CHAPTER 1

INTRODUCTION

1.1 Robot Manipulator System

Industrial robots have gained a wide popularity as essential components for the realization of automated manufacturing systems. Reduction of manufacturing costs, increase of productivity, improvement of product quality standards and last but not least, the possibility of eliminating harmful or alienating tasks for the human operator in manufacturing system, represent the main factors that have spearhead the spreading of robotics technology in a wide range of applications in manufacturing industry [1].

An industrial robot is constituted by a mechanical structure or manipulator that consists of sequence of rigid bodies (links) connected by means of articulation whether revolute or prismatic joints and this manipulator is characterized by an arm that ensures mobility, a wrist that confers dexterity and an end effector that performs the task required of the robot, actuators that set the manipulator in motion through actuation of the joints while the motors employed are typically electric and hydraulic, and occasionally pneumatic, sensors that measure the status of the manipulator and if necessary the status of the environment and a control system (computer) that enables control and supervision of manipulator motion [1].

Although electrically driven robots are widely used in an increasing number of applications, there are many industrial tasks where hydraulic actuators can be used advantageously. For special applications such as for very large robots and civil service robots, hydraulic actuator may be an appropriate choice [2]. Machinery in construction, forming, mining, forestry industry, heavy load motion control and mobile equipment applications as well as large flight simulators take the advantage of the high power to weight ratio, possible speed reversals and continuous operation, the stiffness and short response time of hydraulic drives.

Electrohydraulic system uses low power electrical signals for precisely controlling the movements of large power pistons and motors. The interface between the electrical equipment and the hydraulic (power) equipment is called 'hydraulic servo valve'. These valves used in the system must respond quickly and accurately. A schematic diagram of a typical hydraulic system is shown in Figure 1.1.

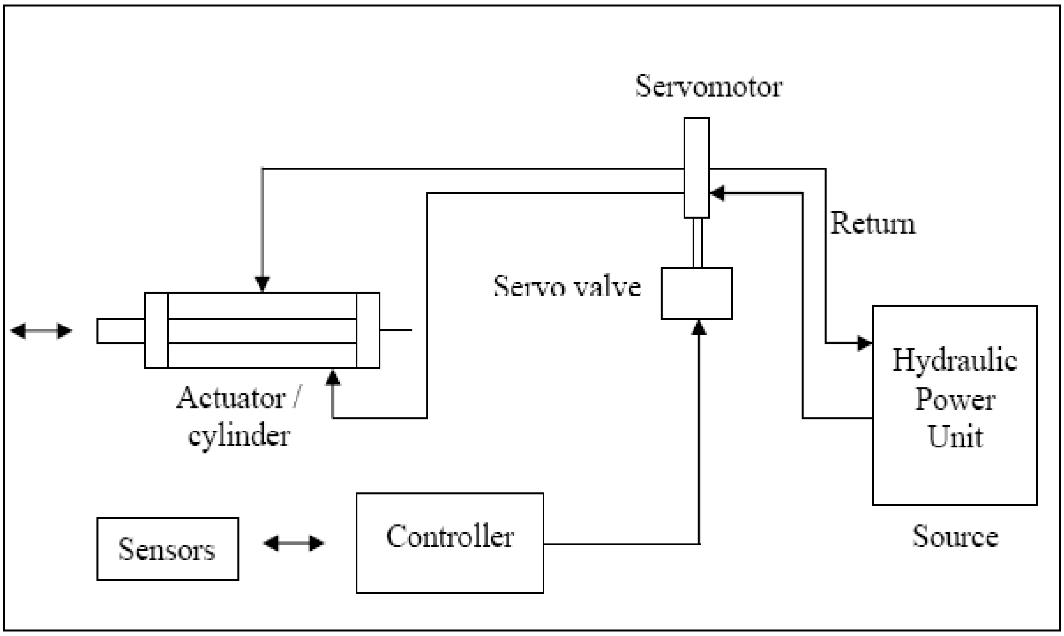

Figure 1.1: Schematic diagram of a hydraulic system and its components

A servo valve is created when a servomotor is attached to the spool valve and the servo valve. The servo valve together with the hydraulic actuator will form the hydraulic servomotor. A simple movement of the spool valve controls the motion of the actuator. As the spool moves up and down, it opens the supply and returns to the port through which the fluid travels to the cylinder or return to the reservoir as shown in Figure 1.2. The amount of the supply fluid and the displacement of the cylinder can be controlled by adjusting the size of these ports opening. Similarly, the flow rate of the supply fluid and the velocity of the cylinder can be controlled by adjusting the rate of the ports opening [2].

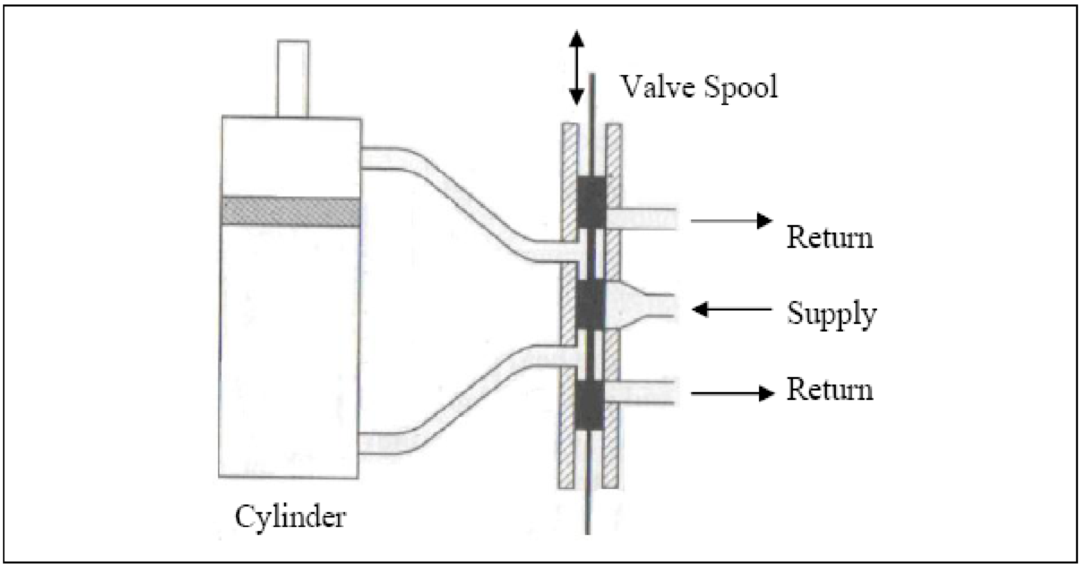

Figure 1.2: Schematic diagram of a spool valve in a neutral position

In electrohydraulic manipulator system, each joint is driven by a hydraulic servomotor. A higher control input voltage will produce larger valve flow from the servo valve into the hydraulic motor. This will eventually results in a faster rotational motion of the motor and thus the path (position and the orientation) of the manipulator can be done in a specified time. The timed path is called trajectory of the manipulator's end effector [3]. However, it is difficult to precisely control the position of electrohydraulic robot both theoretically and practically due to the nonlinearities and coupling effects present in the system.

The control variable for the DC motor is either motor voltage or current that is proportional to the actuation torque. The hydraulic actuator on the other hand, the control voltage or current signal to the valve of hydraulic actuator controls the speed of the actuator rather than its force or torque. The system also has large extent of parametric uncertainties due to the large variations of inertial load and the change of bulk modulus caused by the entrapped air or change of temperature. Besides, the system may also have large extent of lumped uncertain nonlinearities including external disturbances and unmodeled friction forces. Therefore, the electrohydraulically driven revolute robot manipulator dynamics are more complex than electrically driven manipulator dynamics. All of these factors make the modeling and control of such system a challenging task [4].

In all industrial robot applications, completion of a generic task requires the execution of a specific motion that prescribed by the desired path trajectory and performance. However, when faster trajectories are demanded, the performance of the manipulator will be worst. Therefore, the correct execution is entrusted to the control system which shall provide the joint actuators of the manipulator with the command consistent with the desired motion trajectory. Thus, an accurate analysis of the characteristics of the manipulator dynamics is therefore a necessary premise to finding motion control strategies. In general, motion control problem consists of obtaining the dynamics model of the electrohydraulic robot manipulator in which these models will be used to determine the control laws or strategies to achieve the desired system response and performance.

1.2 Electrohydraulic Robot Manipulator

Nowadays, hydraulic robots are widely used in the construction and mining industries. However, majority of earlier work in the design of the control laws for manipulators deal with electrically actuated manipulators. In terms of hydraulic actuators, comparatively less work has been done [5]. However, by taking the dynamics of the actuator alone is not sufficient to represent the dynamic of hydraulic manipulator, since it does not take into account the arm dynamic forces such as the inertia forces, the coriolis and centrifugal effects and also the gravity effects that will affect the performance of the controller. Tracking performance of the system can be improved by implementing mechanical linkage dynamic model in the controller design since it is part of the overall control system. This approach has been successfully shown in many electrical robots in the past [6].

[7] has used 6 DOF hydraulic robot and the models incorporate manipulator dynamics. The limitation with this project is that it did not include the hydraulic motor nonlinear spring stiffness, viscous damping and inertia. Same goes with [8] who has incorporated manipulator dynamics in developing 2 DOF hydraulic robot arm models, but the hydraulic motor nonlinear spring stiffness, viscous damping and inertia are not taken into account in the design. [9] on the other hand, have used hydraulic cylinders with the application to robot manipulators. The problem with the study is that it did not incorporate the mechanical linkage dynamics in the design model.

[5] has incorporated both rigid body dynamics and hydraulic actuator dynamics into the design. However, the mathematical model presented was not in state-space form. For some recent development on mathematical model derivation of this type of manipulator, [10] has developed the mathematical model in state-space form for the electrohydraulic robot manipulator that integrated both the manipulator dynamics and hydraulic actuator dynamics including the hydraulic motor nonlinear spring stiffness, viscous damping and inertia.

The mathematical model derived in [10] will be used in this project to synthesize different control laws in providing the trajectory tracking control of the 3 DOF electrohydraulically driven revolute robot manipulator.

The robot control problem revolves around the computation of the required actuator inputs in order to maintain the dynamic response of manipulator in accordance with the desired response and performance. This control problem will become complex due to the nonlinear dependence of system parameters on variables such as displacement and velocity, on the geometry and inertia of the links, uncertainties associated with gravity, coriolis and centrifugal forces, variations in payload handled by the manipulator, and environmental influences.

In classical control theory, it is assumed that the control actions are undertaken by a single controller that has all the available information about the system and treat each joint of the manipulator as a simple linear servomechanism as in most of industrial robots, whereby the simple controller like Independent Joint Control (IJC), proportional plus derivative (PD), or proportional plus integral plus derivative (PID) controllers are adopted. In these methods, the nonlinear, coupled and time-varying dynamics of the mechanical linkage of the robot manipulator have been excluded and completely ignored, or assumed as disturbances. Manipulators that have been controlled by this method usually move at slow speeds with unnecessary vibrations. In general, the method is only suitable for relatively slow manipulation and limited precision tasks [11]. However, when the manipulator joints are moving simultaneously and at high speed, the nonlinear coupling effects and the interaction forces between the manipulator links may affect the performance of the overall system and increase the tracking error. The disturbances and uncertainties such as variable payload in a task cycle may also reduce the tracking quality of the robot manipulator system [12].

Therefore, control strategies for high speed robotic system are of great interest for both industrial and academic fields, whereby various advanced and sophisticated control techniques have been proposed by numerous researchers in providing the necessary tracking trajectory of robot manipulator and at the same time guaranteeing the stability of the system. In general, these strategies can be divided into two categories; the non-model based or usually known as Artifical Intelligence approaches and model based approaches. While for the structures of these controllers can be grouped into three categories; the centralized, decentralized, and multilevel hierarchical. For the model based approaches, among the major control approaches considered in the literature for the uncertainties nonlinear systems are the Adaptive Control method [13], Lyapunov based control and Variable Structure Control [14]. While for the non-model based approaches, where the knowledge of the mathematical model is not needed, Fuzzy Logic system, Genetic Algorithm and Neural Networks controls have become important research topics [15].

In [8], PID and Computed Torque Control (CTC) strategies have been implemented for the hydraulic robot and the performance of both methods did not give satisfactory results. As mentioned earlier, the limitation with PID controllers is that they are not meant for high speed robots and in situations that require precise trajectory tracking. While for the CTC, it only can be applied to robots allowing joint torque control. Moreover, the problem with CTC is essentially based on exact robot arm dynamic model; the explicit use of an incorrect robot model will affect the performance of control. He further synthesized the Kinematic Compensation Control integrating a feedforward kinematic compensation and conventional regulatory control techniques. Even though the system shows good experimental result, it still lacks mathematical stability proof.

[16] has proposed a link-space pressure feedback controller for Stewart type hydraulic manipulator. However, this approach lacks stability proofs that are important from both theoretical and implementations points of view. [17] has developed a generalized predictive control algorithm for hydraulic control system but the limitation of this approach is that it relies heavily on online parameter estimation and consequently, is computationally expensive. [18] on the other hand, have adopted a Lyapunov based Model-based Adaptive Control for hydraulic manipulator. Even though the technique possesses mathematical stability proof but it needs persistent excitation and pressure feedback. A strategy based on Backstepping approach has been developed by [19] to provide necessary position tracking for the hydraulic robot. However, the proposed strategy also relies on online computation for converting into task-space coordinates. Furthermore, it is said to be sensitive to sensor noise, hence high-quality measurements are needed. To overcome this drawback is by introducing heuristic limitation of time derivatives in the control law so that the influence of sensor noise in the simulations reduces significantly, but may deteriorate the control performance.

Non-adaptive control techniques such as computed torque methods and optimal control have serious disadvantages, namely complex controller structure, excessive on-line computation, and sensitivity to uncertainties and nonlinearities in the system. These difficulties become more complicated by their being centralized approaches. Adaptive control methods tackle the robot control problem fairly effective, but the controller is greatly complicated. In much of the works on adaptive control of manipulators, the justification for this added complexity is not addressed [20]. Despite the fact that the centralized approaches have attained significant achievements to improve the tracking performance of robots, but when the degree of freedom (D.O.F) of robots is large, they stumble upon time consuming computations and complexity of the controller structure. Furthermore, very few results could be transferred into practice due to the high implementation cost. Besides, the centralized approach treats the robot manipulator as a single entity plant, which is unfavorable and impractical for implementation and maintenance of the controllers [21]. Therefore control methods that reduce these problems by changing the problem to control smaller scale subsystems by using the decentralized controllers have the advantage of computation simplicity and low-cost hardware setup. For this reason, improving the performance of the trajectory tracking problem of robot manipulator through decentralized control is an interesting topic.

Variable Structure Control utilizes a high-speed switching control law to drive the nonlinear plant’s state trajectory onto a specified and user-chosen surface in the state space and to maintain the plant’s state trajectory on this surface for all subsequent time [22]. This property of remaining on the switching surface once intercepted is called a sliding mode. The plant dynamics will be restricted to this surface to represent the controlled system’s behavior. Hence, it is suitable for complex systems and is insensitive to parameters variations and uncertainties. SMC is particularly well suited for the manipulator control problem for the following reasons. First, the application of SMC does not require an exact knowledge of the system dynamics, provided there is no un-modeled structural uncertainty. This property is desirable since the complexity of the manipulator dynamics makes the exact calculation of the dynamics infeasible if not impossible. Second, when the SMC is applied, the performance of the system can be made insensitive to bounded disturbances. This property is important in rejecting effects due to the Coulomb and viscous frictions. It is also important when the manipulator is carrying payloads because the payload exerts at the robot end-effector can be translated into forces or disturbances at each of the joints. Thus, the application of the SMC technique results in a performance that is robust with respect to disturbances and modeling errors, while provides accurate tracking [21].

This project will extend the control strategies proposed in controlling two coupled pendulums in [23] to provide trajectory tracking control of a three DOF electrohydraulically driven revolute robot manipulator. The approach stabilizes a system through a fast switching global control to render that the system to behave as a second linear time invariant system which can be chosen to be stable. This method incorporated the ideas of variable structure system with the technique of pole placement in a decentralized nature. This is done by constructing a decentralized sliding mode controller which will force the original nonlinear interconnected uncertain subsystems to behave as a second linear interconnected uncertain subsystem which has had its pole placed in the left half of the s-plane by pole placement method.

1.3 Research Objective

The objectives of this project are:

i) To decompose the 3 degree of freedom (DOF) electrohydraulic robot manipulator into interconnected uncertain subsystems;

ii) To design a decentralized robust controller based on Sliding Mode Control (SMC) for the 3 degree of freedom (DOF) electrohydraulic robot manipulator;

iii) To evaluate the performance of the system based on the proposed controller and to compare the performance of the decentralized robust controller with a centralized robust controller.

1.4 Scope of Research

The scope of work for this project includes:

i) To decompose the integrated nonlinear dynamic model of the 3 DOF revolute electrohydraulic robot manipulator as described in [10] into a set of interconnected subsystem by treating it as a large-scale system. The interconnected model will be transformed into interconnected uncertain subsystems models using the known parameters of the robot;

ii) To synthesize a decentralized tracking trajectory controller based on a variant of the VSC approach, which is the SMC for large-scale uncertain system. This proposed controller will be applied to the 3 DOF electrohydraulically driven revolute robot manipulator models developed in part (i);

iii) A centralized tracking trajectory controller will be designed based on the deterministic approach for an uncertain system, where the transformation-free SMC will be utilized;

iv) Simulation studies will be done to investigate the performance of the proposed controller and the effectiveness of the decentralized SMC as compared to the centralized SMC in providing the necessary position tracking control for the system. These will be done using SIMULINK and MATLAB 7.0.

1.5 Research Methodology

The research work is undertaken in the following three developmental stages:

a) Development of an interconnected uncertain system models of a 3 DOF revolute hydraulic robot manipulator. The steps taken in this stage are:

i) Conduct literature review on the existing electrohydraulic robot manipulator mathematical model in order to understand the dynamics behavior of the system. Based on the information obtained, the integrated model will be decomposed into three interconnected subsystems in order to apply the decentralized tracking controller;

ii) Conduct literature review on the existing techniques for decomposing the system into interconnected uncertain subsystems.

b) Application of a decentralized robust controller based on VSC technique to the robotic system. The steps taken in this stage are:

i) Conduct literature review on the existing control technique for robotic systems;

ii) Conduct literature review on the existing robust control technique based on decentralized Sliding Mode Control algorithm;

iii) Synthesize the decentralized SMC technique cited from [23] to the robotic system. The procedures performed in this stage are:

- Decomposition of the complete model into an large-scale uncertain model
- Definition of each local sliding surface
- Determination of the system dynamics during Sliding Mode
- Establishment of the final control law for each subsystem

c) Perform computer simulation of the proposed controller by using MATLAB and SIMULINK to investigate the effectiveness of the decentralized SMC as compared to a centralized SMC.

1.6 Structure and Layout of Thesis

This report is organized into five chapters. In Chapter 2, the formulation of the mathematical modeling of the integrated electrohydraulic robot manipulator, in which, first, a general dynamic model of a hydraulic actuator dynamics and a rigid manipulator link are described separately. Then, based on these equations, an integrated model in state space representation is presented. At the end of the chapter, the complete integrated dynamic model of three DOF electrohydraulically driven revolute robot manipulator is determined.

Chapter 3 deals with the controller design using decentralized sliding mode control strategies with specific application to the plant described in Chapter 2. Firstly, by treating the electrohydraulic robot manipulator as a large-scale system and each joint as a subsystem, a linear interconnected uncertain system is developed to represent the manipulator as interconnected subsystems. Secondly, based on the known allowable range of operation of the manipulator and the maximum allowable payloads, the nominal and bounded uncertainties of the system may be developed and the manipulator can be represented as an interconnected uncertain subsystems. Finally, the decentralized SMC controller is designed for the system.

Chapter 4 outlines the performance of the proposed control system which is evaluated by means of computer simulation study through MATLAB/SIMULINK. The simulation begins with a pre-specified desired trajectory for each of the manipulator joints in terms of joint displacement, velocities and accelerations. In order to analyze the effectiveness of the decentralized SMC, centralized SMC strategy is used as a mean of comparison. Conclusion on the robustness of the approach in handling the nonlinearities, uncertainties and couplings effect present in the system and the necessary trajectory tracking control of the plant is also made and discussed based on the results obtained.

This thesis ends with Chapter 5, where the summary of the synthesized approach while undertaking this project is described. Recommendations for future work are also presented at the end of the chapter.