CHAPTER-1
INTRODUCTION
1. INTRODUCTION

1.1 Robot Manipulator

In robotics manipulator is a device used to manipulate materials without direct contact. The applications were originally for dealing with radioactive or biohazardous materials, using robotic arm where, they were used in inaccessible places. In more recent developments they have been used in applications such as robotically-assisted surgery and in space. It is an arm-like mechanism that consists of a series of segments, usually sliding or jointed, which grasp and move objects with a number of degrees of freedom. Robotic manipulators are widely used to help in dangerous, monotonous, and tedious jobs. Most of the existing robotic manipulators are designed and built in a manner to maximize stiffness in an attempt to minimize the vibration of the end-effectors. This high stiffness is achieved by using heavy material and bulky design. Hence, the existing heavy rigid manipulators are shown to be inefficient in terms of power consumption or speed with respect to the operating payload. Also the operation of high precision robots is severely limited by their dynamic deflection, which persists for a period of time after a move is completed. The settling time required for this residual vibration delays subsequent operations, thus conflicting with the demand of increased productivity. These conflicting requirements between high speed and high accuracy have rendered the robotic assembly task a challenging research problem. In addition, many industrial manipulators face the problem of arm vibrations during high-speed motion. In order to improve industrial productivity, it is required to reduce the weight of the arms and/or to increase their speed of operation. For these purposes, it is very desirable to build flexible robotic manipulators.

In modern robot systems, flexibility has become very important due to satisfying special needs of industrial automation. To date, control engineers have been working on the development of a mathematical model and control of flexible structures. Flexible mechanisms and flexible joint manipulators are usually used in servicing sector, various space station building and maintenance, gantry cranes, atomic force microscopes, medical and defense industries.
A robot manipulator is a spatial mechanism consisting essentially of a series of bodies, called “links”, connected to each other at “joints”. The joints can be of various types: revolute, rotary, planar, prismatic, and telescopic or combinations of these. A serial connection of the link results in an open-chain manipulator. Closed-chain manipulators result from non-serial (or parallel) connections between links. Actuators at the joints of the manipulator provide power for motion.

A robot is usually not designed for a specific or repetitive task which can be done equally well by task-specific machines. Its strength lies in its ability to handle a range of tasks by virtue of being “re-programmable”. Therefore, in addition to the mechanical hardware two other elements are integral to the description of a robot: sensors and control. With the advent of micro-electronics and digital computers the availability of sensors is ever increasing and the control is usually done by software executed by computers which also collect the sensory data. It is possible to model quite accurately, the dynamics of robot manipulators for purposes of control. However, for most practical robots the models are complex and numerically intensive to calculate in real-time.

Traditional analyses of robot manipulators consider the whole mechanism to be rigid. Relaxation of the assumption of rigidity leads to further complications of the dynamics of the manipulators, leading to more difficulties in control. The overall motion of the manipulator is augmented by additional motion due to the dynamics of flexibility which must be considered. Sending is also made more difficult. However, the ability to control robots with significant structural flexibilities, referred to as flexible robots in the rest of this thesis, influences robotics in many ways. It allows for considerations of new applications, observance of less conservative structural design and performance enhancements in certain classes of robotic tasks.

The original motivation for doing work on flexible manipulators comes from the field of medicine. Endoscopes, used for surgically non-invasive examination of the alimentary canal could be enormously enhanced by attaching robotic fingers at their tip, controlled teleoperatively by a surgeon wearing a “data glove”. This would not only aid in examination but could conceivably be used for manipulation of bodies like tumors and polyps and even in the performance of surgical procedures. It is estimated that a lumen
3mm in diameter would be available to accommodate these fingers at the tip of the endoscope into which the fingers would have to fit during insertion of the device to prevent snagging and interference. If we consider a set of three fingers, which would be the minimum required for sufficient dexterity, the dimensions of the fingers make it difficult to ensure sufficient rigidity. This is a scenario in which flexibility is unavoidable. Flexible manipulators can perform better than rigid manipulators in certain tasks where control of both positions and forces are desired. Being that the nature of the manipulation task for the endoscopic fingers requires simultaneous force and position control, it may indeed be that in this case, additionally, flexibility is desirable.

There are more common place scenarios than the fairly esoteric one mentioned above that encounter flexibility. With improvements in electric motor technology modern manipulators can not only carry or move bigger loads, but can do so with faster accelerations. This can cause flexure even in nominally rigid manipulators, thus creating performance shortcomings. To avoid dealing with flexibilities robots are usually over-designed. Thus present generation manipulators are limited to carry loads no more that 5-10% of their weight. The ability to control flexibility immediately translates to a reduction in weight. Reduction in weight of manipulators is beneficial for the reasons mentioned below.

- Lower energy consumption: reduced inertias of the lighter robots required less power to produce the same accelerations and load-carrying capacity as heavier robots.
- Smaller actuators: reduced power requirements can be satisfied by smaller actuators, which are generally cheaper.
- Safer operation: collision of the smaller inertia causes lesser damage.
- Lower mounting strength: this is relevant to gantry and wall mounted robots.
- Simplification of drive mechanism: lighter links can be direct-driven, given the improving power to weight (or size) ratios for electric motors. This would eliminate the need for drive elements like gears, which introduce backlash.
- Faster operation: greater acceleration can be achieved for lighter robots. For certain modern applications of robots, for example, the testing of microchip and
printed circuit contacts, a high speed of operation is very important because of the
large number of operations needed to be carried out. As the task does not require a
rigid robot (there being no loads to carry) the overhead incurred due to the
inability to control flexibility is significant.

- Significant cost reduction in development of space robots: robots like the space
  shuttle arm and the robots envisaged for the construction and maintenance of the
  international space station have to be boosted into orbit. Considering that about
  95% of the takeoff weight of the space shuttle is the weight of the fuel, it is
evident that the savings in fuel due to any reduction in the weight of the fuel, it is
evident that the savings in fuel due to any reduction in the weight of the payload
  are significant.

From the above points it is clear that there are a variety of applications which
would benefit significantly from the ability to control robots which are light and fast, and
therefore naturally flexible.

Increasingly, the tasks performed by robots involve physical interaction with their
environment. This naturally gives rise to interactive forces between the robot and its
environment. The task of the controller increases from merely position control to
simultaneous force and position control called hybrid control. The mechanical
compliance introduced by flexibility is useful in hybrid control in two respects. First, the
flexible links can themselves be used for sensing the forces and torques. Second and
more importantly, the compliances in the structure increase the robustness properties of
the manipulator. This can be very significant because it is difficult, if not impossible to
predict all events which might happen in the real working environment of the robot, and
which will have an effect on the robot. Related to this is the issue of contact transition-
the transition from a free state to a state where the robot is in physical contact with some
components of the its environment.

There is an effort to incorporate flexibility into the robot dynamics and control. It
is motivated by the need to decrease the size and weight of robot manipulators, while at
the same time increasing performance. Rather than try to design away flexibilities
because of their complexity, it is important to gain an understating of how to use
flexibilities to increase the performance of the system.
Rigid-link manipulators are usually made of strong materials consequently, the manipulator is heavy. Also, the rigid structures require a large power to operate since the dynamics is sluggish and slow. These drawbacks are avoided by making the links light. Manipulators constructed with light and thin links/arms are called as flexible-link manipulators (FLM). Due to lightweight, these manipulators exhibit many advantages such as achieving high-speed operation, lower energy consumption, and increase in payload carrying capacity over their rigid counterparts. FLM are preferred in applications requiring large workspace where rigid ones may not be suitable, for example assembly of free-flying space structures and hazardous material management from safer distance. Research on flexible manipulators is motivating and interesting due to the fact that field of robotics and automation has advanced significantly in recent years, driven by industrial requirements for quicker response times and lower power consumption. These demands have led to changes in robot arm design, using lightweight materials and modifying the physical configuration of a robot such that the links are longer and thinner. The FLM have also several other potential applications in space exploration. In space robotics, it is in particular emphasized to use FLM that are suitable to move pay-loads and to carry out specialized jobs (Shuttle Manipulator that is used to help the Astronauts during extra vehicular activities). Also, use of light weight flexible structured robots in space is necessary when the weight of the robots is a concern to prevent unnecessary energy consumption and to achieve higher payload-to-mass ratio.

Tip position control of a FLM is challenging due to distributed link flexibility, which makes the system non-minimum phase, under-actuated and infinite dimensional. But controlling a flexible manipulator is more difficult compared to a rigid one. The control complexities are as follows. The motion control of flexible manipulators is difficult owing to occurrence of oscillation due to flexibility distributed along the links and thus it is difficult to achieve accuracy in positioning of the end-effector. It may be
noted that if one applies the control design for a rigid-manipulator to a FLM, it may lead to nonlinear control spill over into the flexible modes causing poor performance and instability. Thus, applying rigid-link manipulator control strategies to flexible robots (elasticity in both links and joints) may lead to significant deflections and the endpoint/tip/end-effector oscillates around the desired path. Thus, the static deflections could lead to non-zero values of the tip deflections due to these flexibilities. Therefore, to improve tip trajectory tracking and dynamic response near the target point, the elastic properties of the manipulator have to be taken into account when developing a control strategy for this class of robots. Tip trajectory tracking control of flexible manipulators is also difficult owing to the non-minimum phase problems due to non-collocation of actuator torques at the base of the manipulator and sensor at the end-effector. But in space applications, the use of non-collocated servo-control is essential for any automated satellite servicing module. As the manipulator is expected to maneuver with unanticipated payload at the end-effector, thus payload variability is also an important concern. Further, due to sudden change in payload, there may be large variation in manipulator parameters and that in turn adds further complexities to the FLM dynamics.
Fig.1.1 The FLM system has two degree of freedoms and the joint which is mounted to the shaft moves according to rotate direction of the motor.
Fig. 1.2 Flexible modes of the FLM with initial payload

Fig. 1.3 Flexible modes of the FLM with an additional payload
It can be observed from Fig.1.2 and Fig.1.3 that due to change in payload, the rigid modes remain unchanged whereas there is a large variation in the shape of the flexible modes. Thus it becomes very difficult to control a FLM under variable payload condition using conventional fixed gain controllers. Hence, the torque applied to the actuators of a FLM to control the tip position and its deflection with changes in payload should be adaptive in nature.

The field of control theory has a rich heritage of intellectual depth and practical achievements. From a simple temperature regulator, to the space probes and the automated manufacturing plants of today, control systems have played a key role in technological and scientific advancements.

In engineering and decision-making systems, the paradigm of feedback control of feedback control addresses the problem of using the information about the output (effect) to design or modify the input (cause) for a given task. Tasks range from controlling a robotic manipulator to grasping an object to stabilizing a large space structure. The complexity of control for even a small-scale system such as a compact disk drive may be due to the very stringent accuracy and speed requirements. In large-scale systems, the task of meeting rigorous performance requirements is much more challenging because of the uncertainty of the system model and its environment.

Most engineering system encountered in practice exhibit significant nonlinear behaviour. For systems exhibiting nonlinearities, the normal design procedure is to employ a linearized approximation of the process model followed by the application of a linear control methodology. However, this procedure can yield unsatisfactory performance, especially when the system is highly nonlinear and undergoes large motions, and thus operates over wide nonlinear dynamical regimes, as is often the case in the problems of attitude control, advanced aircraft control, and the control of robot manipulators. During the past fifteen years, there has been considerable progress in the understanding of nonlinear systems, primarily due to the application of mathematical concepts derived from the field of differential geometry. There has been substantial work on qualitative concepts, such as controllability and observability for nonlinear systems. Techniques for the control of nonlinear systems described by nonlinear mathematical
models were difficult to find until a major breakthrough occurred during the past decade with the development of solution to such problems as disturbance decoupling, input-output decoupling, and feedback linearization. Feedback linearization utilizes state and feedback transformations to transform a nonlinear system into an equivalent linear system so that the standard well-known linear control tools may be used for design. This technique has been successfully applied to very difficult problems such as controlling aircraft with multi-axis nonlinear dynamics and tracking in robot manipulators that have highly nonlinear dynamics.

In addition to being nonlinear, most realistic systems are seldom completely known. Control theorists are now challenged to expand their concepts and schemes to be applicable to incompletely modeled nonlinear systems. A control theory for incompletely known systems and systems described by non-traditional models will produce a wider repertoire of control laws, algorithms, and strategies.

In the presence of mode uncertainty and unmeasurable disturbances it has been found that the use of feedback control can satisfy performance specifications, whereas open-loop control simply cannot meet stringent command-following and/or disturbance rejection requirements. Thus the most fundamental reason for using feedback is to guarantee good performance in the presence of uncertainty; also, feedback is used to enable operating conditions, i.e., to stabilize unstable plants. Care must be exercised so that feedback system is reliable, i.e., that it should continue to operate in the presence of hardware and software failures.

Uncertainty and achievable performance tend to oppose each other, even though the very reason for using feedback is to obtain better performance over open-loop control. The controller is required to be robust with respect to modelling uncertainty and to alter to slow changes in the system dynamics. Robust control strives to characterize the uncertainty in the model of the plant to be controlled and to evaluate the degrees of freedom left to achieve the control task within specified bounds. Considerable efforts have been made in the literature to satisfy the stability robustness requirement, which is to guarantee closed-loop stability under a wide range of plant variations and disturbances. Bounds under which stability can be preserved have been derived and a rigorous
mathematical theory has been developed to minimize sensitivity with respect to disturbances and norm-bounded uncertainty. More research is under way to reduce the conservatism of available stability robustness results. Specifically, the “directional information” should be exploited to decrease the conservatism of results. The payoff will be improved performance, because in the linear systems, for instance, stability robustness tends to limit the bandwidths of the closed-loop system, and thereby deteriorate command-following and/or disturbance-rejection performance.

A new and relevant topic in this respect is the motion of performance-robustness. This issue is concerned with the characterization of and feedback design in the presence of the so called “structured” and/or “unstructured” uncertainties to meet predefined performance specifications. Meanwhile, it should be guaranteed that these performance specifications will be met by a fixed controller for any value of the plant “structured/unstructured” uncertainty in a prior known plant set which is defined in an appropriate topology.

One of the important classes of plants is the class of distributed parameter systems in which the variables of importance depend on both spatial and time variations. Such systems are usually modeled by partial or integral-differential equations. Although there has been considerable progress in understanding the stabilization of distributed parameter systems, and in the development of fast algorithms and computational schemes specifically for control of systems governed by partial and integral-differential equations, there remains a number of theoretical and practical problems that must be considered before distributed parameter control becomes a systematic tool for the design of these complex systems.

The development of models specifically suited for control design and analysis is an important area of current research. For example, the sensors and actuators which may be used on flexible structures can strongly affect the dynamic performance of the structure, and this must be taken into account both in the design of the structure and in the design of the control system.
A flexible link robot arm is a distributed parameter system of infinite order. Due to elastic properties of flexible manipulators, the development of a mathematical description and subsequent model-based control of the system is a complicated task. This is made difficult by the presence of a large (infinite) number of modes of vibration in the system. The modes become significant in two ways: firstly, because the oscillations themselves prolong the settling time and secondly, because attempts to actively control some modes result in instability of the other modes. This non-linear behavior of the structure at high speeds, first degrades end-point accuracy and secondly complicates controller development. Furthermore, the performance of such a control system depends mainly on the parameters during operation. These limitations of conventional model-based control for flexible manipulator systems have stimulated the development of intelligent control mechanisms incorporating adaptive control, Neural Network (NN) and fuzzy logic controllers.

Flexible arms have drawn more and more attentions in robotics since they can be safely operated at higher speeds due to the low inertia of the flexible links; the reduced mass of flexible links requires smaller actuators and therefore less energy for operation; there is lower overall mass to be transported when the robot is used in mobile or space applications. Most current approaches for this issue require the mathematical model or partial model information. However, it is very difficult to model accurately the flexible arms due to their flexible structure. Therefore, it is desired to develop a kind of controllers that do not require the mathematical model. Neural controllers are one of these kinds of controllers.
1.2 Literature Survey

Flexible Manipulator Systems (FMS) offer several advantages in contrast to their traditional rigid counterparts. These include faster system response, lower energy consumption, the requirement of relatively smaller actuators, reduced non-linearity owing to elimination of gearing, lower overall mass and, in general, lower overall cost. However, owing to the distributed nature of the governing equations describing dynamics of such systems, the control of flexible manipulators has traditionally involved complex processes [1, 2, 3]. Moreover, to compensate for flexural effects and thus yield robust control the design focuses primarily on non-collocated controllers [4, 5]. Research on FMS ranges from a single-link manipulator rotating about a fixed axis [6] to three-dimensional multi-link arms [7]. However, research and experimental work, in general, is almost exclusively limited to single-link manipulators. This is because of the complexity of multi-link manipulator systems, resulting from more degrees of freedom and the increased interactions between gross and deformed motions. It is important for control purposes to recognize the flexible nature of the manipulator system and to build a suitable mathematical framework for modelling of the system. The use of dynamic models for FMS is three parts: forward dynamics, inverse dynamics and controller design. Single link flexible manipulators are distributed parameter systems with rigid body as well as flexible movements. There are two physical limitations associated with the system:

- The control torque can only be applied at the joint,
- Only a finite number of sensors of bounded bandwidth can be used and at restricted locations along the length of the manipulator.

Such issues are considered in this chapter through a structured overview of techniques for modelling, dynamic simulation and control of flexible manipulators.

1.2.1 Modelling and Simulation Techniques

According to reported results, dynamic models of flexible manipulators are described either by Partial Differential Equations (PDE) or by finite-dimensional Ordinary Differential Equations (ODE) through some kind of approximation.
Owing to the principles used, various types of models of flexible manipulator have been developed [8].

These can be classified as

- Lagrange’s equation and modal expansion (Ritz–Kantrovitch)
- Lagrange’s equation and finite element (FE) method
- Euler–Newton equation and modal expansion
- Euler–Newton equation and FE method
- Singular perturbation and frequency-domain techniques.

A commonly used approach for solving a PDE that represents the dynamics of a manipulator, sometimes referred to as the separation of variables method, is to utilize a representation of the PDE, obtained through a simplification process, by a finite set of ordinary differential equations. This model, however, does not always represent the fine details of the system [9]. A method in which the flexible manipulator is modelled as a mass less spring with a lumped mass at one end and a lumped rotary inertia at the other end has previously been proposed [10, 11]. In practice, dynamic models are mostly formulated on the basis of considering forward and inverse dynamics. In this manner, consideration is given to computational efficiency, simplicity and accuracy of the model. Here, a means of predicting changes in the dynamics of the manipulator resulting from changing configurations and loading is proposed, where predictions of changes in mode shapes and frequencies can be made without the need to solve the differential equation of the system.

An alternative to modelling the manipulator in the time domain is to use a method based on frequency domain analysis [12, 13]. This method develops a concise transfer matrix model using the Euler–Bernoulli 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. In another approach, a chain of flexible links is modelled by considering a flexible multi-body dynamic approach, based on an Equivalent Rigid Link System (ERLS), where an ERLS (which is
the closest possible to the deformed linkage) is defined, in order to match, at best, the requirements of a small displacement assumption. As the choice of ERLS is completely arbitrary, it could introduce artificial kinematic constraints, which in turn introduce modelling error [14].

Unfortunately, the solutions obtained through the above modelling processes are approximate and do not represent fine details of a system. To resolve this problem, numerical solution of the system’s equation is performed allowing development of simulation environments. Dynamic simulation is important from a system design and evaluation viewpoint. It provides a characterization of the system in the real sense as well as allowing online evaluation of controller designs. Commonly used simulation approaches involve finite element (FE), finite difference (FD) and symbolic manipulation (SM) methods. The FE method has been previously utilized to describe the flexible behavior of manipulators [15, 16].

The steps involved in FE simulation are discretisation of the structure into small elements; selection of an approximating function to interpolate the result; derivation of an equation for these small elements; calculation of the system equation and solving the system equation considering the boundary conditions. The development of the algorithm can be divided into three main parts: the FE analysis, state-space representation and obtaining and analyzing the system transfer function. The computational complexity and consequent software coding involved in the FE method is a major disadvantage of this technique. However, as the FE method allows irregularities in the structure and mixed boundary conditions to be handled, the technique is found to be suitable in applications involving irregular structures. In applications involving uniform structures, such as manipulator systems, the FD method is found to be more appropriate. Simulation studies of flexible beam systems have demonstrated the relative simplicity of the FD method [17].

The FD method is used to obtain an efficient numerical means of solving the PDE by developing a finite-dimensional simulation of the FMS through a discretisation, both, in time and space (distance) coordinates. The algorithm allows inclusion of distributed actuator and sensor terms in the PDE and modification of boundary conditions. The
development of such an algorithm for a FMS has previously been reported [18, 19]. The algorithm thus developed has been implemented digitally and simulation results characterizing the behaviour of the system under various loading conditions have been reported.

Investigations with symbolic manipulation have resulted in automated symbolic derivation of dynamic equations of motion of rigid and flexible manipulators utilizing Lagrangian formulation and assumed mode methods [20, 21, 22], Hamilton’s principle and non-linear integral-differential equations [23] and FD approximations [24]. These methods have demonstrated that the approach has some advantages, due to allowing independent variation of flexible parameters. A study on utilizing the symbolic manipulation approach, for the modelling and analysis of a flexible manipulator using FE methods has also been reported [25]. It is argued that 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 developed model has been verified by using an experimental rig to demonstrate the performance of the symbolic algorithm in modelling and analysis of a flexible manipulator.

1.2.2 Control Techniques

The dynamic behaviour of a flexible manipulator may be considered as a combination of rigid-body and flexible dynamics. Accordingly, control strategies devised for such systems are to take account of both rigid-body motion and flexible motion control. The former corresponds to methods developed within the framework of conventional rigid manipulator control. The latter, on the other hand, corresponds to approaches developed within the framework of vibration control of flexible structures.

Vibration control techniques for flexible structures are generally classified into two categories: passive and active control [26]. Active control utilizes the principle of wave interference. This is realized by artificially generating anti-source(s) (actuator(s)) to destructively interfere with the unwanted disturbances and thus result in reduction in the level of vibration. Active control of FMS can be divided into two categories: open-loop
and closed-loop control. Open-loop control involves altering the shape of actuator commands by considering the physical and vibration properties of the FMS. The approach may account for changes in the system after the control input is developed. Closed-loop control differs from open loop control in that it uses measurements of the system state and change the actuator input accordingly to reduce the system response oscillation.

1.2.2.1 Passive Control

Passive control utilizes the absorption property of matter and thus is realized by a fixed change in the physical parameters of the structure, for example, adding viscoelastic material to increase the damping properties of the flexible manipulator. It has been reported that the control of vibration of a flexible manipulator by passive means is nonsufficient by itself to eliminate structural deflection [27]. On the other hand, if only active control is used then, owing to actuator and sensor dynamics, destabilization of modes near the bandwidth of the actuator or sensor may result. To avoid such destabilization, a certain amount of passive damping will be required to be employed, thus using hybrid control, that is, a combination of active and passive control methods. Combined active/passive control strategies have been proposed previously where low-frequency modes of vibration are controlled by active means and the modes with frequencies just above the actively controlled modes are controlled by passive means.

Several methods of passive vibration control of FMS have been developed over the years. These mainly include methods of implementation of a constrained viscoelastic damping layer to provide an energy dissipation medium [28] and the utilization of composite materials in the construction of a flexible manipulator to provide higher strength and stiffness-to-weight ratio and larger structural damping than a metallic flexible manipulator [29, 30]. Observations have shown that although passive damping provides a sharp increase in damping at higher frequency modes, the lower frequency modes still remain uncontrolled. Moreover, the addition of viscoelastic material and a constraining layer leads to an increase in the size and dynamic load of the system [31].
1.2.2.2 Open-Loop Control

Open-loop control methods have been considered in vibration control where the control input is developed by considering the physical and vibration properties of the FMS. Although, the mathematical theory of open-loop control is well established, only few successful applications in the control of distributed parameter systems, including flexible manipulator, have been reported [32, 33]. The method involves the development of suitable forcing functions in order to reduce the vibration at resonance modes. The methods developed include shape command methods, the computed torque technique and bang-bang control.

Shaped command methods attempt to develop forcing functions that minimize vibrations and the effect of parameters that affect the resonance modes [34-37]. Common problems of concern encountered in these methods include long move (response) time, instability owing to un-reduced modes and controller robustness in the case of a large change of the manipulator dynamics.

In the computed torque approach, depending on the detailed model of the system and desired output trajectory, the joint torque input is calculated using a model inversion process [38]. The technique suffers from several problems, owing to, for instance, model inaccuracy, uncertainty over implement ability of the desired trajectory, sensitivity to system parameter variations and response time penalties for a causal input.

Bang-bang control involves the utilization of single and multiple switched Bang bang control functions [39]. Bang-bang control functions require accurate selection of switching time, depending on the representative dynamic model of the system. A minor modelling error could cause switching error and thus result in a substantial increase in the residual vibrations. Although, utilization of minimum energy inputs has been shown to eliminate the problem of switching times that arise in the bang-bang input [40], the total response time, however, becomes longer.
1.2.2.3 Closed-Loop Control

Effective control of a system always depends on accurate real-time monitoring and the corresponding control effort. Initial discussions on feedback control of a flexible manipulator and the usefulness of optimal regulator as applied to this problem date back to the early 1970s. It is known in the conventional approach that compensation can alter the first vibration mode by either adding some damping or extending the bandwidth of the system [41]. Compensation, however, will limit the performance of the manipulator because inputs with frequency contents above the first flexible mode could still cause vibration. Various modern control designs have been proposed during the last two decades for FMS with different types of vibration measuring systems.

When free motion of a system consists mainly of a limited number of clearly separable modes, then it is possible to control these modes directly using the so-called Independent Modal Space Control (IMSC) method, where the controller is designed for each mode independent of other modes [42, 43].

Modal space control has been used for suppression of flexible motion in a three-link log loading manipulator with which considerable improvement has been achieved over conventional joint-based collocated controller. Although, initial investigations on the use of IMSC lack consideration of the location of the actuator [44], later investigations have shown that actuator placement is important for suppression of spillover and, thus, methods for optimal placement of sensors and actuators have been developed [45]. Variable structure control (VSC) utilizes a viable high-speed switching feedback control law to drive the plant’s state trajectory onto a specified and user-specified surface in the state-space, and to maintain the plant’s state trajectory on this surface for all subsequent times.

One of the first studies on the application of VSC to one-link flexible manipulators was reported by Qian and Ma [46], where they controlled the end-point position in a non-collocated manner. In this study, a sliding surface (a line in the study) is constructed from the end-point position and its derivative is employed in the design. The authors claim that if the slope of this line is chosen positive and the system variables are
made to stay on this line, these would converge to zero exponentially, thus yielding a stable system in sliding mode. The performance of the controller was evaluated through a series of simulations, followed by an analysis of the designed control system.

Thomas and Bandyopadhyay [47], however, have pointed out that the choice of a positive constant as the slope for this switching line would not guarantee the stability of the system in sliding mode. The switching line is in fact a switching hyper-surface in view of the functional relationship of the tip (end-point) position with the generalized coordinates of the system through mode shape functions. The stability of the system in sliding mode is guaranteed only if the motion on this hyper-surface is asymptotically stable [48], whereas the positive value for the slope of the switching line employed by Qian and Ma [46] will not guarantee this stability. Moreover, a stable VSC controller based on a state transformation has been designed in this study.

The application of VSC to multi-link flexible manipulators is very limited. There are difficulties in both modelling and controller design. Sira-Ramirez et al. [49] have derived dynamical sliding mode regulators within the context of Generalized Observability Canonical Form (GOCF) [50]. The GOCF is obtained by means of a state elimination procedure, carried out on the system of differential equations describing the manipulator dynamics. Therefore the system can be considered as a linear system. Although simulation examples illustrate the performance of the proposed controller for a robotic manipulator with flexible joint, it is not easy to apply to general multi-link manipulators with flexible links. There are also applications of VSC to other plants similar to flexible manipulators, for example, a spacecraft with flexibility [51], a flexible structure on the ground [52], a disk drive actuator [53] and so on.

An appreciable amount of work carried out on the control of FMS involves the utilization of strain gauges, mainly to measure mode shapes [54]. There are two essential components involved in measuring the modal response using strain gauges. The first is a method of measurement of the modes of vibration of the flexible manipulator. The second is the development of a computational technique for distinguishing different modes in the overall deflection of the flexible manipulator.
Once modal information is available a control loop can be closed for each mode either to damp or to actively drive the manipulator in a manner that reduces the vibration. It appears that the strain gauge measurement is very simple and relatively inexpensive to use. However, the technique may place more stringent requirements on the dynamic modelling and control tasks. Strain gauges have the disadvantage of not giving a direct measurement of manipulator displacement, as they can only provide local information. Thus, displacement measurement by using strain gauges requires more complex and possibly time-consuming computations, which can lead to inaccuracies. To solve the problem of displacement measurement, as encountered in using strain gauges only, attempts have been made to develop schemes that incorporate end-point measurements as well [55].

Some researchers have proposed an approach that utilizes local or global measurement of flexible displacement of a manipulator to control system vibration. In this method, the deflection of the manipulator is detected (measured), using, for example, a Charge Coupled Device (CCD) camera or laser beam, relative to a rotating reference X–Y frame fixed to the hub of the manipulator. However, as an end-point position control system has a smaller stability margin than collocated control, it is necessary to include a collocated rate feedback (hub-velocity) to obtain acceptable performance of the closed-loop system.

By using an end-point sensor, more accurate end-point positioning can be accomplished, but the resulting controller is less robust to plant uncertainties than the corresponding collocated design. The difficulty in maintaining stability and performance robustness, owing to spillover effects from unmodelled modes that occur when a high-order system is controlled by a low-order controller, is of major concern in the control of flexible systems. To improve robustness it is typically required that the controller bandwidth be sufficiently reduced [56]. Studies have shown that most robust control techniques that ensure stability in the presence of parameter errors can only increase damping by a limited amount [57]. If the inherent damping is very low, this increase may be insufficient to adequately improve the response.
Moreover, the controllers rely on accurate system models. This makes the controller very sensitive to modelling errors, leading to degradation in system performance and, in some cases, instability. It is evident that in using either global or local displacement measurement a device is required to be attached on the manipulator. This affects the behaviour of the manipulator [58]. Both feed forward and feedback control structures have been utilized in the control of vibration of FMS [59,60]. These include combined feed forward and feedback methods based on control law partitioning schemes, which use end-point position signal in an outer loop to control the flexible modes and the inner loop to control the rigid-body motion. Although, the pole-zero cancellation property of the feed forward control speeds up the system response, it increases overshoot and oscillation. However, it is found that, in contrast to many high-order compensators, systems with feed forward control incorporating proportional and derivative (PD) feedback are not highly sensitive to plant parameter variations.

In investigations carried out on control of FMS the only non-collocated sensor/actuator pairs that have successfully been employed include motor torque with either the manipulator strain or global/local end-point position. However, practical realization of both methods has associated short- and long-term drawbacks. If a state-space description of the closed-loop dynamics is available, it is possible to use acceleration feedback to stabilize a rigid manipulator [61].

Investigation son the control of a FMS using acceleration feedback to design the compensator and the end-point position feedback using a design based on a full-state feedback observer have shown that the controller using end-point position feedback exhibits relatively slow and rough response in comparison with an acceleration feedback controller; the difference becoming more noticeable with increasing slewing angle[55]. Moreover, acceleration feedback produces relatively higher overshoot. The use of acceleration feedback appears to have intuitive appeal from an engineering design viewpoint, particularly because of the relative ease of implementation and low cost. Moreover, in sensing acceleration for control implementation, all sensing and actuation equipment is structure mounted. This implies that issues such as camera positioning or fields of view are not of major concern, which is an important consideration, specifically, in large-scale applications such as telerobotics. Furthermore, applications to multi-link
flexible manipulators (MLFMs) could benefit from such methods to a greater extent. Some researchers have also proposed adaptive control methods to compensate for parameter variations [62]. However, these approaches utilize optical methods of global/local end-point sensing for obtaining the feedback signal.

Many of the controllers have been designed on the basis of various input shaping mechanisms using both open-loop and closed-loop configurations. [63] Designed a closed-loop control mechanism based on shaped input filter, to reduce or eliminate vibrations and to reject external disturbances of a multi-link manipulator. An adaptive input shaping control scheme for vibration suppression in slewing flexible structures with particular application to flexible-link robotic manipulators has been reported by A. Tzes and S. Yurkovich [64]. The scheme combines a frequency-domain identification technique, with input shaping, in order to adjust critical parameters of the input shapers in the case of payload variation or other unmodelled dynamics. The scheme was realized through simulation and experimentation.

Hillsley and Yurkovich [65] have reported a composite control strategy for a two-link flexible robotic arm in conjunction with post-slew feedback scheme. In this work attention has been focused on end-point position control, for point-to-point movements assuming a fixed reference frame for the base with two rotary joints.

Khorrami et al. [66] addressed experimentation on rigid-body-based controllers with input pre shaping for a Two-Link Flexible Manipulator (TLFM). The scheme is shown to be effective when the plant dynamics are linear and time invariant. It has also been shown that application of an inner-loop non-linear control to cancel some of the non-linearities and to reduce configuration dependence of structural frequencies enhances the performance of the input pre-shaping scheme. Borowiec and Tzes [67] proposed a frequency-shaped explicit output feedback force control for a TLFM. In this work the frequency shaping dependence has been included to eliminate the undesirable effects associated with control and observation spillover. Magee et al. [68] developed a control approach, combining command shaping and internal damping, to control a small robot attached to the end of a flexible manipulator. They also verified the proposed control system experimentally using two separate test-beds.
1.2.2.4 Artificial Intelligence Control

It is noted that the non-linear dynamics of rigid manipulators are compensated by an inverse-dynamic strategy, and use of such an approach for a flexible manipulator is restricted by non-minimum phase characteristics of the arm when end-point response is taken as output of the system [69]. Several conventional approaches have been proposed as solutions to this problem based on different methods such as non-causal torque, singular perturbation, integral manifold, transmission zero and redefined output [70-80]. However, performance of these control strategies may not be satisfactory in real-applications as it is difficult to accurately model a flexible manipulator.

In many cases, when it is difficult to obtain a model structure for a system with traditional system identification techniques, intelligent techniques are desired that can describe the system in the best possible way [81]. Genetic Algorithms (GA) and Artificial Neural Networks (ANN) are commonly used for modelling dynamic systems. The main advantages of utilizing GA for system identification are that they simultaneously evaluate many points in the parameter space and converge towards the global solution [82, 83]. The superiority of a GA over Recursive Least Squares (RLS) in modelling a fixed-free flexible beam has been addressed by Hossain et al. [84]. In contrast, Neural Network (NN) approaches for system identification offer many advantages over traditional ones especially in terms of flexibility and hardware realization [85]. This technique is quite efficient in modelling non-linear systems or if the system possesses non-linearities to any degree.

Application of Neural Networks for identification and control of dynamic systems has gained significant momentum in recent years. Narendra and Parthasarathy [86] addressed system identification using the globally approximating characteristics of NN. Neuro modelling with different approaches, involving back propagation has been reported by various researchers [87, 88]. The successful application of radial basis function (RBF) networks for modelling dynamic systems is also widely addressed in the literature [89-91]. Chen et al. [92] proposed orthogonal least square learning algorithm for RBF networks to model non-linear dynamic systems. Elanayar and Yung have addressed the use of RBF to approximate dynamic and state equations and to estimate state variables of stochastic systems.
A considerable amount of work has been carried out to develop and implement NN-based controllers for flexible manipulators. Cheng and Wen [93] proposed a neuro-controller to drive a flexible arm to a desired trajectory along with using hub position and velocity measurement techniques for stabilizing the system. Newton and Xu [94] has addressed the joint tracking control problem for a space manipulator using feedback error learning technique. In this case, end-point position tracking cannot be guaranteed especially for high-speed desired trajectories.

Control of a Single-Link Flexible Manipulator (SLFM) whose dynamics are partially known has been considered by Donne and Ozguner [95]. In this work, a model-based predictive control scheme is adopted for the known dynamics and unsupervised NN-based control scheme is utilized to control the unknown system dynamics. Identification and control are implemented as a two-stage process where identification of the unknown part of the system is done using a NN in supervised learning mode. Talebi et al. [96] proposed a NN-based adaptive controller for single flexible-link manipulator. Output redefined approach is used in designing the controller. They examined three different types of NN scheme. The controller has been realized both in simulation and experimental environments. The advantage of this controller over conventional PD type controllers has also been demonstrated.

Gutierrez et al. [97] have reported implementation of a NN tracking controller for a single flexible link. In this work the practical implementation of a multi-loop on-linear NN tracking controller for a single flexible link has been tested and its performance compared to that of the standard PD and proportional, integral, derivative (PID) controllers. The controller includes an outer PD tracking loop and a singular perturbation inner loop for stabilization of the fast dynamics, and a NN inner loop is used for feedback linearization of the slow dynamics.

Song and Koivo [98] addressed NN-based control of a flexible manipulator, where a non-linear predictive control approach is presented using a discrete-time multi-layered perceptron network model for the plant. The predictive control framework allows variations in the model order, time delay and non-minimum phase effects in the plant. The method has been compared against a collocated passive PD controller. Development
of a multi loop non-linear NN tracking controller for a multi-link flexible arm using singular perturbation based fast control and outer loop slow control has been addressed by Yesildirek et al. [99]. Adaptive NN control of flexible manipulators based on singular perturbation has been reported by Geet et al. [100]. In this work the full model dynamics of the flexible manipulator were separated into the slow subsystem and the fast subsystem by applying singular perturbation techniques. Thus, an adaptive NN control based on direct adaptive techniques is designed to control the slow subsystem, and the fast control is designed as a simple Linear Quadratic Regulator (LQR) control to stabilize the fast subsystem along the trajectory of the slow subsystem.

Talebi et al. [101] addressed inverse-dynamic control of flexible-link manipulators using NN, where a modified output redefined approach is utilized to overcome the problem caused by the non-minimum phase characteristics of the flexible-link system. Neural network applications often incorporate a large number of neurons, thus requiring a great deal of computation for training and causing problems for error reduction [102]. A recent trend in NN design for large-scale problems is to split the original task into simpler subtasks, and uses a sub network module for each one [103-106]. This divide-and-conquer strategy then leads to super-linear speedup in training and one can improve the generalization ability over that of a single large network [107]. It is also easier to encode a priori knowledge in a modular framework.

In general, a Modular Neural Network (MNN) is constructed from two types of network, namely, expert networks and a gating network [104,105]. Expert networks compete to learn the training patterns and the gating network mediates this competition. During training, the weights of the expert and gating networks are adjusted simultaneously using the back propagation algorithm [109].

Sharma et al. [109] reported work involving this strategy for modelling of a flexible manipulator. In this approach MNN learns to partition an input task into subtasks, allocating a different NN to learn each one. However, accuracy of the MNN depends greatly on accurate fusion of the individual networks as decided by a gating network.
Researchers have presented a new method, using GA [110, 111], which removes the need for a gating network. Fusion of individual networks is decided by optimum slope selection of the activation function. The GA also optimizes the structure and weights of the individual networks in the MNN.

1.2.3 Single Link Flexible Manipulator System

The first experimental Single Link Flexible Manipulator (SLFM) systems were developed in the early 1980s. Typical Flexible Manipulator System (FMS) configurations have not changed much since the early experimental systems. A good survey of initial efforts in flexible manipulator research is given in Hu [112]. Many of the manipulators discussed in Hu [112] are now decommissioned. The current commercial availability of sensor and actuator hardware has made it much easier to build an experimental FMS. The manipulator at the University of Sheffield (UK) and manipulator at the Technical University of Lisbon (Portugal) are good examples of the many experimental flexible manipulators used for research purposes [113].
A typical FMS has a flexible link as shown in Fig.1.4, an actuator-gear mechanism to rotate the link, an optical encoder to measure joint rotation, accelerometers and strain gauges to sense flexible motion, an optical arrangement to measure the endpoint position and an occasional force sensor attached to the end-point. There are variations in configuration among different FMS setups, for example, many setups have directly driven servo motors and others use harmonic drive gears with servo motors, some use only accelerometers or strain gauges to measure flexible deflections while others have cameras, some have semi-rigid flexible links while others have very flexible links. The sensor and actuator hardware is available in a wide variety and researchers make a selection to meet the needs of their experimental research.
1.2.3.1 Applications of Flexible Manipulators

The properties and capabilities provided by flexible manipulators stand for a clear challenge in opening new applications for robots. The situations, where the workspace is constrained, or when it is required to perform operations such as assembly in space, prevents the use of classical, rigid-link, industrial robot configurations. For these applications structural mass and stiffness must be reduced, to allow entering very confined workspaces and/or to permit cost-effective launching, and to enlarge manipulator reach out and dexterity. This could be of interest not only in space applications, but also in the industrial sector. Flexible manipulators, equipped with an active vibration control system, can reach quite the same accuracy of traditional industrial robots with low mass of moving parts and reduced cost and power consumption.

Some known examples are the application of fast, flexible manipulators in the food industry (robotic packing and palletising) and in assembly tasks. Flexibility is also becoming an important issue for other fields such as machine tools and civil engineering machinery, for example, tunnel boring machines, excavators, and so on, where requirements for extending tools life, increasing accuracy and speeding up overall performance entail making control systems fully aware of true system dynamics. Existing robotic systems tend to overkill, they are too complex, which makes them expensive to purchase and maintain.

As the potential of flexible manipulator technology is being demonstrated in laboratories, and some results are moving to industry, new ideas on their applicability are arising. One very important aspect of flexible robot technology is their intrinsic capability to accommodate forces with the environment, which could be a main issue when developing robots for direct cooperation with humans. Thus, a number of foreseen robot applications regarding safety and dependability could take clear advantage of structural flexibility. The emerging humanoid robots, where a clear need in mass reduction is mandatory for their operation, constitute undoubtedly an area where flexible robot technology is to play a major role in the future.
Although numerous potential industrial applications of flexible robotic manipulator systems have been identified, there are a number of technological issues, which need to be addressed before the industry can accept flexible robotic manipulator systems. These are development and study of flexible manipulator construction material, efficient actuation and sensing technologies, and simple and effective controller designs. Developments in these areas require assistance from government agencies and investment from industries.

Despite all of these, flexible robotic manipulators are in use to some extent in space applications. This is because of the weight restriction for a spacecraft. One such manipulator is made of a composite rod that is lifted by a longitudinal rope actuator and has an end-effector gripper with bending Electro Active Polymer (EAP) driven fingers allowing grabbing and holding an object [124]. The EAP surface wiper operates like a human finger and can be used to remove dust from windows and solar cells. Other potential areas of application are manipulation in nuclear and other hazardous environments, car/vehicle painting, manufacturing of electronic hardware and food industry.

1.3 Objectives of the Research Work

The large mass and energy requirements of standard rigid link manipulators have led to a desire for flexible link manipulators characterized by low-mass links and actuators with low power requirements. This is particularly desirable in certain applications, such as space systems, where mass and energy requirements must be minimized for transport purposes. Flexible link dynamics are also found in certain mechanical pointing systems and in systems with links having high length-to-width ratios. These dynamics make the system outputs such as tip position more difficult to control. Therefore, before flexible link manipulators can be the realistically implemented, it is necessary to study the nature of flexible link manipulators and determine effective methods for position control.
The main objectives of the thesis work are as follows:

- A method is proposed for mathematical modelling of single flexible link manipulator.

- A method with classical PID (Proportional–Integral–Derivative) control is proposed for flexible link manipulator and different errors like steady state error, settling time and peak over shoot were observed.

- A method with optimal controller like LQR (Linear Quadratic Regulator) controller is proposed which calculates the steady state error, peak over shoot and settling time were observed. The enhancement of reduction of these errors were observed and compared with classical PID controller on single flexible link manipulator.

- A method with intelligent controller of Adaptive Neuro-Fuzzy Inference System (ANFIS) is proposed to enhance the reduction of the steady state error, settling time and peak over shoot. These errors are compared with classical PID controller and LQR controller. It was observed that ANFIS controller gives better performance than LQR and PID controllers.

- Finally analyzed the best suitable controller for the proposed mathematical modelling of single flexible link manipulator

1.4 Organization of Thesis

This work deals with the modelling and control of a single flexible link manipulator. The report is organized into six chapters including introductory chapter 1.

- Chapter 2 gives a brief overview of the mathematical modelling of flexible link system, which is derived in the form of state space model. Explained the different mode of operations along with the values to see the performance of the single link flexible manipulator

- Chapter 3 gives the brief overview of the PID controller part to find the steady state error, settling time and peak over shoot along with the different integral errors and these were further analyzed in chapter 4 and 5 with advanced controllers.
- Chapter 4 gives the optimal controller part in which linear quadrant regulator (LQR) method is discussed to find the steady state error, settling time and peak over shoot along with the different integral errors and these were analyzed with classical PID controller and enhancement of reduction in these errors were observed.

- Chapter 5 gives the intelligent controller of Adaptive Neuro fuzzy controller were developed to find steady state error, settling time and peak over shoot along with the different integral errors and these were compared and analyzed with results of the chapter 3 and 4. The improvement of reduction of these errors was discussed. A comparison is made with all the controllers along with various inputs such as step input and pulse input and explained which controller is performing excellently without any much errors.

- Conclusions and future scope of the work are discussed in chapter 6.