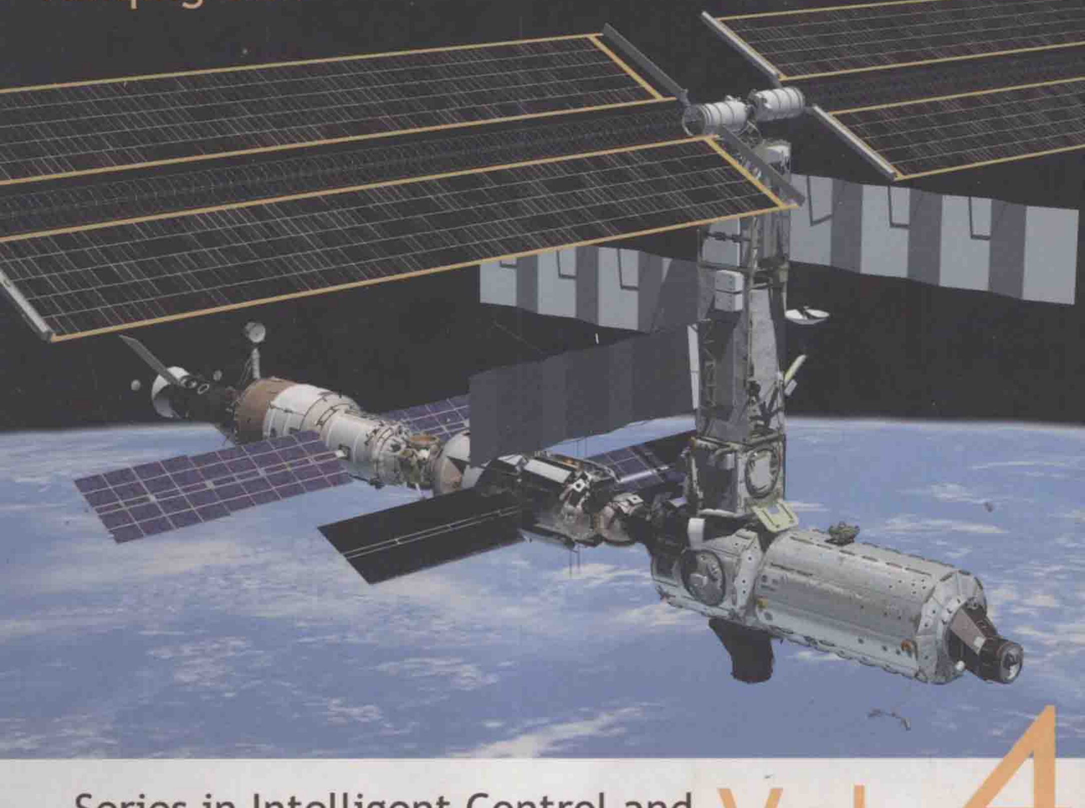
Advanced Studies of Flexible Robotic Manipulators

Modeling, Design, Control and Applications

Fei-Yue Wang
Yanqing Gao



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Preface

The research interest in flexible manipulators, i.e., lightweight and large dimension robotic manipulators, has increased significantly in recent years. Major advantages of flexible manipulators include, but not limited to, small mass, fast motion, and large force to mass ratio, which are reflected directly in the reduced energy consumption, increased productivity, and enhanced payload capacity. Flexible manipulators have important applications in space exploration, manufacturing automation, construction, mining, hazardous operations, and many other areas.

However, flexible robotic manipulators also impose various challenges in research in comparison to rigid robotic manipulators, ranging from system design, structural optimization, construction, to modeling, sensing, and control. Although significant progresses have been made in many aspects over the last one and half decades, many issues are not resolved yet, and simple, effective, and reliable controls of flexible manipulators still remain an open quest. Clearly, further efforts and results in this area would contribute significantly to robotics, and in particular, automation, as well as its application and education in general control engineering. To accelerate this process, this book presents the state of art of advanced studies in design, modeling, control and applications of flexible manipulators, from the leading experts in this important research area.

The book starts the modeling and control of flexible robotic manipulators, from chapters 1 to 7. It begins with Arteaga and Siciliano's chapter on modeling, nonlinear control and observer of flexible-link manipulators, where motion equations are derived with a combined Lagrange-assumed mode approach. The resulting model shows several similarities with that of a rigid manipulator, thus allowing important properties to be derived for designing controllers and observers. A nonlinear control scheme based on robust control techniques is proposed in order to improve the damping of the system. Since typically link coordinate rates cannot be measured, a nonlinear observer is presented which provides estimates of both joint and link coordinate rates while keeping stability of the system. Chapter 2 presents energy-based robust control strategies for the control of flexible link robots without using the dynamics of the systems explicitly. The energy-based controllers are independent of system parameters and thus possess stability robustness to system parametric uncertainties. Through the evaluation of vibrations of the links, direct control of link deflection is possible. Simulation results are provided to show the effectiveness of the presented approach. Chapter 3 addresses issues related to coordinating two robot manipulators to handle flexible materials, an application that has a wide range of applications in the manufacturing industry. In this case, the two robot manipulators have to follow complicated trajectories to maintain a minimum interaction force with the flexible beam. These trajectories are very complicated and not suitable for real time systems. Three approximation methods of the optimal trajectories and a compliant control scheme are introduced in this chapter. The first one uses a piece-wise linear approximation of the optimal trajectories, while the second one uses adaptive piece-wise linear approximation. The third method applies a continuous approximation of the optimal trajectories using an ellipsoid. Finally, a compliant motion scheme is proposed to reduce the interaction forces and moments in the first method. The stability of the proposed system is investigated. Experimental results encourage the proposed schemes. Chapter 4 discusses modeling methodology and force control scheme of constrained flexible manipulators. It is concluded that for the modeling of constrained flexible manipulators: 1) the end-point of the flexible manipulator is constrained and the boundary condition is non-homogeneous; and 2) the exact model can be described as a distributed parameter system, which can be approximated with an finite-dimensional model for designing controllers. The result here indicates that in order to suppress the spillover instability caused by the residual modes neglected at the controller design phase, a robust controller should be constructed. In chapter 5, the control of flexible link robots is examined. Modeling methods pertinent to control are briefly described and significant results from the control literature are discussed. Comparisons of some of these control techniques are conducted experimentally. The single flexible link and multi-link/multi-axis flexible link manipulators are both examined here. Chapter 6 presents sensor output feedback control laws for one-link flexible robot arms with rotational joints or prismatic joints driven by velocity-controlled motors. Specifically, issues related to mission function, strain feedback control, gain adaptive strain feedback control, and shear force feedback are discussed. Emphasis has been laid on the stability analysis of various sensor feedback closed-loop systems. It is shown that, in addition to being easily implemented, strain feedback and shear force feedback controls introduce damping for motion/vibration control, resulting in good control performance. It is also shown that simple gain adaptive strain feedback control can cope with tip load variations of the flexible arm in maintaining good vibration control performance. Chapter 7 addresses the issues related to the design of robust controllers using genetic algorithms (GA) for lightweight, one-link flexible manipulators working under dynamic environments and other uncertain influences. First, a design procedure based on improved GA is proposed to tune parameters in PID controllers to achieve mixed H_2/H_∞ optimal performances for flexible robotic manipulators. Graphic method, local search strategy, refusal strategy and renewal strategy are used to solve successfully constrains imposed in the design problem. Second, by selecting sensitivity weight functions properly using the GA method, a mixed sensitivity H_∞ controller is developed to ensure robustness of manipulator control systems for varying payloads and other modeling uncertainties. Numeric simulation has been conducted and the results have demonstrated the effectiveness of the proposed method.

The second part of the book, from chapters 8 to 10, focuses on various issues related to the optimal design of flexible manipulators. Chapter 8 analyzes the pole/zero locations of a linearly-tapered Euler-Bernoulli beam pinned at one end and free at the other end. Of particular interest is the location of zeros of the transfer function from torque applied at the pin to displacement of the free end. When tapered beams are used as the links of light-weight robots, the existence of non-minimum phase (right half plane) zeros complicates the robot control problem. Tapering the beam gives the robot designer an additional design parameter when establishing the flexible dynamics. The pole and zero locations are determined from a transfer matrix that is the exact solution for a uniform beam. The approximate results for a tapered model result from segmentation of the beam into segments of different but constant cross sections. The relative position of poles and zeros varies significantly as the rate of taper changes, which will have consequences on feedback stability and non-causal effects in inverse dynamics. Chapter 9 and 10 discuss the problem of optimum shape design of flexible manipulators using two different approaches. One approach employs an iterative method to solve the unconstrained analytical formulation of the optimal equations, while an optimization approach is developed that uses mathematical programming to solve the segmentized equation in order to accommodate various constraints on link design. The goal of each approach is to find the shape that maximizes the fundamental frequency, since this frequency is the governing factor for manipulator speeds. The requirement of multiple tip loads is formulated as a mini-max problem. Also, a multi-link design is implemented which utilizes single-link solutions. A sensitivity analysis of design parameters is conducted to reveal the robustness of optimum designs.

Finally, chapter 11 presents a comprehensive study of dynamic behaviors of flexible robotic links that may have more educational than research values, where dynamic models of flexible manipulators have been formulated using both the Euler-Bernoulli and Timoshenko beam theories. Based on a complete analysis of natural frequencies and modal shape functions, analytic expressions of step responses and general solutions of flexible manipulators have been obtained. Using the method of modal expansion, a finite dimensional nonlinear dynamic model has been derived. Explicit solutions of the asymptotic behavior of high order modal frequencies and vibration modes are given and verified with the numerical results. Both asymptotic analysis and numerical results indicate that the effect of shear deformation is significant for high frequency vibrations or shorter manipulators. Simulations indicate that the effects of both rotary inertia and shear deformation are significant and should be included in the high precision and high performance control design of flexible manipulators.

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Contents

Chapter 1

Flexible-link Manipulators: Modeling, Nonlinear Control and Observer

The interest in flexible robot manipulators has become greater in the latest years. In order to adequately exploit the advantages of this class of manipulators, accurate models and effective control schemes are necessary. This work collects a number of recent results on modeling, nonlinear control and observer for flexible–link manipulators. The equations of motion are derived on the basis of a combined Lagrange–assumed modes approach. The resulting model shows several similarities with that of a rigid manipulator, thus allowing important properties to be derived which are used to design controllers and observers. A nonlinear control scheme based on robust control techniques is proposed in order to improve the damping of the system. Since typically link coordinate rates cannot be measured, a nonlinear observer is presented which provides estimates of both joint and link coordinate rates while keeping stability of the system.

1.1 Introduction

Lightweight manipulators offer many challenges in comparison to rigid and bulky robot manipulators. Energy consumption is smaller, so that the payload–to–arm weight ratio can be increased as well as faster movements can be achieved. Due to their characteristics, this class of manipulators are specially suitable for a number of nonconventional robotic applications, including space missions. On the other hand, the study of link flexibility is enforced also for some kind of heavy manipulators such as large scale systems. In either case, it is no longer possible to assume that link deformation can be neglected. All these factors make the study of flexible robot manipulators quite interesting. The present work aims at presenting some of the latest results on modeling, nonlinear control and observer in