoid the use of the regressor matrix, a new representation for the system uncertainties is needed. In this case, it is more practical to regard the uncertainties in the robot model to be general uncertainties, and the controller design problem is a challenge. Here, in this book, we employ the function approximation technique to represent the uncertainties into finite combinations of basis functions. This effectively transforms a general uncertainty into a known basis vector multiplied by a vector of unknown coefficients. Since these coefficients are constants, update laws can be derived by using the Lyapunov-like methods. Due to the fact that the mathematical background for the function approximation has well been established and the controller design portion follows the traditional adaptive strategies, the FAT-based adaptive method provides an effective tool in dealing with controller design problems involving the general uncertainties.

Organization of the book

Robot systems considered in this book are all listed in Tables 1.1 according to the complexity in their dynamics. For better presentation, however, they will be arranged into the chapters different from the order as shown in the table. In Chapter 2, the backgrounds for mathematics and control theories useful in this book are reviewed. Readers familiar to these fundamentals are suggested to go directly to the next chapter. Various concepts from the linear algebra and real analysis are briefly presented in this chapter. Some emphasis will be placed on the spaces where the function approximation techniques are valid. Various orthonormal functions are also listed with their effective ranges for the convenience in the selection of basis functions for the FAT-based designs. Then the Lyapunov stability theory and the Lyapunov-like methods are reviewed in detail followed by the introduction of the control theories such as the sliding control and model reference adaptive control. After these conventional robust and adaptive designs, the concept of general uncertainties is presented. Limitations in the sliding controller designs when the variation bounds for the uncertainties are not available are investigated. Likewise, the problem for the model reference adaptive control when the system contains time-varying parameters is illustrated. Finally, the FAT-based adaptive controller is designed for these systems with general uncertainties in detail.

Chapter 3 collects all dynamic equations for systems listed in Table 1.1. These equations will be used in later chapters for controller designs. Examples for these systems will also be presented, and they will also be used in the simulation studies later. Adaptive control strategies for the rigid robots are introduced in Chapter 4. Traditional regressor-based adaptive rules will be derived first followed by some investigation into the detail of the regressor matrix and the parameter vector. This justifies the necessity for the regressor-free adaptive designs. A FAT-based regressor-free adaptive controller is then derived for the rigid robot with consideration of the approximation errors. The rigorous proof for the closed loop stability is presented to give uniformly ultimately bounded performance. Next, the actuator dynamics is included into the system model and adaptive controllers are derived using regressor-based designs and regressor-free designs. Significant amount of simulation results are provided to justify the efficacy of the controllers when actuator dynamics are considered.

Chapter 5 considers the compliant motion control of rigid robot manipulators. The impedance controller is employed to enable the robot to interact with the environment compliantly while maintaining good performance in the free space tracking. The traditional impedance controller is reviewed first for the system with known dynamics. A regressor-based and a regressor-free adaptive controller are then derived. Finally, the actuator dynamics is considered to improve the control performance.

Chapter 6 includes joint flexibility into consideration such that the order of the system model is doubled compared with its rigid joint counterpart. Control of a known FJR is firstly reviewed. The regressor-based adaptive controller is then introduced followed by the derivation of the regressor-free controller. The actuator dynamics will be considered in the last section of this chapter. A 5^{th}

order differential equation should be used to describe a single link in this case which makes the controller design problem become extremely challenging.

The last chapter deals with the problem of the adaptive impedance control for FJR. We review the control of a known robot first to have some basic understanding of this problem. The regressor-based adaptive controller is then designed, but it requires some impractical knowledge in the real-time implementation. The regressor-free adaptive controller is derived without any requirements on additional information. Consideration of the actuator dynamics further complicated the problem, and the regressor-free adaptive design is still able to give good performance to the closed loop system.