Chapter 1

Introduction

In this chapter, a brief introduction is given to the problems of robotic systems. A literature survey related to the studies on two robotic systems, namely 2-DOF manipulator and 7-DOF biped robot has been included. The gaps in literature have also been indicated here. The aims and objective of the present thesis have been stated in this chapter.

1.1 Introduction to Robotic Systems

Robotic system is a mechatronic machine designed and developed to perform a given task. It is a combination of mechanical, electrical, electronics and computer elements. Robotic systems have been developed in various forms, such as manipulator (that is, a robot with fixed base), wheeled robots, multi-legged robots, and others

A manipulator performs an assigned task within a given workspace. Generally, the tasks performed by such manipulators are repetitive in nature. These tasks include automatic assembly, welding, painting and others. Again, the manipulators may be of two types: serial and parallel manipulators. The serial manipulators can have 2 or more DOFs with a single end-effector, where the links are in series. A parallel manipulator consists of a few links placed in parallel, and as usual it has a fixed base and a moving platform or end-effector. Stewart platform is an example of parallel manipulator. These are mostly used for machining and material handling tasks in manufacturing industries.

Manipulators with moving base can be classified as wheeled robots and legged robots. The wheeled robots can navigate on flat terrains, sloping surfaces and they can have high speed also. They can be used to solve a variety of problems, like venturing into hazardous environments of nuclear power plants, sea-bed mining, space explorations, and others. The legged robots have contrastingly different advantages over the wheeled robots. They can navigate through any uneven terrain. Legged locomotion robots, especially biped robots are akin to human beings. They are expected to perform the same tasks in future, as the current industrial workers do. Legged robots are preferred to the wheeled robots while moving through the environments, which generally do contain irregularities. In such an environment, legged robots offer better mobility than the wheeled ones due to the fact that the former use isolated footholds. They can choose the best places for their feet placement. On the contrary, wheeled and tracked systems follow the surface of the terrain in a continuous manner; therefore, their performances are dependent on the quality of the terrains. A legged system is well adaptive to uneven terrains. Considering the vehicle-environment interaction, the legged locomotion is the most advantageous, since they give less damage to the surface of the terrain compared to the wheeled and tracked systems do (Song and Waldron, 1989). Due to these advantages over the wheeled and tracked systems, legged locomotion has found applications in various fields. These include the robots used for unexploded ordnance removal, military and civilian de-mining (Gonzalez de Santos et al. 2007), recoveries from the regions of fire or earthquake disasters, hazardous waste inspection and disposal, and planetary exploration, and others. Regardless of its advantages, legged robots have some drawbacks, which need to be addressed. For example, the legged mechanisms have complicated kinematics and dynamics, and a lot of actuators are to be controlled through a continuous coordination. Therefore, control of the legged systems is considerably hard. Moreover, its energy consumption and payload-to-weight ratio are the higher and lower, respectively, compared to those of the wheeled and tracked robotic systems.

1.1.1 Work on Two Robotic Systems

Two robotic systems have been studied in the present thesis, such as 2-DOF manipulator and 7-DOF biped robot. At first, a 2-DOF manipulator with two rotary joints and hallow circular cross-section links is designed to track a given trajectory. The objective of this study is to simultaneously design a controller and mechanical structure, so that, the manipulator can track the trajectory accurately. A PD controller's gains are adaptively adjusted to track the straight and circular trajectories by the manipulator. Both the structural design parameter, namely thickness of hallow circular cross-section and bending stress are optimized using some evolutionary algorithms.

Secondly, a biped robot having 7-DOF (2-DOFs for ankle joints, 2-DOFs for knee joints. 3-DOFs at hip joint) is considered. The biped robot has seven links: two feet, two femurs, two thighs and a trunk. The biped robot's gait planning has been studied for walking through the staircases. Both single support phase (where one foot is in contact with the ground and the other one is in air) and double support phase (when both the feet are on the ground) have been studied in detail.

1.2 Literature Survey

In the past three decades, a great deal of research effort had been made on gait planning, dynamics, control and stability analysis of multi-legged robots because these are very important issues to be considered for their design and development. These aspects deserve great interest and in order to study them, different approaches could be adopted. One possible approach is to design and develop a prototype and then study, in details, the said four important issues. An alternative approach to solve the problem can be to develop simulation models of legged robot that serve as the basis for the study. The second approach has several advantages over the first, namely lower development cost and a less time for design modification and prototype development. Due to these reasons, several different simulation models of complex multi-legged robot were developed for design optimization, stability, and gait analysis and development of control algorithms. During locomotion, a multi-legged robot might have to move along straight paths, ascend and descend sloping terrains, take turns to avoid some obstacles, and others, as the situation demands. Some of the existing methodologies for modeling and simulation of the said locomotion of multi-legged robots are mentioned below.

1.2.1 Design and Control of 2-DOF Manipulator for Trajectory Tracking

In the age of high precision manufacturing of components and parts, there is a need to develop precisely controlled manipulator for handling micro-precision jobs and machining applications. Also, the manipulator has to traverse a given trajectory as accurately as possible to avoid variations in trajectory causing damage to other parts in assembly or distorted machining of geometric components or inaccurate welding of jobs. Thus, trajectory tracking is one of the most important tasks to be performed by the manipulator.

A user specifies motions as the sequences of points through which a tool fixed to the end-effector of a manipulator has to pass. The effectiveness of such motion specifying mechanism is greatly increased, if the tool moves in a specified path between the user-specified points. Intermediate points are interpolated along the path at regular intervals of time during the motion, and the manipulator's kinematics equations are solved to produce the corresponding joint parameter values. The developed path interpolating function offers several advantages, including less computational cost and improved motion characteristics. A second method uses a motion planning phase to pre-compute enough intermediate points, so that the manipulator may be driven by interpolation of joint parameter values, while keeping the tool on an approximately pre-specified path. This technique allows a substantial reduction in real-time computation. The planning is done by an efficient recursive algorithm, which generates enough intermediate points to guarantee that the tool's deviation from the path to be tracked stays within a pre-specified error bounds.

Several attempts were made by various investigators to design and develop suitable controllers for the robots. The following model-based robot controllers had been used: computed torque control, non-adaptive Proportional Derivative (PD) control, PD control with feed-back, and others. Some of those attempts are discussed below.

Qu (1994) developed PD control scheme to solve trajectory tracking problem of a manipulator. He concluded that PD control with time-varying gains could guarantee global stability for the trajectory following problem of a manipulator. Homsup and Anderson (1987) proposed a model-based PD control for a 2-DOF planar manipulator. Its performance was measured using system performance ellipsoids drawn utilizing the information of control parameters, manipulator's Jacobian and inertia matrices. Thus, the performance was dependent not only on the robot's kinematics and dynamics, but also on the control algorithm. A correlation between trajectory tracking errors and workspace location was established. Kelly and Salgado (1994) developed a design procedure for selecting gain values (that is, K_p and K_d) of PD control with computed feed-forward of robot dynamics and desired trajectory. The performance of their approach was tested through computer simulations on 2-DOF manipulator. An evolutionary PD control strategy was used by Ouyang and Zhang (2002) to improve trajectory tracking performance of a closed-loop robot manipulator. It could ensure good trajectory tracking performance without using the knowledge of robot dynamics. The performance of their strategy was tested through computer simulations and found to be better than conventional PD and non-linear PD control strategies in terms of trajectory tracking performance and fluctuation in the actuator's torques.

Ravichandran et al. (2006) developed a scheme for simultaneous plant-controller design optimization for a 2-DOF planar rigid manipulator and non-linear PD controller. During optimization, a heuristic search technique named evolution strategy and a weighted-sum problem formulation were adopted to take care of multiple objectives and generate a single Pareto-optimal solution. The performance of the developed scheme was demonstrated on computer simulations, and the potential of the scheme to yield desirable designs of the manipulator and controller was realized.

Soft computing-based tools (Pratihar, 2008) had also been used to design and develop suitable controller for the robots. Some of those studies are discussed here. Ozaki et al. (1991) proposed a non-linear compensator using neural networks for trajectory control of a 2-DOF manipulator. Its performance was compared with that of an adaptive controller proposed by Craig (1998) in compensating unstructured uncertainties of the manipulator. The neural network-based approach was found to be effective and efficient in learning manipulator dynamics, and consequently could track the trajectory accurately. Ghalia and Alouani (1995) designed a fuzzy logic-based controller of a 2-DOF manipulator to determine appropriate gain values of the compensator for tracking some trajectories accurately. The performance of their approach was tested on computer simulations. Rueda and Pedrycz (1994) proposed a hierarchical fuzzy-neural-PD controller for N-DOF robot manipulators to solve tracking problems accurately. In their approach, a coordinator was implemented as a fuzzy-neural network, whose purpose was to select activation levels for local regulators implemented as time-varying PD controllers.

Park and Asada (1994) developed a concurrent design method of determining mechanical structure and suitable controller for a 2-DOF planar non-rigid manipulator. An attempt was made to achieve high speed positioning by optimizing arm link geometry, actuator locations and feedback gains. In their study, optimal feed-back gains minimizing the settling time were obtained as the fluctuations of structural parameters, which were optimized using a non-linear programming technique. Based on the obtained optimal design, one prototype robot was built and an outstanding performance was observed.

The concept of Particle Swarm Optimization (PSO) algorithm was introduced by Kennedy and Eberhart in 1995. It is a population-based search algorithm, which is initialized with the population of random solutions, called particles, and the population is known as swarm. Several modifications in the PSO algorithm had been done by various researchers. Shi and Eberhert (1998) introduced a new parameter called inertia weight into the original PSO algorithm, which played an important role in balancing the global and local searches. Clerc and Kennedy (2002) analyzed how a particle carries out its search in a complex problem space and modified the original PSO on the basis of this analysis. Chen et al. (2009) improved the PSO algorithm with adaptive inertia weight W and acceleration coefficients in order to maintain population diversity and sustain good convergence capacity to optimize back-propagation neural networks.

PSO is simple in concept, as it has a few parameters only to be adjusted. It has found applications in various areas like constrained optimization problems, min-max problems, multi-objective optimization problems and many more. In addition to these application areas, it has been applied to evolve weights and structure of some neural networks (NNs). Han and Jiang (2010) proposed an endpoint prediction model for Basic Oxygen Furnace (BOF) steelmaking based on PSO-tuned radial basis function neural network. Braik et al. (2008) developed a mechanism to improve performance of NN in modeling a chemical process through PSO. Abe and Komuro (2010) utilized an NN, tuned by PSO to save energy of the flexible manipulator for point-to-point motion. Joint angles generated by the NN suppressed the residual vibration and hence, minimized the motor torques, which was kept as the objective function. The authors conducted numerical studies and verified the same with experiments and concluded that PSO is an efficient optimizer.

1.2.2 Gait Planning of Biped Robots Ascending and Descending Staircases

Gait planning problems of biped robots ascending and descending some staircases had been studies by various researches, as discussed below.

Biped Robot Gait Planning in Single Support Phase

Recent research in robotics aims to build intelligent, energy efficient and dynamically balanced biped robots capable of moving through various terrains, as the situation demands. Intelligence is incorporated in a robot artificially, in the form of adaptive motion (path and/or gait) planner. The robot can be made energy efficient through the optimization of its mechanical structure. Moreover, Dynamic Balance Margin (DBM) of a biped robot can be measured using the concept of Zero Moment Point (ZMP) (Vukobratavic, 1970) A ZMP is defined as a point lying on the foot-ground contact plane, about which the algebraic sum of all moments becomes equal to zero. In order to maintain the dynamic balance, the ZMP should lie within the support polygon of the biped robot.

A considerable amount of effort was made in the past to design and develop energy efficient biped robots and their gaits using evolutionary algorithms. Some of those studies are discussed here. Capi et al. (2002) used a Genetic Algorithm (GA) in order to minimize energy consumption in trajectory generation of a biped robot for its stable walking on flat surface and its performance was verified experimentally. Capi et al. (2003) developed another approach using a GA and

Radial Basis Function Neural Network (RBFNN) for gait synthesis of a biped robot in terms of two objectives like minimization of consumed energy and change in torque. The optimal gaits determined by the GA were used to train the RBFNN for on-line gait generations of the robot, but their approach was found to be computationally expensive. Jeon et al. (2004) utilized a real-coded GA to minimize total energy consumption of a biped robot ascending and descending the staircase. The optimal gait trajectory was generated for stable walking on a staircase. Results of Matlab simulations showed that a significantly higher amount of energy was consumed for ascending the staircase compared to that necessary for descending the staircase. Salatian and Zheng (1992 a,b) used a Neural Network (NN) to update rhythmic motion of a two-legged robot walking on slopping surface. The gait parameters were dynamically modified by the network according to the change in slope of the surface. Fan et al. (2007) developed an approach for real-time gait generation of a biped robot utilizing a Fuzzy Neural Network (FNN). They used Matlab software to determine optimal gait parameters for a biped robot after considering three energy consumption indices, namely mean power, mean power deviation and mean torque change. The minimum energy gaits were used to train the FNN.

Several attempts were also made by various investigators to maximize dynamic balance margin of biped robots. Some of those studies are discussed here. Kun and Miller III (1996) proposed an adaptive dynamic balance scheme for a biped robot using Cerebellar Model Arithmetic Computer (CMAC) NNs, which were responsible for maintaining good balance and foot contact. Miller III (1994) developed control strategies based on hierarchy of simple gait oscillators, PID controllers, and NN learning without using the detailed dynamic or kinematics models. Real-time control of a 10-DOF biped robot with force sensing capability was implemented, and the experimental biped robot could learn the quasi-static balance required to avoid falling and maintain dynamic balance necessary for lifting the foot. Zhou and Meng (2003) developed a neuro-fuzzy network, in which a Fuzzy Reinforcement Learning (FRL) method had been utilized for dynamic control of the biped robot. Jha et al. (2005) used a genetic-fuzzy system for on-line gait generation of a biped robot. A GA was utilized to optimize the rule base of Fuzzy Logic Controller (FLC) offline. The optimized FLC was able to develop on-line stable gaits for the biped robot. Udai (2008) utilized a GA to optimize hip trajectory of a biped robot during its single support phase. Here, the objective was to minimize the deviation of ZMP from the geometric center of supporting foot area using the input parameters like swing foot trajectory and physical parameters of the robot. The results were verified through Matlab simulations. Vundavilli et al. (2007 a,b) developed two different hybrid approaches, namely GA-NN and GA-FLC systems for dynamically balanced gait generation of a biped robot ascending and descending some staircases. The GA was used to optimize the weights of NN in GA-NN and rule base in GA-FLC systems, offline. The optimized GA-NN and GA-FLC approaches were able to successfully generate dynamically balanced gaits for the biped robot in computer simulations.

The issues related to gait planning of biped robots had been formulated as multi-objective optimization problems also, where each of the objectives was a function of some common design variables. Moreover, those objectives were seen to contradict each other, so that Pareto-optimal front of solutions could be obtained. In these connections, the following studies are worth mentioning. Lee and Lee (2004) generated walking patterns for the best performance of a biped robot using multi-objective evolutionary algorithm. They considered three contrasting objectives, namely mobility, energy efficiency and stability of a robot to obtain optimal set of solutions for generating walking gaits on flat surface. Capi et al. (2005) used a multi-objective evolutionary algorithm to determine optimal and stable gaits of a biped robot walking on flat surface, after considering the objectives like minimization of energy consumption and change in torque simultaneously. The results were successfully implemented on BONTEN-MARU biped robot for flat surface walking. Goswami et al. (2009) carried out a GA-based optimal bipedal walking gait synthesis considering a trade-off between stability margin and walking speed. The stable gait walking parameters were optimized using a GA, verified through Matlab simulations and then implemented on an experimental biped robot walking along a straight path on flat surface.

Kennedy and Eberhart (1995) proposed a concept for the optimization of nonlinear functions using Particle Swarm Optimization (PSO) algorithm. It fulfills the necessary conditions laid in accordance with a paper by Millonas (1994), who developed his model for applications in artificial life, and articulated five basic principles of swarm intelligence, namely proximity, quality, diverse response, stability and adaptability. Coello Coello et al. (2004) developed a multi-objective PSO (MOPSO), which was able to cover the full Pareto-optimal front of solutions. However, they did not use the concept of crowding distance proposed by Deb et al. (2002) in NSGA-II. Reyes-Sierra and Coello Coello (2006) predicted the future trends of the current MOPSO. It would be more efficient and self–adaptive in nature. They opined that more theoretical work should be done to make it applicable to real-time industrial problems. Poli (2008) reviewed the articles and indicated the broad application areas of PSO. He forecasted its immense scope of applications in various areas like medical science, electrical and electronics sciences, combinatorial problems, image analysis, signal analysis, graphics, robotics, and others. Sivakumar et al. (2009) compared the performances of NSGA-II and MOPSO in terms of the quality of Pareto-optimal front, spread of solutions, strength of non-dominated individuals in the optimal fronts, computational complexity, and others. MOPSO could outperform the NSGA-II with respect to all the above mentioned parameters. Rokbani et al. (2010) utilized the PSO to optimize gait stability of the biped robot. The obtained optimal results were used to test the stability of the biped robot. The PSO algorithm could generate optimal angular positions of joints for the stable walking. The obtained optimal results were used to test the stability of a biped robot kit for its standing posture on flat surface. Niehaus et al. (2007) used the PSO algorithm for walking gait optimization of a humanoid robot. The biped gait was modeled utilizing a number of parameterizable trajectories to achieve omni-directional walking. The optimized set of walking parameters was successfully implemented on a modified Kondo KHR-1 robot in flat surface. Kim et al. (2009) used nonparametric estimation-based PSO for finding the parameters of Central Pattern Generator (CPG). The PSO algorithm was able to efficiently determine CPG parameters for a biped gait.

1.2.2.2 Biped Robot Gait Planning in Double Support Phase

Biped robots are extensively studied by researchers. A biped robot should be able to walk on various terrains, such as flat, sloping surfaces, staircases and others, as the situation demands. A biped robot's walking cycle consists of single support phase (SSP) and double support phase (DSP). It is in the single support phase during the major portion of its walking cycle, and only a small fraction of the cycle time is utilized in the double support phase. Hence, both the phases of walking are needed to be studied in detail to arrive at a complete knowledge of the biped walking systems on different terrains. An extensive study had been conducted on a biped walking in single support phase for different terrains, namely flat surface, sloping surface, staircase and others using different approaches. Most of the studies used center of mass (COM), center of gravity (COG), zero-moment point (ZMP), or the concept of inverted pendulum to dynamically balance the biped robot while walking on different terrains. Although the double support is an important phase in the walking cycle, it has received less attention in terms of research. Only some limited studies have been conducted on the double support phase both experimentally and theoretically. Some of these studies are stated and discussed below.

Hemami and Farnsworth (1977) studied postural and gait stability of a planar five-link model of the biped robot in its double support phase by considering both open and closed loops and solved it by using d'Alembert's principle of motions. Simulations were conducted on the nonlinear system with linear feedbacks and satisfactory results had been obtained. Li et al. (1991) proposed that if the preset ZMP of the trunk was measured, and control was achieved using a set of joint motion patterns, then stable walking could have been obtained by the biped robot for the walking cycle (both SSP and DSP). They experimentally verified the same on biped robot named: WL-12RIII. They used force-moment sensors to calculate the ZMP in SSP for both the feet on flat surface walking. The system ZMP was calculated off-line by considering the ZMP of each foot for the DSP. It is to be noted that there was a variation between the preset and measured values of ZMP of the system. Mitobe et al. (1997) discussed the control problem of a biped walking robot during its DSP. The biped robot's DSP motion was considered as that of a manipulator under holonomic constraints. The trunk's COG position was controlled to track a desired trajectory for stability with respect to the world frame. This approach could achieve efficient walking. The control scheme was successfully applied to an experimental walking robot, and the results demonstrated the effectiveness of the method. Ito and Kawasaki (2000) focussed on maintaining stability by controlling the ZMP in-between the two support regions of a two-link mechanism in a sagittal plane. To maintain the balance of the robot, the ground reactions forces should be positive. Hence, control laws for the ground reaction were proposed and verified through computer simulations. Pierre-Brice (2002) predicted that as long as the projection of mass of a robot walking on flat surface could lie within the convex hull of the support region, the stability of walking system could be guaranteed. This stability criterion was tested through numerical analysis. Maki et al. (2006) proposed a method for trajectory planning of biped robot using COG of linear pendulum mode (LPM) for stable waking. According to this, if LPM point could lie within the support region (area), then the biped robot could achieve various motions through LPM dynamism. The LPM mode was used for DSP and linear inverted pendulum mode (LIPM) was utilized for SSP. The trajectory planning could be achieved by switching between these two modes. The proposal was demonstrated through an example of "stop motion" of the biped robot in DSP through experiments and simulations. Zhu and Kawamura (2007) stated that synchronization of the motions in sagittal and lateral planes during DSP could be achieved by simply altering the initial and final points in the lateral plane causing variations in motion parameters, and thus, forming a new biped gait walking pattern. It was useful for adjusting the speed of biped walking. The proposal was verified through numerical simulations.

Jamshidi and Rostami (2008) exploited the pure dynamic synthesis of multi-body systems with sophisticated kinematics to study the motion of the robot during its DSP motion using Pontryagins maximum principle. The closed chain DSP was considered as an open one at specific joint, and a penalty method was used to locate the leg at prescribed location. A feasible set of motions was taken into consideration by using inequality constraints to limit the joint motion. Ground reaction force components were also used as control variables. The proposed technique could generate optimal free motions. The proposal was implemented for solving a numerical simulation using two-point boundary value problems using a shooting method, which required a less number of parameters to characterize the gait. Ito et al. (2008) had studied side to side walking of biped robot in DSP in a lateral plane, where the variation of environment and ZMP were kept constant. This method was applied in the in-place stepping motion and stability of the method was examined both analytically as well as through computer simulations. Finally, the effectiveness of this method was demonstrated on an experiment using real robot. Sardain and Bessonnet (2004) tried to solve the problem in DSP motion for the implementation of fast and dynamic walking gaits (anthropomorphic gaits), especially on uneven terrain. For flat or uneven terrain, the authors analytically proved the coincidence of center of pressure (COP) and ZMP for dynamic stable walking. But, for the non-coincidental or parallel planes, they proposed the existence of virtual ZMP for dynamically stable walking and the same was proved by solving numerical examples related to walking on some staircases.

Some studies were also reported related to the design and development of different control algorithms and their performance testing. Silva and Machado (2004) investigated the adaptive position-force interaction control of the swing foot of biped robot, while entering the DSP from its SSP. They studied impact absorption of the swing foot while landing and gradually accepting the load of the body with other supporting foot through a hybrid position-force control nonlinear spring-damper mechanism. The studies had been conducted for various pre- and post-DSP condition walking phases by placing two contact sensors under the foot considering stability and robustness of the algorithm. The control scheme was successfully implemented on experimental robot. Kim et al. (2009) proposed a control algorithm for the dynamically stable stair climbing of a biped robot. Pattern generation analysis of stair climbing was conducted with the help of on-line controllers. The effectiveness of the control algorithm was tested experimentally on KHR-2 and found to be satisfactory. Erbatur and Kurt (2009) proposed a reference generation algorithm based on Fourier series approximation using the LIPM and moving support foot ZMP references. This could provide a simple solution and generate a smooth ZMP reference. To implement the proposal, a 12-DOF biped robot model with simple inverse kinematics-based joint space controller was used for testing the developed reference trajectory through full-dynamics in 3-D simulations. Simulation studies suggested that the moving ZMP references were more energy efficient than the ones with fixed ZMP under the supporting foot. Shih and Gruver (1992) developed and implemented an advanced control system for a seven-link biped robot in its DSP for sway motion by using feed-forward compensation and linear state feedback for tracking the joint trajectories. The experiment showed that its performance was superior to conventional PD control. Mu and Wu (2004) developed a sliding mode control algorithm for the regulation of motion during the DSP of a five-link biped robot under holonomic constraints. The proposed control algorithm was used to track the hip and trunk motions. The control scheme was evaluated through computer simulations.

A few studies dealt with intelligent control of biped robots also, some of those work are discussed here. Lin et al. (2010) developed a fuzzy logic (FL)-based technique combined with modern control theory for dynamic stabilization and locomotion control of biped motion. The performance of fuzzy control rules was evaluated for the biped walking on horizontal plane surface and climbing up a flight of stairs. Experimental results confirmed the effectiveness and applicability of the proposed fuzzy stabilization tuning approach. Vundavilli et al. (2007 a,b) used soft computing-based approaches to study dynamically balanced gaits of a 7-DOF biped robot in its SSP for different terrains, namely staircase, sloping surface and ditches. However, their study focused on optimization of a single objective in a cycle.

1.3 Gaps in the Literature

From the above literature survey, the following gaps have been identified:

(a) Although a considerable amount of work had been carried out, there is still a need for the development of an integrated scheme to obtain optimal mechanical structure and controllers with adaptive gain values of 2-DOF manipulator solving tracking problems. The aim of this study is to obtain an optimal mechanical structure of the manipulator along with adaptive controller that enables high precision positioning. The links of the manipulator are treated as rigid bodies. To speed up operations, one needs powerful actuators and lightweight arm links. In positioning, however, the major issue is to minimize the settling time of the controller. The settling time depends on a broad range of design parameters including mass and stiffness properties of the links, gain values of the compensator, and others. These parameters are coupled to each other and have intricate interactions with respect to the robot's settling time. For instance, increasing the structural stiffness alone does not always decrease the settling time. All the design parameters must be considered in an integrated manner in order to optimize the performance.

(b) Most of the studies on biped robots available in the literature are related to their walking on flat surface. However, a biped robot should be able to walk on rough terrains also, such as staircases, and others. The problems related to locomotion of biped robots on rough terrains are more complex (from the analysis and control points of view) compared to those on flat surface. Rough terrain locomotion of biped robots has not yet received much attention, till date.

1.4 Aims and Objective

The aims and objective of the present thesis have been set as follows:

1. The aim of this study is to obtain an optimal mechanical structure of the manipulator along with adaptive controller that enables high precision positioning. In the present thesis, an integrated scheme for obtaining optimal mechanical structure and controller of a 2-DOF manipulator solving path tracking problems, has been proposed. Four approaches are developed, and their performances have been compared on two path tracking problems.

2. In the present thesis, an attempt has been made to formulate gait planning problem of a 7-DOF biped robot ascending and descending the staircase as a multi-objective optimization one. Two modules of adaptive neuro-fuzzy inference system (ANFIS) have been utilized to model gait planning problem of the biped robot in its single support phase (SSP). Two conflicting objectives, such as minimization of power consumption and maximization of dynamic balance margin have been considered in the present study, and a Genetic Algorithm (GA) and a Particle Swarm Optimization (PSO) algorithm have been utilized to yield Pareto-optimal front of solutions separately. A comparison on the performances of these two optimization algorithms has also been presented.

3. In the present study, an attempt has been made to formulate gait planning problem of a 7-DOF biped robot in its double support phase (DSP) by considering two separate SSPs. During each SSP, the robot is assumed to be a serial manipulator consisting of four links. The zero moment point (ZMP) is determined for each SSP. Then, both the SSPs are combined to form a DSP. This problem related to the DSP of the biped robot has been posed as a multi-objective optimization one. Two conflicting objectives, such as minimization of power consumption and maximization of dynamic balance margin have been considered in the present study. A GA and PSO algorithm have been utilized to determine Pareto-optimal front of solutions separately. A comparison on the performances of these two optimization algorithms has also been presented.

1.5 Contributions Made by the Scholar

The scholar has made the following contributions in the present thesis:

- A systematic analytical approach has been developed through kinematics and dynamic analysis of a 2-DOF manipulator designed for its optimal structure with controller. The manipulator's task is to trace straight and circular path trajectories accurately. Four approaches have been developed and their performances have been compared with each other for trajectory tracking problems. Their performances have been tested through computer simulations. A detailed study has been carried out in order to find the variation of controller gains to estimate the effects of various parameters on power consumption and quality of the path tracked by the manipulator.
- Soft computing-based approaches, namely GA- and PSO algorithms - based adaptive neuro-fuzzy inferences systems have been developed for the gait planning of biped robot in its SSP, while moving through staircases.
- Optimal gait planning problems of the biped robot have also been tackled in its DSP using the GA and PSO algorithm separately. The combined analytical model with soft computing-based approaches, thus developed, might be useful to the designers in order to predict the outputs for a set of input parameters, beforehand.

1.6 Layout of the Thesis

The thesis has been organized in seven chapters. The contents of chapters 2 through 7 are described below in brief.

- Chapter 2: It introduces tools and techniques used for developing soft computing-based models of the robotic systems.
- Chapter 3: It includes design of an integrated scheme for obtaining optimal structure and adaptive controller of 2-DOF manipulator.
- Chapter 4: It deals with multi-objective optimization in gait planning of biped robot (during its SSP) using the GA and PSO Algorithm, separately.
- Chapter 5: It concentrates on multi-objective optimization in DSP of the biped robot utilizing the GA and PSO algorithms, separately.
- Chapter 6: Some concluding remarks have been made and the scopes for future study are indicated in this chapter

1.7 Summary

This chapter provides a survey of various approaches used for kinematics, dynamics and power efficiency analysis of two robotic systems. Their drawbacks have been identified. After conducting a thorough literature review, the gaps in the literature have been identified and based on these gaps, the aims and objective of the present thesis have been set. Finally, it provides the layout of this thesis.