MODELLING AND CONTROL OF DIRECT DRIVE ROBOT MANIPULATORS

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DEDICATIONS

To my dearest parents for their love and blessing.
To my beloved wife for her support and encouragement.
To my children Luqman, Naqib, Taufiq, Rasyiqah and Sabiq for making my life wonderful.

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PUBLICATIONS

The following papers, based on the work described in this thesis, has been published:

1. Ahmad, M. N., Osman, J. H. S., and Ghani, M. R. A., (2001). "Decentralized Proportional-Integral Sliding Mode Tracking Control for a Class of Nonlinear Interconnected Uncertain System", *Jurnal Teknologi*, 35(D), December 2001, pp 77-98.

2. Ahmad, M. N., Osman, J. H. S., and Ghani, M. R. A., (2002). "Decentralized Tracking Controller Design using Proportional-Integral Sliding Mode Control", *Proc. IASTED Int. Conf. On Modelling, Identification, and Control (MIC 2002)*, Innsbruck, Austria, February 18-21, 2002, pp 368-373.

3. Ahmad, M. N., Osman, J. H. S., and Ghani, M. R. A., (2002). "Sliding Mode Control of a Robot Manipulator using Proportional-Integral Switching Surface", *Proc. IASTED Int. Conf. On Intelligent System and Control (ISC2002)*, Tsukuba, Japan, October 1-4, 2002, pp 186-191.

4. Ahmad, M. N., Osman, J. H. S., and Ghani, M. R. A., (2002). "A Decentralized Proportional-Integral Sliding Mode Tracking Controller for Robot Manipulators", *Proc. IEEE Region 10 Conf. On Computers, Communications, Control and Power Engineering (TENCON'02)*, Vol. 3, Beijing, China, October 28-31, 2002, pp 1314-1317.

5. Ahmad, M. N., Osman, J. H. S., and Ghani, M. R. A., (2002). "Proportional-Integral Sliding Mode Tracking Controller with Application to a Robot Manipulators", *Proc. 7th. Int. Conf. On Control, Automation, Robotics and Vision (ICARCV'02)*, Singapore, December 2-5, 2002, pp. 863-868.

6. Ahmad, M. N., Osman, J. H. S., and Ghani, M. R. A., (2003). "Robust Tracking Controller for a Class of Uncertain Dynamical Systems using Proportional-Integral Sliding Mode Control", *Proc. Int. Conf. On Robotics, Vision, Information and Signal Processing (ROVISP 2003)*, Penang, Malaysia, January 22 - 24, 2003, pp. 361-366.

7. Mohamad Noh Ahmad and Johari H. S. Osman, (2003). "Robust Sliding Mode Control for Robot Manipulator Tracking Problem using a Proportional-Integral Switching Surface", *IEEE Student Conf. On Research and Development (SCOReD 2003)*, Putrajaya, Malaysia, May 2003 (Accepted for presentation).

8. Mohamad Noh Ahmad and Johari H. S. Osman, (2003). "Application of Proportional-Integral Sliding Mode Tracking Controller to Robot Manipulators", *IEEE Int. Conf. On Control Applications (CCA 2003)*, Istanbul, Turkey, June 23 – 25, 2003 (Accepted for presentation).

ABSTRACT

This thesis is concerned with the problems of modeling and controlling of direct drive robot manipulators. To achieve these goals, an integrated mathematical model of direct drive robot manipulator is developed. The model considered comprises the mechanical part of the robot manipulator as well as the actuators that drive the joint of the robot. The formulation results in nonlinear time varying state equations, which represent a realistic model of the robotic system. Based on the known bounds on the system parameters, the robot dynamic is treated as an uncertain system whereby deterministic approach can be used in controlling the system. By treating the uncertain robot system as a large-scale system, the MIMO direct drive robot manipulator dynamics may be decomposed into an interconnected uncertain system whereby decentralized approach may be used in the design of the controller. In the second part of this study, two robust output tracking controllers using the concept of Sliding Mode Control (SMC) are proposed under centralized and decentralized frameworks. In the centralized approach, the controller is designed with assumption that the state information of each sub-system can be sensed and transmitted to the centralized controller. The calculation for the control signals is also centered in one location. On the other hand, the decentralized control presented in this research adopts the local approach, where the local controllers utilize only the state information of each sub-system. In each of the approach, a variant of the SMC known as the Proportional-Integral Sliding Mode (PISMC) is chosen to ensure the stability of the system dynamics during the sliding phase. The system dynamics during the sliding phase may be determined using any conventional pole placement method. Using Lyapunov's stability theory, it is shown theoretically that for system with matched uncertainties, the system's trajectories are guaranteed to be stable during the reaching phase. A tuning algorithm is also presented to assure that not only the desired tracking response is achieved, but also assure that the system control input is within the permissible range of operation. The proposed controllers are synthesized with the assumptions that the upper bounds on the non-linearities, couplings and uncertainties present in the direct drive robot system are available. The performance and robustness of each controller design is evaluated through extensive computer simulations and the results show that the proposed centralized and decentralized PISMC controllers render the nonlinear direct drive robot manipulator practically stable to track the desired reference trajectory.

ABSTRAK

Tesis ini membincangkan permasalahan pemodelan dan kawalan pengolah robot pacuan terus. Untuk mencapai matlamat ini, model bersepadu untuk lengan robot pacuan terus telah dibangunkan. Model yang dibangunkan ini merangkumi dinamik bahagian-bahagian mekanikal robot disamping dinamik pemacu. Kaedah pemodelan sebegini menghasilkan persamaan keadaan berubah dengan masa yang juga merupakan model yang lebih realistik untuk robot. Berdasarkan kepada had-had parameter sistem, model ini kemudiannya ditukar menjadi suatu sistem tak pasti agar kawalan berasaskan kepada pendekatan deterministik boleh direka bentuk. Dengan menganggap sistem robot sebagai suatu sistem berskala besar, model bersepadu yang terhasil boleh dipecahkan menjadi beberapa sub-sistem yang saling terhubungkait, dan berguna untuk reka bentuk kawalan berasaskan kepada pendekatan kawalan ternyahpusat. Didalam bahagian kedua kajian ini, dua pengawal penjejakan menggunakan konsep kawalan gelincir telah dicadangkan, di mana pengawal pertama menggunakan konsep sepusat, manakala pengawal kedua menggunakan konsep ternyahpusat. Dalam pendekatan sepusat, pengawal telah direka bentuk dengan anggapan bahawa maklumat-maklumat keadaan setiap sub-sistem boleh diperolehi dan dihantar kepengawal sepusat. Pengiraan isyarat kawalan juga dilakukan pada satu lokasi sahaja. Untuk kawalan ternyahpusat, reka bentuk pengawal dalam kajian ini telah menggunapakai pendekatan setempat, di mana setiap pengawal ternyahpusat hanya menggunakan maklumat keadaan di sub-sistem berkenaan sahaja. Kawalan ragam gelincir berkadaran-kamiran (PISMC) iaitu variasi daripada kawalan ragam gelincir (SMC) telah dipilih untuk memastikan kestabilan sistem semasa fasa gelincir. Dinamik sistem semasa fasa gelincir boleh ditentukan menggunakan kaedah perletakan kutub lazim. Dengan menggunakan teorem kestabilan Lyapunov, telah dibuktikan secara teori bahawa untuk sistem dengan ketakpastian sepadan, trajektori sistem adalah stabil semasa fasa menjangkau. Satu algoritma penalaan juga telah dibentangkan untuk memastikan bahawa sambutan penjejakan yang dikehendaki dapat diperolehi, dan pada masa yang sama memastikan isyarat kawalan sentiasa pada julat yang dibenarkan. Pengawal telah disintesis dengan anggapan bahawa nilai-nilai had untuk ketaklelurusan, gandingan dan ketakpastian di dalam sistem robot diketahui. Prestasi pengawal yang telah dibangunkan dinilai melalui penyelakuan komputer. Keputusan daripada penyelakuan menunjukkan bahawa pengawal yang dicadangkan mampu mengawal robot pacuan terus menjejak trajektori yang dikehendaki dengan stabil.

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CHAPTER I

INTRODUCTION

1.1 The Direct Drive Robot Manipulator

An industrial robot is a general-purpose, computer-controlled manipulator consisting of several interconnected rigid links. The connection between two links is called a joint. Typically, one actuator is used to control the motion of each joint. The first industrial robot was successfully installed in the early 1960's (Fu *et al.*, 1987). The key to this device was the use of a computer in conjunction with a mechanical manipulator to produce a machine that could be taught to carry out a variety of tasks such as trajectory tracking automatically. The positioning accuracy of the arm end-effector is low and the mechanical stiffness of the arm construction is inherently poor. As the applications of industrial robots expanded, different types of robots were developed to meet a wide variety of tasks. For light-duty applications such as arc welding and spray painting, electrically powered robots became the most prominent design. Since electrical motors generally operate at a quite high speed, appropriate gearing is needed to develop a sufficient torque to drive the loads. Robot arms are normally moved at low speed while the motors run at a rather high speed. As a result, a large gear reduction as high as 1:1000 is typically required.

A conventional robot manipulator normally employs a speed reducer such as gear and belting so that the manipulator inertia is reduced and hence permitting the use of a smaller actuator. However, backlash in a gear reduction unit can cause position error at the end-effector. Direct drive technique eliminates the problems associated with gear backlash as well as reducing the friction significantly. Moreover, the mechanical construction is much stiffer than the conventional robot manipulator with gearing, wear and tear is not a problem, and the construction is more reliable and easy to maintain due to its simplicity. These features make the direct drive robots suitable for the high-speed application of industrial robot such as the laser cutting application (Asada and Youcef-Toumi, 1987).

The concept of robot movement directly driven by electrical motors is a rather appealing idea to control engineering community. Figure 1.1 shows the basic configuration of a three Degree Of Freedom (DOF) serial direct drive robot. The direct drive joint consists of a pair of arm links, the motor, and the bearings (not shown in the figure for clarity). The motor is comprised of a stator and a rotor. The stator is housed in the case connected to a proximal link, and the rotor is directly coupled to the joint shaft, which is connected to the other arm link at a distal end. Thus the distal arm link is rotated directly by the torque exerted between the rotor and the stator, hence producing direct drive. So far, quite a number of direct drive robots have been constructed in research laboratories throughout the world. In fact some of the prototype models have been commercialised and made their presence felt in the industry. Table 1.1 shows some of the direct drive robots reported in the literature (Asada and Kanade, 1981), (Kanade and Schmitz, 1985), (Asada and Youcef-Toumi, 1987), (An *et al.*, 1988), (Kazerooni and Kim, 1988), (Terbuc *et al.*, 1995a), (Safaric *et al.*, 1997).

1.2 Background of the Problem

Although the introduction of gearing mechanisms resolved the actuation problems, it however posses unwanted characteristics. It is important to note that gearing will definitely introduce backlash or lost of motion, which directly degrade positioning accuracy. Even a small amount of backlash at a proximal joint leads to a substantial large error at the arm tip. The introduction of anti-backlash gears offers no help but will only introduce considerable large amount of friction (Asada and Youcef-Toumi, 1987). Beside the backlash problems, gearing mechanisms are also the major source of mechanical deflections or compliances. Robots with poor stiffness will for sure deteriorate the positioning accuracy. It may also causes undesirable vibrations especially at the high speed.

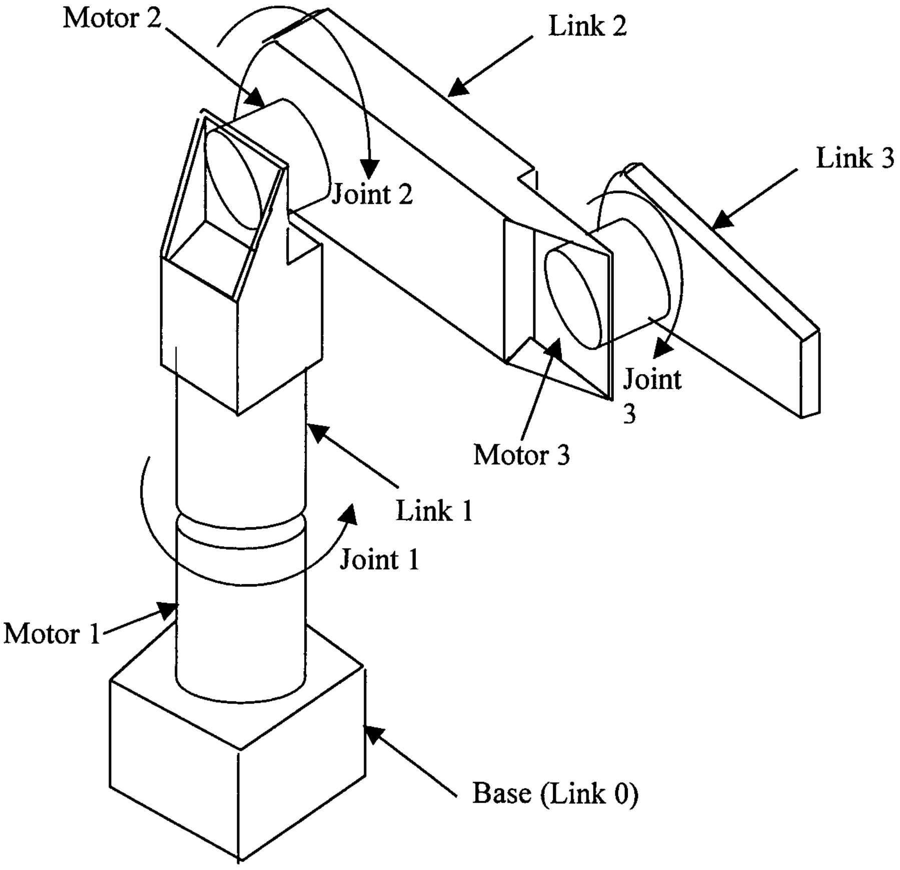


Figure 1.1: Basic configuration of a three DOF serial direct drive robot

Table 1.1: Some of the direct drive robots reported in the literature

No.	Model	DOF	Special Features
1.	CMU D-D Arm Model I	6	- First direct-drive robot ever built - Serial drive
2.	MIT D-D Arm Model I	3	- Gravity balanced - Serial drive
3.	MIT D-D Arm Model II	3	- De-coupled dynamics - Parallel drive
4.	MIT D-D Arm Model III	3	- De-coupled dynamics - Parallel drive - Max. tip speed of 12 m/s - Acceleration > 5G
5.	MIT D-D Arm Model IV	2	- De-coupled and invariant dynamics - Parallel drive
6.	PUMA-like DD Arm	3	- Serial drive - Counterweight balanced
7.	University of Minnesota DD Arm	3	- "Gravity-Free" design - Acceleration +/- 5G
8.	Adept One	4	- First commercialized direct-drive robot - Max. arm speed of 9 m/s - Repeatability of +/- 0.0254 mm
9.	Matsushita's Pana Robo HDD-1	2	- High accuracy - Repeatability of +/- 0.01 mm
10.	Shin Meiwa	N.A.	- High speed laser cutting application - Acceleration > 5G

A robot manipulator is typically modelled as a serial chain of rigid bodies. In general, one end of the chain is fixed to some reference surface while the other end is free, thus forming an open kinematic chain of moving rigid bodies. For an N DOF manipulator, the dynamic equations describing the motion of the manipulator in the absence of actuator dynamics, friction, and other disturbances can be written in the following matrix form (Fu *et al.*, 1987), (Craig, 1989):

$$M(\theta(t),\xi)\ddot{\theta}(t) + D(\theta(t),\dot{\theta}(t),\xi) + G(\theta(t),\xi) = T_L(t) \qquad (1.1)$$

$$\theta(t) = [\theta_1(t),\ \theta_2(t),\cdots,\ \theta_N(t)]^T$$

$$\theta(t) \in R^N\ ,\ \dot{\theta}(t) \in R^N\ ,\ \ddot{\theta}(t) \in R^N$$

where

$M(\theta(t),\xi)$: $N \times N$ inertia matrix of the manipulator

$D(\theta(t),\dot{\theta}(t),\xi)$: $N \times 1$ vector of centrifugal and Coriolis forces

$G(\theta(t),\xi)$: $N \times 1$ vector of gravitational forces

$T_L(t)$: $N \times 1$ vector of joint actuator torques

$\theta(t),\dot{\theta}(t),\ddot{\theta}(t)$: $N \times 1$ vector of joint positions, velocities, and acceleration, respectively

ξ : a vector (with appropriate dimension) of parameters of the mechanism such as payload mass carried by the manipulator.

Equation (1.1) shows that the dynamic behaviour of a manipulator is highly coupled and nonlinear. The arm inertia varies depending upon the arm configuration. The acceleration of one joint affects other joints due to the reaction of the accelerated joint. This reaction causes coupling among the multiple joints. The configuration dependency of the manipulator inertia matrix induces the Coriolis and centrifugal torques, which are nonlinear torques comprising products of joint velocities.

In conventional geared robots, the highly coupled and nonlinear dynamics are attenuated by the gearing when reflected to the motor shafts. Consider the *i*th manipulator link (load), which is mechanically coupled to the motor shaft through gears as shown in Figure 1.2(a). Let h_i be the gear reduction ratio of the drive mechanism. Then, the equivalent system at the motor shaft after reflection of the *i*th link dynamics is as shown in Figure 1.2(b). The dynamic equation governing this kind of rotational system can be written as:

$$\left(J_m + \frac{J_{arm}}{h_i^2}\right)\ddot{\theta}_{m_i}(t) + \left(F_m + \frac{F_{arm}}{h_i^2}\right)\dot{\theta}_{m_i}(t) + \frac{T_{non}(t)}{h_i} = T_{m_i}(t) \qquad (1.2)$$

where

J_m : the moment of inertia of the *i*th joint motor including the gear inertia,

J_{arm} : the inertia of the *i*th link,

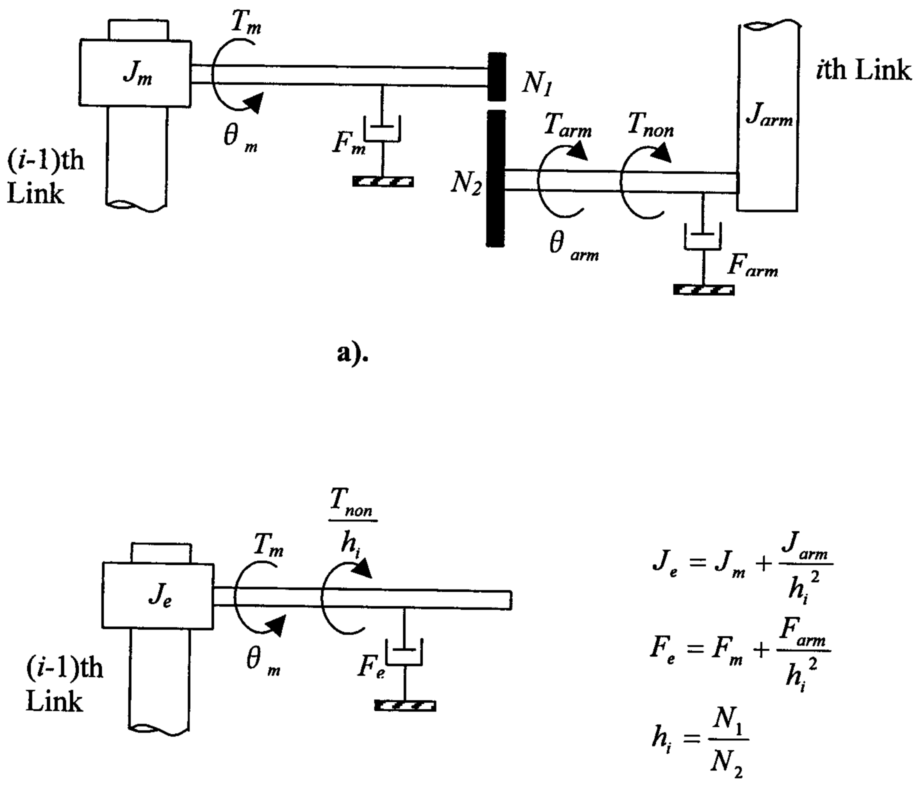
F_m : the viscous damping of the *i*th joint motor rotor,

F_{arm} : the viscous damping of the *i*th link,

$\dot{\theta}_{m_i}, \ddot{\theta}_{m_i}$: the speed and acceleration of the *i*th joint motor, respectively

T_m : the torque exerted by the *i*th joint motor,

T_{non} : the nonlinear torques due to other sources such as friction.



a).

$$J_e = J_m + \frac{J_{arm}}{h_i^2}$$

$$F_e = F_m + \frac{F_{arm}}{h_i^2}$$

$$h_i = \frac{N_1}{N_2}$$

b).

Figure 1.2: a) The *i*th manipulator link actuated by motor through gear train
b) Equivalent system at the motor shaft after reflection of impedances

The first term in equation (1.2) accounts for the inertial torque associated with the acceleration of the actuator. The moment of inertia is comprised of the inertia of the motor rotor (including the gear inertia), and the inertia of the arm link, which is reduced by the square of the gear ratio h_i when reflected to the motor axis. The arm link inertia varies depending upon the arm configuration, but the rotor inertia is invariant regardless of the arm configuration. As for the viscous damping and nonlinear torque, the values are reduced by the factor of h_i^2 and h_i, respectively, as described in the second and third term of equation (1.2). If the gear ratio h_i is sufficiently large (as normally used in the practice), then the effect of varying inertia is negligibly small and the system parameters can be modelled as constants for the manipulator arm. In direct-drive arm, where the gear ratio h_i is equal to 1, the complex dynamics of the arm are directly reflected to the motor axes. The varying inertia effect and the effects of the coupling and nonlinear torques will have a substantial dynamical effect. As a result, the challenge to design a robust controller for direct-drive robot is becoming an uphill task.

Another significant problem encountered in the direct-drive robot control is the motor inductance effects. Direct drive motors for robotics applications such as Brush-less DC Motors (BLDCM) and Variable Reluctance Motors (VRM) are generally designed for maximum output torques. However, this design specification leads to the use of large windings, which have significantly large inductances (Gieras and Wing, 1997). These large inductances will have a direct influence on the overall dynamics of the direct drive arm.

In all industrial robot applications, the main objective is to execute a specific motion prescribed to the manipulator's end-effector. This requires the joint actuators of the manipulators be provided with the commands consistent with the desired motion trajectory. The desired motion is typically specified either as a sequence of end-effector positions and orientations, or a continuous path in the manipulator space. In most of the current industrial robot control, each joint of the robot arm is treated as an independent servomechanism. Conventional feedback control design methods are then applied to each joint, assuming that it is dynamically de-coupled from all other joints. This approach is quite inadequate because it neglects the motion and varying configuration of the whole manipulator mechanism. The result is reduced servo response, speed and damping, limiting the precision and speed of the end-effector and making it inappropriate for high precision tasks. Looking at the nature of the direct drive dynamical structure, the simple control algorithm as normally used in the conventional geared robot is not appropriate for the direct drive application. Moreover, the parameters in manipulator model are usually unknown or poorly known. This imprecision, known as structured and unstructured uncertainties will further deteriorate the performance of the conventional controller if it were to be applied to the direct drive robot.

1.3 Robot Manipulator Control Strategies

The robot control problem revolves around the computation of the required actuator inputs in order to make the robot joints follow a desired joint trajectory. In most industrial robots, the objective is achieved by treating each joint of the robot arm as a simple joint servomechanism. This method is called Independent Joint Control (IJC), or classical joint control and usually utilizes the well known Proportional plus Derivative (PD), or Proportional plus Integral plus Derivative (PID) controllers. In this approach, the nonlinear, coupled and time-varying dynamics of the mechanical part of the robot manipulator is completely ignored, or assumed as disturbances. Manipulators controlled this way normally move at slow speeds with unnecessary vibrations. In general, the method is only suitable for relatively slow manipulation and limited precision tasks (Craig, 1989), (Fu *et al.*, 1987).

Nonlinearity, interactive dynamics, parameter variations, and other uncertainties in robotic systems prevent linear servo controllers from providing a satisfactory performance especially during transient and high-speed mode of operation. Significant improvement in robot control requires a more sophisticated control technique. Many strategies have been developed for the trajectory control of robot. These strategies can basically be divided into two groups: the model-based approach, and the approach of mimicking the behaviour of human operator known as the Intelligent Control (IC) method. For the model-based approach, among the well-known control approaches considered in the literature are the Computed Torque technique (Craig, 1989), the Adaptive Control method (Ortega and Spong, 1988), and the Variable Structure Control (VSC) (Young, 1978). As for the latter approach, where the knowledge of the mathematical model is not needed, Fuzzy Logic System (FLS), knowledge-based or expert systems, Genetic Algorithm (GA), and Neural Network (NN) controls have become the important researched topics (Sinha, 1998).

The Computed Torque technique, also known as the Inverse Dynamics problem (Lewis *et al.*, 1993), is composed of a feed-forward torque-computing component. The method requires exact modelling of the manipulator arm dynamics and based on the desired joint trajectories, the feed-forward component is computed to compensate the actual manipulator arm dynamics. Hence, the nonlinear, coupled manipulator dynamics is reduced to a linear de-coupled time invariant plant and standard linear control technique can then be used to design the feedback loops. The drawback of this controller is that they require on-line computation of the joint torques to compensate for any deviations from the desired trajectory. To overcome this problem, Liu (1995) proposed an adaptive controller without computing the inverse of the estimated inertial matrix, which originally needed in the computed torque scheme. The method utilizes a two-component structures consisting of a linear PD control component and an adaptive component. The PD control, using some reasonable estimates of system parameters, is used to stabilize the robot, while the adaptive control component is to reduce the tracking errors for the resultant error dynamics.

The Model Reference Adaptive Control (MRAC) technique is based on the selection of an appropriate reference model that fits to the design objective, and an adaptation mechanism to modify the system feedback gains. The objective of the control system is to minimize the error between the reference model states and the actual robot manipulator states using chosen adaptation mechanism. The linear second order time invariant reference models were normally employed for each DOF of the robot manipulator. To nullify the difference between the behaviour of the robot and the reference model, Balestrino *et al.* (1983) proposed a technique based on the hyperstability theory, while Osman (1985) and Young (1988) presented a technique based on the Variable Structure theory. Both approaches require perfect model matching to be satisfied. The control algorithms are insensitive against parameter variations and disturbances, and force the nonlinear, coupled time varying robot manipulator to behave like its reference model. The practical implementation of MRAC technique on the real industrial robot was carried-out by Ekrekli and Brookfield (1997). Their thorough investigation showed that MRAC provides effectively perfect control of real robot manipulator provided that a correct dynamic model is assumed.

The algorithms for continuous-time direct adaptive control of robot manipulators was presented in Johansson (1990). In this work, Lyapunov theory is used for controller design and stability investigation. Uniform global asymptotic stability with respect to the manipulator positions and velocities is guaranteed for constant, unknown parameters. The identification may be supported by prediction error estimation whether acceleration measurement is available or not. However, prediction error estimation based on acceleration measurement improves the adaptation properties considerably.

During the last two decades, significant interest on Variable Structure Systems (VSS) and Sliding Mode Control (SMC) has been generated in the control research community worldwide (Young and Ozguner, 1999), (Young *et al.*, 1996). One of the fascinating phenomena of Variable Structure Control (VSC) is the discontinuous nature of the control action whose primary function is to switch between two distinctively different system structures such that a new type of system motion called Sliding Mode exists in the manifold. When a system is in the sliding mode, its dynamics is strictly determined by the dynamics of the sliding surfaces and hence insensitive to parameter variations and system disturbances if certain matching conditions are satisfied (Itkis, 1976). 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-modelled 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 modelling errors, while provides accurate tracking.

The first extension of the SMC technique to robotics was initiated by Young (1978). The study involves the application of a hierarchical variable structure control (VSC) law on a two-link manipulator. The VSC law provides compensations that eliminate nonlinear dynamic interactions of the manipulator joints by introducing sliding mode. Compared with the conventional control laws which emphasize complex nonlinear compensation, the VSC law is easier to implement and require less a priori knowledge of the physical parameters of the manipulator. Despite the discontinuous nature of the control signals, the joint position trajectories in the simulations are observed to be smooth.

One of the basic assumptions in the design and analysis of VSC systems is that the control can be switched from one value to another at an infinitely fast rate (DeCarlo *et al.*, 1988), (Hung *et al.*, 1993). Although VSC with sliding mode provides excellent robot trajectory tracking capabilities, the discontinuous control input on the predetermined switching surface however results in an unwanted behaviour called the chattering problems. However, these sorts of problems have been successfully addressed by a handful of researchers using various techniques.

Young's idea was then tested experimentally by Hashimoto *et al.* (1987) but with a slight modification to eliminate the chattering problem. Instead of implementing the pure hierarchical VSC method, a simple nonlinear compensator and continuous function are used. A two DOF robot arm with two DC servomotors (60 W and 200 W) mounted on each joint and are coupled to the links through appropriate gearing is used as a test-bed. The control system hardware is comprised of a microcomputer and a proper interface circuitry. It was shown that by using the SMC law, the nonlinear dynamic interaction of the manipulator joints are effectively suppressed and the system is insensitive to the physical parameter variations. The experimental results showed robust performance against the payload variations and the good tracking capability for continuous path motion.

A chattering-free robust tracking controller was also addressed by Chern and Wu (1992a) via an Integral Variable Structure Control (IVSC). A zero steady state error for step input with arbitrary eigenvalue assignment is possible by combining an integral controller, a Variable Structure Controller (VSC), and the robot dynamics into a single unified model. With a proper choices of piecewise linear input functions and the determination of the switching function and integral control gain such that the system has the desired eigenvalues, the system is forced into sliding mode and hence insensitive against the payload variations and external disturbances. The modified piecewise linear input functions were then introduced to overcome the chattering problem. The proposed approach has been simulated for the first three links of a PUMA 560 robot arm.

Habibi and Richards (1992) used variable structure control strategy as an additional input to rectify the uncertainties in the estimated control model of the computed torque technique. Variable structure control is shown to have two benefits: it can be used to guarantee stability in uncertain systems or it can act as an additional torque component to improve the system performance and load toleration. Practical applications of the controller to joint two and joint three of the PUMA 560 robot indicate a significant improvement of tracking performance in comparison to the computed torque control where the tracking precision is approximately doubled. Moreover, it is shown that the controller virtually removes the effect of load variations in the trajectory tracking mode without affecting the system's stability.

A multiple-control strategy comprises of the linear control method, the VSC, and the Adaptive Control scheme was presented in (Zein-Sabatto *et al.*, 1991), (Zein-Sabatto and Cook, 1992). A restructuring control mechanism is suggested and used to coordinate between the operational behaviour of the controllers and, to dynamically select the proper control action for a pre-specified sub-task. Simulations done on a two DOF planar robot manipulator and PUMA 560 robot arm have shown that the method is superior when compared to single control strategy.

Park *et al.* (1994) presented an adaptive SMC algorithm for trajectory control of robot manipulators. The proposed algorithm eliminates the requirement for inversion of the inertia matrix, the requirement for measurement of joint acceleration, and the requirement for calculating a regressor (an algorithm for on-line calculation of the modelled part of the plant dynamics). The control scheme can be easily implemented requiring only position and velocity tracking errors. Computer simulation results showed good properties of the proposed algorithm under large manipulator parameter uncertainties and disturbances.

It is well known that VSC have strong robustness of feedback stability in the presence of system uncertainties such as parametric variations or disturbances. The main drawback of this kind of control is that the resulting control input is discontinuous on the predetermined switching surface, and consequently, the control input chatters at a theoretically infinite frequency. To overcome this problem, much effort has been devoted to exploit smoothing methods to reduce, or if possible, remove the chattering while the whole system remains robust. One of the approaches is by introducing a boundary layer located around the switching surface (Slotine and Sastry, 1983), (Slotine, 1984), (Slotine and Li, 1991). In this approach, the sliding surface is allowed to be time varying and the control procedure consists of two steps. First, the control law forces the trajectory towards the sliding surface while in the second step, the controller is smoothed inside a possible time varying boundary layer. This will achieve optimal trade-off between the control bandwidth and tracking precision, therefore eliminating chattering and the sensitivity of the controller to high frequency un-modelled dynamics. Although chattering can be reduced, robustness and tracking accuracy are compromised, that is, the larger the boundary layers the smaller the control chatter and the greater the tracking error. To further improve the performance of VSC with boundary layer, Bekit *et al.* (1998) used the time varying switching gains instead of the constant one. Beside the time varying switching gains, a smoothing algorithm is also presented which poses powerful smoothing capability to reduce or remove undesirable chattering while keeping the robust characteristics that reject system uncertainties and external disturbances.

Due to the complexity of decision making in a centralised situation, the control of the robot manipulators cannot be handled in a processor, and multiprocessor architectures with dedicated joint processors are often used to control industrial robots (Henrich and Honiger, 1997). Advances in microcomputer technology have intensified interest in distributed computation schemes. Aside from modular expandability, another potential advantage of these schemes is a reduction in computation time for solving the tracking problem due to parallelism of computation. In this regard, hierarchical and decentralised control has become a necessity due to the nature of the problems. In should be noted however that in most of the cases, these two approaches are normally implemented along with various nonlinear compensation schemes to eliminate the interactions.

A method based on the decentralised pole-placement feedback deduced from the computed torque method was proposed by Bestaoui (1989). The proposed controller consists of two levels of a hierarchical structure designed for the coordinated control of multiple DOF manipulators. Each DOF was considered as a subsystem and the algorithm used the horizontal division notion, which takes into account the interconnected aspect between the joints. The first stage is the reference torque and coordination parameters computing level. A decentralised control system was designed for each DOF with all the gains were calculated by simple laws derived from the computed torque method. Simulation results showed that the algorithm was quite effective in compensating the parameter uncertainties.

A decentralised adaptive control scheme for robot manipulators was introduced by Liu (1997). The adaptive control is developed based on the passivity and linear-in-parameters properties of the robot motion equation. The proposed scheme consists of a PD term, a nonlinear term, and an adaptation term, to ensure globally ultimately bounded tracking errors and parameter estimation errors. The stability analysis was carried out by employing a generalized kinematic energy function as a candidate of Lyapunov function of the entire system so that the passivity property of the robot dynamics can be used to decouple input torque for each error subsystem. Simulation on a two DOF planar robot arm showed that the approach guarantees the global stability of the tracking errors and parameter estimation errors.

Osman and Roberts (1991) treated the dynamics of a conventional geared robot manipulator as a set of interconnected subsystems with bounded uncertainties and presented a class of decentralised continuous nonlinear feedback control law for the tracking problem via the deterministic approach. However, their works only considered the systems whose subsystems have no control inputs couplings. That is, they only considered a class of particular robot manipulators whose subsystems have no coupling among the control joint torques or the couplings can be considered negligible. Since each joint of robot manipulators is treated as a subsystem, the couplings among the control joint torques are significant and the class of manipulators considered by Osman and Roberts (1995) is very small. Moreover, the decentralised controller designed using their method needs the local states as well as the neighbouring states and hence do not constitute a true decentralised controller.

The decentralised control design of robot manipulators, whose subsystems have control input couplings, was considered by Wang and Wend (1999). By first representing the robot manipulators as a set of interconnected subsystems, the dynamics of the subsystems is then divided into a nominal system and uncertainties. Based on the nominal system and the bounds on the uncertainties, a robust decentralised control law was then designed based on the Ricatti equation approach, utilizing only the local states. It was shown theoretically that the manipulator systems are practically stable. Simulation performed on two-link planar arm confirmed the findings.

Another decentralised control approach of eliminating the interaction between the joints is by using the variable structure based controllers (Morgan and Ozguner, 1985). In this work, the problem of forcing the system into the switching surfaces is achieved by regulating the derivative of the switching surface to a constant so that the reaching time can be completely specified. This technique yielded a very predictable reaching phase, and in the process, satisfied the reaching condition to guarantee the existence of the sliding mode. The effectiveness of the controller was successfully demonstrated through the simulation experiments performed. The results showed that the reaching times were as predicted, the control inputs were within the specified limit, and chattering was reduced to an acceptable limits.

In (Pandian *et al.*, 1988a), a decentralised variable structure model following controller for robot manipulators was proposed. The dynamic models of the joint actuators were considered along with that of the manipulator, where, the manipulator dynamics was considered as the disturbance to the actuators dynamics. By considering the desired trajectory as the reference dynamics, a nominal control, which forces the subsystem dynamics to track the pre-specified desired trajectories in the absence of uncertainties was proposed. As for compensating the effects of nonzero initial error and the effects of interlink coupling torques, Coriolis, centrifugal and gravity forces, as well as payload variations, a SMC based controller with properly selected gains to ensure the existence and reachability of the sliding mode was then added to the nominal control. It was assumed that the measured joint forces are considered as disturbance to the system. This scheme however suffers from the drawbacks of high cost of precision sensors and introduction of noise in the transducers. In order to overcome this problem, a relay component was introduced as a substitute. The tracking performance is quite satisfactory and is robust to payload variations. High-gain control in the vicinity of the sliding plane was also employed to eliminate the chattering effect and the integral feedback term is added to eliminate the steady state tracking error.

Similar to the development of tracking control of conventional geared robot manipulator, research works were also carried out for the tracking control of direct drive robot manipulator. The first comparisons of control algorithms applied to the control of direct-drive arm was reported back in 1983 by Asada *et al.* (1983). The linear PD controller and its combination with feed-forward compensation were implemented on a six DOF direct drive arm. The experimental study showed that the linear PD controller gave a large fluctuation of control torque and decreases control accuracy. The benefit of the feed-forward compensation was concluded from the study, where no significant interaction between the joint trajectories was observed and the trajectories showed excellent agreements with the reference trajectories. Further experiments conducted on the same direct drive robot manipulator were later described in Asada and Youcef-Toumi (1987). The application of the dynamic compensation, in particular the feed-forward and the computed torque controllers to control the direct drive robot manipulator were also carried out by An *et al.* (1988). It was reported that the techniques improve trajectory accuracy significantly, when compared to independent joint PD control (An *et al.*, 1989). Their findings were in fact produced through thorough simulations and experiments conducted on a three DOF direct drive robot manipulator described in An (1986).

The comparison of the computed torque control scheme with the PD control with feed-forward on the direct drive robot manipulator was also carried out by Khosla and Kanade (1989). It was reported that the computed torque scheme clearly outperforms the conventional IJC scheme in the absence of torque saturation. The experimental study also found that in the direct drive robot control, the effect of Coriolis and centrifugal forces introduce trajectory errors even at small joint velocities. This is in contrary with the belief that the effect of Coriolis and centrifugal forces become important only at high speeds. Reyes and Kelly (2001) concluded that while simple PD control is comparable to those controllers compensating for robot dynamics such as the computed torque technique for slow trajectories, its tracking performance decreases tremendously for fast trajectories. Their findings were based on the Computed Torque control, PD control, and PD control with computed feed-forward control applied to a two DOF direct drive robot manipulator.

Uecker *et al.* (1991) compared the tracking performance of the computed torque control method with the individual joint PID control and the resolved acceleration control with the inverse Jacobian PID control method. Experimental results on a three DOF closed-chain direct drive robot manipulator showed that the model-based methods achieved two to four times better performance than the PID control method.

The tracking control of a two DOF direct drive robot manipulator was addressed in Kim and Hori (1995). The experimental evaluation was performed using the adaptive and robust control schemes. Similar study was also conducted by Jaritz and Spong (1996) but with four different robust control methods. The study concluded that all methods showed good performance. However, they noted that friction compensation has proven to improve tracking performance quite well although the approximation of the friction model was rather inaccurate. Further improvement of the tracking performance is possible by improving the friction model.

Aghili *et al.* (1997) address the dynamic control of direct drive robots with positive joint torque feedback. The system dynamics in closed form was analytically derived. The conditions on the kinematic structure of the robot to possess linear dynamics have also been presented. The resulting rotor dynamics are determined solely by the polar inertia of motor rotors and joint twist angles, which can be identified precisely in practice. A comparison of the dynamical equations with those of a three DOF robot without joint torque feedback showed an essential simplification. For the linear dynamics, a centralised PD controller was designed for accurate and high bandwidth control, while in the nonlinear case feedback linearization is used.

Application of the SMC technique in the trajectory control of direct drive robot manipulator has also been reported in the literature. The advantages and the disadvantages of Variable Structure Control and Adaptive Control strategies when applied to the direct drive robot manipulator was reviewed by Er *at al.* (1995). A comparative study of these two strategies was performed on a commercial Adept One direct drive Selective Compliance Assembly Robot Arm (SCARA) robot. Simulation studies reconfirmed that when a manipulator system is forced into sliding mode, the nonlinear interactions in the manipulator dynamics are eliminated completely and the manipulator is insensitive to load variations, joint friction and disturbances. However, due to switching delays in the real system, the control is switched at a finite frequency and ideal sliding mode does not occur. Non-ideal sliding mode results in chatters in the control torque signals. Their findings also conclude that Adaptive Control also performs well in terms of robustness to changes in the payload and joint friction as well as in the presence of external disturbances. Furthermore, asymptotic stability of the control system is ensured as a by-product of the design.

Erbatur *et al.* (1998) has developed a chattering free sliding mode control algorithm based on the combination of Variable Structure Systems and the Lyapunov design method. A robust trajectory controller for direct drive manipulator is designed with an assumption that the system can be represented in the regular form. Experiments are carried out on a direct drive SCARA type manipulator carrying various payload configurations. The results obtained from the proposed controller show that the tracking performance is better than a well-tuned conventional PD control scheme. Unlike the conventional sliding mode controllers, the resulting control signals are smooth and hence the possibility of exciting un-modelled dynamics is thus eliminated.

A Neural Network (NN) based motion control with fuzzy adaptive learning of a direct drive robot manipulator was experimented by Rodic *et al.* (1996). An NN controller using fuzzy logic for the adaptation of learning algorithm was proposed to assure the highest speed and robustness of learning. The control algorithm is robust against parameter variations and external influences, and precise trajectory tracking is assured. Nevertheless, the proposed controller was tested only on a single axis direct drive robot manipulator where additional mass-spring-damper load was attached to emulate the second link, and hence not reflecting the true direct drive environment.

The development and implementation of a robust tracking control onto a three DOF direct drive BLDCM driven robot manipulator using an adaptive fuzzy logic SMC was presented in (Rojko and Jezernik, 2001). The actuators dynamics, represented by a DC equivalent of BLDCM motor was included in the plant dynamic. A Multi-Input-Single-Output (MISO) FLS for the disturbance estimation was designed for each DOF of the robots and an adaptive mechanism was employed to solve the disturbance compensation problem. The stability of the adaptation procedure was given via the Lyapunov stability theorem. The control scheme is completely decentralised and experiments performed showed accurate tracking of the commanded trajectory even in the presence of the abrupt changes of dynamics caused by the varying load.

Although there has been much research on the model-based control of direct drive robot manipulators, all works are confined to the use of dynamic model of the mechanical arm only. That is, the actuators dynamic was totally left out to simplify the overall model. Since the importance of modelling the manipulator accurately has been increasingly apparent with the demand for high performance controller, further researches are needed to incorporate the actuators dynamics as part of the overall robot system dynamics. Even in the conventional geared robots, only handfuls of research had been done to consider the integration of the actuators dynamic along with the manipulator dynamic (Troch, 1986), (Troch *et al.,* 1986), (Tarn *et al.,* 1985), (Tarn *et al.,* 1991), (Osman, 1991). In direct drive environment, only Rojko and Jezernik (2001) were known to include the complete BLDCM dynamics into the overall direct drive model. It should be noted however that while Rojko and Jezernik work was done under the non-model based environment, there are no known reported progress on the model-based control approach.

The VSC based techniques via the SMC theory had produced excellent results when applied to the control of the robot manipulator. This method however suffers some form of difficulties in the design procedure. This is due to the fact that the system is designed in the Regular Form via the similarity transformation. Recent advances in the SMC theory had produced a modified SMC where the order of the motion equation is remain unchanged. Among the methods reported in the literature are the Integral Sliding Mode Control (ISMC) (Cao and Stepanenko, 1993), (Utkin and Shi, 1996), Wang *et al.* (1996), (Yan *et al.*, 1997), (Yang *et al.*, 1999), (Shyu *et al.*, 1999), (Wu, 2000), (Cao and Xu, 2001), (Bouri and Thomasset, 2001) and the Complex Valued Sliding Mode (CVSM) (Shepit and Pieper, 2003). These methods, however, were never been applied to the control of the robot manipulators, whether on a conventional geared robots or on a contemporary direct drive mechanism. As such, the exploration on the utilization of this kind of approach into the direct drive robot mechanism can be considered as a natural research area topic.

Another point to consider is that some of the aforementioned centralised control methods exhibit excellent and promising results in simulation or in the laboratory environment, but very few results could be transferred into practice. This is due to the fact that the centralised schemes, in general, require excessive computation time, complex and are not cost effective to implement. The centralised approach treats the robot manipulator as a single entity plant, which is unfavourable and impractical for implementation and maintenance of the controllers.

From the surveys and discussions presented in this section, it is necessary to conduct a thorough study on the modelling and control aspects of the direct drive robot manipulators. The study is needed to complement the research works found in the literature through new findings and new experience, and enriching the existing control methods through new innovative ideas. The inclusion of the actuators dynamics into the robot dynamic, in particular the BLDCM dynamics, due to the fact that this type of actuator is among the most commonly used direct drive mechanism, should not be left out in the modelling aspect of the direct drive robot manipulator. On the other hand, the recent advances on the SMC theory with the introduction of a transformation-free SMC should be fully capitalized in the control aspect of the arm. Lastly, the cost saving and running time efficiency of the decentralised control approach should be employed and tested to take advantage of their true benefits.

1.4 Research Objectives

The objectives of this research are as follows:

I. To formulate the complete mathematical dynamic model of the BLDCM driven direct drive revolute robot manipulators in state variable form. The complete model will be made available by integrating the dynamics of the direct drive robot manipulator with the BLDCM dynamics. The formulation will be applied to two direct drive robot manipulators, namely, ROBOT 1 and ROBOT 2.

II. To transform the integrated nonlinear dynamic model of the BLDCM driven direct drive robots into a set of nonlinear uncertain model comprising the nominal values and the bounded uncertainties. These structured uncertainties exist due to the limit of the angular positions, speeds, accelerations as well as the varying payload carried by the manipulator.

III. To decompose the direct drive manipulators into interconnected subsystems, by treating it as a large scale system. The interconnected models will then be transformed into interconnected uncertain system models using the known parameters of the robots.

IV. To synthesize a centralised tracking controller based on the deterministic approach for an uncertain system. In particular, the VSC approach along with the transformation-free SMC will be utilized. The proposed controller will then be applied to the direct drive robot manipulator models developed in II.

V. To synthesize a decentralised tracking controller based on the theory of VSC for large-scale uncertain system. The proposed controller will be tested and simulated to control the direct drive robot manipulators models developed in III.

Verification of the proposed controller on its stability will be accomplished using the well-established Lyapunov's second method while the complete computer simulation and analysis using two different three DOF revolute direct drive robot manipulators will be performed on MATLAB platform with SIMULINK as the user-end interface.

1.5 Structure and Layout of Thesis

This thesis is organized into six chapters. In Chapter 2, the formulation of the integrated dynamic models of direct drive robot manipulators is presented. First, the state space representation of the actuator dynamics comprising of BLDCM motors is formulated. Then, the state space representations of the dynamic model of the mechanical linkage of the direct drive robot manipulators are established. Based on the actuator dynamics model, the integrated dynamic model of the robot manipulator in state space is presented. The technique is then used to model two different three DOF direct drive robot manipulators, namely, ROBOT 1 and ROBOT 2.

Chapter 3 establishes the basis for the synthesis of the controllers presented in the next few chapters. In the first part, the direct drive robot manipulators are treated as an uncertain system. Based on the known allowable range of operation of the direct drive robot manipulators and the maximum allowable payloads, the model comprising the nominal and bounded uncertain parts is developed. In the second part, the direct drive robot manipulators are considered as a large-scale system. By treating each robot joint as a subsystem, a linear interconnected uncertain system is developed to represent direct drive robot as interconnected subsystems. Similar to the procedure applied earlier in the chapter, the nominal and bounded uncertain parts of the interconnected subsystems may be computed based on the known allowable range of operation of the direct drive robot manipulators and the maximum allowable payloads. Each of the approaches is then applied to the two direct drive robot manipulators considered in Chapter 2.

Chapter 4 describes a centralised control strategy for direct drive robot manipulators based on the SMC approach. The controller is designed with assumption that the state information of each sub-system can be sensed and transmitted to the centralised controller. A variant of the SMC known as the Proportional-Integral Sliding Mode (PISMC) is chosen to ensure the stability of the system dynamics during the sliding phase. The system dynamics during the sliding phase can be determined using any conventional pole placement method. Using Lyapunov's stability theory, it is shown that for system with matched uncertainties, the system's trajectories is guaranteed to be stable during the reaching phase. A tuning algorithm is also presented to assure that not only the desired tracking response is achieved, but also assures that the system control input is within the permissible range of operation. The performance of the proposed tracking controller is evaluated by means of computer simulation study.

Chapter 5 outlines a tracking controller design using the method presented in the previous chapter but in a decentralised nature of control. The method uses the bounds on the uncertainties by using the local approach, where only the local states are required while the states from the neighbouring sub-systems are not needed. Similar to the design procedure adopted in the previous chapter the mathematical derivation and the tuning algorithm are outlined. The simulation results for two case studies involving two different types of three DOF direct drive robot manipulators are presented and discussed.

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