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Flexible Robot Manipulators

Modelling, simulation and control

Edited by
M.O. Tokhi and A.K.M. Azad

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Contents

Preface

The ever-increasing utilization of robotic manipulators in various applications in recent years has been motivated by the requirements and demands of industrial automation. Among the rigid and flexible manipulator types, attention is focused more towards flexible manipulators. This is owing to various advantages such manipulators offer as compared to their rigid counterparts. Exploitation of the potential benefits and capabilities of rigid and flexible manipulators introduces a further emerging line of research in which hybrid rigid–flexible manipulator structures are considered.

Flexural dynamics (vibration) in flexible manipulators has been the main research challenge in the modelling and control of such systems. Accordingly, research activities in flexible manipulators have looked into the development of methodologies to cope with the flexural motion dynamics of such systems.

A considerable amount of research on the development of dynamic models of flexible manipulators has been carried out. These have led to descriptions in the form of either partial differential equations, or finite-dimensional ordinary differential equations. From a control perspective, an input/output characterisation of the system is desired, which can be obtained through suitable online estimation and adaptation mechanisms. Given the dynamic nature of flexible manipulator systems, the practical realisation of such methodologies presents new challenges.

Numerical techniques using finite difference and finite element methods have been researched for dynamic characterisation of flexible manipulators. Accordingly, simulation algorithms characterising the dynamic behaviour of flexible manipulators have been developed that provide flexible means of analysis, test and verification of control techniques. With the widely available use of digital computing technology, such platforms are first-step favoured option in a wide range of applications.

Control structures adopted for flexible manipulators can broadly be separated into open loop and closed loop. Although the mathematical theory of open loop control is well established, only a limited number of successful applications in the control of distributed parameter flexible manipulator systems have been reported. A further research dimension, with this class of control structures, is online adaptation of the input shaping mechanism with the changing behaviour of the system and the environment. With closed-loop control techniques, a common trend that has been adopted by researchers is partitioning of the dynamics of the system into the slow (rigid-body) and fast (flexural motion) dynamics and accordingly devising separate control loops. An important consideration with this has been to adequately cope with the non-minimum phase behaviour exhibited by the system characterisation, which with optimal feedback control techniques leads to unstable control. Although this problem can be avoided with some traditional techniques, emerging intelligent control methodologies incorporating soft-computing paradigms offer a great deal of potential in solving such problems.

This book reports on recent and new developments in modelling, simulation and control of flexible robot manipulators, in light of the issues mentioned above. The contents of the book are divided into 19 chapters. Following a general overview of flexible manipulators from the perspective of modelling, simulation, control and applications in Chapter 1, the rest of the book may be grouped into four parts, although some overlap between the parts is allowed for reasons of completeness and coherency as far as required: (1) Chapters 2–4 provide a range of modelling approaches including classical techniques based on the Lagrange equation formulation and parametric approaches based on linear input–output models using system identification techniques and neuro-modelling approaches; (2) Chapters 5–7 present numerical modelling/simulation techniques for dynamic characterisation of flexible manipulators using the finite difference, finite element, symbolic manipulation and customised software techniques, with Chapter 7 dedicated to manipulators in space; (3) Chapters 8–17 present a range of open-loop and closed-loop control techniques based on classical and modern intelligent control methods including soft-computing and smart structures for flexible manipulators; (4) Chapters 18 and 19 are dedicated to software environments for analysis, design, simulation and control of flexible manipulators.

The book is intended for teaching in graduate courses on robotics, mechatronics, control, electrical and mechanical engineering. It can also serve as a source of reference for research in areas of modelling, simulation and control of dynamic flexible structures in general and, specifically, of flexible robotic manipulators.

The material presented in this book comprises contributions of worldwide researchers in the field, and the editors are grateful for their professional and scientific support. The editors would also like to thank Professor Derek Atherton for his encouragement and support during the initial planning of this project, and the IET publication team for their patience and support throughout this project.

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Chapter 11

Force and position control of flexible manipulators

B. Siciliano and L. Villani

While several control schemes have been proposed for force and position control of rigid robot manipulators, only a few related to flexible manipulators have been published so far. In this chapter the main force and position control strategies for flexible manipulators are surveyed and two different approaches are illustrated in depth. One achieves force and position regulation in an indirect way, by computing the joint and deflection variables in the presence of an external contact via a suitable closed-loop inverse kinematics scheme. The other exploits singular perturbation techniques to design force and position control schemes similar to those adopted for rigid robot manipulators, with an additional control action used to stabilise the fast dynamics related to link flexibility. A planar two-link flexible manipulator in contact with a compliant surface is considered, and simulation studies demonstrating the performance of the control techniques are presented and discussed.

11.1 Introduction

In a wide number of applications, such as polishing, debarring, machining or assembling, it is necessary to control the interaction between the robot manipulator and the environment. During the interaction, the environment sets constraints on the geometric paths that can be followed by the end-effector. In such a case, purely motion control strategies for controlling the interaction will fail. In fact, any motion planning or position tracking error may give rise to a contact force that, if not controlled, may produce an unstable behaviour and will inflect damage either to the robot or to the environment. The higher the environment stiffness and position control accuracy are, the easier such a situation can occur.

On the other hand, the intrinsic compliance of a flexible-link manipulator may contribute to reduction in the value of the forces that can be generated when the interaction task is executed by a rigid robot. This means that by using flexible robots to perform interaction tasks, some benefits may be gained (Sur and Murray, 1997), even though the distributed flexibility of the links makes the interaction control problem more complex than for rigid robots.

The most common solution to interaction control is to use a force/torque sensor, mounted between the last link and the end-effector, to provide force measurements that can be used to achieve force control.

Robot force control has attracted a wide number of researchers in the past two decades. Several control schemes have been proposed, and a state of the art on force control of rigid robot manipulators can be found in Gorinevski *et al.* (1997) and Siciliano and Villani (1999). For the specific case of flexible manipulators, however, only few papers have been published.

Interaction control strategies can be grouped into two categories: those performing indirect force controls and those performing direct force controls. The main difference between the two categories is that the former achieves force control via motion control, without explicit closure of a force feedback loop, and the latter offers the possibility of controlling the contact force to a desired value with the closure of a force feedback loop.

The first category includes compliance control (Salisbury, 1980) and impedance control (Hogan, 1985), where the end-effector is made compliant by relating the position error to the contact force through a static or dynamic relationship of adjustable parameters. If a detailed model of the environment is available then a widely adopted strategy, which belongs to the second category, known as the hybrid position/force control may be used. This strategy aims to control position along the unconstrained task directions and force along the constrained task directions. A selection matrix acting on both desired and feedback quantities serves this purpose for typically planar contact surfaces (Raibert and Craig, 1981), whereas the explicit constraint equations have to be taken into account for general curved contact surfaces (McClamroch and Wang, 1988; Yoshikawa, 1987).

In most practical situations, a detailed model of the environment is not available. In such a case, an effective strategy, still in the second category, that may be adopted is the inner/outer motion/force control where an outer force control loop is closed around the inner motion control loop, which is typically available in a robot manipulator (De Schutter and Van Brussel, 1988). In order to embed the possibility of controlling motion along the unconstrained task directions, the desired motion of the end-effector can be input to the inner loop of an inner/outer motion/force control scheme. The resulting parallel control is composed of a force control action and a motion control action, where the former is designed so as to dominate the latter in order to ensure force control along the constrained task directions (Chiaverini and Sciavicco, 1993).

For the case of flexible manipulators, early works addressing the stability problems of force control are reported in Chiou and Shahinpoor (1990) and Mills (1992). Hybrid force/position control is adopted in Matsuno and Yamamoto (1994), Matsuno *et al.* (1994) and Rocco and Book (1996), and is used in Hu and Ulsoy (1994) and

Yang *et al.* (1995) to design robust and adaptive control strategies, respectively. The problem of controlling the interaction of flexible macro-manipulators carrying a rigid micro-link is considered in Lew and Book (1993) and Yoshikawa *et al.* (1996) in the framework of hybrid control as well. Force and position control strategies conceived to manage the interaction with more or less compliant environments, without requiring a detailed model, are proposed in Siciliano and Villani, (1999, 2001).

The inherent difficulty of force control of flexible manipulators is due to problems similar to those arising in motion control (Book, 1993; Canudas de Wit *et al.,* 1996). Moreover, the kinematics and the dynamics of the robot cannot be stated independent of the forces acting on the robot tip (end-point).

In fact, when a robot interacts with the environment, the additional deflections caused by contact forces must be suitably taken into account for the computation of inverse kinematic solution. This can be done by adding a corrective term to the Jacobian, as in the solution based on the closed-loop inverse kinematics (CLIK) algorithm developed in Siciliano (1999) for the case of contact with an infinitely stiff environment and in Siciliano (1998) for the case of a compliant environment.

As for the dynamics of a flexible manipulator in contact with the environment, Matsuno and Yamamoto (1994) proposed a model derived using the Hamilton's principle, where the boundary condition of the link in contact with the environment depends on the contact force and input torque, as well as on the contact position. This makes the flexible manipulator equation very difficult to solve and simplification must be made. For example, in Matsuno *et al.* (1994), the boundary conditions are simplified by considering a quasi-static model derived on the basis of the static relationship between the elastic deformations and the contact force.

On the other hand, if the assumed mode technique is adopted to model the flexible manipulator, the mode functions must satisfy the geometric boundary conditions, which are not altered by the contact with the environment, while the natural boundary conditions (i.e. those involving the balance of forces and moments at the ends of the links) are automatically taken into account by the Lagrange formulation of the mathematical model (Book, 1984; Meirovitch, 1967; Rocco and Book, 1996). This modelling approach is also pursued in Hu and Ulsoy (1994), Kim *et al.* (1996), Lin (2003), Mills (1992), Siciliano and Villani (1999) and Yang *et al.* (1995).

Another difficulty in controlling flexible robots is the problem of damping the vibrations that are naturally excited during the task execution. An effective approach is based on singular perturbation theory (Kokotovic *et al.*, 1986). When the link stiffness is large, a two-timescale model of the flexible manipulator can be derived (Siciliano and Book, 1988) consisting of a slow subsystem corresponding to the rigid-body motion and a fast subsystem describing the flexible motion. A composite control strategy can then be applied, based on a slow control designed for the equivalent rigid manipulator and a fast control, which stabilises the fast subsystem. Further developments of perturbation techniques can be found in Fraser and Daniel (1991), Moallem *et al.* (1997), Siciliano *et al.* (1992) and Vandegrift *et al.* (1994) for the case of flexible manipulators moving in free space, and in Matsuno and Yamamoto (1994), Rocco and Book (1996), Siciliano and Villani (2000) and Yang *et al.* (1995) for the case of contact with the environment.

The focus of this chapter is on force control strategies for flexible manipulators, which are conceived to manage the interaction with a more or less compliant environment without requiring an accurate model thereof. Two different approaches are presented.

The first approach, based on Siciliano and Villani (2001) achieves force and position regulation in an indirect way as long as the arm kinematic model, the mass distribution and stiffness of the links as well as the environment stiffness and position are known. In detail, assuming a simple elastic model for the contact surface, a position set-point is assigned, corresponding to the desired force applied to the desired point on the surface. Then a closed-loop inverse kinematics algorithm based on a Jacobian transpose scheme described in (Siciliano, 1998) is adopted to compute the joint and deflection variables. These are input to a simple proportional, derivative (PD) joint regulator (De Luca and Siciliano, 1993).

The second approach, based on Siciliano and Villani (2000), exploits singular perturbation techniques to design interaction control schemes in the framework of parallel force and position control with an additional control action used to stabilise the fast dynamics related to link flexibility.

Simulation results are presented for a two-link planar manipulator under gravity in contact with an elastically compliant surface.

The chapter is organized as follows. In Section 11.2 the model of a planar n-link flexible manipulator in contact with an elastic environment is presented. The two-stage algorithm achieving indirect force and position control is presented in Section 11.3. In Section 11.4 a singular perturbed model for the flexible manipulator is developed and two different parallel control schemes are considered for the slow dynamics: the first ensures force and position regulation and the second guarantees force regulation and position tracking. Section 11.5 provides concluding remarks.

11.2 Modelling

For the purpose of this chapter, planar n-link flexible manipulators with revolute joints are considered. The links are subject to bending deformation in the plane of motion only, that is, torsional effects are neglected. A sketch of a two-link arm, with coordinate frame assignment, is shown in Figure 11.1. The rigid motion is described by the joint-angle θ_i, while $w_i(x_i)$ denotes the transversal deflection of link i at x_i, $0 \le x_i \le L_i$, with L_i as the length of the link.

Let ${}^i\mathbf{p}_i(x_i) = \begin{bmatrix} x_i & w_i(x_i) \end{bmatrix}^{\mathrm{T}}$ be the position of a point along the deflected link i with respect to frame (X_i, Y_i) and $\mathbf{p}_i$ the position of the same point in the base frame. Also let ${}^i\mathbf{r}_{i+1} = {}^i\mathbf{p}_i(L_i)$ be the position of the origin of frame (X_{i+1}, Y_{i+1}) with respect to frame (X_i, Y_i), and $\mathbf{r}_{i+1}$ its position in the base frame.

The joint (rigid) rotation matrix $\mathbf{R}_i$ and the rotation matrix $\mathbf{E}_i$ of the (flexible) link at the end-point are, respectively,

$$\mathbf{R}_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix}$$

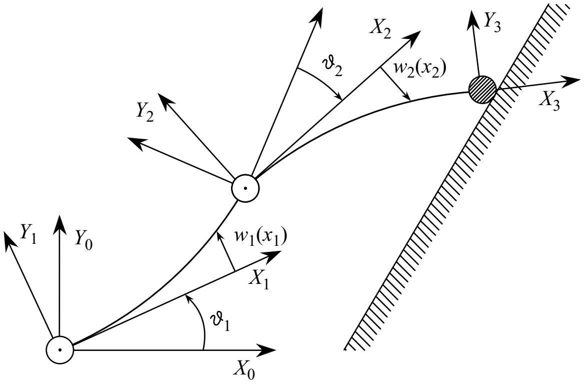

Figure 11.1 Planar two-link flexible manipulator

and

$$\mathbf{R}_i = \begin{bmatrix} 1 & -w'_{ie} \\ w'_{ie} & {}_{\iota}1 \end{bmatrix}$$

where $w'_{ie} = (\partial w_i/\partial x_i)\,|_{x_i=L_i}$, and the small deflection approximation $\tan^{-1}\left(w'_{ie}\right) \cong w'_{ie}$ has been made. Hence the above absolute position vectors can be expressed as

$$\mathbf{p}_i = \mathbf{r}_i + \mathbf{W}_i{}^i\mathbf{p}_i$$

and

$$\mathbf{r}_{i+1} = \mathbf{r}_i + \mathbf{W}_i{}^i\mathbf{r}_{i+1}$$

where $\mathbf{W}_i$ is the global transformation matrix from the base frame to the frame (X_i, Y_i) given by the recursive equation,

$$\mathbf{W}_i = \mathbf{W}_{i-1}\mathbf{E}_{i-1}\mathbf{R}_i = \hat{\mathbf{W}}_{i-1}\mathbf{R}_i$$

with

$$\hat{\mathbf{W}}_0 = \mathbf{I}$$

On the basis of the above relations, the kinematics of any point along the manipulator is completely specified as a function of joint angles and link deflections.

A finite-dimensional model (of order m_i) of link flexibility can be obtained by the assumed modes technique. By exploiting the separability in time and space of solutions to the Euler–Bernoulli equation for flexible beams;

$$(EI)_i \frac{\partial^4 w_i\,(x_i,t)}{\partial x_i^4} + \frac{\partial^2 w_i\,(x_i,t)}{\partial t^2} = 0$$

for $i = 1, \dots, n$ where ρ_i is the uniform mass density and $(EI)_i$ is the constant flexural rigidity of link i, the link deflection can be expressed as

$$w_i(x_i, t) = \sum_{j=1}^{m_i} \phi_{ij}(x_i)\, \delta_{ij}(t) \tag{11.1}$$

where $\delta_{ij}(t)$ are the time-varying variables associated with the assumed spatial mode shapes $\phi_{ij}(x_i)$ of link i. The mode shapes have to satisfy proper boundary conditions at the base (clamped) and at the end of each link (mass).

In view of equation (11.1), a direct kinematics equation can be derived expressing the position $\mathbf{p}$ of the manipulator end-point as a function of the $(n \times 1)$ joint variable vector $\boldsymbol{\theta}$ and the $(m \times 1)$ deflection variable vector $\boldsymbol{\delta}$ that is,

$$\mathbf{p} = \mathbf{k}(\boldsymbol{\theta}, \boldsymbol{\delta}) \tag{11.2}$$

where $m = \sum_{i=1}^{n} m_i$. For later use in the inverse kinematics scheme, the differential kinematics is also needed. The absolute linear velocity of a point on the arm is

$$\dot{\mathbf{p}}_i = \mathbf{P}_i + \dot{\mathbf{W}}_i {}^i\mathbf{p}_i + \mathbf{W}_i {}^i\dot{\mathbf{p}}_i \tag{11.3}$$

with ${}^i\dot{\mathbf{r}}_{i+1} = {}^i\dot{\mathbf{p}}_i(L_i)$. Since the links are assumed to be inextensible ($\dot{x}_i = 0$), then ${}^i\dot{\mathbf{p}}_i(x_i) = \begin{bmatrix} 0 & \dot{w}_i(x_i) \end{bmatrix}^{\mathrm{T}}$. The computation of equation (11.3) takes advantage of the recursion

$$\dot{\mathbf{W}}_i = \dot{\mathbf{W}}_{i-1}\mathbf{R}_i + \hat{\mathbf{W}}_{i-1} {}^i\dot{\mathbf{R}}_i \tag{11.4}$$

with

$$\dot{\mathbf{W}}_i = \dot{\mathbf{W}}_i\mathbf{E}_i + \mathbf{W}_i {}^i\dot{\mathbf{E}}_i \tag{11.5}$$

Also, note that

$$\dot{\mathbf{R}}_i = \mathbf{S}\mathbf{R}_i\dot{\theta}_i, \qquad \dot{\mathbf{E}}_i = \mathbf{S}\dot{w}'_{ie} \tag{11.6}$$

with

$$\mathbf{S} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \tag{11.7}$$

In view of equations (11.2)–(11.7), it is not difficult to show that the differential kinematics equation expressing the end-point velocity $\dot{\mathbf{p}}$ as a function of $\dot{\boldsymbol{\theta}}$ and $\dot{\boldsymbol{\delta}}$ can be written in the form:

$$\dot{\mathbf{p}} = \mathbf{J}_\theta(\boldsymbol{\theta}, \boldsymbol{\delta})\, \dot{\boldsymbol{\theta}} + \mathbf{J}_\delta(\boldsymbol{\theta}, \boldsymbol{\delta})\, \dot{\boldsymbol{\delta}} \tag{11.8}$$

where $\mathbf{J}_\theta = \partial\mathbf{k}/\partial\boldsymbol{\theta}$ and $\mathbf{J}_\delta = \partial\mathbf{k}/\partial\boldsymbol{\delta}$.

Assume that the manipulator is in contact with the environment. By virtue of the virtual work principle, the vector $\mathbf{f}$ of the forces exerted by the manipulator on the environment performing work on $\mathbf{p}$ has to be related to the $(n \times 1)$ vector $\mathbf{J}_\theta^{\mathrm{T}}\mathbf{f}$ of joint torques performing work on $\boldsymbol{\theta}$ and the $(m \times 1)$ vector $\mathbf{J}_\delta^{\mathrm{T}}\mathbf{f}$ of the elastic reaction forces performing work on $\boldsymbol{\delta}$.

A finite-dimensional Lagrangian dynamic model of the planar manipulator in contact with the environment can be obtained in terms of $\boldsymbol{\theta}$ and $\boldsymbol{\delta}$ in the form (De Luca and Siciliano, 1991):

$$\mathbf{M}_{\theta\theta}(\boldsymbol{\theta},\boldsymbol{\delta})\ddot{\boldsymbol{\theta}}+\mathbf{M}_{\theta\delta}(\boldsymbol{\theta},\boldsymbol{\delta})\ddot{\boldsymbol{\delta}}+\mathbf{c}_{\theta}\left(\boldsymbol{\theta},\boldsymbol{\delta},\dot{\boldsymbol{\theta}},\dot{\boldsymbol{\delta}}\right)+\mathbf{g}_{\theta}(\boldsymbol{\theta},\boldsymbol{\delta})=-\mathbf{J}_{\theta}^{T}(\boldsymbol{\theta},\boldsymbol{\delta})\mathbf{f} \qquad (11.9)$$

$$\mathbf{M}_{\theta\delta}^{T}(\boldsymbol{\theta},\boldsymbol{\delta})\ddot{\boldsymbol{\theta}}+\mathbf{M}_{\delta\delta}(\boldsymbol{\theta},\boldsymbol{\delta})\ddot{\boldsymbol{\delta}}+\mathbf{c}_{\delta}\left(\boldsymbol{\theta},\boldsymbol{\delta},\dot{\boldsymbol{\theta}},\dot{\boldsymbol{\delta}}\right)+\mathbf{g}_{\delta}(\boldsymbol{\theta},\boldsymbol{\delta})+\mathbf{D}\dot{\boldsymbol{\delta}}+\mathbf{K}\boldsymbol{\delta}=-\mathbf{J}_{\delta}^{T}(\boldsymbol{\theta},\boldsymbol{\delta})\mathbf{f} \qquad (11.10)$$

where $\mathbf{M}_{\theta\theta}$, $\mathbf{M}_{\theta\delta}$ and $\mathbf{M}_{\delta\delta}$ are the matrix blocks of the positive definite symmetric inertia matrix, $\mathbf{c}_{\theta}$, $\mathbf{c}_{\delta}$ are the vectors of Coriolis and centrifugal forces, $\mathbf{g}_{\theta}$, $\mathbf{g}_{\delta}$ are the vector of gravitational forces, $\mathbf{K}$ is the diagonal and positive definite link stiffness matrix, $\mathbf{D}$ is the diagonal and positive semi definite link damping matrix, and τ is the vector of the input joint torques.

To analyse the performance of the position and force control algorithms, a model of the contact force is required. A real contact is a naturally distributed phenomenon in which the local characteristics of both the end-effector and the environment are involved. Moreover, friction effects between parts typically exist, which greatly complicate the nature of the contact itself. A simplified analysis can be pursued by considering a frictionless and planar surface, which is locally a good approximation to surfaces of regular curvature, and considering an elastic force given by

$$\mathbf{f}=k_{\mathrm{e}}\mathbf{n}\mathbf{n}^{T}(\mathbf{p}-\mathbf{p}_{\mathrm{e}})=k_{\mathrm{e}}\mathbf{n}\mathbf{n}^{T}(\mathbf{k}(\boldsymbol{\theta},\boldsymbol{\delta})-\mathbf{p}_{\mathrm{e}}) \qquad (11.11)$$

where k_{e} is the surface stiffness, $\mathbf{p}_{\mathrm{e}}$ is the un-deformed (constant) position of the surface, $\mathbf{n}$ is the (constant) unit vector of the direction normal to the surface, and the direct kinematics equation (11.2) has been used to express the position of the contact point in terms of joint and deflection variables. Also, it is assumed that contact is not lost.

Notice that for the derivation of the dynamic model in equations (11.9) and (11.10), the presence of the contact with the environment does not affect the choice of the mode shapes $\phi_{ij}(x_i)$ in equation (11.1) and the force enters into the equations of motion through the Jacobian (Rocco and Book, 1996).

Also, in this chapter only the interaction with a more or less compliant environment described by relations of the form in equation (11.11) is considered. On the other hand, in case of interaction with an infinitely rigid environment, kinematic constraints are imposed on the coordinates of robot end-point and a constraint force must be considered in the dynamic model of the flexible manipulator, expressed in terms of Lagrange multipliers (McClamroch and Wang, 1988). As in the case of rigid robots, the presence of the constraints reduces the number of degrees of freedom of the system. Moreover, it is possible to reduce the number of differential equations by resorting to a coordinate partitioning procedure (Hu and Ulsoy, 1994; Matsuno and Yamamoto, 1994; Matsuno *et al.*, 1994; Mills, 1992; Rocco and Book, 1996; Yang *et al.*, 1995).

11.3 Indirect force and position regulation

The interaction of a flexible-link manipulator with a compliant environment can be managed by controlling both the contact force and the end-point position. In view of the model of the contact force in equation (11.11), the control objective can be specified in terms of a desired force $f_d\mathbf{n}$ aligned with $\mathbf{n}$ and a desired position $\mathbf{p}_d$ on the contact plane. Nevertheless, the quantities f_d and $\mathbf{p}_d$ cannot be assigned independently, since they have to be consistent with the model in equation (11.11). In other words, the desired value of the force f_d can be achieved only if the component normal to the plane of the desired position $\mathbf{p}_d$ is chosen as

$$p_{dn} = \mathbf{n}^{\mathrm{T}}\mathbf{p}_d = k_e^{-1}f_d + p_{en} \tag{11.12}$$

Hence, force control can be realised indirectly via position control, provided that the surface stiffness k_e and the component p_{en} of the un-deformed position of the surface are known.

In this section, a force and position regulator is presented, which achieves a desired position on the contact plane as well as a desired force, provided that equation (11.12) is satisfied, without requiring direct measurement of the contact force.

The controller is based on a two-stage algorithm. The first stage is in charge of solving the inverse kinematics problem to compute the desired vectors of joint variables $\boldsymbol{\theta}_d$ and deflection variables $\boldsymbol{\delta}_d$ that place the end-point of the flexible arm at a desired position $\mathbf{p}_d$; the component p_{dn} of $\mathbf{p}_d$ is chosen according to equation (11.12) to achieve a desired force f_d, while the components of the desired position tangential to the plane can be freely chosen. In the second stage, which constitutes a joint regulator, the variables $\boldsymbol{\theta}_d$ and $\boldsymbol{\delta}_d$ are used as set-points.

11.3.1 First stage

The first stage of the algorithm computes the inverse kinematics solution. To derive a Jacobian-based inverse kinematics scheme, the differential kinematic equation accounting for link deflections caused by gravity and contact with the environment must be considered.

For the regulation problem, a static situation can be considered. By virtue of equation (11.10), in a static situation the deflections satisfy the equation

$$\mathbf{g}_\delta\left(\boldsymbol{\theta}, \boldsymbol{\delta}\right) + \mathbf{K}\delta = -\mathbf{J}_\delta^T\left(\boldsymbol{\theta}, \boldsymbol{\delta}\right)\mathbf{f}$$

According to the small deflection approximation, it can be assumed that $\mathbf{g}_\delta$ is only a function of $\boldsymbol{\theta}$ (De Luca and Siciliano, 1993) and so is the case for $\mathbf{J}_\delta$ in equation (11.8) and $\mathbf{p}$ in equation (11.11). Hence, the deflection variables can be computed from equation (11.12) as

$$\boldsymbol{\delta} = -\mathbf{K}^{-1}\left(k_{\mathrm{e}}\mathbf{j}_{\delta n}\left(\boldsymbol{\theta}\right)\left(p_n\left(\boldsymbol{\theta}\right) - p_{en}\right) + \mathbf{g}_\delta\left(\boldsymbol{\theta}\right)\right) \tag{11.13}$$

where

$$\mathbf{j}_{\delta n}\left(\boldsymbol{\theta}\right) = \mathbf{J}^T\mathbf{n}, \qquad p_n = \mathbf{n}^T\mathbf{p}, \qquad p_{en} = \mathbf{n}^T\mathbf{p}_e$$

For later use in the inverse kinematics scheme, differentiating equation (11.13) with respect to time gives

$$\dot{\boldsymbol{\delta}} = \mathbf{J}_{fg}(\boldsymbol{\theta})\,\dot{\boldsymbol{\theta}} \tag{11.14}$$

where

$$\mathbf{J}_{fg} = -\mathbf{K}^{-1}\left(k_e \mathbf{J}_f(\boldsymbol{\theta}) + \mathbf{J}_g(\boldsymbol{\theta})\right)$$

with

$$\mathbf{J}_f = \frac{\partial \mathbf{j}_{\delta n}}{\partial \boldsymbol{\theta}}(p_n - p_{en}) + \mathbf{j}_{\delta n}\frac{\partial p_n}{\partial \boldsymbol{\theta}}$$

and $\mathbf{J}_g = \partial \mathbf{g}_\delta / \partial \boldsymbol{\theta}$. Substituting for $\dot{\boldsymbol{\delta}}$ from equation (11.14) into equation (11.8) yields

$$\dot{\mathbf{p}} = \mathbf{J}_p(\boldsymbol{\theta}, \boldsymbol{\delta})\,\dot{\boldsymbol{\theta}} \tag{11.15}$$

where

$$\mathbf{J}_p = \mathbf{J}_\theta + \mathbf{J}_\delta \mathbf{J}_{fg}$$

is the overall Jacobian matrix relating joint velocity to end-point velocity. Notice that the Jacobian in equation (11.15) is obtained by modifying the rigid-body Jacobian $\mathbf{J}_\theta$ with two terms that account for the deflections induced by the contact force and gravity, respectively.

The attractive feature of the differential kinematics in equation (11.15) is its formal analogy with the differential kinematics equation for a rigid arm. Therefore, any Jacobian-based inverse kinematics scheme can be adopted in principle. In this respect, one of the most effective schemes is the CLIK scheme (Siciliano, 1990) that reformulates the inverse kinematics problem in terms of the convergence of a suitable closed-loop dynamic system.

According to the Jacobian transpose scheme, the joint variables vector is computed by integrating the joint velocity vector chosen as

$$\dot{\boldsymbol{\theta}} = \mathbf{J}_p^T(\boldsymbol{\theta}, \boldsymbol{\delta})\,\mathbf{K}_p(\mathbf{p}_d - \mathbf{p}) \tag{11.16}$$

Using a Lyapunov argument (Sicilano, 1990) it can be shown that, as long as the vector $\mathbf{K}_p(\mathbf{p}_d - \mathbf{p})$ in equation (11.16) is outside the null space of $\mathbf{J}_p^T$, the end-point position error $\mathbf{p}_\mathrm{d} - \mathbf{p}$ asymptotically tends to zero. In fact, a suitable choice of the matrix $\mathbf{K}_p$ can be made to avoid that the scheme gets stuck with $\mathbf{p}_d - \mathbf{p} \neq \mathbf{0}$ and $\dot{\boldsymbol{\theta}} = \mathbf{0}$. In summary, $\boldsymbol{\theta}$ and $\boldsymbol{\delta}$ tend asymptotically to the constant values $\boldsymbol{\theta}_d$ and $\boldsymbol{\delta}_d$ such that $\mathbf{p}_d = \mathbf{k}(\boldsymbol{\theta}_d, \boldsymbol{\delta}_d)$.

Notice that one of the attractive features of this approach is that, similar to the rigid arm case, any Jacobian-based inverse kinematics scheme can be adopted in principle, as well as any joint-space control law. The solution chosen in this work for kinematic inversion does not require the inverse of the Jacobian and thus it works well in the neighbourhood of singularities.

11.3.2 Second stage

The second stage of the algorithm is in charge of regulating the joint and deflection variables to the values $\boldsymbol{\theta}_d$ and $\boldsymbol{\delta}_d$ computed in the first stage. To this aim, the simple PD regulator presented in (De Luca and Siciliano, 1993) can be adopted:

$$\tau = \mathbf{K}_1 (\boldsymbol{\theta}_d - \boldsymbol{\theta}) - \mathbf{K}_2\dot{\boldsymbol{\theta}} + \mathbf{g}_\theta (\boldsymbol{\theta}_d, \boldsymbol{\delta}_d) + \mathbf{J}_\theta^T (\boldsymbol{\theta}_d, \boldsymbol{\delta}_d) f_d \mathbf{n} \tag{11.17}$$

where $\mathbf{K}_1$ and $\mathbf{K}_2$ are suitable positive definite matrix gains. The feedforward terms $\mathbf{g}_\theta (\boldsymbol{\theta}_d, \boldsymbol{\delta}_d)$ and $\mathbf{J}_\theta^T (\boldsymbol{\theta}_d, \boldsymbol{\delta}_d) f_d \mathbf{n}$ are required to compensate for the gravity torque and contact force respectively, at steady state.

The control law in equation (11.17) ensures asymptotic convergence of $\boldsymbol{\theta}$ and $\boldsymbol{\delta}$ to the corresponding set-points. Hence, the two-stage control scheme in equations (11.16) and (11.17) guarantees that $\mathbf{p} \rightarrow \mathbf{p}_d$ and $\mathbf{f} \rightarrow f_d \mathbf{n}$ as $t \rightarrow \infty$.

Notice that the PD regulator ensures asymptotic stability only in the presence of significant damping. When passive damping is too low, active vibration damping can be achieved by using full state-feedback (Canudas de Wit *et al.*, 1996).

It is also worth noting that the scheme only makes use of joint position and velocity measurements. Obviously, any joint position control law for flexible arms may be used in the second stage of the scheme in lieu of the simple PD regulator in equation (11.17). In any case, the overall performance in terms of end-point position and force errors strongly depends on the accuracy of the static model of the flexible arm, as well as on the accuracy of the available estimates of the stiffness and position of the contact surface.

11.3.3 Simulation

To illustrate the performance of the two-stage algorithm, a planar two-link flexible manipulator is considered (see Figure 11.1):

$$\boldsymbol{\theta} = \begin{bmatrix} \theta_1 & \theta_2 \end{bmatrix}^T$$

and a payload of 0.1 kg is assumed to be placed at the end-point of the manipulator. An expansion with two clamped-mass assumed modes is taken for each link:

$$\boldsymbol{\delta} = \begin{bmatrix} \delta_{11} & \delta_{12} & \delta_{21} & \delta_{22} \end{bmatrix}^T$$

The parameters of the manipulator are given in Table 11.1.

The resulting natural frequencies of vibration are

$$f_{11} = 1.40\,\text{Hz}, \qquad f_{12} = 5.10\,\text{Hz}$$
$$f_{21} = 536.09\,\text{Hz}, \qquad f_{22} = 20792.09\,\text{Hz}.$$

The stiffness matrix $\mathbf{K}$ is

$$\mathbf{K} = \begin{bmatrix} 38.79 & 513.37 \\ 536.09 & 20792.09 \end{bmatrix}$$

Table 11.1 Link parameters

Parameter (unit)	Link 1	Link 2
Density (kg/m)	1	1
Length (m)	0.5	0.5
Centre of mass (m)	0.25	0.25
Mass (kg)	0.5	0.5
Hub mass (kg)	1	1

The dynamic model of the manipulator and the missing numerical data can be found in (De Luca and Siciliano, 1991) while the direct and differential kinematics equations are reported in (Siciliano and Villani, 2001).

The contact surface is a vertical plane, thus the normal vector in equation (11.11) is $\mathbf{n} = \begin{bmatrix} 1 & 0 \end{bmatrix}^T$; a point of the un-deformed plane is

$$\mathbf{p}_e = \begin{bmatrix} 0.55 & 0 \end{bmatrix}^T \mathrm{m}$$

and the contact stiffness is $k_e = 50\mathrm{N/m}$.

The feedback gain matrix $\mathbf{K}_p$ of the CLIK algorithm in equation (11.16) is chosen as

$$\mathbf{K}_p = \mathrm{diag}\left\{ 500 \quad 500 \right\}$$

and the inverse kinematics scheme is discretised at a sampling time $T_c = 1\mathrm{ms}$, using the Euler integration rule. In particular, according to equation (11.16), the joint variables vector $\boldsymbol{\theta}_d$ is computed as

$$\boldsymbol{\theta}_d\left(t_{k+1}\right) = \boldsymbol{\theta}_d\left(t_k\right) + T_c \mathbf{J}_p^T\left(\boldsymbol{\theta}_d\left(t_k\right), \boldsymbol{\delta}_d\left(t_k\right)\right) \mathbf{K}_p \left(\mathbf{p}_d\left(t_k\right) - \mathbf{p}\left(t_k\right)\right)$$

and, according to equation (11.13), the deflection variables vector $\boldsymbol{\delta}_d$ is computed as

$$\boldsymbol{\delta}_d\left(t_{k+1}\right) = -\mathbf{K}^{-1}\left(k_e \mathbf{j}_{\delta n}\left(\boldsymbol{\theta}_d\left(t_k\right)\right)\left(p_n\left(\boldsymbol{\theta}\left(t_k\right)\right) - p_{en}\right) + \mathbf{g}_\delta\left(\boldsymbol{\theta}_d\left(t_k\right)\right)\right)$$

The feedback matrix gains in (11.17) are chosen as:

$$\mathbf{K}_1 = \mathrm{diag}\left\{ 25 \quad 25 \right\}, \qquad \mathbf{K}_2 = \mathrm{diag}\left\{ 3 \quad 3 \right\}$$

Numerical simulations were performed using Matlab with Simulink. The arm was initially placed with the end-point in contact with the un-deformed plane at the position

$$\mathbf{p}_e = \begin{bmatrix} 0.55 & -0.55 \end{bmatrix}^T \mathrm{m}$$

with null contact force; the corresponding generalized coordinates of the manipulator, computed using the CLIK algorithm in equation (11.16), are

$$\boldsymbol{\theta} = \begin{bmatrix} -1.396 & 1.462 \end{bmatrix}^T \mathrm{rad}$$

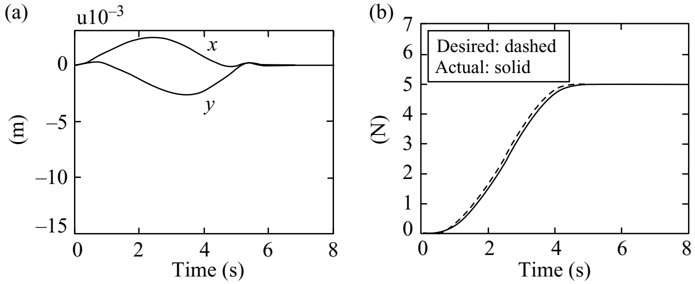

Figure 11.2 Time histories of the position error and of the contact force for the first example: (a) position error, (b) control force

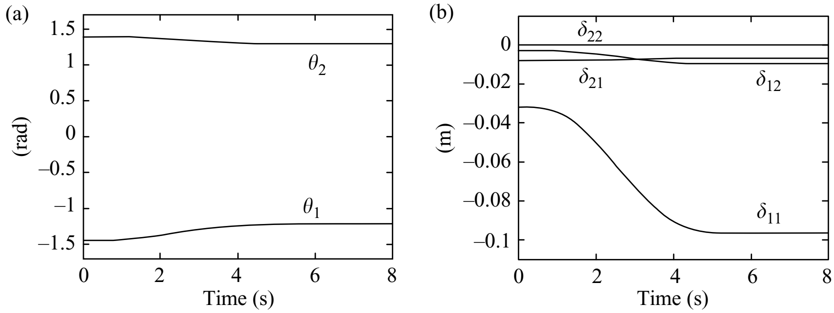

Figure 11.3 Time histories of the joint angles and of the link deflections for the first example: (a) joint angle, (b) link defliction

$$\boldsymbol{\delta} = \begin{bmatrix} -0.106 & 0.001 & -0.009 & -0.0001 \end{bmatrix}^T \text{m}$$

It is desired to reach the end-point position

$$\mathbf{p}_d = \begin{bmatrix} 0.55 & -0.50 \end{bmatrix}^T \text{m}$$

and a fifth-order polynomial trajectory with null initial and final velocity and acceleration is imposed from the initial to the final position with a duration of 5 s.

In the first example, it is assumed that the stiffness of the environment is known, hence the desired force corresponding to the desired position is

$$\mathbf{f}_d = \begin{bmatrix} 5 & 0 \end{bmatrix}^T \text{N}$$

The time histories of the position errors and of the actual and desired contact forces are shown in Figure 11.2, and the time histories of the joint angles and link deflections are shown in Figure 11.3. It can be seen that the tracking error along the trajectory is small, although the scheme was conceived as a regulator. Moreover, both the desired force and position are achieved at steady state. Note also that, because of gravity and contact force, the arm has to bend to reach the desired end-point position properly.

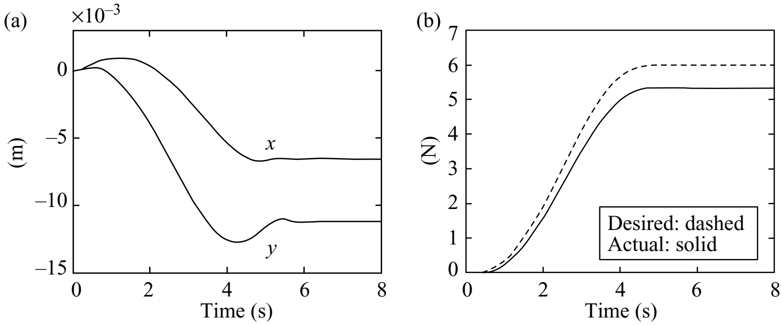

Figure 11.4 Time histories of the position error and of the contact force for the second example: (a) position error, (b) contact force

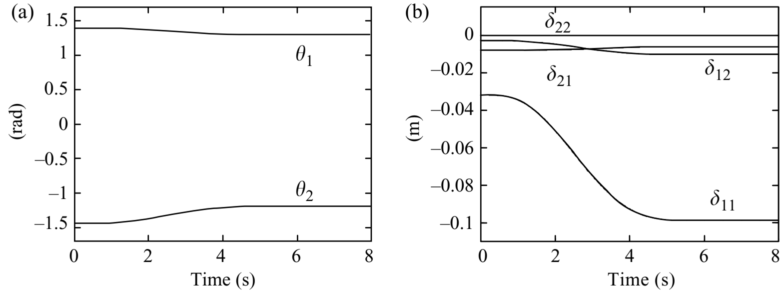

Figure 11.5 Time histories of the joint angles and of the link deflections for the second example: (a) joint angle, (b) link deflection

Actually the bending is much larger on the first link as expected (the links have the same parameters).

In the second numerical example, all the data are the same except for the estimated contact stiffness, which is assumed to be 60 Nm in lieu of the true value of 50 N/m. Hence, the desired force

$$\mathbf{f}_d = \begin{bmatrix} 6 & 0 \end{bmatrix}^T \mathrm{N}$$

is expected, with the same desired position.

The resulting time histories of the position errors and of the actual and desired contact forces are shown in Figure 11.4, and the time histories of the joint angles and link deflections are shown in Figure 11.5. It can be seen that the tracking error along the trajectory is limited, but a constant offset remains at steady state. Accordingly, the contact force reaches a constant value that is lower than the desired one, due to the fact that the contact stiffness was overestimated.

11.4 Direct force and position control

If a force sensor is available at the end-point of the manipulator, it is possible to achieve direct force control without requiring an exact estimate of the stiffness and of the position of the environment at rest. Moreover, if the dynamics related to link flexibility are suitably taken into account, tracking of a time-varying desired position can be achieved as well as regulation to a constant force.

In this section two different force and position control algorithms are presented, based on the parallel force and position approach of Chiaverini and Sciavicco (1993). The first scheme only requires partial knowledge of the model of the manipulator and guarantees force and position regulation. The second scheme achieves force regulation and position tracking by using more modelling information. Both schemes are part of a composite control strategy based on a two-time scale model of the flexible manipulator.

11.4.1 Composite control strategy

When stiffness of the link is large, it is reasonable to expect that the dynamics related to link flexibility are much faster than the dynamics associated with rigid motion of the robot so that the system naturally exhibits a two-timescale dynamic behaviour in terms of rigid and flexible variables. This feature can be conveniently exploited for control design (Matsuno and Yamamoto, 1994; Mills, 1992; Rocco and Book, 1996; Siciliano and Book, 1988; Yang *et al.*, 1995).

Following the approach proposed in (Siciliano and Book, 1988), the system can be decomposed into slow and fast subsystems by using singular perturbation theory; this leads to a composite control strategy for the full system based on separate control designs for the two reduced-order subsystems.

Assuming that full-state measurement is available and that a force sensor is mounted at the end-point of the manipulator, the joint torques can be conveniently chosen as

$$\boldsymbol{\tau} = \mathbf{g}_\theta(\boldsymbol{\theta}, \boldsymbol{\delta}) + \mathbf{J}_\theta^T(\boldsymbol{\theta}_d, \boldsymbol{\delta}_d)\,\mathbf{f} + \mathbf{u} \tag{11.18}$$

to cancel out the effects of the static torques acting on the rigid part of the manipulator dynamics; the vector $\mathbf{u}$ is the new control input to be designed on the basis of the singular perturbation approach.

The timescale separation between the slow and fast dynamics can be determined by defining the singular perturbation parameter $\varepsilon = 1/\sqrt{k_m}$, where k_m is the smallest coefficient of the diagonal stiffness matrix $\mathbf{K}$, and the new variable

$$\mathbf{z} = \mathbf{K}\boldsymbol{\delta} = \frac{1}{\varepsilon^2}\hat{\mathbf{K}}\boldsymbol{\delta}$$

corresponds to the elastic force, where $\mathbf{K} = k_m\hat{\mathbf{K}}$. Considering the inverse $\mathbf{H}$ of the inertia matrix $\mathbf{M}$, the dynamic model in equations (11.9) and (11.10) with control law in equation (11.18), can be rewritten in terms of the new variable $\mathbf{z}$ as

$$\begin{aligned}\ddot{\boldsymbol{\theta}} = {} & \mathbf{H}_{\theta\theta}^T\left(\boldsymbol{\theta},\varepsilon^2\mathbf{z}\right)\left(\mathbf{u}-\mathbf{c}_\theta\left(\boldsymbol{\theta},\varepsilon^2\mathbf{z},\dot{\boldsymbol{\theta}},\varepsilon^2\dot{\mathbf{z}}\right)\right)-\mathbf{H}_{\theta\delta}\left(\boldsymbol{\theta},\varepsilon^2\mathbf{z}\right)\Big[\mathbf{c}_\delta\left(\boldsymbol{\theta},\varepsilon^2\mathbf{z},\dot{\boldsymbol{\theta}},\varepsilon^2\dot{\mathbf{z}}\right)\\ & +\mathbf{g}_\delta\left(\boldsymbol{\theta},\varepsilon^2\mathbf{z}\right)+\varepsilon^2\mathbf{D}\hat{\mathbf{K}}^{-1}\dot{\mathbf{z}}+\mathbf{z}+\mathbf{J}_\delta^T\left(\boldsymbol{\theta},\varepsilon^2\mathbf{z}\right)\mathbf{f}\Big]\end{aligned} \tag{11.19}$$

$$\begin{aligned}\varepsilon^2\mathbf{z} = {} & \hat{\mathbf{K}}\mathbf{H}_{\theta\delta}^T\left(\boldsymbol{\theta},\varepsilon^2\mathbf{z}\right)\left(\mathbf{u}-\mathbf{c}_\theta\left(\boldsymbol{\theta},\varepsilon^2\mathbf{z},\dot{\boldsymbol{\theta}},\varepsilon^2\dot{\mathbf{z}}\right)\right)-\hat{\mathbf{K}}\mathbf{H}_{\delta\delta}\left(\boldsymbol{\theta},\varepsilon^2\mathbf{z}\right)\Big[\mathbf{c}_\delta\left(\boldsymbol{\theta},\varepsilon^2\mathbf{z},\dot{\boldsymbol{\theta}},\varepsilon^2\dot{\mathbf{z}}\right)\\ & +\mathbf{g}_\delta\left(\boldsymbol{\theta},\varepsilon^2\mathbf{z}\right)+\varepsilon^2\mathbf{D}\hat{\mathbf{K}}^{-1}\dot{\mathbf{z}}+\mathbf{z}+\mathbf{J}_\delta^T\left(\boldsymbol{\theta},\varepsilon^2\mathbf{z}\right)\mathbf{f}\Big]\end{aligned} \tag{11.20}$$

where a suitable partition of $\mathbf{H}$ has been considered:

$$\mathbf{H}=\mathbf{M}^{-1}=\begin{bmatrix}\mathbf{H}_{\theta\theta} & \mathbf{H}_{\theta\delta}\\ \mathbf{H}_{\theta\delta}^T & \mathbf{H}_{\delta\delta}\end{bmatrix}$$

Equations (11.19) and (11.20) represent a singularly perturbed form of the flexible manipulator model; when$\varepsilon \to \infty$, the model of an equivalent rigid manipulator is recovered. In fact, setting $\varepsilon = 0$ and solving for $\mathbf{z}$ in equation (11.20) gives

$$\mathbf{z}_s=\overline{\mathbf{H}}_{\delta\delta}^{-1}\left(\boldsymbol{\theta}_s\right)\overline{\mathbf{H}}_{\theta\delta}^T\left(\boldsymbol{\theta}_s\right)\left(\mathbf{u}_s-\overline{\mathbf{c}}_\theta\left(\boldsymbol{\theta}_s,\dot{\boldsymbol{\theta}}_s\right)\right)-\overline{\mathbf{c}}_\delta\left(\boldsymbol{\theta}_s,\dot{\boldsymbol{\theta}}_s\right)-\overline{\mathbf{g}}_\delta\left(\boldsymbol{\theta}_s\right)-\overline{\mathbf{J}}_\delta^T\left(\boldsymbol{\theta}_s\right)\mathbf{f}_s \tag{11.21}$$

where the subscript s indicates that the system is considered in the *slow* timescale and the bar denotes that a quantity is computed with $\varepsilon = 0$. Substituting equation (11.21) into equation (11.19) with $\varepsilon = 0$ yields

$$\ddot{\boldsymbol{\theta}}_s=\overline{\mathbf{M}}_{\theta\theta}^{-1}\left(\boldsymbol{\theta}_s\right)\left(\mathbf{u}_s-\overline{\mathbf{c}}_\theta\left(\boldsymbol{\theta}_s,\dot{\boldsymbol{\theta}}_s\right)\right) \tag{11.22}$$

where the equality:

$$\overline{\mathbf{M}}_{\theta\theta}^{-1}\left(\boldsymbol{\theta}_s\right)=\left(\overline{\mathbf{M}}_{\theta\theta}\left(\boldsymbol{\theta}_s\right)-\overline{\mathbf{M}}_{\theta\delta}\left(\boldsymbol{\theta}_s\right)\overline{\mathbf{M}}_{\delta\delta}^{-1}\left(\boldsymbol{\theta}_s\right)\overline{\mathbf{M}}_{\theta\delta}^T\left(\boldsymbol{\theta}_s\right)\right)$$

has been exploited, where $\overline{\mathbf{M}}_{\theta\theta}\left(\boldsymbol{\theta}_s\right)$ represents the inertia matrix of the equivalent rigid manipulator and $\overline{\mathbf{c}}_\theta\left(\boldsymbol{\theta}_s,\dot{\boldsymbol{\theta}}_s\right)$ the vector of the corresponding Coriolis and centrifugal torques.

The dynamics of the system in the *fast* timescale can be obtained by setting $t_f = t/\varepsilon$, treating the slow variables as constants in the fast timescale, and introducing the fast variables $\mathbf{z}_f = \mathbf{z} - \mathbf{z}_s$. Thus, the fast system in equation (11.20) is

$$\frac{\mathrm{d}^2\mathbf{z}_f}{\mathrm{d}t_f^2}=-\hat{\mathbf{K}}\overline{\mathbf{H}}_{\delta\delta}\left(\boldsymbol{\theta}_s\right)\mathbf{z}_f+\hat{\mathbf{K}}\mathbf{H}_{\theta\delta}^T\left(\boldsymbol{\theta}_s\right)\mathbf{u}_f \tag{11.23}$$

where the fast control $\mathbf{u}_f = \mathbf{u} - \mathbf{u}_s$ has been introduced accordingly.

On the basis of the above two-timescale model, the design of a feedback controller for the system in equations (11.19) and (11.20) can be performed according to a composite control strategy, that is,

$$\mathbf{u}=\mathbf{u}_s\left(\boldsymbol{\theta}_s,\dot{\boldsymbol{\theta}}_s\right)+\mathbf{u}_f\left(\mathbf{z}_f,\mathrm{d}\mathbf{z}_f/\mathrm{d}t_f\right) \tag{11.24}$$

with the constraint that $\mathbf{u}_f(\mathbf{0},\mathbf{0}) = \mathbf{0}$ so that $\mathbf{u}_f$ is inactive along the equilibrium manifold specified by equation (11.21).

To design the slow control for the rigid nonlinear system in equation (11.22), it is useful to derive the slow dynamics corresponding to the end-point position. Differentiating equation (11.8) gives the end-point acceleration;

$$\dot{\mathbf{p}} = \mathbf{J}_\theta(\boldsymbol{\theta},\boldsymbol{\delta})\,\ddot{\boldsymbol{\theta}} + \mathbf{J}_\delta(\boldsymbol{\theta},\boldsymbol{\delta})\,\ddot{\boldsymbol{\delta}} + \mathbf{h}\left(\boldsymbol{\theta},\boldsymbol{\delta},\dot{\boldsymbol{\theta}},\dot{\boldsymbol{\delta}}\right)$$

where $\mathbf{h} = \dot{\mathbf{J}}_\theta\dot{\boldsymbol{\theta}} + \dot{\mathbf{J}}_\delta\dot{\boldsymbol{\delta}}$. Hence, the corresponding slow system is

$$\dot{\mathbf{p}}_s = \overline{\mathbf{J}}_\theta(\boldsymbol{\theta}_s)\,\overline{\mathbf{M}}_{\theta\theta}^{-1}(\boldsymbol{\theta}_s)\left(\mathbf{u}_s - \overline{\mathbf{c}}_\theta\left(\boldsymbol{\theta}_s,\dot{\boldsymbol{\theta}}_s\right)\right) + \overline{\mathbf{h}}\left(\boldsymbol{\theta}_s,\dot{\boldsymbol{\theta}}_s\right) \tag{11.25}$$

where equation (11.22) has been used. The slow dynamic models in equations (11.22) and (11.25) enjoy the same notable properties of the rigid robot dynamic models (Canudas de Wit *et al.*, 1996), hence the control strategies used for rigid manipulators can be adopted.

The fast system in equation (11.23) is a marginally stable linear slowly time-varying system that can be stabilised to the equilibrium manifold $\dot{\mathbf{z}}_f = \mathbf{0}$ ($\dot{\mathbf{z}} = \mathbf{0}$) and $\mathbf{z}_f = \mathbf{0}$ ($\mathbf{z} = \mathbf{z}_s$) by a proper choice of the control input $\mathbf{u}_f$. A reasonable way to achieve this goal is to design a state-space control law of the form:

$$\mathbf{u}_f = \mathbf{K}_1\dot{\mathbf{z}}_f + \mathbf{K}_2\mathbf{z}_f \tag{11.26}$$

where, in principle, the matrices $\mathbf{K}_1$ and $\mathbf{K}_2$ should be tuned for every configuration $\boldsymbol{\theta}_s$. However, the computational burden necessary to perform this strategy can be avoided by using constant matrix gains tuned with reference to a given robot configuration (Siciliano and Book, 1988); any state-space technique can be used, for example, based on classical pole placement algorithms.

11.4.2 Force and position regulation

The control objective consists of simultaneous regulation of the contact force $\mathbf{f}$ to a constant set point $\mathbf{f}_\mathrm{d}$ and of the position $\mathbf{p}$ to a constant set-point $\mathbf{p}_d$.

In case of contact with an elastically compliant surface, a viable strategy is the parallel control approach (Chiaverini and Sciavicco, 1993), which is especially effective in the case of inaccurate contact modelling. The key feature is to have a force control loop working in parallel to a position control loop along each task space direction. The logical conflict between the two loops is managed by imposing dominance of the force control action over position control, that is, force regulation is always guaranteed at the expense of a position error along the constrained directions.

A force/position parallel regulator controller for rigid robots was proposed in Chiaverini *et al.* (1994), based on position PD position control, gravity compensation, desired force feedforward and PI force control.

For the case of the flexible-link manipulator in equations (11.9) and (11.10), with reference to the slow system in equation (11.25), the following parallel regulator can be adopted:

$$\mathbf{u}_s = \overline{\mathbf{J}}_\theta^T(\boldsymbol{\theta}_s)\,k_P(\mathbf{p}_r - \mathbf{p}_s) - k_\mathrm{D}\dot{\boldsymbol{\theta}}_s \tag{11.27}$$

where $\mathbf{p}_r$ is defined as:

$$\mathbf{p}_r = \mathbf{p}_d + k_P^{-1}\left(k_F\left(\mathbf{f}_d - \mathbf{f}_s\right) + k_I\int_0^t\left(\mathbf{f}_d - \mathbf{f}_s\right)d\tau\right) \tag{11.28}$$

and $k_P, k_D, k_F, k_F > 0$ are suitable feedback gains.

A better insight into the behaviour of the system during the interaction can be achieved by considering a model of the compliant environment. For the purpose of this work, it is assumed that the same equation can be established in terms of the slow variables, that is,

$$\mathbf{f}_s = k_e\mathbf{nn}^T\left(\mathbf{p}_s - \mathbf{p}_o\right)$$

The above elastic model shows that the contact force is normal to the plane, and thus a null force error can be obtained only if the desired force $\mathbf{f}_d$ is aligned with $\mathbf{n}$. Also, it can be recognised that null position errors can be obtained only on the contact plane while the component of the position along $\mathbf{n}$ has to accommodate the force requirement specified by $\mathbf{f}_d$.

The stability analysis for the slow system in equation (11.25) with the control law in equations (11.27) and (11.28) can be carried out with the same arguments used in Chiaverini *et al.* (1994) for the case of rigid robots. In particular, it can be shown that if the Jacobian $\bar{\mathbf{J}}_\theta\left(\boldsymbol{\theta}_\mathrm{s}\right)$ of the equivalent rigid manipulator is full-rank, then the closed-loop system has an exponentially stable equilibrium at

$$\mathbf{p}_{s\infty} = \left(\mathbf{I} - \mathbf{nn}^T\right)\mathbf{p}_d + \mathbf{nn}^T\left(k_e^{-1}\mathbf{f}_d + \mathbf{p}_\mathrm{o}\right) \tag{11.29}$$

$$\mathbf{f}_{s\infty} = k_e\mathbf{nn}^T\left(\mathbf{p}_{s\infty} - \mathbf{p}_\mathrm{o}\right) = \mathbf{f}_d \tag{11.30}$$

where the matrix $\left(\mathbf{I} - \mathbf{nn}^T\right)$ projects the vectors on the contact plane. The equilibrium position is depicted in Figure 11.6. It can be seen that $\mathbf{p}_{s\infty}$ differs from $\mathbf{p}_d$ by a vector aligned along the normal to the contact plane whose magnitude is that necessary to

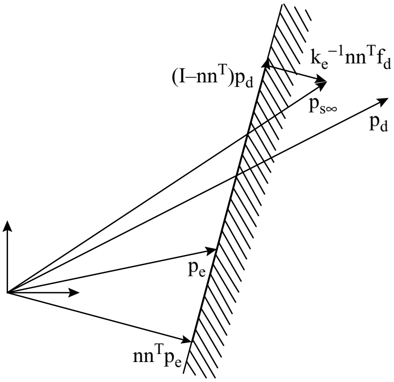

Figure 11.6 Equilibrium position with parallel force and position control

guarantee $\mathbf{f}_{s\infty} = \mathbf{f}_d$ in view of equation (11.30). Therefore, (for the slow system) force regulation is ensured while a null position error is achieved only for the component parallel to the contact plane.

If $\mathbf{f}_d$ is not aligned with $\mathbf{n}$, then it can be found that a drift motion of the end-point of the manipulator is generated along the plane; for this reason, if the contact geometry is unknown, it is advisable to set $\mathbf{f}_d = \mathbf{0}$.

As a final step, the full-order system in equations (11.9) and (11.10) and the composite control law in equation (11.27) with $\mathbf{u}_s$ in equation (11.27) and $\mathbf{u}_f$ in equation (11.26) have to be analysed. By virtue of Tikhonov's theorem it can be shown that regulation of the force $\mathbf{f}$ and of the position $\mathbf{p}$ is achieved with an order ε approximation.

11.4.3 Force regulation and position tracking

If tracking of a time-varying position $\mathbf{p}_\mathrm{d}(t)$ on the contact plane is desired (with an order ε approximation), an inverse dynamics parallel control scheme can be adopted for the slow system, that is,

$$\mathbf{u}_s = \overline{\mathbf{B}}_{\theta\theta}(\boldsymbol{\theta}_s)\,\overline{\mathbf{J}}_\theta^{-1}(\boldsymbol{\theta}_s)\left(\mathbf{a}_s - \overline{\mathbf{h}}\left(\boldsymbol{\theta}_s, \dot{\boldsymbol{\theta}}_s\right)\right) + \overline{\mathbf{c}}_\theta\left(\boldsymbol{\theta}_s, \dot{\boldsymbol{\theta}}_s\right) \tag{11.31}$$

where $\mathbf{a}_s$ is a new control input and a non-redundant manipulator has been considered.

Substituting equation (11.31) into equation (11.25) gives

$$\dot{\mathbf{p}}_s = \mathbf{a}_s$$

Hence, the control input $\mathbf{a}_s$ can be chosen as

$$\mathbf{a}_s = \dot{\mathbf{p}}_r + k_D(\dot{\mathbf{p}}_r - \dot{\mathbf{p}}_s) + k_P(\mathbf{p}_r - \mathbf{p}_s) \tag{11.32}$$

where

$$\mathbf{p}_r = \mathbf{p}_d + \mathbf{p}_C \tag{11.33}$$

and $\mathbf{p}_C$ is the solution of the differential equation

$$k_A\dot{\mathbf{p}}_C + k_V\dot{\mathbf{p}}_C = \mathbf{f}_d - \mathbf{f}_s \tag{11.34}$$

where $k_P, k_D, k_A, k_V > 0$ are suitable feedback gains.

Using the same arguments developed in Siciliano and Villani (1999) for rigid robots, it can be easily shown for the slow system that the control law in equations (11.31)–(11.34) ensures regulation of the contact force to the desired set-point $\mathbf{f}_d$ and tracking of the time-varying component of the desired position on the contact plane $\left(\mathbf{I} - \mathbf{n}\mathbf{n}^T\right)\mathbf{p}_d(t)$.

As before, Tikhonov's theorem has to be applied to the full-order system in equations (11.9) and (11.10) with the composite control law in equations (11.24), (11.26) and (11.31)–(11.34), and it can be shown that force regulation and position tracking are achieved with an order ε approximation.

11.4.4 Simulation

The above control laws are tested in simulation on the planar two-link flexible manipulator considered in Section 11.3, placed in the same initial position with the end-point in contact with the plane and null contact force. It is desired to reach the end-point position

$$\mathbf{p}_d = \begin{bmatrix} 0.55 & -0.35 \end{bmatrix}^T \text{m}$$

and a fifth-order polynomial trajectory with null initial and final velocity and acceleration is imposed from the initial to the final position with a duration of 5 s.

The desired force is taken from zero to the desired value

$$\mathbf{f}_d = \begin{bmatrix} 5 & 0 \end{bmatrix}^T \text{N}$$

according to a fifth-order polynomial trajectory with null initial and final velocity and acceleration and duration of 1s.

The fast control law $\mathbf{u}_f$ has been implemented with $\varepsilon = 0.1606$ and the matrix gains in equation (11.26) were tuned by solving a linear quadratic (LQ) problem for the system in equation (11.23) with the configuration dependent terms computed in the initial manipulator configuration. The matrix weights of the index performance have been chosen so that to preserve the timescale separation between slow and fast dynamics for both the control schemes. The resulting matrix gains are

$$\mathbf{K}_1 = \begin{bmatrix} -0.0372 & -0.0204 & -0.0375 & 0.1495 \\ 0.0573 & 0.0903 & 0.0080 & -0.7856 \end{bmatrix}$$

$$\mathbf{K}_2 = \begin{bmatrix} -0.1033 & -0.0132 & -0.0059 & -0.0053 \\ -0.0882 & 0.0327 & -0.0537 & -0.0217 \end{bmatrix}$$

In order to reproduce in simulation a real situation of a continuous-time system with a digital controller, the control laws are discretised with 5 ms sampling time, while the equations of motion are integrated using a variable step Runge–Kutta method with a minimum step size of 1 ms.

In the first case study, the slow controller in equations (11.27) and (11.28) is considered with the composite control law in equation (11.24). The actual force $\mathbf{f}$ and position $\mathbf{p}$ are used in the slow control law instead of the corresponding slow values, assuming that direct force measurement is available and that the end-point position is computed from joint angles and link deflection measurements via the direct kinematics equation (11.2). The control gains were set to $k_P = 100$ and $k_D = 4$.

Figure 11.7 shows the position error together with the time histories of the desired and actual contact force. It is easy to see that the contact force remains close to the desired value during the end-point motion (notice that the commanded position trajectory has a duration of 5 s) and reaches the desired set-point at steady state. The y-component of the desired position, which corresponds to a direction parallel to the contact plane, is regulated to the desired value. On the other hand, significant error occurs for the x-component; which corresponds to the direction normal to the contact plane, as expected. Notice that the steady-state value of the position error is exactly

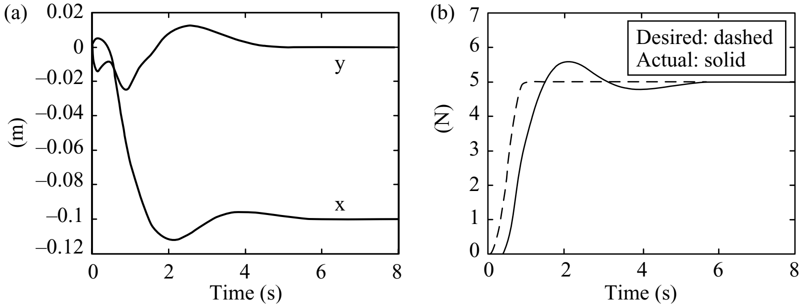

Figure 11.7 Time histories of the position error and of the contact force for the first case study: (a) position error, (b) contact force

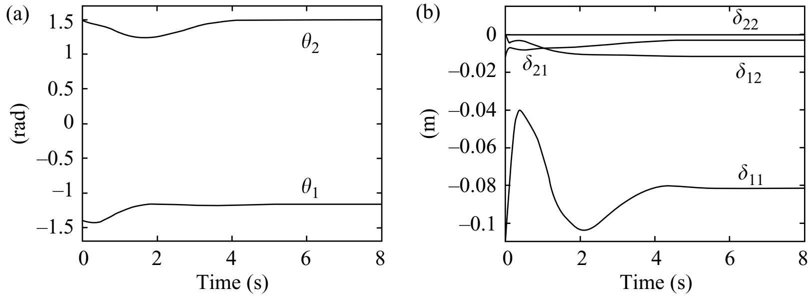

Figure 11.8 Time histories of the joint angles and of the link deflections for the first case study: (a) joint, angle, (b) link deflection

that required to achieve null force error, according to the equilibrium equations (11.29) and (11.30).

It can be seen from the time histories of the joint angles and link deflections shown in Figure 11.8 that the link response oscillations are well damped; moreover, because of gravity and contact force, the manipulator has to bend to reach the desired force and position.

Figure 11.9 shows the time history of the joint torque **u** and the first 0.5 s of the time history of the fast torque $\mathbf{u}_f$. It can be observed that the control effort keeps limited values during task execution; remarkably, the control torque $\mathbf{u}_f$ converges to zero with a transient much faster than the transient of **u** as expected.

In the second case study, the slow system in equations (11.31)–(11.34) is considered with the composite control law in equation (11.24). As before, the actual force **f** and position **p** are used in the controller in lieu of the corresponding slow variables. The control gains were set to $k_P = 100$, $k_D = 22$, $k_A = 0.7813$ and $k_V = 13.75$.

The time histories of the contact force and position errors are shown in Figure 11.10. This time the desired force set-point is reached after about 3 s, before

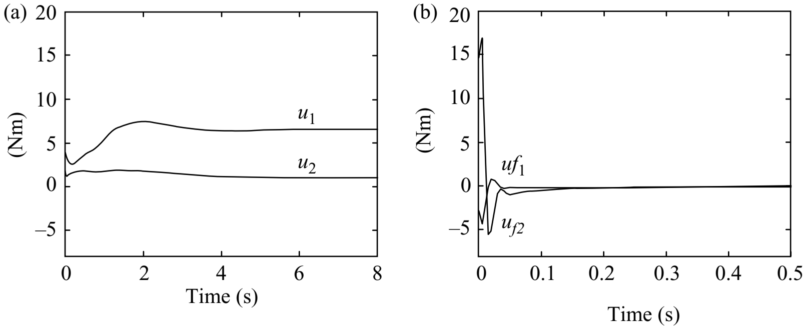

Figure 11.9 Time histories of the joint torques and fast control for the first case study: (a) joint torque, (b) fast control

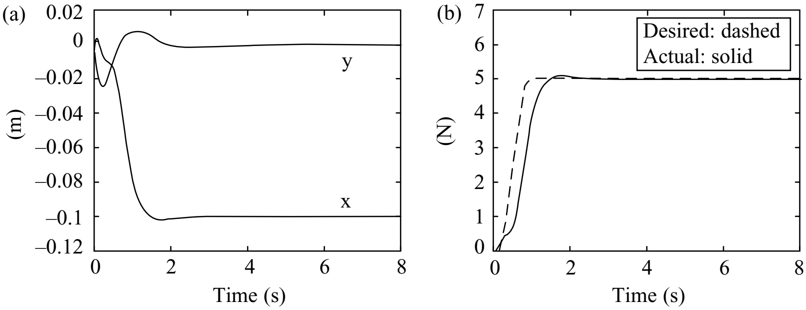

Figure 11.10 Time histories of the position error and of the contact force for the second case study: (a) position error, (b) contact force

the completion of the end-point motion. Moreover, the tracking performance for the y-component of the desired position is better than that in the previous case study.

The time histories of the joint angles and of the link deflections are shown in Figure 11.11, while the time histories of the components of the joint torque vector $\mathbf{u}$ and of the fast torque vector $\mathbf{u}_f$ are shown in Figure 11.12. It can be seen that although the performance is better than that in the previous case study, a similar control effort is required.

It is worth pointing out that the simulation of both the slow control laws without the fast control action in equation (11.26) has revealed an unstable behaviour; the results have not been reported for brevity.

11.5 Summary

The force control problem for a flexible manipulator in contact with a compliant environment has been considered. A dynamic model for a planar manipulator has been presented, which takes into account the forces acting on the end-point of the

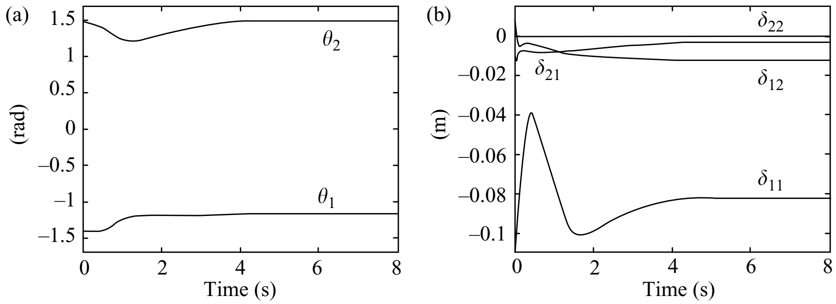

Figure 11.11 *Time histories of the joint angles and of the link deflections for the second case study: (a) joint angle, (b) link deflection*

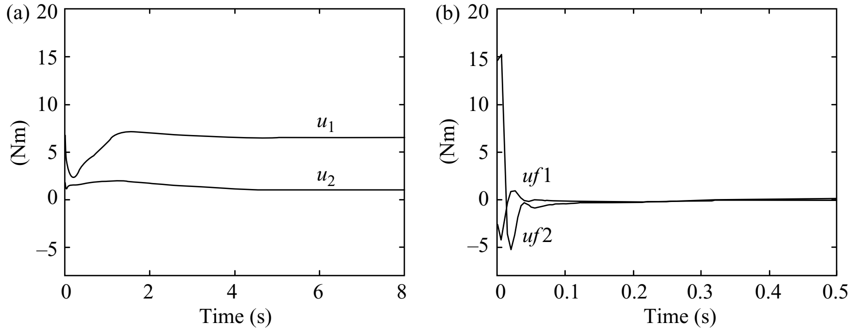

Figure 11.12 *Time histories of the joint torques and fast control for the second case study: (a) joint torque, (b) fast control*

robot. Two different approaches have been presented: a two-stage algorithm and a composite control law.

The attractive feature of the two-stage scheme is that it does not require force and deflection measurements. The price to pay is that an exact knowledge of the arm kinematics as well as the stiffness and position of the environment at rest are required to guarantee regulation of the force and of end-point position to a constant value.

In the composite control law, on the other hand, the additional objective of damping the vibrations that are naturally excited during the task execution is explicitly considered. By using the singular perturbation theory, the system has been split into a slow subsystem describing the rigid motion dynamics and a fast subsystem describing the flexible dynamics. This allows designing a fast control action for vibration damping as well as adopting algorithms designed for the rigid motion to achieve force and position control. Two different controllers have been considered, in the framework of parallel force and position control.

The simulation case studies developed on the model of a two-link flexible manipulator under gravity in contact with a compliant environment have confirmed the theoretical results.

References

AGHILI, F., DUPUIS, E., MARTIN, E. and PIEDBOEUF, J.-C. (2001). Force/moment accommodation control for tele-operated manipulators performing contact tasks in stiff environment. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robotics and Systems*, Maui, Hawaii, USA, 29 October–30 November 2001, 2227–2233.

ALBERTS, T. E. and COLVIN, J. A. (1991). Observations on the nature of transfer functions for control of piezoelectric laminates. *Journal of Intelligent Material Systems & Structures*, **2** (4), 528–541.

ALBERTS, T. E., DuBOIS, T. V. and POTA, H. R. (1995). Experimental verification of transfer functions for a slewing piezoelectric laminate beam. *Control Engineering Practice*, **3** (2), 163–170.

AMIROUCHE, F. M. L. (1992). *Computational methods in multibody dynamics*. Prentice Hall, Englewood Cliffs, New Jersey, USA.

ARMADA, M. (1987). Análisis y diseño de sistemas de control de robots industriales en el dominio multivariable de la frecuencia. *Automática e Instrumentación*, **175**, 147–153.

ASADA, H., MA, Z. D. and TOKUMARU, H. (1990). Inverse dynamics of flexible robot arms: Modeling and computation for trajectory control. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*. **112**, 177–185.

ASADA, H. and SLOTINE J. J. E. (1986). *Robot analysis and control*, John Wiley and Sons, Inc., New York, USA.

ASCHER, U., PAI, D. K. and CLOUTIER, B. (1997). Forward dynamics, elimination methods and formulation stiffness in robot simulation. *International Journal of Robotics Research*, **16** (2), 749–758.

ASPINWALL, D. M. (1980). Acceleration profiles for minimising residual response. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **102** (1), 3–6.

ÅSTRÖM, K. J. and HÄGGLUND, T. (1984). Automatic tuning of simple regulators with specifications on phase and amplitude margins. *Automatica*, **20** (5), 645–651.

ÅSTRÖM, K. J. and HÄGGLUND, T. (1995). *PID controllers: Theory, design, and tuning*, second edition. Instrument Society of America (ISA), North Carolina, USA.

ÅSTRÖM, K. J. and WITTENMARK, B. (1997). *Computer-controlled systems: Theory and design*, third edition. Prentice-Hall Inc., Englewood Cliffs, New Jersey, USA.

ATHERTON, D. P. (1999). PID controller tuning. *Computing and Control Engineering Journal*, **10** (2), 44–50.

ATHERTON, D. P. and BOZ, A. F. (1998). Using standard forms for controller design. *Proceedings of the UKACC International Conference on Control*, Swansea, UK, 1–4 September 1998, 1066–1071.

ATHERTON, D. P. and MAJHI, S. (1998). Tuning of optimum PIPD controllers. *Proceedings of the 3rd Portuguese Conference on Automatic Control (CONTROLO '98)*, Coimbra, Portugal, 9–11 September 1998, 549–554.

ATHERTON, D. P. and MAJHI, S. (1999). Limitations of PID controllers. *Proceedings of the American Control Conference*, San Diego, California, USA, 2–4 June 1999, 3843–3847.

AUBRUN, J.-N. (1980). Theory of the control structures by low-authority controllers. *Journal of Guidance and Control*, **3**, 444–451.

AZAD, A. K. M. (1994). Analysis and design of control mechanisms for flexible manipulator systems. PhD thesis, Department of Automatic Control and Systems Engineering, The University of Sheffield, UK.

AZAD, A. K. M., TOKHI, M. O., PATHANIA, A. and SHAHEED, M. H. (2004). A Matlab/Simulink based environment for intelligent modelling and simulation of flexible manipulator systems. *Proceedings of American Society for Engineering Education Annual Conference & Exposition*, Utah, USA, 20–23 June 2004, Document-826.

AZAM, M., SINGH, S. N., IYER, A. and KAKAD, Y. P. (1992). Detumbling and reorientation maneuvers and stabilization of NASA SCOLE system. *IEEE Transactions on Aerospace and Electronics Systems*, **28** (1), 80–92.

BAI, M., ZHOU, D.-H. and SCHWARZ, H. (1998). Adaptive augmented state feedback control for an experimental planar two-link flexible manipulator. *IEEE Transactions on Robotics and Automation*, **14** (6), 940–950.

BAILEY, T. and HUBBARD, J. E. (1985). Distributed piezoelectric-polymer active vibration control of a cantilever beam. *Journal of Guidance, Control, and Dynamics*, **8** (5), 605–611.

BALAS, M. J. (1978). Feedback control of flexible systems. *IEEE Transactions on Automatic Control*, **AC-23** (4), 673–679.

BALAS, M. J. (1979). Direct velocity feedback control of large space structures. *Journal of Guidance and Control*, **2** (3), 252–253.

BANKS, S. (1990). *Signal processing image processing and pattern recognition.* Prentice Hall International, Englewood Cliffs, New Jersey, USA.

BANERJEE, A., PEDREIRO, N. and SINGHOSE, W. (2001). Vibration reduction for flexible spacecraft following momentum dumping with/without slewing. *AIAA Journal of Guidance, Control, and Dynamics*, **24** (May–June), 417–428.

BAR-COHEN, Y., XUE, T, SHAHINPOOR, M., SIMPSON, J. and SMITH, J. (1998). Flexible, low-mass robotic arm actuated by electroactive polymers and operated equivalently to human arm and hand. *Rototics 98: The 3rd Conference and Exposition/Demonstration on Robotics for Challenging Environments*, New Mexico, USA, 26–30 April 1998, 15–21.

BARKER, H. A., JOBLING, C. P., RAVN, O., and SZYMKAT, M. (1993). A requirements analysis of future environments for computer aided control engineering. *The 12th IFAC World Congress*, Sydney, Australia, 13–18 July 1993, **8**, 373–376.

BATTITI, R. (1992). First and second order methods for learning: Between steepest descent and Newton's method. *Neural Computation*, **4** (2), 141–166.

BAUNGAARD, J. R. (1996). Modelling and control of flexible robot links. Ph.D. *thesis*, Department of Automation, Technical University of Denmark.

BAYO, E. (1987). A finite-element approach to control the end-point motion of a single-link flexible robot. *Journal of Robotic Systems*, **4** (1), 63–75.

BAYO, E. (1988). Computed torque for the position control of open-loop flexible robots, *Proceedings of IEEE International Conference on Robotics and Automation*, Philadelphia, USA, 25–29 April 1988, 316–321.

BAYO, E. (1989). Timoshenko versus Bernoulli–Euler beam theories for the inverse dynamics of flexible robots. *International Journal of Robotics and Automation*, **4** (1), 53–56.

BAYO, E. and MOULIN, H. (1989). An efficient computation of the inverse dynamics of flexible manipulators in the time domain. *Proceedings of the IEEE International Conference on Robotics and Automation*, Scottsdale, Arizona, USA, 14–19 May 1989, 710–715.

BAYO, E., SERNA, M. A., PAPADOPOULOS, P. and STUBBE, J. (1989). Inverse dynamics and kinematics of multi-link elastic robots: An iterative frequency domain approach. *The International Journal of Robotics Research*, **8** (6), 49–62.

BAZ, A. and POH, S. (1988). Performance of an active control system with piezoelectric actuators. *Journal of Sound and Vibrations*, **126** (2), 327–343.

BAZ, A., POH, S. and FEDOR, J. (1992). Independent modal space control with positive position feedback. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **114**, 96–103.

BENDAT, J. S. and PIERSOL, A. G. (1986). *Random data: Analysis and measurement procedures*. Wiley Interscience, New York, USA.

BENNETT, S. (1994). *Real-time computer control: An introduction*, second edition. Prentice-Hall, London, UK.

BENOSMAN, M. and LE VEY, G. (2002). Joint trajectory tracking for planar multi-link flexible manipulator: Simulation and experiment for a two-link flexible manipulator. *Proceedings of the IEEE International Conference on Robotics and Automation*, Washington DC, USA, 11–15 May 2002, 2461–2466.

BHAT, S. P. and MIU, D. K. (1990). Precise point-to-point positioning control of flexible structures. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **112** (4), 667–674.

BHAT, S. P., TANAKA, M. and MIU, D. K. (1991). Experiments on point-to-point position control of a flexible beam using Laplace transform technique-Part 1: Open-loop. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **113**, 432–437.

BIGRAS, P., SAAD, M. and O'SHEA, J. (1998). Exponential trajectory tracking in the workspace of a class of flexible robots. *Journal of Robotic Systems*, **15** (9), 487–504.

BILLINGS, S. A. and VOON, W. S. F. (1986). Correlation based model validity tests for non-linear systems. *International Journal of Control*, **15** (6), 601–615.

BISHOP, C. M. (1995). *Neural networks for pattern recognition*. Clarendon Press, Oxford, UK.

BLUM, E. K. and LI, L. K. (1991). Approximation theory and feedforward theory. *Neural Networks*, **4**, 511–515.

BOLZ, R. E. and TUVE, G. L. (1973). *CRC Handbook of tables for applied engineering science*. CRC Press, Inc., Boca Raton, Florida, USA.

BOOK, W. J. (1984). Recursive Lagrangian dynamics of flexible manipulator arms. *International Journal of Robotics Research*, **3** (3), 87–101.

BOOK, W. J. (1990). Modeling, design and control flexible manipulator arms: A tutorial review. *Proceedings of 29th Conference on Decision and Control*, Honolulu, Hawaii, USA, 5–7 December 1990, 500–506.

BOOK, W. J. (1993). Controlled motion in an elastic world. *Transactions of ASME:Journal of Dynamic Systems, Measurement, and Control*, **115**, 252–261.

BOOK, W. J., ALBERTS, T. E. and HASTINGS, G. G. (1986). Design strategies for high-speed lightweight robots. *Computers in Mechanical Engineering*, **5** (2), 26–33.

BOOK, W. J., MAIZZA-NETO, O. and WHITNEY, D. E. (1975). Feedback control of two beam, two joint systems with distributed flexibility. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **97** (4), 424–431.

BOOK, W. J. and MAJETTE, M. (1983). Controller design for flexible distributed parameter mechanical arms via combined state-space and frequency domain techniques. *Transactions of ASME: Journal of Dynamic Systems, Measurement and Control*, **105** (4), 245–254.

BOROWIEC, J. and TZES, A. (1996). Frequency-shaped explicit output feedback for flexible link manipulators. *Proceedings of the 35th Conference on Decision and Control*, Kobe, Japan, 11–13 December 1996, 4106–4111.

BOSSERT, D., LY U.-L. and VAGNERS, J. (1996). Experimental evaluation of robust reduced-order hybrid position/force control on a two-link manipulator. *Proceedings of the IEEE International Conference on Robotics and Automation*, Minneapolis, Minnesota USA, 22–28 April 1996, 2573–2578.

BOYER, F. and COIFFET, P. (1996). Generalization of Newton–Euler model for flexible manipulators. *Journal of Robotic Systems*, **13** (1), 11–24.

BREAKWELL, J. A. (1980). Control of flexible spacecraft. PhD thesis, Department of Aeronautics and Astronautics, Stanford University, USA.

BREHM, T. (1994). Hybrid fuzzy logic PID controller. *Proceedings of 3rd IEEE Conference on Fuzzy Systems*, **3**, 1682–1687.

BREMER, H. and PFEIFFER, F. (1992). *Elastic multibody systems*. Teubner, Stuttgard, Germany. In German.

BUENO, S. S., DE KEYSER, R. M. C. and FAVIER, G. (1991). Auto-tuning and adaptive tuning of PID controllers. *Journal of Acoustics*, **32** (1), 28–34.

BUFFINTON, K. W. (1992). Dynamics of elastic manipulators with prismatic joints. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **114**, 41–49.

BUFFINTON, K. W. and LAM, J. (1992). A comparative study of simple dynamic models and control schemes for elastic manipulators. *Proceedings of the American Control Conference*, Chicago, Illinois, USA, 24–26 June 1992, 3334–3339.

BURDEN, R. L. and FAIRES, J. D. (1989). *Numerical analysis*. PWS-KENT Publishing Company, Boston, Massachusetts, USA.

CALVERT, J. F. and GIMPEL, D. J. (1957). Method and apparatus for control of system output response to system input. US Patent No. 2,801,351.

CANNON, R. H. and SCHMITZ, E. (1984). Initial experiments on the end-point control of a flexible one-link robot. *International Journal of Robotics Research*, **3** (3), 62–75.

CANUDAS DE WIT, C., SICILIANO, B. and BASTIN, G. (Eds) (1996). *Theory of robot control*. Springer-Verlag, London.

CAPONETTO, R. C., FORTUNA, L., MANGANARO, G. and XIBILIA M. G. (1995). Chaotic system identification via genetic algorithm. *Proceedings of*

GALESIA-95: 1st IEE/IEEE International Conference on GAs in Engineering Systems: Innovations and Applications, Sheffield, UK, 12–14 September 1995, 170–174.

CASDAGLI, M. (1989). Non-linear prediction of chaotic time series. *Physics D*, **35**, 335–356.

CASPERSEN, M. K. (2000). Control of a flexible link robot. Master thesis, Department of Automation, The Technical University of Denmark, Denmark.

CETINKUNT, S. and BOOK, W. J. (1989). Symbolic modeling and dynamic simulation of robotic manipulators with compliant links and joints. *Robotics and Computer-Integrated Manufacturing*, **5** (4), 301–310.

CETINKUNT, S. and ITTOP, B. (1992). Computer-automated symbolic modeling of dynamics of robotic manipulators with flexible links.*IEEE Transactions on Robotics and Automation*, **8** (1), 94–105.

CETINKUNT, S. and YU, W.-L. (1991). Closed-loop behavior of a feedback-controlled flexible arm: A comparative study. *The International Journal of Robotics Research*, **10** (3), 263–275.

CHALHOUB, N. G. and ULSOY, A. G. (1987). Control of a flexible robot arm: Experimental and theoretical results. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **109** (4), 299–309.

CHAO, C.-T. and TENG, C.-C. (1997). A PD-like self-tuning fuzzy controller without steady-state error. *Fuzzy Sets and Systems*, **87**, 141–154.

CHAPNIK, B. V., HEPPLER, G. R., and APLEVICH, J. D. (1991). Modelling impact on a one-link flexible robotic arm. *IEEE Transactions on Robotics and Automation*, **7** (4), 479–488.

CHAPRA, S. and CANALE, R. (1988). *Numerical methods for engineers*, second edition. McGraw-Hill, New York, USA.

CHEN, J.-S. and MENQ, C.-H. (1990). Experiments on the payload-adaptation of a flexible one-link manipulator with unknown payload. *IEEE International Conference on Robotics and Automation*, Cincinnati, Ohio, USA, 13–18 May 1990, 1614–1619.

CHEN, M. and LINKENS, D.A. (1998). A hybrid neuro-fuzzy PID controller. *Fuzzy Sets and Systems*, **99**, 27–36.

CHEN, S., COWAN, C. F. N. and GRANT, P. M. (1991). Orthogonal least squares learning algorithm for radial basis function networks. The *IEEE Transactions on Neural Networks*, **2** (2), 302–309.

CHENG, W. and WEN, J. T. (1993). A neural controller for the tracking control of flexible arms. *Proceedings of the IEEE International Conference on Neural Networks*, San Francisco, USA, 28 March-01 April 1993, 749–754.

CHEONG, J., CHUNG, W. and YOUM, Y. (2001). Fast suppression of vibration for multi-link flexible robots using parameter adaptive control. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Maui, Hawaii, USA, 29 October–03 November 2001, 913–918.

CHIANG, W.-W., KRAFT, R. and CANNON, Jr., R. H. (1991). Design and experimental demonstration of rapid precise end-point control of a wrist carried by a very flexible manipulator. *The International Journal of Robotics Research*, **10** (1), 30–40.

CHIAVERINI, S. and SCIAVICCO, L. (1993). The parallel approach to force/position control of robotic manipulators. *IEEE Transactions on Robotics and Automation*, **9**, 361–373.

CHIAVERINI, S., SICILIANO, B. and VILLANI, L. (1994). Force/position regulation of compliant robot manipulators. *IEEE Transactions on Automatic Control*, **39**, 647–652.

CHIOU, B. C. and SHAHINPOOR, M. (1990). Dynamic stability analysis of a two-link force-controlled flexible manipulator. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **112**, 661–666.

CHIPPERFIELD, A. J., FLEMING, P. J., POHLHEIM, H. and FONSECA, C. (1994). A genetic algorithm toolbox for MATLAB. *Proceedings of the International Conference on Systems Engineering*, Coventry, UK, 6–8 September 1994, 200–207.

CHO, K., HORI, N. and ANGELES, J. (1991). On the controllability and observability of flexible beams under rigid-body motion. *Proceedings of the 1991 International Conference on Industrial Electronics, Control and Instrumentation*, Kobe, 28 October–1 November 1991, 455–460.

CHOI, S. B., GANDHI, M. V. and THOMPSON, B. S. (1988). An experimental investigation of an articulating robotic manipulator with a graphite epoxy arm. *Journal of Robotic Systems*, **5**, 73–79.

CHOURA, S. and YIGIT, A. S. (2001). Control of a two-link rigid-flexible manipulator with a moving payload mass. *Journal of Sound and Vibration*, **243**, 883–897.

CHOW, J. H. and KOKOTOVIC, P. V. (1978). Two-time-scale feedback design of a class of non-linear systems. *IEEE Transactions on Automatic Control*, **23** (3), 438–443.

CHUNG, H.-Y., CHEN, B.-C. and LIN, J.-J. (1998). A PI-type fuzzy controller with self-tuning scaling factors. *Fuzzy Sets and Systems*, **93**, 23–28.

CLOUGH, R. W. and PENZIEN, J. (1975). *Dynamics of structures*. McGraw-Hill Book Company, New York, USA.

COOK, R. D. (1981). *Concepts and applications of finite element analysis*. Wiley, New York, USA.

CRANDALL, S. H., KARNOPP, D. C., KURTZ, E. F. and PRIDMORE-BROWN, D. C. (1968). *Dynamics of mechanical and electromechanical systems*. McGraw-Hill Inc., New York, USA.

CRAWLEY, E. F. and ANDERSON, E. H. (1990). Detailed models of piezoelectric actuation of beams. *Journal of Intelligent Material Systems and Structures*, **1**, 4–25.

CRAWLEY, E. F. and LUIS, J. (1987). Use of piezoelectric actuators as elements of intelligent structures. *AIAA Journal*, **25** (10), 1373–1385.

CUNDARI, M. and ABEDIAN, B. (1991). The dynamic behavior of a polyvinylidene fluoride piezoelectric motional device. *Proceedings of Smart Structures and Materials, Winter Annual Meeting of the American Society of Mechanical Engineers*, Atlanta, Georgia, USA, 1–6 December 1991, 25–31.

DADO, M. and SONI, A. H. (1986). A generalized approach for forward and inverse dynamics of elastic manipulators. *Proceedings of IEEE Conference on Robotics and Automation*, San Francisco, California, USA, 7–10 April 1986, 359–364.

DALEY, S. and LIU, G. P. (1999). Optimal PID tuning using direct search algorithms. *Computing and Control Engineering Journal*, **10** (2), 51–56.

DANCOSE, S. and ANGELES, J. (1989). Modelling and simulation of flexible beams using cubic splines and zero-order holds. *International Symposium on the Mathematical Theory of Networks and Systems*, Amsterdam, The Netherlands, 19–23 June 1989, 553–564.

DANCOSE, S., ANGELES, J. and HORI, N. (1989). Optimal vibration control of a rotating flexible beam. *Proceedings of the 12th Biennial ASME Conference on Mechanical Vibration and Noise, Diagnostics, Vehicle Dynamics and Special Topics*, Montreal, Canada, 17–20 September 1989, DE-Vol. 18-5, 259–264.

DAVIS, J. H. and HIRSCHORN, R. M. (1988). Tracking control of flexible robot link. *IEEE Transactions on Automatic Control*, **33** (3), 238–248.

DE CARUFEL, J., MARTIN, E. and PIEDBOEUF, J.-C. (2000). Control strategies for hardware-in-the-loop simulation of flexible space robots. *IEE Proceedings – D: Control Theory and Applications*, **147** (6), 569–579.

D'ELEUTERIO, G. M. T. (1992). Dynamics of an elastic multibody chain: Part C-Recursive dynamics. *Dynamics and Stability of Systems*, **7** (2), 61–89.

DE LUCA, A., ISIDORI, A. and NICOLO, F. (1985*a*). An application of nonlinear model matching to the dynamic control of robot arms with elastic joints. *Proceedings of Syroco '85: IFAC Symposium on Robotic Control*, Barcelona, Spain, 6–8 November 1985, 219–225.

DE LUCA, A., ISIDORI, A. and NICOLO, F. (1985*b*). Control of robot arm with elastic joints via nonlinear dynamic feedback. *Proceedings of the 24th IEEE Conference on Decision and Control*, Fort Lauderdale, Florida, USA, 11–13 December 1985, 1671–1679.

DE LUCA, A., LUCIBELLO, P. and NICOLO, F. (1988). Automatic symbolic modelling and non-linear control of robots with flexible links. *Proceedings of IEE Seminar on Robotics and Control*, Oxford, UK, 13–15 April 1988, 62–70.

DE LUCA, A. and PANZIERI, S. (1994). An iterative scheme for learning gravity compensation in flexible robot arms. *Automatica*, **30** (6), 993–1002.

DEWCA, A. and SICILIANO, B. (1989). Trajectory control of a non-linear one-line flexible arm. *International Journal of Control*, **50**, 1699–1715.

DE LUCA, A. and SICILIANO, B. (1991). Closed-form dynamic model of planar multilink lightweight robots. *IEEE Transactions on Systems, Man, and Cybernetics*, **21** (4), 826–839.

DE LUCA, A. and SICILIANO, B. (1993). Regulation of flexible arms under gravity. *IEEE Transactions on Robotics and Automation*, **9**, 463–467.

DE SCHUTTER, J. and VAN BRUSSEL, H. (1988). Compliant robot motion II. A control approach based on external control loops. *International Journal of Robotics Research*, **7** (4), 18–33.

DELLMAN, R., GLICKSBER, I. and GROSS, O. (1956). On the bang-bang control problem. *Quarterly of Applied Mechanics*, **14**, 11–18.

DEROOVER, D., BOSGRA, O. H., SPERLING, F. B. and STEINBUCH, M. (1996). High-performance motion control of a wafer stage. *Philips Conference on Applications of Control Technology*, Epe, The Netherlands, 29–30 October 1996.

DEROOVER, D., SPERLING, F. B. and BOSGRA, O. H. (1998). Point-to-point control of a MIMO servomechanism. *Proceedings of* the *American Control Conference*, Philadelphia, Pennsylvania, USA, June 1998, 2648–2651.

DOETSCH, K. H. and MIDDLETON, J. A. (1987). Canada's space program. *Canadian Aeronautics and Space Journal*, **33** (4), 61–89.

DONNE, J. D. and ÖZGÜNER, U. (1994). Neural control of a flexible-link manipulator. *Proceedings of the IEEE International Conference on Neural Networks*, Orlando, Florida, USA, 27 June–2 July 1994, 2327–2332.

DORATO, P. (1987). A historical review of robust control. *IEEE Control Systems Magazine*, **7**, 44–47.

DOYON, M., PIEDBOEUF, J.-C., AGHILI, F., GONTHIER, Y. and MARTIN, E. (2003). The SPDM task verification facility: On the dynamic emulation in one-g environment using hardware-in-the-loop simulation. *The 7th International Symposium on Artificial Intelligence and Robotics & Automation in Space: i-SAIRAS 2003*, Nara, Japan, 19–23 May 2003.

DRAPEAU, V. and WANG, D. (1993). Verification of a closed-loop shaped-input controller for a five-bar-linkage manipulator. *Proceedings of IEEE International Conference on Robotics and Automation*, Atlanta, Georgia, USA, 2–6 May 1993, 216–221.

DUBOWSKY, S. and PAPADOPOULOS, E. (1993). The kinematics, dynamics, and control of free-flying and free-floating space robotic systems. *IEEE Transactions on Robotics and Automation*, **9** (5), 531–543.

DUTTON, K., THOMPSON, S. and BARRACLOUGH, B. (1997). *The Art of Control Engineering*. Addison-Wesley, Harlow, VK.

DWIGHT, H. B. (1957). *Tables and integrals and other mathematical data*, third edition. Macmillan, New York, USA.

ELANAYAR, S. V. T. and YUNG, C. S. (1994). Radial basis function neural network for approximation and estimation of non-linear stochastic dynamic systems. The *IEEE Transactions on Neural Networks*, **5** (4), 594–603.

EPPINGER, S. and SEERING, W. (1988). Modeling robot flexibility for endpoint force control. A.I. Memo 1046. MIT Artificial Intelligence Lab., May 1988.

FEATHERSTONE, R. (1987). *Robot dynamics algorithms*. Kluwer Academic Publishers, London.

FEDDEMA, J. T. (1993). Digital filter control of remotely operated flexible robotic structures. *Proceedings of the American Control Conference*, San Francisco, California, USA, 2–4 June 1993, 2710–2715.

FEDDEMA, J., DOHRMANN, C., PARKER, G., ROBINETT, R., ROMERO, V. and SCHMITT, D. (1997). Control for slosh-free motion of an open container. *IEEE Control Systems Magazine*, **17** (1), 29–36.

FEDDEMA, J., PETTERSON, B. and ROBINETT, R. (1998). Operator control systems and methods for swing-free Gantry-style cranes, US Patent No. 5, 785, 191.

FELIÚ, V., RATTAN, K. S. and BROWN, Jr, H. (1990). Adaptive control of a single-link flexible manipulator. *IEEE Control Systems Magazine*, **10**, 29–33.

FELIÚ, V., RATTAN, K. S. and BROWN Jr, H. B. (1992). Modelling and control of single link flexible arms with lumped masses. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **114**, 59–69.

FELIÚ, V., RATTAN, K. and BROWN Jr, H. (1995). Control of a two-degree-of-freedom lightweight flexible arm with friction in the joints. *Journal of Robotic Systems*, **12** (1), 1391–1395.

FERNÁNDEZ, G. (1997). *Control multivariable en el dominio de la frecuencia de robots rígidos y flexibles*. PhD thesis, University of Valladolid, Valladolid, Spain.

FERNÁNDEZ, G., ARMADA, M. and GRIECO, J. C. (1993). Estudio del acoplamiento en modelos de robots industriales. *3er Congreso de la Asociación Española de Robótica.* 17–19 November 1993, Zaragoza, Spain, **1**, 75–84.

FERNÁNDEZ, G., GRIECO, J. C. and ARMADA, M. (1994*a*). Decoupling control for robot manipulators using multivariable frequency domain techniques.

5th International Symposium on Application of Multivariable System Techniques. Mechanical Engineering Publishers Ltd, UK, London, 235–245.

FERNÁNDEZ, G., GRIECO, J. C. and ARMADA, M. (1994*b*). Achieving diagonal dominance for robot control. *Studies in Informatics and Control*, **3** (2), 241–252.

FERNÁNDEZ, G., GRIECO, J. C., ARMADA, M. and GONZÁLEZ de SANTOS, P. (2002*a*). Following strategy for deflection avoiding on a flexible manipulator. *CLCA 2002: IFAC Latin-American Conference on Automatic Control*. Guadalajara, México, 3–5 December, 2002.

FERNÁNDEZ, G., GRIECO, J. C. and ARMADA, M. (2002*b*). Pre-filter design for decoupling control of a flexible manipulator. *CLCA 2002: IFAC Latin-American Conference on Automatic Control*. Guadalajara, México, 3–5 December, 2002.

FLIESS, M. (1989). Nonlinear control theory and differential algebra. In *Modelling and Adaptive Control*. Lecture Notes in Control and Information Sciences, **15**, Springer-Verlag, Berlin, 135–145.

FONSECA, C. M., MENDES, E. M., FLEMING, P. J. and BILLINGS, S. A. (1993). Non-linear model term selection with genetic algorithms. *Proceedings of Workshop on Natural Algorithms in Signal Processing*, Essex, UK, 15–16 November 1993, 27/1–27/8.

FORD, M. P. and DALY, K. C. (1979). Dominance improvement by pseudodecoupling. *Proceedings of the IEE*, **126**, 1316–1320.

FRASER, A. R. and DANIEL, R. W. (1991). *Perturbation techniques for flexible manipulators*. Kluwer Academic Publishers, Boston, Massachusetts, USA.

FRIEDLAND, B. (1986). *Control system design – An introduction to state-space methods*. McGraw-Hill, New York, USA.

FRIMAN, M. and WALLER, K. V. (1994). Autotuning of multiloop control systems. *Journal of Industrial and Engineering Chemistry Research*, **33** (7), 1708–1717.

FUKUDA, T. (1985). Flexibility control of elastic robot arms. *Journal of Robotic Systems*, **2** (1), 73–88.

GE, S. S., LEE, T. H. and GONG, J. Q. (1998*a*). Dynamic modeling of a smart materials robot. *AIAA Journal*, **36** (8), 1466–1478.

GE, S. S., LEE, T. H., GONG, J. Q. and WANG, Z. P. (2000). Model-free controller design for a single-link flexible smart materials robot. *International Journal of Control*, **73** (6), 531–544.

GE, S. S., LEE, T. H. and HARRIS, C. J. (1998*b*). *Adaptive neural network control of robot manipulators*. World Scientific, New Jersey, USA.

GE, S. S., LEE, T. H. and TAN, E. G. (1997). Adaptive neural network control of flexible link robots based on singular perturbation. *Proceedings of the IEEE International*

Conference on Control Applications, Hardford, Maryland, USA, 5–7 October 1997, 365–369.

GE, S. S., LEE, T. H. and WANG, Z. P. (2001*a*). Adaptive neural network control for smart materials robots using singular perturbation technique. *Asian Journal of Control*, **3** (2), 143–155.

GE, S. S., LEE, T. H. and WANG, Z. P. (2001*b*). Model-free regulation of multi-link flexible smart materials robots. *IEEE/ASME Transactions on Mechatronics*, **6** (3), 346–351.

GE, S. S., LEE, T. H. and ZHU, G. (1996). Energy-based robust controller design for multi-link flexible robots. *Mechatronics*, **6** (7), 779–798.

GE, S. S., LEE, T. H. and ZHU, G. (1998*c*). Improving regulation of a single-link flexible manipulator with strain feedback. *IEEE Transactions on Robotics and Automation*, **14** (1), 179–185.

GE, S. S. and POSTLETHWAITE, I. (1995). Adaptive neural network controller design for flexible joint robots using singular perturbation technique. *Transactions of the Institute of Measurement and Control*, **17** (2), 120–131.

GENIELE, H., PATEL, R.V. and KHORASANI, K. (1992). Control of flexible manipulator. *Proceedings of the 4th ASME International Symposium on Robotics and Manufacturing*, New Mexico, USA, 11–13 November 1992, 567–572.

GÉRADIN, M. and CARDONA, A. (2001). *Flexible multibody dynamics: A finite element approach*. John Whiley and Sons, Chichester, UK.

GERALD, C. F. and WHEATLEY, P. O. (1985). *Applied Numerical Analysis*. Addison-Wesley Publishing Company, Reading, Massachusetts, USA.

GEVARTER, W. B. (1970). Basic relations for control of flexible vehicles. *AIAA Journal*, **8**, 666–672.

GIOVAGNONI, M. (1994). A numerical and experimental analysis of a chain of flexible bodies. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **106** (1), 73–80.

GOH, S. P. (2001). Investigation and implementation of advanced control techniques for flexible manipulators. PhD thesis, Department of Mechanical Engineering, the University of Leeds, UK.

GOH, S. P., PLUMMER, A. R. and BROWN, M. D. (2000*a*). Decoupling multivariable pole-placement controller of a flexible manipulator. *EUREL European Advanced Robotics Systems Masterclass and Conference – Robotics 2000*, Salford, UK, 12–14 April 2000.

GOH, S. P., PLUMMER, A. R. and BROWN, M. D. (2000*b*). Digital control of a flexible manipulator. *Proceedings of the American Control Conference*, Chicago, Illinois, USA, 28–30 June 2000, 2205–2209.

GOLDBERG, D. E. (1989). *Genetic algorithms in search, optimisation and machine learning*. Addison-Wesley, Reading, Massachusetts, USA.

GONTHIER, Y., MCPHEE, J., LANGE, C. and PIEDBOEUF, J.-C. (2004). A regularized contact model with asymmetric damping and dwell-time dependent friction. *Multibody System Dynamics*, **11** (3), 209–233.

GORINEVSKI, D. M., FORMALSKY, A. M. and SCHNEIDER. A. Y. (1997). *Force control of robotics systems*. CRC Press, Boca Raton, Florida, USA.

GREFENSTETTE, J. J. (1986). Optimisation of control parameters for genetic algorithms. *IEEE Transactions on Systems, Man and Cybernetics*, **16** (1), 122–128.

GU, M. (2002). Statics of flexible manipulator: Modeling and validation. Technical Report CSA-TR-2002-0003, Canadian Space Agency, Canada.

GU, M. and PIEDBOEUF, J.-C. (2002). Three-dimensional kinematic analysis and verification for a flexible robot arm. *ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Montreal, Canada, 29 September–2 October 2002, Paper No. MECH-34260.

GUTIÉRREZ, L. B., LEWIS, F. L. and LOWE J. A. (1998). Implementation of a neural network tracking controller for a single flexible link: Comparison with PD and PID controllers. The *IEEE Transactions on Industrial Electronics*, **45** (2), 307–318.

GUYAN, R. J. (1965). Reduction of stiffness and mass matrices. *AIAA Journal*, **3** (2), 380.

HAGAN, M. T. and MENHAJ, M. B. (1994). Training feedforward networks with Marquardt algorithm. *IEEE Transactions on Neural Networks*, **5** (6), 989–993.

HANSON, L. and SALAMON, P. (1990). Neural network ensembles. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **12**, 993–1001.

HAPPEL, B. M. and MURRE, J. J. (1994). Design and evolution of modular neural network architectures. *Neural Networks*, **7**, 985–1004.

HARA, S. and YOSHIDA, K. (1994). Simultaneous optimization of positioning and vibration controls using time-varying criterion function. *Journal of Robotics and Mechatronics*, **6** (4), 278–284.

HARASHIMA, F. and UESHIBA, T. (1986). Adaptive control of flexible arm using the end-point position sensing. *Proceedings of Japan-USA Symposium on Flexible Automation*, Osaka, 15–20 July, 225–229.

HARDT, M. W. (1999). Multibody dynamical algorithms, numerical optimal control, with detailed studies in the control of jet engine compressors and biped walking. PhD Thesis, Electrical Engineering, University of California, San Diego, California, USA.

HARRIS, C. J., MOORE, C. G. and BROWN, M. (1993). *Intelligent control: Aspects of fuzzy logic and neural nets*. World Scientific, London.

HASHTRUDI-ZAAD, K. and KHORASANI, K. (1996). Control of non-minimum phase singularly perturbed systems with applications to flexible manipulators. *International Journal of Control*, **63**, 679–701.

HASTINGS, G. G. and BOOK, W. J. (1987). A linear dynamic model for flexible robotic manipulator. *IEEE Control Systems Magazine*, **7** (1), 61–64.

HE, S. Z., TAN, S. H., XU, F. L. and WANG, P. Z. (1993). PID self-tuning control using a fuzzy adaptive mechanism. *Proceedings of the 2nd IEEE International Conference on Fuzzy Systems*, San Francisco, California, USA, 28 March–01 April 1993, **2**, 708–713.

HE, X. and LAPEDES, A. (1993). Non-linear modelling and prediction by successive approximation using radial basis functions. *Physics D*, **70**, 289–301.

HILLSLEY, K. L. and YURKOVICH, S. (1993). Vibration control of a two-link flexible robot arm. *Dynamics and Control*, **3**, 261–280.

HODGE, L., AUDA, G. and KAMEL, M. (1999). Learning decision fusion in cooperative modular neural networks. *International Joint Conference on Neural Networks: IJCNN'99*, Piscataway, New Jersey, USA, 10–16 July 1999, **4**, 2777–2781.

HOGAN, N. (1985). Impedance control: An approach to manipulation: Parts I–III. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **107**, 1–24.

HOGAN, N. (1987). Stable execution of contact task using impedance control. *Proceedings of IEEE International Conference on Robotics and Automation*, Raleigh, North Carolina, USA, 31 March–3 April 1987, 1047–1054.

HOLLAND, J. (1975). *Adaptation in natural and artificial systems*, University of Michigan Press, Michigan, USA.

HOLLAND, J. (1992). *Adaptation in natural and artificial systems: An introductory analysis with applications to biology*. MIT Press, Massachusetts, USA.

HOSSAIN, M. A., TOKHI, M. O., CHIPPERFIELD, A. J., FONSECA, C. M. and DAKEV, N. V. (1995). Adaptive active vibration control using genetic algorithms. *Proceedings of GALESIA-95: 1st IEE/IEEE International Conference on GAs in Engineering Systems: Innovations and Applications*, Sheffield, UK, 12–14 September 1995, 175–180.

HU, A. (1993). A survey of experiments for modeling verification and control of flexible robotic manipulators. *Proceedings of The 1st IEEE Regional Conference on Aerospace Control Systems*, Westlake, California, USA, 25–27 May 1993, 344–353.

HU, F. L. and ULSOY, A. G. (1994). Force and motion control of a constrained flexible robot arm. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **116**, 336–343.

HUGHES P. C. (1987). Space structure vibration modes: How many exists? Which are important. *IEEE Control Systems Magazine*, **7** (1), 22–28.

HURTY, W. C. (1965). Dynamic analysis of structural systems using component modes. *AIAA Journal*, **3** (4), 678–685.

HYDE, J. M. and SEERING, W. P. (1991). Using input command pre-shaping to suppress multiple mode vibration. *Proceedings of IEEE International Conference on Robotics and Automation*, Sacramento, California, USA, 9–11 April 1991, 2604–2609.

ISERMANN, R. (1989). *Digital control systems – Vol. 1: Fundamentals, deterministic control*, second revised edition. Springer-Verlag, Berlin Heidelberg, Germany.

IWAMOTO, K., KOIKE, Y., NONAMI, K., TANIDA, K. and IWASAKI, I. (2002). Output feedback sliding mode control for bending and torsional vibration control of 6-story flexible structure. *JSME International Journal*, Series C. **45** (1), 150–158.

JACKSON, L. B. (1989). *Digital filters and signal processing*. Kluwer Academic Publishers, London.

JACOBS, R. A. and JORDAN, M. I. (1993). Learning piecewise control strategies in a modular neural network architecture. *IEEE Transactions on Systems, Man, and Cybernetics*, **23** (2), 337–345.

JAIN, A. and RODRIGUEZ, G. (1992). Recursive flexible multibody system dynamics using spatial operators. *AIAA Journal of Guidance, Control, and Dynamics*, **15** (6), 1453–1466.

JAIN, A. K. and MOHIUDDIN K. M. (1996). Artificial neural networks: A tutorial. *Computer*, **29** (3), 31–44.

JANSEN, J. F. (1992). Control and analysis of a single-link flexible beam with experimental verification. ORNL/TM-12198, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

JAYASURIYA, S. and CHOURA, S. (1991). On the finite settling time and residual vibration control of flexible structures. *Journal of Sound and Vibration*, **148**, 117–136.

JOHANSSON, K. H., JAMES, B., BRYAN, G. F. and ÅSTRÖM, K. J. (1998). Multivariable controller tuning. *Proceedings of the American Control Conference*, Philadelphia, Pennsylvania, USA, 24–26 June 1998, **6**, 3514–3518.

JONES, J. F., PETTERSON, B. J. and STRIP, D. R. (1991). Methods of and system for swing damping movement of suspended objects. US Patent No. 4, 997, 095.

JONES, S. and ULSOY, A. G. (1999). An approach to control input shaping with application to coordinate measuring machines. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **121** (June), 242–247.

JORDAN, S. (2002). Eliminating vibration in the nano-world. *Photonics Spectra*, **36** (July), 60–62.

JUNKINS, J. L. and BANG, H. (1993). Maneuver and vibration control of hybrid coordinate systems using Lyapunov stability theory. *AIAA Journal of Guidance, Control, and Dynamics*, **16** (4), 668–676.

KANE, T. R., RYAN, R. R. and BANERJEE, A. K. (1987). Dynamics of a cantilever beam attached to a moving base. *AIAA Journal of Guidance, Control and Dynamics*, **10** (12), 139–151.

KANOH, H., TZAFESTAS, S., LEE, H. G. and KALAL, J. (1986). Modelling and control of flexible robot arms. *Proceedings of 25th Conference on Decision & Control*, Athens, Greece, 10–12 December 1986, 1866–1870.

KARAKASOGLU, A., SUDHARSANAN, S. I. and SUNDARESHAN, M. K. (1993). Identification and decentralised adaptive control using dynamical neural networks with application to robotic manipulators. *IEEE Transactions on Neural Networks*, **4** (6), 919–930.

KARGUPTA, H. and SMITH, R. E. (1991). System identification with evolving polynomial networks. *Proceedings of the 4th International Conference on Genetic Algorithms*, San Diego, California, USA, 14–17 July 1991, 370–376.

KARR, C. L. (1991). Design of an adaptive fuzzy logic controller using genetic algorithms. *Proceedings of the 4th International Conference on Genetic Algorithms*, San Diego, California, USA, 13–16 July 1991, 450–457.

KARRAY, F. and MODI, V. (1995). On the pointing robustness issue of a class of new generation spacecraft. *IEEE Transactions on Automatic Control*, **40** (12), 2132–2137.

KECMAN, V. (1996). System identification using modular neural network with improved learning. *Proceedings of the International Workshop on Neural Networks for Identification, Control, Robotics, and Signal/Image Processing*, Los Alamitos, California, USA, 21–23 August 1996, 40–48.

KELKAR, A. G., ALBERTS, T. E. and JOSHI, S. M. (1992). Asymptotic stability of dissipative compensators for flexible multibody systems in the presence of actuator dynamics and actuator/sensor nonlinearities. *Proceedings of ASME 1992 Winter Annual Meeting,* Anaheim, California, USA, 8–13 November 1992, **AMD-141**, 35–38.

KENISON, M. and SINGHOSE, W. (1999). Input shaper design for double-pendulum planar gantry cranes. *Proceedings of IEEE Conference on Control Applications*, Hawaii, USA, 22–27 August 1999, 539–544.

KENISON, M. and SINGHOSE, W. (2002). Concurrent design of input shaping and proportional plus derivative feedback control. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **124** (3), 398–405.

KERWIN Jr, E. M. (1959). Damping of flexural waves by a constrained viscoelastic layer. *Journal of the Acoustical Society of America*, **31**, 952–962.

KHORRAMI, F. and JAIN, S. (1993). Nonlinear control with end-point acceleration feedback for a two-link flexible manipulator: Experimental results. *Journal of Robotic Systems*, **10** (4), 505–530.

KHORRAMI, F., JAIN, S. and TZES, A. (1993). Adaptive nonlinear control and input preshaping for flexible-link manipulators. *Proceedings of the American Control Conference*, San Francisco, California, USA, 2–4 June 1993, 2705–2709.

KHORRAMI, F., JAIN, S. and TZES, A. (1994). Experiments of rigid body-based controllers with input preshaping for a two-link flexible manipulator.*IEEE Transactions on Robotics and Automation*, **10** (1), 55–65.

KHORRAMI, F. and ÖZGÜNER, Ü. (1988). Perturbation methods in control of flexible link manipulators, *Proceedings of the IEEE International Conference on Robotics and Automation*, Philadelphia, Pennsylvania, USA, 25–29 April 1988, 310–315.

KIM J.-S., SUZUKI, K., KONNO A. and UCHIYAMA M. (1996). Force control of constrained flexible manipulators. *Proceedings of the 1996 IEEE International Conference on Robotics and Automation*, Minneapolis, Minnesota, USA, 22–28 April 1996, 635–640.

KINO, M., GODEN, T., MURAKAMI, T. and OHNISHI, K. (1998). Reaction torque feedback based vibration control in multi-degrees of freedom motion system. *Proceedings of the 24th Annual Conference of the Industrial Electronics Society of the IEEE*, Aachen, Germany, 31 August–4 September 1998, **3**, 1807–1811.

KOJIMA, H. (1986). Transient vibrations of a beam/mass system fixed to a rotating body. *Journal of Sound and Vibration*, **107**, 149–154.

KOJIMA, H. and NAKAJIMA, N. (2003). Multi-objective trajectory optimization by a hierarchical gradient algorithm with fuzzy decision logic. *AIAA Guidance, Navigation, and Control Conference*, Austin, Texas, USA, 11–14 August 2003, AIAA2003–5568.

KOKOTOVIC, P. V. (1984). Applications of singular perturbation techniques to control problems. *SIAM Review*, **26** (4), 502–550.

KOKOTOVIC, P., KHALIL, H. K. and O'REILLY, J. (1986). *Singular perturbation methods in control: Analysis and design*. Academic Press, New York, USA.

KOMATSU, T., UEYAMA, M., IIKURA, S., MIURA, H. and SHIMOYAMA, I. (1990). Autonomous satellite robot testbed. *Proceedings of International Symposium on Artificial Intelligence, Robotics and Automation in Space*, Kobe, Japan, 18–20 November 1990, 113–116.

KOROLOV, V. V. and CHEN, Y. H. (1988). Robust control of a flexible manipulator arm. *Proceedings of 1988 IEEE International Conference on Robotics and Automation*, Philadelphia, Pennsylvania, USA, 24–29 April 1988, 159–164.

KOROLOV, V. V. and CHEN, Y. H. (1989). Controller design robust to frequency variation in a one-link flexible robot arm. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **111** (1), 9–14.

KOTNIK, P. T., YORKOVICH, S. and ÖZGÜNER, Ü. (1988). Acceleration feedback for control of a flexible manipulator arm. *Journal of Robotic Systems*, **5** (3), 181–196.

KOURMOULIS, P. K. (1990). Parallel processing in the simulation and control of flexible beam structures. PhD thesis, Department of Automatic Control and Systems Engineering, The University of Sheffield, UK.

KRESS, R. L., JANSEN, J. F. and NOAKES, M. W. (1994). Experimental implementation of a robust damped-oscillation control algorithm on a full sized, two-DOF, AC induction motor-driven crane. *Proceedings of 5th International Symposium on Robotics and Manufacturing*, Maui, Hawaii, USA, 15–17 August 1994, 585–592.

KRESS, R. L., LOVE, L., DUBEY, R. and GIZELAR. A (1997). Waste tank cleanup manipulator modeling and control. *IEEE International Conference on Robotics and Automation*, Albuquerque, New Mexico, USA, 20–25 April 1997, 662–668.

KRISHNAN, H. (1988). *Bounded input discrete-time control of a single-link flexible beam*. Master thesis, Department of Electrical Engineering, University of Waterloo, Canada.

KRISTINSSON, K. and DUMONT, G. (1992). System identification and control using genetic algorithms. *IEEE Transactions on Systems, Man, and Cybernetics*, **22** (5), 1033–1046.

KRUISE, L. (1990). Modelling and control of a flexible beam and robot arm. PhD thesis, University of Twente, The Netherlands.

KWAK, H. J., SUNG, S. W. and LEE, I.-B. (1997). On-line process identification and autotuning for integrating processes. *Journal of Industrial and Engineering Chemistry Research*, **36** (12), 5329–5338.

KWOK, D. P., TAM, D., LI, C. K. and WANG, P. (1990). Linguistic PID controllers. *Proceedings of 11th IFAC World Congress*, Tallin, USSR, 13–17 August 1990, 192–197.

KWOK, D. P., TAM, D., LI, C. K. and WANG, P. (1991). Analysis and design of fuzzy PID control systems, *Proceedings of IEE Control '91 Conference*, Edinburgh, UK, 25–28 March 1991, **2**, 955–960.

KWON, D.-S. and BOOK, W. J. (1990). An inverse dynamic method yielding flexible manipulator state trajectories. *Proceedings of the American Control Conference*, San Diego, California, USA, 23 – 25 May 1990, 186–193.

LAMBERT, M., MOORE, B. and AHMADI, M. (2001). Essential real-time and modeling tools for robot rapid prototyping. *The 6th International Symposium on Artificial Intelligence and Robotics & Automation in Space: i-SAIRAS 2001*, Montreal, Canada, 18–22 June 2001.

LANDAU, I. D. (1998). The R–S–T digital controller design and applications. *Control EngineeringPractice*, **6** (2), 155–165.

LANDAU, I., LANGER, J., REY, D. and BARNIER, J. (1996). Robust control of a 360^oflexible arm using the combined pole placement/sensitivity function shaping method. *IEEE Transactions on Control Systems Technology*, **4** (4), 369–383.

LAPIDUS, L. (1982). *Numerical solution of partial differential equations in science and engineering*. John Wiley and Sons, New York, USA.

L'ARCHEVÊQUE, R., DOYON, M., PIEDBOEUF, J.-C. and GONTHIER, Y. (2000). SYMOFROS: Software architecture and real time issues. *Proceedings of DASIA 2000 – Data Systems in Aerospace*, ESA, Montreal, Canada, 22–26 May 2000, **SP-457**, 41–46.

LARCOMBE, P. J. and BROWN, I. C. (1997). Computer algebra: A brief overview and application to dynamic modelling. *Journal of Computing and Control Engineering*, **8** (2), 53–57.

LA SALLE, J. and LEFSCHETZ, S. (1961). *Stability by Liapunov's direct method.* Academic Press, San Diego, California, USA.

LAU, M. and PAO, L. (2002). Characteristics of time-optimal commands for flexible structures with limited fuel usage. *Journal of Guidance, Control, and Dynamics*, **25** (1), 222–231.

LEE, J. (1993). On methods for improving performance of PI-type fuzzy logic controllers. *IEEE Transactions on Fuzzy Systems*, **1** (1), 298–301.

LEE, J. X., VUKOVICH, G. and SASAIDEK, J. Z. (1994). Fuzzy control of a flexible link manipulator. *Proceedings of the American Control Conference*, Baltimore, Maryland, USA, 29 June–1 July 1994, 568–574.

LEE, M. A. and TAKAGI, H. (1993). Dynamic control of genetic algorithms using fuzzy logic techniques. *Proceedings of 5th International Conference on Genetic Algorithms*, Illinois, USA, 17–21 July 1993, 76–83.

LESHNO, M. (1993). Multilayer feedforward networks with a nonpolynomial activation function can approximate any function. *Neural Networks*, **6**, 861–867.

LEW, J. Y. and BOOK, W. J. (1993). Hybrid control of flexible manipulators with multiple contact. *Proceedings of the IEEE International Conference on Robotics and Automation*, Atlanta, Georgia, USA, 2–6 May 1993, **2**, 242–247.

LEWIS, D., PARKER, G. G., DRIESSEN, B. and ROBINETT, R. D. (1998). Command shaping control of an operator-in-the-loop boom crane. *Proceedings of the American Control Conference*, Philadelphia, Pennsylvania, USA, 24–26, June 1998, 2643–2647.

LEWIS, H. W. (1997). *The foundation of fuzzy control.* Plenum Press, New York, USA.

LI, D. (1994). Nonlinear control design for tip position tracking of a flexible manipulator arm. *International Journal of Control*, **69** (6), 1065–1082.

LI, Y. F. and CHEN, X. B. (2001). End-Point sensing and state observation of a flexible-link robot. *IEEE/ASME Transactions on Mechatronics*, **6** (3), 351–356.

LIN, C.-T. and LEE, C. S. G. (1991). Neural-network-based fuzzy logic control and decision system. *IEEE Transactions on Computer*, **40**, 1320–1336.

LIN, C.-T. and LEE, C. S. G. (1992). Real-time supervised structure-parameter learning for fuzzy neural network. *Proceeding of the IEEE International Conference on Fuzzy Systems*, San Diego, California, USA, 8–12 March 1992, 1283–1290.

LIN, C.-T. and LEE, C. S. G. (1993). Reinforced structure-parameter learning for neural-network-based fuzzy logic control systems. *Proceeding of the IEEE International Conference on Fuzzy Systems*, San Francisco, California, USA, 28 March–1 April 1993, 88–93.

LIN, C.-T. and LEE, C. S. G. (1995). A neural fuzzy control system with structure and parameter learning. *Fuzzy Sets and Systems*, **70**, 183–212.

LIN, I.-C. and FU, L.-C. (1998). Adaptive hybrid force/position control of a flexible manipulator for automated deburring with on-line cutting trajectory modification. *Proceedings of the IEEE International Conference on Robotics and Automation*, Leuven, Belgium, 16–20 May 1998, 818–825.

LIN J. (2003). Hierarchical fuzzy logic controller for a flexible link robot arm performing constrained motion tasks. *IEE Proceedings – D: Control Theory and Applications*, **150** (4), 355–364.

LIN, J. and LEWIS, F. L. (1994). A symbolic formulation of dynamic equations for a manipulator with rigid and flexible links, *International Journal of Robotics Research*, **13** (5), 454–466.

LITTLE, J. N. and SHURE, L. (1988). *Signal processing toolbox for MATLAB*. The MathWorks, Inc., Natick, Massachusetts, USA.

LIU, Q. and WIE, B. (1992). Robust time-optimal control of uncertain flexible spacecraft. *Journal of Guidance, Control, and Dynamics*, **15** (3), 597–604.

LJUNG, L. and SJÖBERG, J. (1992). A system identification perspective on neural networks. *Neural Networks for Signal Processing II. Proceedings of the IEEE-SP Workshop*, Helsingoer, Denmark, 31 August–2 September 1992, 423–435.

LOH, A. P. and VASNANI, V. U. (1992). Multiloop controller design for multivariable plants. *Proceedings of the 31st Conference on Decision and Control*, Tucson, Arizona, USA, 16–18, December 1992, 181–182.

LONGMAN, R. W. (1990). Attitude tumbling due to flexibility in satellite-mounted robots. *The Journal of Astronautical Sciences*, **38** (4), 487–509.

LONGMAN, R. W. and LINDBERG, R. E. (Eds) (1990). Special issue on robotics in space. *The Journal of the Astronautical Sciences*, **38** (4), 395–396.

LÓPEZ-LINARES, S. (1993). Control de robots flexibles. Tesis Doctoral. Escuela Superior de Ingenieros Industriales. Universidad de Navarra. San Sebastián.

LORON, L. (1997). Tuning of PID controllers by the non-symmetrical optimum method. *Automatica*, **33** (1), 103–107.

LOW, K. H. and VIDYASAGAR, M. (1988). A Lagragian formulation of dynamic model for flexible manipulator systems. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **110**, 175–181.

LUBICH, C., NOWAK, U., POHLE, U. and ENGSTLER, C. (1992). MEXX – numerical software for the integration of constrained mechanical multibody systems. Tech Report SC92-12, Konrad-Zuse-Zentrum für Informationstechnik, Berlin.

LUCIBELLO, P. and DI BENEDETTO, M. D. (1993). Output tracking for a nonlinear flexible arm. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **115**, 78–85.

LUCIBELLO, P., NICOLO, F. and PIMPINELLI, R. (1986). Automatic symbolic modelling of robots with a deformable link. *Proceedings of IFAC International Symposium on Theory of Robots*, Vienna, 3–5 December 1986, 183–187.

LUCIBELLO, P. and ULIVI, G. (1993). Design and realization of a two-link direct-drive robot with a very flexible forearm. *International Journal of Robotics and Automation*, **8** (3), 113–128.

LUH, J. Y. S., WALKER, M. W. and PAUL, R. P. (1982). Resolved motion force control of robot manipulators, *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **102**, 126–133.

LUO, F-L. and UNBEHAUEN, R. (1997). *Applied neural networks for signal processing*. Cambridge University Press, Cambridge, UK.

LUO, Z. H. (1993). Direct strain feedback control of flexible robot arms: new theoretical and experimental results. *IEEE Transactions on Automatic Control*, **38** (11), 1610–1622.

MA, O. (1995). Contact dynamics modelling for the simulation of the space station manipulators handling payloads. *Proceedings of IEEE International Conference on Robotics and Automation*, Nagoya, Japan, 21–27 May, 1995, 1252–1258.

MA, O. (2000). CDT – A general contact dynamics toolkit. *Proceedings of the 31st International Symposium on Robotics*, Montreal, Canada, 14–17 May 2000, 468–473.

MA, O. (2002). *Contact dynamics toolkit (cdt) user's guide*. MacDonald Dettwiler Space and Advanced Robotics Ltd., Research and Development. Version CDT_2000, Release 3.

MA, O., BUHARIWALA, K., ROGER, N., MACLEAN, J. and CARR, R. (1997). MDSF – a generic development and simulation facility for flexible, complex robotic systems. *Robotica*, **15**, 49–62.

MACE, B. R. (1991). The effects of transducer inertia on beam vibration measurements. *Journal of Sound and Vibration*, **145**, 365–379.

MACFARLANE, A. G. J., GRÜBEL, G. and ACKERMANN, J. (1989). Future design environments for control engineering.*Automatica*, **25** (2), 165–176.

MACIEJOWSKI, J. M. (1991). *Multivariable feedback design*. Addison-Wesley, Workingham, UK.

MADHAVAN, S. K. and SINGH, S. N. (1991). Inverse trajectory control and dynamic sensitivity of an elastic manipulator. *International Journal of Robotics and Automation*, **6** (4), 179–191.

MAGEE, D. P. and BOOK, W. J. (1993). Eliminating multiple modes of vibration in a flexible manipulator. *Proceedings of the IEEE International Conference on Robotics and Automation*, Atlanta, Georgia, USA, 2–6 May 1993, 474–479.

MAGEE, D. P. and BOOK, W. J. (1995). Filtering micro-manipulator wrist commands to prevent flexible base motion. *Proceedings of the American Control Conference*, Seattle, Washington, USA, 21–23 June 1995, 924–928.

MAGEE, D. P., CANNON, D. W. and BOOK, W. J. (1997). Combined command shaping and inertial damping for flexure control. *Proceedings of the American Control Conference*, Albuquerque, New Mexico, USA, 4–6 June 1997, 1330–1334.

MAHIL, S. S. (1982). On the application of Lagrange's method to the description of dynamic systems. *IEEE Transactions on System, Man, and Cybernetics*, **SMC-12** (6), 877–889.

MARCHAND, P. and HOLLAND, T. (2003). *Graphics and GUI's with MATLAB*, third edition. CRC Press, Boca Raton, Florida, USA.

MARQUARDT, D. (1963). An algorithm for least squares estimation of non-linear parameters. *Journal of the Society for Industrial and Applied Mathematics*, **11** (2), 431–441.

MARTIN, G. (1978). On the control of flexible mechanical system. PhD thesis, Department of Aeronautics and Astronautics, Stanford University, Stanford, California, USA.

MARTINS, J. M., BOTTO, M. A. and SÁ DA COSTA, J. (2002). Modelling of flexible beams for robotic manipulators. *Multibody System Dynamics*, **7** (1), 79–100.

MARTINS, J. M., MOHAMED, Z., TOKHI, M. O., SÁ DA COSTA, J. and BOTTO, M. A. (2003). Approaches for dynamic modelling of flexible manipulator systems. *IEE Proceedings – D: Control Theory and Applications*, **150** (4), 401–411.

MASUTANI, Y., MIYAZAKI, F. and ARIMOTO, S. (1989). Sensory feedback control for space manipulators. *Proceedings of IEEE International Conference on Robotics and Automation*, Scottsdale, Arizona, USA, 14–19 May, 1346–1351.

MATSUNO, F., ASANO, T. and SAKAWA, Y. (1994). Modeling and quasi-static hybrid position/force control of constrained planar two-link flexible manipulators. *IEEE Transactions on Robotics and Automation*, **10**, 287–297.

MATSUNO, F., OHNO, T. and ORLOV, Y. V. (2002). Proportional derivative and strain (PDS) boundary feedback control of a flexible space structure with a closed-loop chain mechanism. *Automatica*, **38** (7), 1201–1211.

MATSUNO, F. and YAMAMOTO, K. (1994). Dynamic hybrid position/force control of a two degree-of-freedom flexible manipulator. *Journal of Robotic Systems*, **11** (5), 355–366.

MCCLAMROCH, N. H. and WANG, D. (1988). Feedback stabilization and tracking of constrained robots. *IEEE Transactions on Automatic Control*, **33**, 419–426.

MECKL, P. H. and SEERING, W. P. (1990). Experimental evaluation of shaped inputs to reduce vibration of a cartesian robot. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **112** (6), 159–165.

MEIROVITCH, L. (1967). *Analytical methods in vibrations*. Macmillan, New York, USA.

MEIROVITCH, L. (1970). *Methods of analytical dynamics*. McGraw-Hill, New York, USA.

MEIROVITCH, L. (1975). *Elements of vibration analysis*. McGraw-Hill, Inc., New York, USA.

MEIROVITCH, L. (1980). *Computational methods in structural dynamics*. Sijthhoff and Noordhoff, Amsterdam.

MEIROVITCH, L. (1986). *Elements of vibration analysis*. McGraw-Hill, New York, USA.

MEIROVITCH, L., BARUH, H. and OZ, H. (1983). A comparison of control techniques for large flexible systems.*Journal of Guidance, Control, and Dynamics*, **6**, 302–310.

MENQ, C. and CHEN, J. (1988). Dynamic modeling and payload-adaptive control of a flexible manipulator. *Proceedings of the IEEE International Conference on Robotics and Automation*, Philadelphia, Pennsylvania, USA, 24–29 April 1988, 488–493.

MEYER, G. E. (1971). *Analytical methods in conduction heat transfer*. McGraw-Hill, New York, USA.

MEYER, J. L. and SILVERBERG, L. (1996). Fuel optimal propulsive maneuver of an experimental structure exhibiting spacelike dynamics. *Journal of Guidance, Control, and Dynamics*, **19** (1), 141–149.

MICHALEWICZ, Z. (1994). *Genetic algorithms + Data structures = Evolution programs*. Springer-Verlag, New York, USA.

MILLS, J. K. (1992). Stability and control aspects of flexible link robot manipulators during constrained motion tasks. *Journal of Robotic Systems*, **9**, 933–953.

MINSKY, M. and PAPERT, S. (1969). *Perceptrons: An Introduction to Computational Geometry*, MIT Press, Cambridge, USA.

MISIR, D., MALKI, H. A. and CHEN, G. (1996). Design and analysis of a fuzzy proportional-integral-derivative controller. *Fuzzy Sets and Systems*, **79** (3), 297–314.

MIYABE, T., YAMANO, M., KONNO, A. and UCHIYAMA, M. (2001). An approach toward a robust object recovery with flexible manipulators. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Maui Hawaii, USA, 29 October–3 November 2001, 907–912.

MOALLEM, M., KHORASANI, K. and PATEL, R. V. (1997). An integral manifold approach for tip-position tracking of flexible multi-link manipulators. *IEEE Transactions on Robotics and Automation*, **13** (6), 823–837.

MOHAMMED, Z. and TOKHI, M. O. (2002). A symbolic manipulation approach for modelling and performance analysis of flexible manipulator systems. *International Journal of Acoustics and Vibration*, **7** (1), 27–37.

MOHAMED, Z. and TOKHI, M. O. (2004). Command shaping techniques for vibration control of a flexible robot manipulators. *Mechatronics*, **14** (1), 69–90.

MOORE, B., KÖVECSES, J. and PIEDBOEUF, J.-C. (2003). Symbolic model formulation for dynamic parameters identification. In J. A. Ambrósio (Ed.), *Proceedings of Multibody Dynamics 2003*, Lisbon, Portugal, 1–4 July 2003, 1–11. MB2003-058.

MOORE, B., PIEDBOEUF, J.-C. and BERNARDIN, L. (2002). Maple as an automatic code generator? *Maple Summer Workshop*, Ontario, Canada, 28–30 July 2002.

MOULIN, H. and BAYO, E. (1991). On the accuracy of end-point trajectory tracking for flexible arms by noncausal inverse dynamic solution. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **113**, 320–324.

MUDI, R. K. and PAL, N. R. (1999). A robust self-tuning scheme for PI- and PD-type fuzzy controllers. *IEEE Transactions on Fuzzy Systems*, **7** (1), 2–16.

MUENCHHOF, M. and SINGH, T. (2002). Concurrent feedforward/feedback controller design using time-delay filters. *AIAA Guidance, Navigation and Control Conference*, Monterey, California, USA, 5–8 August 2002.

MUROTSU, Y., SENDA, K., MITSUYA, A., YAMANE, K., HAYASHI, M. and NUNOHARA, T. (1993). Theoretical and experimental studies for continuous path control of flexible manipulators mounted on a free-flying space robot. *Proceedings of AIAA Guidance, Navigation and Control Conference*, Monterey, California, USA, 17–19 August 1993, **3**, 1458–1471.

MUROTSU, Y., TSUJIO, S., SENDA, K. and HAYASHI, M. (1990). Dynamics and positioning control of space robot with flexible manipulators. *Proceedings of AIAA Guidance, Navigation and Control Conference*, Portland, Oregon, USA, 20–22 August 1990, **1**, 735–742.

MUROTSU, Y., TSUJIO, S., SENDA, K. and HAVASHI, M. (1992). Trajectory control of flexible manipulators on a free-flying space robot. *IEEE Control Systems*, **12** (3), 51–57.

NAGARKATTI, S. P., RAHN, C. D., DAWSON, D. M. and ZERGEROGLU, E., (2001). Observer-based modal control of flexible systems using distributed sensing. *Proceedings of the 40th IEEE Conference on Decision and Control*, Orlando, Florida, USA, 4–7 December 2001, 4268–4273.

NAGATHAN, G. and SONI, A. H. (1986). Non-linear flexibility studies for spatial manipulators. *Proceedings of the IEEE International Conference on Robotics and Automation*, San Francisco, California, USA, 7–10 April 1986, 373–378.

NARENDRA, K. S. and PARTHASARATHY, K. (1990). Identification and control of dynamical systems using neural networks. *IEEE Transactions on Neural Networks*, **1** (1), 4–27.

NAUCK, D. and KRUSE, R. (1992). Interpreting changes in the fuzzy sets of a self-adaptive neural fuzzy controller, *Proceeding of IFIS'92: 2nd Workshop on Industrial Applications of Fuzzy Control and Intelligent Systems*, College Station, Texas, USA, 2–4 December 1992, 146–152.

NAUCK, D. and KRUSE, R. (1993). A fuzzy neural network learning fuzzy control rules and membership functions by fuzzy error backpropagation. *Proceeding of IEEE International Conference on Neural Networks*, San Francisco, California, USA, 28 March–1 April 1993, 1022–1027.

NERRAND, O., ROUSSEL-RAGOT, P., URBANI, D., PERSONNAZ, L. and DREYFUS, G. (1994). Training recurrent neural networks: why and how? An illustration in dynamical process modelling. *IEEE Transactions on Neural Networks*, **5** (2), 178–184.

NESLINE, F. W. and ZARCHAN, P. (1984). Why modern controllers can go unstable in practice. *AIAA Journal of Guidance, Control, and Dynamics*, **7**, 495–500.

NEWLAND, D. E. (1996). *Introduction to random vibrations, spectral and wavelet analysis*. Addison-Wesley Longman, California, USA.

NEWTON, R. T. and XU, Y. (1993). Neural network control of a single-link flexible manipulators, *IEEE Control Systems Magazine*, **12**, 14–22.

NOVOZHILOV, V. V. (1961). *Theory of elasticity*. Pergamon Press Ltd, London, UK.

OAKLEY, C. M., and CANNON, R. H. (1988). Initial experiments on the end-point control of a two-link manipulator with a very flexible forearm, *Proceedings of the American Control Conference*, Atlanta, Georgia, USA, 15–17 June 1988, 996–1002.

OAKLEY, C. M. and CANNON, R. H. (1989). End-point control of a two-link manipulator with a very flexible forearm: Issues and experiments. *Proceedings of the American Control Conference*, Pittsburgh, Pennsylvania, USA, 21–23 June 1989, 1381–1388.

OAKLEY, C. M. and CANNON, R. (1990). Anotomy of an experimental two-link flexible manipulator under end-point control. *Proceedings of the IEEE 29th Conference on Decision and Control*, Honolulu, Hawaii, USA, 5–7 December 1990, 507–513.

OGATA, K. (2001). *Modern control engineering*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, USA.

OLUROTIMI, O. (1994). Recurrent neural network training with feedforward complexity. *IEEE Transactions on Neural Networks*, **5** (2), 185–197.

OMATU, S., KHALID, M. and YUSOF, R. (1996). *Neuro-control and its applications*. Springer, London.

OMATU, S. and SEINFELD, J. H. (1986). Optimal sensor actuator locations for linear distributed parameter systems. *Proceedings of the 4th IFAC Symposium on Control of Distributed Parameter Systems*, Los Angeles, California, USA, 30 June–2 July 1986, 215–220.

ONSAY, T. and AKAY, A. (1991). Vibration reduction of a flexible arm by time optimal open-loop control. *Journal of Sound and Vibration*, **142** (2), 283–300.

OOSTING, K. and DICKERSON, S. L. (1988). Simulation of a high-speed lightweight arm. *Proceedings of the IEEE International Conference on Robotics and Automation*, Philadelphia, Pennsylvania, USA, 24–29 April 1988, 494–496.

ORTEGA, J. M. (1987). *Matrix theory – A second course*. Plenum Press, New York, USA.

OUSSAMA, K., CRAIG, J. and LOZANO-PÉREZ, T. (1989). *The robotics review*. MIT Press, Boston, Massachusetts, USA.

OWER, J. C. and VAN de VEGTE, J. (1987). Classical control design for a flexible manipulator: modeling and control system design. *IEEE Journal of Robotics and Automation*, **RA-3** (5), 485–489.

PADEN, B., CHEN, D., LEDESMA, R. and BAYO, E. (1993). Exponentially stable tracking control for multijoint flexible-link manipulators. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **115**, 53–59.

PAI, D. K., ASCHER, U. M. and KRY, P. G. (2000). Forward dynamics algorythms for multibody chains and contact. *Proceedings of IEEE International Conference on Robotics and Automation*, San Francisco, California, USA, 24–28 April 2000, 857–863.

PALMOR, Z. J., HALEVI, Y. and KRASNEY, N. (1995). Automatic tuning of decentralized PID controllers for TITO processes. *Automatica*, **31** (7), 1001–1010.

PAN, Y. C., ULSOY, A. G. and SCOTT, R. A. (1990). Experimental model validation for a flexible robot with a prismatic joint. *Journal of Mechanical Design*, **112**, 315–323.

PAO, L. Y. (1996). Minimum-time control characteristics of flexible structures. *Journal of Guidance, Control, and Dynamics*, **19** (1), 123–129.

PAO, L. Y. (1999). Multi-input shaping design for vibration reduction. *Automatica*, **35** (1), 81–89.

PAO, L. Y. and SINGHOSE, W. E. (1997). Verifying robust time-optimal commands for multi-mode flexible spacecraft. *AIAA Journal of Guidance, Control, and Dynamics*, **20** (4), 831–833.

PAO, L. Y. and SINGHOSE, W. E. (1998). Robust minimum time control of flexible structures. *Automatica*, **34** (2), 229–236.

PAPOULIS, A. (1962). *The Fourier integral and its applications*. McGraw-Hill Book Company, Inc., New York, USA.

PASSINO, K. M. and YURKOVICH, S. (1998). *Fuzzy control*. Addison-Wesley Longman Inc., Massachusetts, USA.

PFEIFFER, F. (1989). A feedforward decoupling concept for the control of elastic robots. *Journal of Robotic Systems*, **6** (4), 407–416.

PIEDBOEUF, J.-C. (1993). Kane's equations or Jourdain's principle. *36th Midwest Symposium on Circuits and Systems*, Detroit, Michigan, USA, 16–18 August 1993.

PIEDBOEUF, J.-C. (1996). Modelling flexible robots with maple. *Maple Tech: The Maple Technical Newsletter*, **3** (1), 38–47.

PIEDBOEUF, J.-C. (1998). Recursive modelling of serial flexible manipulators. *The Journal of the Austronautical Sciences*, **46** (1), 1–24.

PIEDBOEUF, J.-C., AGHILI, F., DOYON, M., GONTHIER, Y., MARTIN, E. and ZHU, W.-H. (2001). Emulation of space robot through hardware-in-the-loop simulation. *The 6th International Symposium on Artificial Intelligence and Robotics & Automation in Space: i-SAIRAS 2001*, Canadian Space Agency, St-Hubert, Canada, 18–22 June 2001.

PIEDBOEUF, J.-C. and MOORE, B. (2002). On the foreshortening effects of a rotating flexible beam using different modeling methods. *Mechanics of Structure and Machines*, **30** (1), 83–102.

PLUMMER, A. R. and VAUGHAN, N. O. (1997). Decoupling pole-placement control, with application to a multi-channel electro-hydraulic servosystem. *Control Engineering Practice*, **5** (3), 313–323.

PLUNKELL, R. and LEE, C. T. (1970). Length optimization for constrained viscoelastic layer damping. *Journal of the Acoustical Society of America*, **48**, 150–161.

POERWANTO, H. (1998). Dynamic simulation and control of flexible manipulator systems. PhD thesis, Department of Automatic Control and Systems Engineering, The University of Sheffield, Sheffield, UK.

POTA, H. R. and ALBERTS, T. E. (1995). Multivariable transfer functions for a slewing piezoelectric laminate beam. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **117** (3), 352–359.

PREUMONT, A. (1997). *Vibration control of active structures: An introduction*. Kluwer Academic, Dordrecht, The Netherlands.

QIAN, W. T. and MA, C. C. H. (1992). A new controller design for a flexible one-link manipulator. *IEEE Transactions on Automatic Control*, **37** (1), 133–137.

QIN, S.-Z., SU, H.-T., and MCAVOY, T. J. (1992). Comparison of four neural net learning methods for dynamic system identification. *IEEE Transactions on Neural Networks*, **3** (1), 122–130.

QUARANTA, G. and MANTEGAZZA, P. (2001). Using MATLAB-Simulink RTW to build real time control applications in user space with RTAI-LXRT. *Real-Time Linux Workshop*, Milano, Italy, 19–26 November 2001.

RAD, A. B., LO, W. L. and TSANG, K. M. (1997). Self-tuning PID controller using Newton–Raphson search method. *IEEE Transactions on Industrial Electronics*, **44** (5), 717–725.

RAIBERT, M. H. and CRAIG, J. J. (1981). Hybrid position/force control of manipulators. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **103**, 126–133.

RAKSHA, F. and GOLDENBERG, A. A. (1986). Dynamic modelling of a single-link flexible robot. *The IEEE International Conference on Robotics and Automation*, San Francisco, California, USA, 7–10 April 1986, 820–828.

RAO, S. S. (1989). *The finite element method in engineering*. Paragon Press, Oxford, UK.

RAPPOLE, B. W., SINGER, N. C. and SEERING, W. P. (1994). Multiple-mode impulse shaping sequences for reducing residual vibrations. *Proceedings of 23rd Biennial Mechanisms Conference*, Minneapolis, Minnesota, USA, 11–14 September 1989, 11–16.

RAVN, O. and SZYMKAT, M. (1992). The evolution of CACSD tools – a software engineering perspective. *Proceedings of IEEE Control Systems Society Symposium on Computer-Aided Control System Design*, Napa, California, USA, 17–19 March 1992, 225–231.

RAVN, O. and SZYMKAT, M. (1994). Requirements for user interaction support in future CACE environments. *Proceedings of IEEE Control Systems Society Symposium on Computer-Aided Control System Design*, Tucson, Arizona, USA, 7–9 March 1994, 381–386.

RAVN, O. and SZYMKAT, M. (1995). Mechatronics approach to robotic modelling – software engineering perspective. *Proceeding of MMAR'95: 2nd International Symposium on Methods and Models in Automation and Robotics*, Miedzyzdroje, Poland, 30 August–2 September 1995, 455–466.

RAVN, O., SZYMKAT, M., UHL, T., BETEMPS, M., PJETURSSON, A. and ROD, J. (1996). Mechatronic blockset for simulink – concept and implementation. *Proceedings of CACSD'96*, Dearborn, Michigan, USA, 15–18 September 1996, 530–535.

REDDY, J. N. (1993). *An introduction to the finite element method*, second edition. McGraw-Hill, New York, USA.

ROBINETT, R., PARKER, G., FEDDEMA, J., DOHRMANN C. and PETTERSON, B. (1999). Sway control method and system for rotary cranes, US Patent No. 5, 908, 122.

ROCCO, P. and BOOK, W. J. (1996). Modelling for two-time scale force/position control of flexible robots. *Proceedings of the 1996 IEEE International Conference on Robotics and Automation*, Minneapolis, Minnesota, USA, 22–28 April 1996, 1941–1946.

RODRIGUEZ, G., JAIN, A. and KREUTZ-DELGADO, K. (1992). Spatial operator algebra for multibody system dynamics. *The Journal of the Austronautical Sciences*, **40**, 27–50.

ROMANO, M., AGRAWAL, B. and BERNELLI-ZAZZERA, F. (2002). Experiments on command shaping control of a manipulator with flexible links. *Journal of Guidance, Control and Dynamics*, **25** (2), 232–239.

ROSENBROCK, H. H. (1974). *Computer-aided control system design*. Academic Press, London.

ROSS, C. T. F. (1996). *Finite element techniques in structural mechanics*. Albion Publishing Limited, West Sussex, UK.

ROSSI, M., WANG, D. and ZUO, K. (1997). Issues in the design of passive controllers for flexible-link robots. *The International Journal of Robotics Research*, **16** (4), 577–588.

ROSTGAARD, M. (1995): Modelling, estimation and control of fast sampled dynamic systems. PhD theses. Department of Mathematical Modelling, The Technical University of Denmark, Denmark.

RUMELHART, D. E., HINTON, G. E. and WILLIAMS, R. J. (1986). Learning internal representations by error propagation. *Parallel Distributed Processing: Exploration in the Microstructure of Cognition*, MIT Press, Cambridge, Massachusetts, USA, 318–362.

SAAD, M., PIEDBOEUF, J.-C., AKHRIF, O. and SAYDY, L. (2000*a*). A comparison of different shape functions in assumed-mode models of a flexible slewing beam. Technical Report, Canadian Space Agency, Canada.

SAAD, M., PIEDBOEUF, J.-C., AKHRIF, O. and SAYDY, L. (2000*b*). Shape function comparison in a model of a flexible slewing beam. *Proceedings of International Symposium on Robotics and Automation, ISRA'2000*, Monterey, Mexico, 10–12 November 2000, 237–243.

SADEGH, N. (1995). Synthesis of a stable discrete-time repetitive controller for MIMO systems. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **117** (March), 92–97.

SAKAWA, Y., MATSUNO, F. and FUKUSHIMA, S. (1985). Modelling and feedback control of a flexible arm. *Journal of Robotic Systems*, **2**, 453–472.

SALISBURY, J. K. (1980). Active stiffness control of a manipulator in Cartesian coordinates. *Proceedings of 19th IEEE Conference on Decision and Control*, Albuquerque, New Mexico, USA, 10–12 December 1980, 95–100.

SANDIA NATIONAL LABORATORIES (2004). Flexible robotics, Sandia National Laboratories, USA (http://endo.sandia.gov/9234/FlexRobot).

SCHMITZ, E. (1985). Experiments on the end-point position control of a very flexible one-link manipulator. PhD thesis, Stanford University, Stanford, California, USA.

SCHOENWALD, D. A. and Özgüner, U. (1990). On combining slewing vibration control in flexible manipulator via singular perturbation. *Proceedings of the 29th IEEE Conference on Decision and Control*, Honolulu, Hawaii, USA, 5–7 December 1990, 533–538.

SCHULZ, G. and HEIMBOLD, G. (1983). Dislocated actuator/sensor positioning and feedback design of flexible structures. *Journal of Guidance, Control, and Dynamics*, **6**, 361–367.

SCHWERTASSEK, R. and WALLRAPP, O. (1999). *Dynamic flexible multibody systems*. Vieweg, Braunschweig, Germany. In German.

SCIAVICCO, L. and SICILIANO, B. (1996). *Modelling and control of robot manipulators*. McGraw-Hill, Inc., New York, USA.

SELCOM SELECTIVE ELECTRONICS (1994). *SELSPOT hardware users manual and software users manual.* Selcom Selective Electronics Co AB, Partille, Sweden.

SENDA, K. (1993). Dynamics and control of rigid/flexible space manipulators. PhD thesis, Osaka Prefecture University, Osaka, Japan.

SENDA, K. and MUROTSU, Y. (1993). Controlability and observability of flexible manipulators and a stability condition of PD-control. *Proceedings of the Asia–Pacific Vibration Conference*, Kitakyushu, Japan, 14–18 November 1993, **3**, 1343–1348.

SENDA, K. and MUROTSU, Y. (1994a). Stable manipulation variable feedback control for flexible manipulators. *Proceedings of Japan–USA Symposium on Flexible Automation*, Kobe, Japan, **II**, 397–404.

SENDA, K. and MUROTSU, Y. (1994b). Manipulation varible feedback control of flexible manipulators by using virtual rigid manipulator concept. *Proceedings of the AIAA Guidance, Navigation and Control Conference*, Scottsdale, Arizona, USA, 1–3 August 1994, **3**, 1030–1039.

SETH, N., RATTAN, K. and BRANDSTETTER, R. (1993). Vibration control of a coordinate measuring machine. *Proceeding of the IEEE Conference on Control Applications*, Dayton, Ohio, USA, 13–16 September 1993, 368–373.

SHAHEED, M. H. (2000). Neural and genetic modelling, control and real-time finite element simulation of flexible manipulators. PhD thesis, Department of Automatic Control and Systems Engineering, The University of Sheffield, Sheffield, UK.

SHARF, I. (1996). Geometrically non-linear beam element for dynamics simulation of multibody systems. *International Journal for Numerical Methods in Engineering*, **39**, 763–786.

SHARMA, S. K. (2000). Soft computing for modelling and control of fynamic dystems with spplication to flexible manipulators. PhD thesis. Department of Automatic Control and System Engineering, The University of Sheffield, UK.

SHARMA, S. K., IRWIN, G. W., TOKHI, M. O. and MCLOONE, S. F. (2003). Learning soft computing control strategies in a modular neural network architecture. *Engineering Applications of Artificial Intelligence*, **16** (5–6), 395–405.

SHARMA, S. K. and TOKHI, M. O. (2000). Neural network optimisation using genetic algorithm: A hierarchical fuzzy method. *Proceedings of AARTC00: 6th IFAC Workshop on Algorithms and Architectures for Real-Time Control*, Palma de Mallorca, Spain, 15–17 May 2000, 71–76.

SHCHUKA, A. and GOLDENBERG, A. A. (1989). Tip control of a single-link flexible arm using feedforward technique.*Mechanical Machines Theory*, **24**, 439–455.

SHI, Z. X., FUNG, E. H. K. and LI, Y. C. (1999). Dynamic modelling of a rigid-flexible manipulator for constrained motion task control. *Applied Mathematical Modelling*, **23**, 509–525.

SHIFMAN, J. J. (1993). Lyapunov functions and the control of Euler-Bernoulli beam. *International Journal of Control*, **57**, 971–992.

SICILIANO, B. (1990). A closed-loop inverse kinematic scheme for on-line joint based robot control. *Robotica*, **8**, 231–243.

SICILIANO, B. (1998). An inverse kinematics scheme for a flexible arm in contact with a compliant surface. *Proceedings of 37th IEEE Conference on Decision and Control*, Tampa, Florida, USA, 16–18 December 1998, 3617–3622.

SICILIANO, B. (1999). Closed-loop inverse kinematics algorithm for constrained flexible manipulators under gravity. *Journal of Robotic Systems*, **16**, 353–362.

SICILIANO, B. and BOOK, W. J. (1988). A singular perturbation approach control of lightweight flexible manipulators. *International Journal of Robotics Research*, **7** (4), 79–90.

SICILIANO, B., PRASAD, J. V. R. and CALISE, A. J. (1992). Output feedback two-time scale control of multi-link flexible arms. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **114**, 70–77.

SICILIANO, B. and VILLANI, L. (1999). *Robot force control*. Kluwer Academic Publishers, Boston, Massachusetts, USA.

SICILIANO, B. and VILLANI, L. (2000). Parallel force and position control of flexible manipulators. *IEE Proceedings–D: Control Theory and Applications*, **147** (6), 605–612.

SICILIANO, B. and VILLANI, L. (2001). An inverse kinematics algorithm for interaction control of a flexible arm with a compliant surface. *Control Engineering Practice*, **9**, 191–198.

SICILIANO, B., YUAN, B. and BOOK, W. J. (1986). Model reference adaptive control of a one link flexible arm. *Proceedings of 25th Conference on Decision and Control*, Athens, Greece, 10–12 December 1986, 91–95.

SILVA, J. M. M. and MAIA, N. M. M. (1988). Single mode identification techniques for use with small microcomputers. *Journal of Sound and Vibration*, **124** (1), 13–26.

SIMO, J. C. (1985). A finite strain beam formulation. The three-dimensional dynamic problem. Part I. *Computer Methods in Applied Mechanics and Engineering*, **49**, 55–70.

SIMO, J. C. and VU-QUOC, L. (1986). On the dynamics of flexible beams under large overall motions – The plane case: Part I. *ASME Journal of Applied Mechanics*, **53** (4), 849–854.

SIMO, J. C. and VU-QUOC, L. (1987). The role of non-linear theories in transient dynamic analysis of flexible structures. *Journal of Sound and Vibration*, **119** (3), 487–508.

SINCARSIN, G. B. and D'ELEUTERIO, G. M. T. and HUGHES, P. C. (1993). Dynamics of an elastic multibody chain: Part D-Modelling of joints. *Dynamics and Stability of Systems*, **8** (2), 127–146.

SINGER, N. C. (1989). Residual vibration reduction in computer controlled machines, AITR-1030, MIT Artificial Intelligence Lab, Cambridge, Massachusetts, USA.

SINGER, N. C. and SEERING, W. P. (1990). Preshaping command inputs to reduce system vibration. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **112** (1), 76–82.

SINGER, N. C., SEERING, W. P. and PASCH, K. A. (1990). Shaping command inputs to minimize unwanted dynamics. US Patent No. 4, 916, 635.

SINGER, N., SINGHOSE, W. and KRIIKKU, E. (1997). An input shaping controller enabling cranes to move without sway. *Proceedings of ANS 7th Topical Meeting on Robotics and Remote Systems*, Augusta, Georgia, USA, 27 April–1 May 1997, 225–231.

SINGER, N. C., SINGHOSE, W. E. and SEERING, W. P. (1999). Comparison of filtering methods for reducing residual vibration. *European Journal of Control*, **5**, 208–218.

SINGH, T. and HEPPLER, G. R. (1993). Shaped input control of a system with multiple modes. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **115** (September), 341–347.

SINGH, G., KABAMBA, P. T. and McCLAMROCH, N. H. (1989). Planner time-optimal rest-to-rest slewing manoeuvre of flexible spacecraft. *Journal of Guidance, Control, and Dynamics*, **12**, 71–81.

SINGH, T. and VADALI, S. R. (1993). Robust time-delay control. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **115** (June), 303–306.

SINGH, T. and VADALI, S. R. (1994). Robust time-optimal control: A frequency domain approach. *Journal of Guidance, Control, and Dynamics*, **17** (2), 346–353.

SINGHOSE, W. E., BANERJEE, A. and SEERING, W. (1997*a*). Slewing flexible spacecraft with deflection-limiting input shaping. *AIAA Journal of Guidance, Control, and Dynamics*, **20** (2), 291–298.

SINGHOSE, W. E., BOHLKE, K. and SEERING, W. (1996*a*). Fuel-efficient pulse command profiles for flexible spacecraft. *AIAA Journal of Guidance, Control, and Dynamics*, **19** (4), 954–960.

SINGHOSE, W. E., CRAIN, E. A. and SEERING, W. P. (1997*b*). Convolved and simultaneous two-mode input shapers. *IEE Proceedings – D: Control Theory and Applications*, **144** (November), 515–520.

SINGHOSE, W. E., HUEY, J., LAWRENCE, J. and FRAKES, D. (2003). Input shaping curriculum: Integrating interactive simulations and experimental setups. *Proceedings of 11th Mediterranean Conference on Control Automation*, Rhodes, Greece, 18–20 June 2003, **IV**, 05–11.

SINGHOSE, W. E., PORTER, L., KENISON, M. and KRIIKKU, E. (2000). Effects of hoisting on the input shaping control of gantry cranes. *Control Engineering Practice*, **8** (10), 1159–1165.

SINGHOSE, W. E., PORTER, L. J., TUTTLE, T. D. and SINGER, N. C. (1997*c*). Vibration reduction using multi-hump input shapers. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **119** (June), 320–326.

SINGHOSE, W. E., SEERING, W. and SINGER, N. (1994). Residual vibration reduction using vector diagrams to generate shaped inputs. *ASME Journal of Mechanical Design*, **116** (June), 654–659.

SINGHOSE, W. E., SEERING, W. P. and SINGER, N. C. (1996*b*). Input shaping for vibration reduction with specified insensitivity to modeling errors. *Proceedings of the Japan-USA Symposium on Flexible Automation*, Boston, Massachusetts, USA, 8–10 June 1996, 307–313.

SINGHOSE, W. E. and SINGER, N. (1996). Effects of input shaping on two-dimensional trajectory following. *IEEE Transactions on Robotics and Automation*, **12** (6), 881–887.

SINGHOSE, W. E., SINGER, N., RAPPOLE, W., DEREZINSKI, S. and PASCH, K. (1997*d*). Methods and apparatus for minimizing unwanted dynamics in a physical system, US Patent No. 5, 638, 267.

SINGHOSE, W. E., SINGER, N. and SEERING, W. (1996*c*). Improving repeatability of coordinate measuring machines with shaped command signals. *Precision Engineering*, **18** (April), 138–146.

SINGHOSE, W. E., SINGER, N. and SEERING, W. (1997*e*). Time-optimal negative input shapers. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **119** (June), 198–205.

SINGHOSE, W., SINGH, T. and SEERING, W. (1999). On-off control with specified fuel usage. *Journal of Dynamic Systems, Measurement and Control*, **121** (2), 206–212.

SINHA, A. and KAO, C. K. (1991). Independent modal sliding mode control of vibration in flexible manipulator. *Journal of Sound and Vibration*, **147**, 352–358.

SIRA-RAMIREZ, H., AHMAD, S., and ZRIBI, M. (1992). Dynamical feedback control of robotic manipulators with joint flexibility. *IEEE Transactions on Systems, Man, and Cybernetics*, **22** (4), 736–747.

SMITH, C. and BARUH, H. (1991). Dominance of stiffening effects for rotating flexible beams. *AIAA Journal of Guidance, Control, and Dynamics*, **14** (5), 1072–1074.

SMITH, O. J. M. (1957). Posicast control of damped oscillatory systems. *Proceedings of the IRE*, **45** (September), 1249–1255.

SMITH, O. J. M. (1958). *Feedback control systems*. McGraw-Hill Book Co., Inc, New York, USA.

SONG, B. and KOIVO, A. J. (1998). Neural network model based control of a flexible link manipulator. *Proceedings of the IEEE International Conference on Robotics & Automation,* Leuven, Belgium, 16–20 May 1998, 812–817.

SPACE MACHINES LABORATORY (2004*a*). *Aerospace dual arm manipulator*, Tohoko University, Japan (http://www.space.mech.tohoku.ac.jp/research/adam/adam-e.html).

SPACE MACHINES LABORATORY (2004*b*). *The control of a 3D flexible manipulator*, Tohoko University, Japan (http://www.space.mech.tohoku.ac.jp/research/flebot2/flebot2-e.html).

SPECTOR, V. A. and FLASHNER, H. (1990). Modeling and design implications of noncollocated control in flexible systems. *Transactions of ASME: Journal of Dynamic Systems, Measurement and Control*, **112**, 186–193.

SPONG, M. V., KHORASANI, K. and KOKOTOVIC, P. V. (1987). An integral manifold approach to feedback control of flexible joint robots. *IEEE Journal of Robotics and Automation*, **3**, 291–300.

SPONG, M. W. and ORTEGA, R. (1990). On adaptive inverse dynamics control of rigid robots. *IEEE Transactions on Automatic Control*, **35** (1), 92–95.

SRINIVASAN, B., PRASAD, U. R., and RAO, N. J. (1994). Backpropagation through adjoints for the identification of non-linear dynamic systems using recurrent neural models. *IEEE Transactions on Neural Networks*, **5** (2), 213–228.

STADENNY, J. and BELANGER, P. (1986). Robot manipulator control by acceleration feedback: Stability, design and performance issues. *Proceedings of IEEE Conference on Decision and Control*, Athens, 10–12 December 1986, 80–85.

STARR, G. P. (1985). Swing-free transport of suspended objects with a path-controlled robot manipulator. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **107**, 97–100.

STEVENSAND, H. D. and HOW, J. P. (1996). The limitations of independent controller design for a multiple-link flexible macro-manipulator carrying a rigid mini-manipulator. *Proceedings of the 2nd ASCE Conference on Robotics for Challenging Environments*, Albuquerque, New Mexico, USA, 13–15 June 1996, 93–99.

STIEBER, M. E., McKAY, M., VUKOVICH, G. and PETRIU, (1999). Vision-based sensing and control for space robotics applications. *IEEE Transactions on Instrumentation and Measurement*, **48** (4), 807–812.

STRANG, G. and FIX, G. J. (1973). *An analysis of the finite element method.* Prentice-Hall, New York, USA.

SU, Z. and KHORASANI, K. (2001). A neural-network-based controller for a single-link flexible manipulator using the inverse dynamics approach. *IEEE Transactions on Industrial Electronics*, **48** (6), 1074–1086.

SUPINO, L. and ROMANO, P.M. (1997). Chatter reduction in sliding mode control of a disk drive actuator. US Patent No. $5,699,207$.

SUR, S. and MURRAY, R. M. (1997). Simultaneous force-position control for grasping using flexible link manipulators. *Proceedings of the American Control Conference*, Albuquerque, New Mexico, USA, 4–6 June 1997, 1402–1406.

SUZUKI, E., YUH, J. and CHOI, B. (1993). On modeling and control of a 2-D.O.F. flexible robot having a prismatic joint. *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, Le Touquet (France), 17–20 October 1993, **III**, 316–318.

SUZUKI, M. (1981). Composite controls for singularly perturbed systems. *IEEE Transactions on Automatic Control*, **26** (2), 438–443.

SWIGERT, J. C. (1980). Shaped torque techniques. *Journal of Guidance and Control*, **3**, 460–467.

SZE, T. L. (1995). System identification using radial basis neural networks, PhD thesis, Department of Automatic Control and Systems Engineering, The University of Sheffield, Sheffield, UK.

SZYMKAT, M., RAVN, O., TURNAU, A., KOLEK, K. and PJETURSSON, A. (1995). Integrated mechatronic modelling environments. *Proceedings of the International Conference on Recent Advances in Mechatronics*, Istanbul, Turkey, 14–16 August 1995, **II**, 767–772.

TABRIZI, M., JAMALUDDIN, H., BILLINGS, S. A. and SKAGGS, R. (1990). Use of identification techniques to develop a water-table prediction model. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **33** (6), 1913–1918.

TALEBI, H. A., KHORASANI, K. and PATEL, R. V. (1998*a*). Neural network based control schemes for flexible-link manipulator: simulations and experiments. *Neural Networks* (special issue), **11**, 1357–1377.

TALEBI, H. A., PATEL, R.V. and KHORASANI, K. (1997). Experimental evaluation of neural network based controllers for tracking the tip position of a flexible-link manipulator. *Proceedings of the IEEE International Conference on Robotics and Automation*, Albuquerque, New Mexico, USA, 20–25 April 1997, 3300–3305.

TALEBI, H. A., PATEL, R. V. and KHORASANI, K. (1998*b*). Inverse dynamics control of flexible-link manipulators using neural networks. *Proceedings of the IEEE International Conference on Robotics and Automation*, Leuven, Belgium, 16–20 May 1998, 806–811.

TALLMAN, G. H. and SMITH, O. J. M. (1958). Analog study of dead-beat Posicast control. *IRE Transactions on Automatic Control*, **4** (1), 14–21.

TANG, Y., TOMIZUKA, M. and GUERRERO, G. (1996). Robust control of rigid robots. *Proceedings of 36th IEEE Conference on Decision and Control*, Kobe, Japan, 11–13 December 1996, 791–796.

THEODORE, R. J. and GHOSAL, A. (1995). Comparison of the assumed modes and finite element models for flexible multi-link manipulators. *International Journal of Robotics Research*, **14** (2), 91–111.

THOMAS, S. and BANDYOPADHYAY, B. (1997). Comments on A new controller design for a flexible one-link manipulator. *IEEE Transactions on Automatic Control*, **42** (3), 425–429.

THOMPSON, B. S. and SUNG, C. K. (1986). A variational formulation for the dynamic viscoelastic finite element analysis of robotic manipulators constructed from composite materials. *ASME Journal of Mechanisms, Transmissions, and Automation Design*, **106**, 183–190.

TIMOSHENKO, S. and MACCULLOUGH, G. H. (1949). *Elements of strength of materials*, third edition. D. Van Nostrand Company, Inc., New Jersey, USA.

TIMOSHENKO, S., YOUNG, D. H. and WEAVER, W. (1974). *Vibration problems in Engineering*, fourth edition. John Wiley, New York, USA.

TOKHI, M. O. and AZAD, A. K. M. (1995*a*). Real-time finite difference simulation of a single-link flexible manipulator system incorporating hub inertia and payload. *Proceedings of IMechE-I: Journal of Systems and Control Engineering*, **209** (I1), 21–33.

TOKHI, M. O. and AZAD, A. K. M. (1995*b*). Active vibration suppression of flexible manipulator systems – open-loop control methods. *International Journal of Active Control*, **1** (1), 15–43.

TOKHI, M. O. and AZAD, A. K. M. (1996*a*). Control of flexible manipulator systems. *Proceedings of IMechE-I: Journal of Systems and Control Engineering*, **210** (12), 113–130.

TOKHI, M. O. and AZAD, A. K. M. (1996*b*). Collocated and non-collocated feedback control of flexible manipulator systems.*Machine Vibration*, **5**, 170–178.

TOKHI, M. O. and AZAD, A. K. M. (1997). Design and development of an experimental flexible manipulator system. *Robotica*, **15** (3), 283–292.

TOKHI, M. O., AZAD, A. K. M. and POERWANTO, H. (1999). SCEFMAS: A Simulink environment for dynamic characterisation and control of flexible manipulators. *International Journal of Engineering Education*, **15** (3), 213–226.

TOKHI, M. O. and LEITCH, R. R. (1991). Design and implementation of self tuning active noise control systems. *IEE Proceedings–D: Control Theory and Applications*, **138** (5), 421–430.

TOKHI, M. O. and MOHAMED, Z. (2003). Combined input shaping and feedback control of a flexible manipulator. *Proceedings of 10th International Congress on Sound and Vibration*, Stockholm, Sweden, 7–10 July 2003, 299–306.

TOKHI, M.O., MOHAMED, Z. and AZAD, A. K. M. (1997). Finite difference and finite element approaches to dynamic modelling of a flexible manipulator. *Proceedings of IMechE-I: Journal of Systems and Control Engineering*, **211** (I2), 145–156.

TOKHI, M. O., POWERWANTO, H. and AZAD, A. K. M. (1995). Dynamic simulation of flexible manipulator systems incorporating hub inertia, payload and structural damping. *Machine Vibration*, **4**, 106–124.

TOKHI, M. O. and VERES, S. M. (2002). *Active sound and vibration control – Theory and applications*. The Institution of Electrical Engineers, London, UK.

TOMIZUKA, M. (1987). Zero phase error tracking algorithm for digital control. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **109** (March), 65–68.

TRAUTMAN, C. and WANG, D. (1996). Noncollocated passive control of a flexible link manipulator. *Proceedings of the IEEE International Conference on Robotics and Automation*, Minneapolis, Minnesota, 22–28 April 1996, 1107–1114.

TRUCKENBRODT, A. (1980). *Bewegungsverhalten und Regelung hybrider Mehrkörpersysteme mit Anwendung auf Roboter*, Fortschrittsberichte der VDI-Z. Reihe 8, Nr. 33.

TSE, F. S., MORSE, I. E. and HINKEL, R. T. (1978). *Mechanical vibrations: Theory and applications*. Allyn and Bacon Inc, Boston, USA.

TUNG, E. D. and TOMIZUKA, M. (1993). Feedforward tracking controller design based on the identification of low frequency dynamics. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **115** (September), 348–356.

TUTTLE, T. and SEERING, W. (1997). Experimental verification of vibration reduction in flexible spacecraft using input shaping. *Journal of Guidance, Control, and Dynamics*, **20** (4), 658–664.

TUTTLE, T. and SEERING, W. (1999). Creating time optimal commands with practical constraints. *Journal of Guidance, Control, and Dynamics*, **22** (March–April), 241–250.

TZAFESTAS, S. and PAPANIKOLOPOULOS, N. P. (1990). Incremental fuzzy expert PID control. *IEEE Transactions on Industrial Electronics*, **37**, 365–371.

TZES, A. and YURKOVICH, S. (1993). An adaptive input shaping control scheme for vibration suppression in slewing flexible structures. *IEEE Transactions on Control Systems Technology*, **1** (2), 114–121.

TZES, A. P., YURKOVICH, S. and LANGER, F. D. (1989). A method for solution of the Euler-Bernoulli beam equation in flexible-link robotic systems. *Proceedings of the IEEE International Conference on Robotics and Automation*, Scottsdale, Arizona, USA, 14–19 May 1989, 557–560.

TZOU, H. S. (1988). Dynamic analysis and passive control of viscoelastically damped nonlinear dynamic contacts. *Journal of Finite Elements in Analysis and Design*, **4**, 209–224.

UMETANI, Y. and YOSHIDA, K. (1989). Resolved motion rate control of space manipulators with generalized Jacobian matrix. *IEEE Transactions on Robotics and Automation*, **5** (3), 303–314.

USORO, P. B., NADIRA, R. and MAHIL, S. S. (1984). A finite element/Lagrange approach to modelling lightweight flexible manipulator. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **108** (3), 198–205.

USORO, P. B., NADIRA, R., MAHIL, S. S. and MEHRA, R. K. (1983). *Advanced control of flexible manipulators*. Final report, NSF Award No. BCS8260419.

VANDEGRIFT, M. W., LEWIS, F. L. and ZHU, S. Q. (1994). Flexible-link robot arm control by a feedback linearization/singular perturbation approach. *Journal of Robotic Systems*, **11**, 591–603.

VARADAN, V. K., HONG, S. Y. and VARADAN, V. V. (1990). Piezoelectric sensors and actuators for active vibration damping using digital control. *Proceedings of IEEE Symposium on Ultrasonics*, Honolulu, Hawaii, USA, 4–7 December 1990, 1211–1214.

VIDYASAGAR, M. (1978). *Nonlinear systems analysis*, Prentice-Hall, Englewood Cliffs, New Jersey, USA.

VON SCHWERIN, R. (1999). *Multibody System Simulation: numerical methods, algorithms and software*. Springer-Verlag Berlin Heidelberg, Germany.

VUKOVICH, G. and YOUSEFI-KOMA, A. A. (1996). Non-collocated active traveling wave control of smart structures using distributed transducers. *Proceedings of the IEEE International Conference on Control Applications*, Michigan, USA, 15–18 September 1996, 297–302.

WANG, D. and VIDYASAGAR, M. (1989*a*). Transfer function of a single flexible link. *Proceedings of the IEEE International Conference on Robotics and Automation*, Scottsdale, Arizona, USA, 14–19 May 1989, 1042–1047.

WANG, D. and VIDYASAGAR, M. (1989*b*). Feedback linearizability of multi-link manipulators with one flexible link. *Proceedings of the 28th IEEE Conference on Decision and Control*, Florida, USA, 13–15 December 1989, 2072–2077.

WANG, Q.-G., ZOU, B., LEE, T. H. and BI, Q. (1997). Auto-tuning of multivariable PID controllers from decentralized relay feedback. *Automatica*, **33** (3), 319–330.

WANG, S. (1986). Open-loop control of a flexible robot manipulator. *International Journal of Robotics and Automation*, **1**, 54–57.

WANG, W.-J., LU, S.-S. and HSU, C.-F. (1989). Experiments on the position control of a one-link flexible arm. *IEEE Transactions on Robotics and Automation*, **5**, 373–377.

WANG, Z., ZENG, H., HO, D. and UNBENAUEN, H. (2002). Multiobjective control of a four-link flexible manipulator: A robust H_∞ approach. *IEEE Transactions on Control Systems Technology*, **10** (6), 866–875.

WANG, Z. P., GE, S. S. and LEE, T. H. (2001). Model-based and adaptive composite control of smart materials robots. *Proceedings of the 40th IEEE Conference on Decision and Control*, Orlando, Florida, USA, 4–7 December 2001, 4938–4943.

WASSERMAN, P. D. (1993). *Advanced methods in neural computing*. Van Nostrand Reinhold, New York, USA.

WEBER, M., MA, O. and SHARF, I. (2002). Identification of contact dynamics model parameters from contstrained robotic operations. *Proceedings of the DETC'02 ASME Design Engineering Technical Conferences and Computer and Information in Engineering Conference*. Montreal, Canada, 29 September–2 October 2002, DETC2002/MECH-34357.

WELLS, R. L. and SCHUELLER, J. K. (1990). Feedforward and feedback control of a flexible robotic arm. *IEEE Control Systems Magazine*, **10**, 9–15.

WELLSTEAD, P. E. and ZARROP, M. B. (1991). *Self-tuning systems: Control and signal processing*. John Wiley & Sons, Chichester, UK.

WHITNEY, D. E. (1969). Resolved motion rate control of manipulators and human prostheses. *IEEE Transactions on Man-Machine Systems*, **10**, 47–53.

WIDROW, B., GLOVER, J. R., MCCOOL, J. M. et al. (1975). Adaptive noise cancelling: Principles and applications. *Proceedings of the IEEE*, **63**, 1662–1676.

WIE, B., SINHA, R., SUNKEL, J. and COX, K. (1993). Robust fuel- and time-optimal control of uncertain flexible space structures. *Proceedings of* the *AIAA Guidance, Navigation, and Control Conference*, Monterey, California, USA, 17–19 August 1993, 939–948.

WON, C. C. (1995). Piezoelectric transformer. *Journal of Guidance, Control, and Dynamics*, **18**, 96–101.

WORDEN, K., STANSBY, P., TOMLINSON, G. and BILLINGS, S. A. (1994). Identification of non-linear-wave forces. *Journal of Fluids and Structures*, **8** (1), 19–71.

XU, W., ZHANG, X. and NAIR, S. (2001). Dynamic modelling of a two-link flexible manipulator incorporating experimental data. *Proceedings of the American Control Conference*, Arlington, Texas, USA, 25–27 June 2001, 4508–4513.

YAMADA, K. and TSUCHIYA, K. (1990). Efficient computation algorithms for manipulator control of a space robot. *Transactions of Society of Instrument and Control Engineers*, **26** (7), 765–772 (in Japanese).

YANG, J.-H., LIAN, F.-L., and FU, L.-C. (1995). Adaptive hybrid position/force control for robot manipulators with compliant links. *Proceedings of the IEEE International Conference on Robotics and Automation*, Nagoya, Japan, 21–27 May 1995, 603–608.

YANG, T.-C., JACKSON, C. S. and KUDVA, P. (1991). Adaptive control of a flexible link manipulator with unknown load. *IEE Proceedings–D: Control Theory and Applications*, **138**, 1614–1619.

YANG, Y. P. and GIBSON, J. S. (1989). Adaptive control of a manipulator with a flexible link. *Journal of Robotic Systems*, **6** (3), 217–232.

YESILDIREK, A., VANDEGRIFT, M. W. and LEWIS, F. L. (1994). A neural network controller for flexible-link robots. *Proceedings of the IEEE International Symposium on Intelligent Control,* Columbus, Ohio, USA, 16–18 August 1994, 63–68.

YIGIT, A. S. (1988). Dynamics of a radially rotating beam with impact: Implications for robotics, PhD Dissertation, The University of Michigan, USA.

YIGIT, A. S. (1994*a*). On the stability of PD control for a two-link rigid-flexible manipulator. *Transactions of ASME: Journal of Dynamic Systems, Measurement, and Control*, **116**, 208–215.

YIGIT, A. S. (1994*b*). The effect of flexibility on the impact response of a two-link rigid-flexible manipulator. *Journal of Sound and Vibration*, **177**, 349–361.

YIGIT, A. S., SCOTT, R. A. and ULSOY, A. G. (1988). Flexural motion of a radially rotating beam attached to a rigid body. *Journal of Sound and Vibration*, **121** (2), 201–210.

YIGIT, A. and ULSOY, A. G. (1989). Controller design for rigid-flexible multi-body system. *Proceedings of the 28th IEEE Conference on Decision and Control,* Florida, USA, 13–15 December 1989, 665–673.

YIGIT, A. S., ULSOY, A. G. and SCOTT, R. A. (1990). Dynamics of a radially rotating beam with impact, Part 1:Theoretical and computational model; Part 2: Experimental and simulation results. *Transactions of ASME: Journal of Vibration and Acoustics*, **112**, 65–77.

YIM, W. (1993). End-point trajectory control stabilization, and zero dynamics of a three-link flexible manipulator. *Proceeding of the IEEE International Conference on Robotics and Automation*, Atlanta, Georgia, USA, 2–6 May 1993, 468–473.

YOSHIKAWA, T. (1987). Dynamic hybrid position/force control of robot manipulators – Description of hand constraints and calculation of joint driving force. *IEEE Journal of Robotics and Automation*, **3**, 386–392.

YOSHIKAWA, T., HARADA, K. and MATSUMOTO, A. (1996). Hybrid position/force control of flexible-macro/rigid-micro manipulator systems. *IEEE Transactions on Robotics and Automation*, **12**, 633–640.

YOUNG, K.-K. D. (1977). Asymptotic stability of model reference systems with variable structure control. *IEEE Transactions on Automatic Control*, **22** (2), 279–281.

YUAN, B.-S., BOOK, W. J. and SICILIANO, B. (1989). Direct adaptive control of a one-link flexible arm with tracking. *Journal of Robotic Systems,* **6** (6), 663–680.

ZADEH, L. A. (1994). Fuzzy logic, neural networks, and soft computing. *Communications of ACM (Association for Computing Machinery)*, **37**, 77–84.

ZHUANG, M. and ATHERTON, D. P. (1994). PID controller design for a TITO system. *Proceedings of IEE–D: Control Theory and Applications*, **141** (2), 111–120.

ZIEGLER, J. G. and NICHOLS, N. B. (1942). Optimum settings for automatic controllers. *Transactionsof ASME*, **64**, 759–768.

ZIEMER, R. E., TRANTOR, W. H. and FANNIN, D. R. (1998). *Signals and systems: Continuous and Discrete*. Prentice Hall, New Jersey, USA.

ZUO, K. and WANG, D. (1992). Closed loop shaped-input control of a class of manipulators with a single flexible link. *Proceedings of the IEEE International Conference on Robotics and Automation*, Nice, France, 12–14 May 1992, 782–787.

ZVEREV, A. I. (1967). *Handbook of filter synthesis*. Wiley, New York, USA.