Dynamic Modelling and Control of a Flexible Manipulator

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Abstract

This thesis presents investigations into dynamic modelling and control of a flexible manipulator system. The work on dynamic modelling involves finite element and symbolic manipulation techniques. The control strategies investigated include feedforward control using command shaping techniques. and combined feedforward and feedback control schemes. A constrained planar single-link flexible manipulator is used as test and verification platform throughout this work.

Dynamic model of a single-link flexible manipulator incorporating structural damping, hub inertia and payload is developed using the finite element method. Experiments are performed on a laboratory-scale single-link flexible manipulator with and without payload for verification of the developed dynamic model. Simulated and experimental system responses to a single-switch bang-bang torque input are presented in the time and frequency domains. Resonance frequencies of the system for the first three modes are identified. The performance and accuracy of the simulation algorithm are studied in comparison to the experimental results in both domains. The effects of damping and payload on the dynamic behaviour of the manipulator are addressed. Moreover, the impact of using higher number of elements is studied.

The application of a symbolic manipulation approach for modelling and performance analysis of a flexible manipulator system is investigated. System transfer function can be retained in symbolic form using this approach and good approximation of the system transfer function can be obtained. Relationships between system characteristics and parameters such as payload and hub inertia are accordingly explored. Simulation and experimental exercises are presented to demonstrate the effectiveness of the symbolic approach in modelling and simulation of the flexible manipulator system.

Simulation and experimental investigations into the development of feedforward control strategies based on command shaping techniques for vibration control of flexible manipulators are presented. The command shaping techniques using input shaping, low-pass and band-stop filters are considered. The command shaping techniques are designed based on the parameters of the system obtained using the unshaped bang-bang torque input.

Performances of the techniques are evaluated in terms of level of vibration reduction, time response specifications, robustness to error in natural frequencies and processing times. The effect of using higher number of impulses and filter orders on the system performance is also investigated. Moreover, the effectiveness of the command shaping techniques in reducing vibrations due to inclusion of payload into the system is examined. A comparative assessment of the performance of the command shaping techniques in vibration reduction of the system is presented.

The development of hybrid control schemes for input tracking and vibration suppression of flexible manipulators is presented. The hybrid control schemes based on collocated feedback controllers for rigid body motion control with non-collocated PID control and feedforward control for vibration suppression of the system are examined. The non-collocated PID control is designed utilising the end-point deflection (elastic deformation) feedback whereas feedforward control is designed using the input shaping technique. The developed hybrid schemes are tested within the simulation environment of the flexible manipulator with and without payload. The performances of the control schemes are evaluated in terms of input tracking capability and vibration suppression of the flexible manipulator. Initially, a collocated PD utilising the hub-angle and hub-velocity feedback signals is used as a feedback controller. Subsequently, to achieve uniform performance in the presence of a payload, a collocated adaptive control is designed based on pole-assignment self-tuning control scheme. Lastly, a comparative assessment of the performance of the hybrid control schemes is presented.

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Contents

Title i
Abstract ii
Acknowledgements iv
Contents v
List of tables ix
Notation x
Abbreviations xiv

1. Introduction 1
1.1. Background 1
1.2. Literature review 2
1.2.1. Modelling 2
1.2.1.1. Assumed mode method 3
1.2.1.2. Singular perturbation and frequency-domain techniques 3
1.2.1.3. Numerical analysis techniques 4
1.2.2. Control 5
1.2.2.1. Feedforward control 5
1.2.2.2. Closed-loop control 8
1.3. Aims of the research 14
1.4. Contributions of the research 14
1.5. Outline of the thesis 16
1.6. Publications 17
1.6.1. Journal papers 17
1.6.2. Conference papers 18
1.6.3. Research reports 19
1.7. Summary 19

2. The flexible manipulator system **20**

2.1. Introduction 20

2.2. Description of the flexible manipulator 20

2.3. The experimental rig 21

2.3.1. The flexible arm 21

2.3.2. The driving motor with amplifier 21

2.3.3. Measuring devices 24

2.3.4. Digital processor and interfacing system 24

2.4. Summary 25

3. Dynamic modelling of a flexible manipulator **26**

3.1. Introduction 26

3.2. The finite element method 26

3.3. Simulation algorithm 27

3.3.1. Incorporation of hub inertia and payload 31

3.3.2. State-space representation 32

3.4. Simulation results 33

3.4.1. System without payload 34

3.4.2. System with payload 40

3.5. Experiments 42

3.6. Model validation 45

3.7. Summary 46

4. Modelling and analysis using a symbolic manipulation approach **47**

4.1. Introduction 47

4.2. A symbolic manipulation approach 47

4.3. Development of the symbolic algorithm 49

4.3.1. Dynamic equations of motion 49

4.3.2. Transfer functions 52

4.4. Analysis 54

4.4.1. System without payload and hub inertia 54

4.4.2. System with payload and hub inertia 58

4.5. Validation and performance analysis 70

4.6. Summary 71

5. Vibration control using command shaping techniques **72**
5.1. Introduction 72
5.2. Feedforward control techniques 73
5.2.1. Input shaping 73
5.2.2. Filtering techniques 77
5.3. Implementation 78
5.3.1. Input shaping 80
5.3.2. Filtered inputs 81
5.4. Simulation results 83
5.4.1. Input shaping 83
5.4.2. Low-pass filtered inputs 88
5.4.3. Band-stop filtered inputs 93
5.5. Experimental results 98
5.5.1. Input shaping 98
5.5.2. Low-pass filtered inputs 99
5.5.3. Band-stop filtered inputs 106
5.6. Comparative performance assessment 110
5.7. Summary 123

6. Hybrid control schemes for input tracking and vibration control **124**
6.1. Introduction 124
6.2. Hybrid PD control schemes 126
6.2.1. Collocated PD control 126
6.2.2. Hybrid collocated PD and non-collocated control 127
6.2.3. Hybrid collocated PD and feedforward control 128
6.2.4. Implementation and results 129
6.2.4.1. Collocated PD control 129
6.2.4.2. Hybrid control 132
6.3. A hybrid adaptive control scheme 139
6.3.1. Collocated adaptive control 139
6.3.2. Hybrid collocated adaptive and feedforward control 142
6.3.3. Implementation and results 144
6.3.3.1. Collocated adaptive control 144
6.3.3.2. Hybrid control 148

6.4. Summary 154

7. Conclusion and further work **155**

7.1. Conclusion 155

7.2. Further work 157

7.2.1. Development of an accurate dynamic model 157

7.2.2. The application of symbolic manipulation approach 157

7.2.3. The command shaping techniques 158

7.2.4. Hybrid control schemes 158

7.2.5. Development of a two-link flexible manipulator 158

References **159**

List of Tables

Table 2.1 Parameters of the flexible arm 22

Table 3.1 Relation between number of elements, execution time and resonance frequencies of the flexible manipulator 38

Table 3.2 Relation between payload and resonance frequencies of the flexible manipulator. Number of elements=10 42

Table 3.3 Relation between payload and resonance frequencies of the flexible manipulator experimental rig 45

Table 4.1 The first column of RH table for the numerator of $G_1(s)$ 65

Table 4.2 The first column of RH table for the numerator of $G_2(s)$ 66

Table 4.3 The first column of RH table for denominator of the system 66

Table 5.1 Magnitude of the input shapers 81

Table 5.2 Simulated level of vibration reduction using command shaping techniques with exact natural frequencies 111

Table 5.3 Experimental level of vibration reduction with end-point acceleration using command shaping techniques with exact natural frequencies 111

Table 5.4 Settling times of the hub-angle response using command shaping techniques with exact natural frequencies 114

Table 5.5 Overshoot of the experimental hub-angle response using command shaping techniques with exact and erroneous frequencies 114

Table 5.6 Simulated level of vibration reduction using command shaping techniques with erroneous natural frequencies 116

Table 5.7 Experimental level of vibration reduction with end-point acceleration using command shaping techniques with erroneous natural frequencies 116

Table 5.8 Settling times of the hub-angle response using four-impulse sequences, sixth-order low-pass and band-stop filters with erroneous natural frequencies 118

Notation

a_1, a_2, b_0	Coefficients of identified model
a_{ij}	Elements of matrix
$b_1, b_2, c_1, c_2, c_3, g$	Constants
d	Filter order
f_1, f_2	Natural frequency
h_1, h_2, h_3, h_4, h_5	Functions
j	Unit imaginary number
k	Local variable
l	Length of an element
m	Coefficient determining size of a matrix
m_{ij}	Elements of elemental mass matrix
m_p	Payload
n	Number of elements
p	Pole
q	Number of impulses
r	Reference hub angle
r_α	Reference end-point deflection
s	Laplace variable
t	Time
t_i	Time location of impulse i
u	Input matrix
$u(t)$	Input torque as function of time
v	System states
w	Elastic deflection
w_α	End-point deflection

x	Distance from the hub
y	Total displacement
$y_\delta(t)$	Impulse response
z	z-transform variable
A, B, C	Matrices
D	Damping matrix
D_{ww}	Element of damping matrix
E	Young Modulus
E_K	Kinetic energy
E_P	Potential energy
$F(t)$	Force
$G(s)$	System transfer function
$G_1(s), G_{1a}(s), G_{1b}(s)$	Transfer functions from torque input to end-point displacement
$G_2(s), G_{2a}(s), G_{2b}(s)$	Transfer functions from torque input to hub-angle
H	Constant
$H(j\omega)$	Frequency response
I	Area moment of inertia
I_D	Identity matrix
I_h	Hub inertia
J_i, J_j	Magnitudes of impulses
K	Stiffness matrix
K_d, K_i, K_p	Derivative, Integral, Proportional gains of PID controller
K_n	Elemental stiffness matrix
K_v	Derivative gain of PD control
K_{ww}	Element of stiffness matrix
L	Length
M	Mass matrix
M_{ij}	Elements of mass matrix
M_n	Elemental mass matrix

$N(x), N_a(x)$	Shape function vector
$Q(t), Q_a(t)$	Nodal displacement vector
S	Cross sectional area
$R(s)$	Input torque in frequency domain
$U(s)$	Control signal
V, V_1, V_2	Amplitude of residual vibration
W	Impulse response magnitude
Y	Vector of total displacement
Z	Compensator zero
α	Weight of the manipulator
β	Flexural rigidity of the manipulator
χ	A function
δ_1, δ_2	Filter attenuation
ε	Band edge value
$\phi_1, \phi_2, \phi_3, \phi_4$	Elements of shape function vector
Φ	Constant
φ	A function of a matrix
γ_1, γ_2	Coefficients of a damping equation
η	Zero
λ_i	A function of impulse response magnitude
Λ	Langragian
θ	Hub-angle
$\theta(s)$	Hub-angle in frequency domain
θ_α	End-point rotation
$\dot{\theta}$	Hub-velocity
ρ	Mass density per unit volume
σ_i	A function of damped frequency and time
τ	Torque
τ_s	Sampling time

ω	Radian frequency
ω_c	Filter cut-off frequency
ω_d	Damped frequency in radian/sec
ω_n	Natural frequency in radian/sec
ω_p	Pass-band edge frequency
ω_s	Stop-band edge frequency
ψ	Polynomial
ψ_1, ψ_2	Coefficients of polynomial
ζ, ζ_1, ζ_2	Damping ratio

Abbreviations

A/D	Analogue to digital
BS	Band-stop filter (sixth-order)
D/A	Digital to analogue
FD	Finite difference
FE	Finite element
IIR	Infinite impulse response
I/O	Input output
IS	Input shaping (four-impulse sequence)
lhp	Left half of s-plane
LP	Low-pass filter (sixth-order)
MRAC	Model reference adaptive control
NN	Neural networks
PD	Proportional-Derivative
PDE	Partial differential equation
PDIS	Hybrid PD with input shaping
PDPID	Hybrid PD with PID
PID	Proportional-Integral-Derivative
PSD	Power spectral density
RLS	Recursive least squares
RH	Routh-Hurtwiz
rhp	Right half of s-plane
VSC	Variable structure control

Chapter 1

Introduction

1.1. Background

Robot manipulators are finding an increasing number of applications especially in automation and manufacturing industries. Robots that were once used to pick and place work-pieces are now being used in more complex tasks such as assembling and working at unmanned places. Most existing robotic manipulators are designed with maximum stiffness, in an attempt to minimise system vibration and achieve good positional accuracy. High stiffness is achieved by using heavy material. As a consequence, such robots are usually heavy with respect to the operating payload. This, in turn, limits the speed of operation of the robot manipulation, increases the size of actuator, boosts energy consumption and increases the overall cost. Moreover, the payload to robot weight ratio, under such situations, is low. In order to solve these problems, robotic systems are designed to be lightweight and thus possess some level of flexibility. Conversely, flexible robot manipulators exhibit many advantages over their rigid counterparts: they require less material, are lighter in weight, higher manipulation speed, lower energy consumption, require smaller actuators, are more manoeuvrable and transportable, have less overall cost and higher payload to robot weight ratio (Azad, 1994; Book and Majette, 1983). Due to such advantages flexible manipulators are being used in various applications including space exploration and hazardous environments. In space exploration, space robots must be very lightweight to reduce their launching costs to space (Yamano et al., 2000). In hazardous plants where access to underground storage tanks is limited, flexible-link robots are used in handling hazardous waste material (Jamshidi et al., 1998).

The control of flexible robot manipulators to maintain accurate positioning is a challenging problem. Due to the flexible nature and distributed characteristics of the system, the dynamics are highly non-linear and complex. Problems arise due to precise positioning requirement, vibration due to system flexibility, the difficulty in obtaining accurate model and non-minimum phase characteristics of the system (Piedboeuf et al., 1993; Yurkovich, 1992). Therefore, to attain end-point positional accuracy, a control mechanism that accounts for both the rigid body and flexural motions of the system is required. The complexity of this problem increases dramatically when a flexible manipulator carries a payload. Practically, a robot is required to perform a single or a set of tasks in sequence such as to pick up a payload, move to a specified location or along a pre-planned trajectory and place the payload. However, the dynamic behaviour of the manipulator is significantly affected by payload variations (Menq and Chen, 1988; Poerwanto, 1998). If the advantages associated with lightness are not to be sacrificed, accurate models and efficient control strategies for flexible robot manipulators have to be developed.

1.2. Literature Review

A significant amount of research has been carried out to devise methodologies for modelling and control of flexible robot manipulator systems. Various experimental investigations have accordingly been carried out for verification of the proposed modelling and control approaches (Hu, 1993). Most of the experimental work is restricted to either vertical or horizontal planes. Moreover, these are limited to single-link and two-link flexible manipulators due to the complexity of multi-link manipulator systems. This section presents a review of modelling and control of flexible robot manipulators.

1.2.1. Modelling

The main goal in modelling of a flexible manipulator system is to achieve an accurate representation of an actual system. It is important to recognise the flexible nature and dynamic behaviour of the system and construct a mathematical model that accounts for several effects including damping, inertia and payload. By obtaining such a model, a satisfactory and good control algorithm can be designed. The dynamic behaviour of a flexible manipulator is obtained based on a fourth order partial differential equation (PDE) of Bernoulli-Euler beam equation which represents an infinite dimensional model of the system (Book, 1990). In order to approximate the true infinite dimensional model, finite dimensional models are required. Various approaches have previously been utilised for this purpose. The modelling approaches can mainly be divided into three main categories as:

- Assumed mode method.
- Singular perturbation technique and frequency domain analysis.

- Numerical analysis approach.

1.2.1.1. Assumed Mode Method

Assumed mode method is the most widely used approach in modelling of flexible manipulators. This approach looks at obtaining approximate modes by solving the PDE characterising the dynamic behaviour of the system. In this approach, the Lagrange equation is used to derive the dynamic model of a structure. An ordinary differential equation can be obtained by representing the deflection of the manipulator as a summation of modes. Each mode is assumed as a product of two functions, one as a function of the distance along the length of the manipulator and the other, as a generalised co-ordinate dependent upon time. The model contains an infinite number of modes but for practical purposes, a finite number of modes is required. It has been reported that the first two modes are sufficient to identify the dynamics of flexible manipulators (Hasting and Book, 1986).

Previous studies utilising the assumed mode method for modelling a single-link flexible manipulator have been reported (Book, 1984; Cannon and Schmitz, 1984; Hastings and Book, 1987; Wang and Vidyasagar, 1991). Following this, a linear state space representation of the system is developed. It has been shown that a good agreement between theory and experiments is obtained utilising this approach. The model eigen values agree well with experimentally determined frequencies of the vibrational model. However, using this approach, the model does not always represent the fine details of the system (Hughes, 1987). This modelling approach has also been utilised in modelling of two-link flexible manipulator systems (Book, 1984; De Luca and Siciliano, 1991). These investigations have assumed two modes of vibration for each link.

1.2.1.2. Singular Perturbation and Frequency-domain Techniques

In the singular perturbation technique, the characteristic modes of the system are separated into two distinct groups: a set of low frequency or slow modes and a set of high frequency or fast modes. In the case of flexible manipulators, the rigid body modes are the slow modes and the flexible modes are the fast modes. The dynamics of the system can then be divided into two sub-systems. The slow sub-system is of the same order as that of the equivalent rigid manipulator. The slow variables are considered as constant parameters for the fast sub-system (Khorrami and Ozguner, 1988).

An alternative to modelling of the manipulator in the time domain is to use a method based on frequency domain analysis (Book and Majette, 1983). This method develops a concise transfer matrix model using the Bernoulli-Euler beam equation for a uniform beam. The weakness of this method is that it makes no allowance for interaction between the gross motion and the flexible dynamics of the manipulator, nor can these effects be easily included in the model. As a result, the model can only be regarded as approximate.

1.2.1.3. Numerical Analysis Techniques

Numerical analysis techniques based on finite difference (FD) and finite element (FE) methods are commonly used for modelling of flexible manipulator systems. Previous simulation studies with FD method have shown that the method is simple in mathematical terms and is more appropriate in applications involving uniform structures such as flexible manipulator systems. Furthermore, these studies have shown the relative simplicity of the method (Kormoulis, 1990). The method involves discretising the system into several sections and developing a linear relation for the deflection of each section using FD approximations.

The FD approach has previously been utilised in obtaining the dynamic characterisation of single-link flexible manipulator systems incorporating damping, hub inertia and payload (Tokhi and Azad, 1995; Tokhi, et al., 1995; Tzes, et al., 1989). Experiments have also been conducted to verify and validate the theoretical and simulation results. It has been demonstrated that a satisfactory agreement between simulation and experimental results is obtained. However, this modelling approach has not been utilised for modelling of multi-link flexible manipulator systems.

The FE method has been successfully used in solving many materials and structural problems. The method involves discretising the actual system into a number of elements with associated elastic and inertia properties of the system. This gives approximate static and dynamic characterisation of the actual system. The performance of the FE technique in modelling of flexible manipulators has previously been investigated (Aoustin et al., 1994; Menq and Chen, 1988; Tokhi et al., 1997; Usoro et al., 1986). These investigations have shown that the method can be used to obtain a good representation of the system. It has been reported that in using FE methods, a single element is sufficient to describe the dynamic behaviour of a flexible manipulator reasonably well. Using a single element, the first two modes of vibration are well-described (Aoustin et al., 1994). Moreover, the FE method exhibits several advantages over the FD method in terms of accuracy and computational requirements (Tokhi et al., 1997). However, in modelling of the manipulator using FE methods, the effects of structural damping and payload have not been adequately addressed. The study of the effect of payload on the manipulator is important for modelling and control purposes, as successful implementation of a flexible manipulator control is contingent upon achieving acceptable uniform performance in the presence of payload variations. The damping in the real system is expected to make the residual motion to converge to zero as the energy is dissipated, and not to change the resonance modes of the system (Poerwanto, 1998).

1.2.2. Control

The control strategies for flexible robot manipulator systems can be classified as feedforward and feedback control techniques. Feedforward techniques are mainly developed for vibration suppression and involve altering the input command or reference so that system vibrations are reduced whereas feedback control techniques use measurement and estimate of the system states for rigid body motion control and vibration suppression of the system. This section discusses and reviews both feedforward and feedback control techniques for control of flexible robot manipulators.

1.2.2.1. Feedforward Control

Feedforward control techniques for vibration suppression of flexible robot manipulators consists of developing the control input through consideration of the physical and vibrational properties of the system, so that vibrations at response modes are reduced. This method does not require any additional sensors or actuators and does not account for changes in the system once the input is developed.

A number of techniques have been proposed as feedforward control strategies for flexible manipulators. Aspinwall (1980) has used a Fourier expansion for the forcing function through which the controller parameters are chosen to reduce the peaks of the frequency spectrum at discrete points. This only eliminates a few of the peaks and leaves some modes excited. Swigert (1980) has derived a shaped torque that minimises residual vibration and the effect of parameter variations that affect the modal frequencies. However, the forcing function is not time-optimal. Several researchers have presented and studied the application of computed torque techniques for control of flexible manipulators (Alberts et al., 1990; Bayo, 1988; Moulin and Bayo, 1991). In this approach, a detailed model of the system is first obtained, and by inverting the desired output trajectory, the required input needed to generate that trajectory is computed. For linear systems, this might involve dividing the frequency spectrum of the trajectory by the transfer function of the system, thus obtaining the frequency spectrum of the input. For non-linear systems, this technique involves inverting the equations describing the model. However, this technique suffers from several problems (Singer and

Seering, 1990). These are due to inaccuracy of a model, selection of poor trajectory to guarantee that the system can follow it, sensitivity to variations in system parameters and response time penalties for a causal input.

Bang-bang control involves the utilisation of single and multiple-switch bang-bang control functions (Onsay and Akay, 1991) which require accurate selection of switching time, depending on the representative dynamic model of the system. Minor modelling errors could cause switching errors, and result in a substantial increase in the residual vibrations (Sangveraphunsiri, 1984). Although, utilisation of minimum energy inputs has been shown to eliminate the problem of switching times that arise in the bang-bang input (Jayasuriya and Choura, 1991), the total response time, becomes longer (Meckl and Seering, 1990; Onsay and Akay, 1991). Meckl and Seering (1985, 1988) have examined the construction of input functions from either ramped sinusoids or versine functions. This approach involves adding up harmonics of one of these template functions. If all harmonics were included, the input would be a time optimal rectangular input function. The harmonics that have significant spectral energy at the natural frequencies of the system are eliminated. The resulting input which is given to the system approaches the rectangular shape, but does not significantly excite the resonance. The method has subsequently been tested on a cartesian robot, achieving considerable reduction in the residual vibrations (Meckl and Seering, 1990).

Another technique for feedforward control of flexible robot manipulators is the command shaping technique. Within this technique, a significant amount of work on shaped command inputs based on filtering techniques has been reported. In this approach, a shaped torque input is developed on the basis of extracting the input energy around the natural frequencies of the system, so that the vibration of the manipulator during and after the movement is reduced. The process of extracting the energy is based on filtering techniques. The filters are used for pre-processing the input to the plant, so that lower energy is fed into the system near its resonance. Various filtering techniques have been employed. These include low-pass filters, band-stop filters, notch filters and Gaussian shaped inputs (Singhose et al., 1995; Tokhi and Azad, 1996; Tokhi and Poerwanto, 1996). It has been shown that better performance in the reduction of level of vibration of the system is achieved using the low-pass filter. This is due to indiscriminate spectral attenuation in a low-pass filtered torque at all resonance modes of the system. Utilisation of the band-stop filter, however, is important as spectral attenuation in the input at the selected resonance modes of the system can be achieved. On the other hand, a Gaussian shaped torque input provides smooth energy propagation into the system. In this sense, it comfortably excites the flexible manipulator without resulting excessive vibration at the resonance modes.

An approach in command shaping techniques known as input shaping has been proposed by Singer and co-workers which is currently receiving considerable attention in vibration control (Singer and Seering, 1990). The method involves convolving a desired command with a sequence of impulses known as input shaper. The shaped command that results from the convolution is then used to drive the system. Design objectives are to determine the amplitude and time locations of the impulses, so that the shaped command reduces the detrimental effects of system flexibility. These parameters are obtained from the system natural frequencies and damping ratio. Using this method, a response with less vibration can be achieved, however, with a slight time delay approximately equal to the length of the impulse sequence. The method has been shown to be effective in reducing vibration in flexible plants (Murphy and Watanabe, 1992). With more impulses, the system becomes more robust to flexible mode parameter changes, but this will result in longer delay in the system response. Previous investigations have shown that the input shaper can be designed to account for modelling errors in natural frequencies and damping ratio (Pao and Lau, 1999; Singhose et al., 1996).

By designing additional impulse sequences for other vibration modes, and then convolving the impulse sequences together, a combined impulse sequence that attenuates vibration at other modes of the system can be derived. Previous investigations have shown that conventionally designed filters are less effective for command shaping than input shaping (Singhose et al., 1995). The vibration reduction achieved with input shaping methods is considerably greater than that achieved with filters. Moreover, input shaping is far less sensitive to modelling errors as they are designed explicitly to deal with modelling errors in mechanical systems. Several researchers have presented alternative approaches to design input shapers. These include designs both in the time-domain (Singer and Seering, 1990) and the frequency-domain (Singh and Vidali, 1994), input shaper based on the pole-placement technique (Tuttle and Seering, 1994), for multiple modes (Hyde and Seering, 1991; Rappole et al., 1994) and for multi-input systems (Pao, 1996; Cutforth and Pao, 1999).

The major drawback of the command shaping techniques is their limitation in coping with parameter changes and disturbances to the system (Khorrami et al., 1994). Moreover, this technique requires relatively precise knowledge of the dynamics of the flexible manipulator. Modifications to provide some degree of robustness with respect to modelling errors, in respect of natural frequencies and damping ratio, however, decreases the speed of the transient response. The issues of robustness of these methods to unmodelled dynamics have not been adequately addressed. In attempting to solve these problems, a number of researchers have examined closed-loop input shaping methods. Tzes and Yurkovich (1993) have developed an adaptive input shaping control scheme for end-point tracking and vibration control of a flexible manipulator to handle payload variations and disturbances. It has been shown that robustness of the controller can be improved and the length of the impulse sequence can be kept to minimum. Wang and co-workers have developed closed-loop input shaping based on PD control for a single-link flexible manipulator and a five-bar linkage manipulator (Drapeau and Wang, 1993; Zuo and Wang, 1992). A closed-loop input shaping technique using rigid body based controllers and time-delay control has also been proposed (Kapila et al., 2000; Khorrami et al., 1994).

1.2.2.2. Closed-loop Control

In general, control of a flexible robot manipulator can be made easier by locating every sensor exactly at the location of the actuator, as collocation of sensors and actuators guarantees stable servo control (Cannon and Schmitz, 1984; Gevartar, 1970). Therefore, most robots (rigid) are controlled by employing only sensors that are collocated with actuators. For end-point position control, the desired location is converted through real-time kinematics computation into the equivalent angle. Assuming that the robot is stiff enough, the end-point will thus be in the desired location. However, this method of controlling robots has two severe limitations: (a) The inherent flexibility of robot structure makes it difficult to achieve highly accurate manipulation. (b) Member and drive trains of the robot have to be made very stiff, and must therefore be very heavy in order to achieve some degree of precision. In the case of flexible manipulator systems, the end-point position is controlled by obtaining the parameters at the hub and end-point of the manipulator and using the measurement as a basis for applying control torque at the hub. Thus, the feedback control scheme can be divided into collocated and non-collocated control. By applying control torque based on non-collocated sensors, the problem of non-minimum phase and of achieving stability is of concern. Several approaches utilising closed-loop control strategies have been reported for flexible robot manipulators. These approaches can mainly be classified as linear state feedback control, adaptive control, robust control and intelligent control.

Linear State Feedback Control

Linear state feedback control schemes are among the earliest techniques that have been utilised for control of flexible manipulator systems. Cannon and Schmitz (1984) have reported one of the earliest results in this area and their paper is one of the most often cited in the literature. An analytical model utilising Bernoulli-Euler model, Lagrangian formulation and assumed mode method was derived from a single-link apparatus assuming a pinned-free configuration. Important parameters were determined experimentally. Then a control scheme utilising Linear Quadratic Gaussian approach was developed where an estimator was used to estimate all the system states. A good agreement between theoretical and experimental results was obtained. It has been shown that the system response is ultimately limited by the inherent wave propagation in the structure.

Utilising the same technique, Sakawa et al. (1985) proposed a linear quadratic control technique to dampen the flexible modes while tracking the hub reference angle. Stable factorisation (Wang and Vidyasagar, 1987) and optimal control techniques (Hasting and Book, 1987) have also been investigated. However, the proposed control schemes based on linear state feedback control are sensitive to payload variations and disturbances, and therefore, the system performance will deteriorate when a payload and/or a typical parameter of the manipulator vary with time (Menq and Chen, 1988).

Adaptive Control

The importance of an adaptive control technique for control of flexible robot manipulators becomes obvious when realising that successful employment of flexible manipulators is contingent upon achieving uniform performance with regard to payload variations. These control schemes are mostly designed utilising model reference adaptive control (MRAC) or a two-stage process in which a system identification stage is followed by the adaptation of the controller, namely self-tuning control.

A considerable number of schemes of design of adaptive controllers for flexible manipulator systems have been reported. Meldrum and Balas (1986) have utilised the MRAC scheme for control of a flexible manipulator, and have found that with non-collocated output feedback, odd numbered flexural modes tend to be unstable, therefore, small feedback gains are suggested. Harishima and Ueshiba (1986) have used an adaptive controller design based on an auto regressive model with a dead time to avoid unstable pole-zero cancellation. The experimental results have indicated that the algorithm is capable of adapting to payload variations. However, the algorithm has proved to be unstable on the Stanford flexible manipulator (Rovner, 1987). Yuan et al. (1989) have proposed an MRAC scheme where the system is optimally controlled. The load adaptation for two different loading conditions has been demonstrated but the effect of payload changes on the controller has not been discussed.

Rovner and Cannon (1987) have used a recursive least squares (RLS) algorithm with the hub torque as the input and end-point position as the output information to identify the system transfer function with unknown payload at the end-point. Subsequently, the identified parameters were used on-line for the controller design. Experimental study on payload adaptation has been successfully performed. Nelson and Mitra (1986) have proposed a load adaptive control algorithm to control a flexible manipulator with unknown fixed payload. A steepest decent (gradient) algorithm was used to identify the mass and an optimal controller was designed to control the flexible manipulator. The parameter-updating algorithm proposed in this method might tend to diverge with certain inputs and unmodelled dynamics making it difficult to obtain the controller parameters for different systems (Menq and Chen, 1988). Moreover, the manipulator model used does not fully characterise a real flexible manipulator system. For example, if the payload mass is zero the dominant system frequency in that case would be infinite, but for a real flexible beam the dominant system frequency is always finite. Nemir et al. (1988) has experimentally controlled a flexible manipulator using a self-tuning controller. Their work, however, has been limited to the case of a constant payload. Rovner and Franklin (1988) have implemented an adaptive controller for a flexible manipulator that can handle payloads. However, problems due to transient behaviour during payload release have not been addressed. A technique to identify unknown payload, attached at the end-point, has been proposed using a payload adaptation algorithm (Menq and Chen, 1988). Simulation results have shown that the proposed algorithm is able to identify unknown payload and resulted in a good controller.

Feliu et al. (1993) have proposed an adaptive controller for a single-link flexible manipulator in the presence of joint friction and load changes. The proposed controller was developed with an inner loop to control a motor position and outer loop to control the end-point position. A simple control law with minimal computing effort has been achieved. However, the effectiveness of this controller with load variation, which is a common situation occurring in the practical application of robotics, has not been demonstrated. A situation where an unknown payload attached at one position and released at another position has also been investigated (Yang et al., 1992). The controller was designed based on an adaptive pole-assignment technique. However, experimental results have shown that an undesirable transient occurs during payload release. Poerwanto (1998) proposed an adaptive joint based