CHAPTER I

Introduction

1.1 Introduction

Robot manipulators represent an important part of the popular concept of "factory of the future" in modern manufacturing technology. Rapid growth of robot population in wide area of applications insists an advance of the development of the concept. An essential factor behind this success is embedded with manufacturing economy, apart from an apparent advantage of robots over human workers in automated tasking efficiency. For robot manipulators to achieve this target, they must be proved to be able to perform versatile applications with high quality of task manipulation, but with less consumption of power and programming effort. Most of today robot manipulators already installed for industrial applications are still operating under simple fixed-gain controllers which were developed about several decades ago. These robots possess limited manipulation performance, because of inability of the old controllers to maintain acceptable performance in the face of large dynamic uncertainties that may emerge during complex manipulation. These unavoidable uncertainties represent important difficulties to determine an exact amount of dynamics of a manipulator arising during control operation so that the control can utilize this information to suppress their effects. It is, however, generally accepted that numerical values computed from a dynamic model of a physical system are never exact with real quantities, despite true model structure is known, its parameters still face with some uncertainties in acquisition of their values. For high-speed manipulation, especially with a direct-drive robot, the performance of conventional approaches such as the fixed-gain scheme or the computed-torque method could be greatly affected by these parameter uncertainties. Furthermore, at some sever situations, these effects may eventually deteriorate stability of the overall system. Therefore, the case is that there is an essential need to explore more sophisticated control strategies to handle highly complicated physical systems. Adaptive control represents one of the most promising control strategy for a robot manipulator, that is being actively developed to maintain the performance of manipulators in the presence of large dynamic uncertainties.

In the context of modern manipulator control, there are two general ways to synthesize an adaptive scheme for enhancing tracking capability of a high performance manipulator. The one follows an adaptive methodology called the *direct adaptive control* in which the adaptation law incorporated within a closed loop will directly adjust controller parameters based upon present tracking error information. In order to do that there must be a reference model that can produce precisely, achieved by design, desired or ideal output to be the control destination for directing the adaptation law. The approach is also more meaningfully known in modern control context as the *Model Reference Scheme*, stemming from this particular aspect. Another adaptive approach is the *Indirect Adaptive Control* in which a total closed loop control system composes of a plant/controller cascade, plant model identifier and a control design module working based upon parameters of the identified plant model. The latter approach does not directly use the adaptive feature to deal with tracking error regulation capability of the controller what it does is to identify current plant model and redesign the controller by changing its parameters to match with the newly-derived plant model. The quality of error regulation is only dependent upon ability of the controller selected. The particular aspect that the adaptation starts from on-line plant determination and then proceeds to adjust controller parameters using plant model knowledge just derived originates the term *indirect* and a more illustrative name the *Self-Tuning Control* indicating that the plant/controller combination can observe and update its own control information by itself in dealing with variation of operating circumstances.

A robot manipulator represents a highly complicated dynamical plant. The general manipulator equation of dynamics is also of much complexity expressing an amount of highly nonlinear terms even when simple geometrics of a manipulator is considered. Despite many somewhat idealized assumptions aimed to reduce model complexity have been made in dynamic modelling. A six degree-of-freedom manipulator can have thousands of complicated mathematical terms residing in the dynamic equations. During the last two decades, much advance in modern control theory and many computerized ad-hoc techniques successfully applied to other class of physical plants have been adopted to solve manipulator control problems. Meanwhile robot manipulators have continued to considerably engage into industrial applications, the control people could not yet claim to satisfactory achievement of adaptive manipulator control. A large amount of adaptive methods have been proposed to deal with time-varying dynamic changes of a manipulator. They are different in basis of concept and implementation and approach the problem in a continuous-time or discrete-time fashion. Some of the methods aim to compensate changes in dynamics due to changes in geometric configuration directly from using dynamic model computation with more accessibility to high performance computer. Some of them follow the classical control technique tending to robustize the resulting controller in facing of perturbed dynamics and just use manipulator dynamic model as physical information for gaining physical insights to controller design.

There is one approach which has had wide acceptance in modern control context. The approach is to treat the true or exact equations of dynamics of a physical system as a combination of the thoroughly-predictable or nominal model and local effects of perturbation.When one considers a manipulator operating along trajectory, he can describe the dynamics that yield the true or achieved trajectory by a combination of nominal dynamics belong to the nominal trajectory and dynamics of local perturbation which is a linear approximation of the equations of dynamics expanded in the vicinity of the nominal trajectory. The literature (1) investigates the control problems of a manipulator following this approach. The nominal trajectory is represented by the corresponding nominal torque which is precalculated using the general dynamic equations of a manipulator along a reference trajectory. At each nominal point, a linear approximation of perturbed dynamics is carried out. The resulting model is then recursively identified by using least square criterion and is used in immediate designs of a local controller which is a Linear Quadratic Regulator (LQR) applied in a discrete-time manner. The total torque for driving the manipulator along the trajectory is a summation of the precalculated nominal torque and the variational torque from the optimal controller. The total driving torque should be theoretically fit to the appropriate torque of the reference trajectory. But from the basic fact that a physical model is never exact. it subjects to an amount of dynamics that are left out from modelling process and uncertainty in parameters in the derived equations, thereby when actual performance of a real manipulator is tested this inexactness would deviate the nominal operating point so that the assumption basis for linearization would not be further valid and the real circumstance would not be within the designed operating range of the controller. This would degrade tracking performance or eventually lead the system to be unstable. The ultimate failure of the control schema. The extended work in the literature (2) captures this model imperfection concept. They introduced the new dynamic operator replacing fixed analytical dynamic model. The new dynamic operator represents a linear parameterized model of the manipulator dynamics so as to obtain an appropriate linear operator mapping the vector of generalized coordinates into the range of the generalized torques. The formulation was introduced to designate a parameter vector to be used in least square identification just as in the formulation of the perturbed model. Since this identification can immediately derive model parameter information from instantaneous input-output data of the true plant during robot operation. The promise quality of the new dynamic operator, thereby, is addressed on ability to capture the effects of uncertainties in parameters and unmodeled dynamics into the model at once, hence enhancing the ability of the total controller to track the desired trajectory more proper. It is in this sense of the proposed controller that is of much interest to us. The controller, nevertheless, proved to have a significant improvement over the previous (1) on computer simulation results, has got many pitfalls within itself mainly due to extensive use of the least square technique in closed loop system. The unfavorable assumption of persistency of excitation naturally embedded within general identification techniques including the least square is generally known. Despite the thoroughly-understood principle of LQ optimal control is utilized in the servo portion of the scheme, stabilizability and robustizability of its finite horizon version in discrete-time domain is somewhat difficult to find in control literature. Of the most importance to success of the self-tuning scheme intimate dynamic interplay between the controller and the identifier is yet to be revealed on theoretical basis. Furthermore, the recursive identification law itself presents naturally nonlinearity additional into the system and its own process requires measurement of plant output signals thus subjects to a significant amount of measurement noise. Eventually the extreme justification of a controller is certainly based upon actual operating performance. It is where all the effects mentioned above will then be exposed to us.

The thesis is addressed on experimental justification of the indirect adaptive control of a manipulator proposed in (2). A number of experiments are to be established to examine advanced characteristics of the scheme, that are expected to benefit the performance of a robot manipulator in a trajectory tracking manner. The Chula2 manipulator designed and constructed under this thesis is used to base the experimental evaluation. The results will also represent the basic performance characteristics of the manipulator as it is the first time that the robot is officially tested and run. Before we can perform the experiments, some essential mathematical background is needed to be extensively studied to clarify what factors should be considered to be really important to stabilizability and robustizability of the control scheme, when it is implemented on a practical system. Relevant theoretical issues are extensively investigated. The results are presented to certify the scheme in three important points. First, asymptotic stability of a LQ optimal regulator is drawn to guarantee that the methodology of the one-step-ahead optimization will finally yield stabilizing adaptation of the servo gains. Second, it is important guarantee that the LQ optimal design, specifically with the one-step-ahead criterion, possesses a certain bound of a robustness margin. Since, the asymptotic stability proof is just carried out based upon an assumed model of a physical system, hence, it is not sufficient to guarantee stability of the practical system that the assumed model is replaced by the real system. When the resulting regulator is applied with the real plant corresponding to the assumed model, the presence of the demonstrable robustness margin will gain more confidence to us that it will be reasonable to argue that stability of the overall practical system still holds. Third, the recent results in a struggle to find appropriate conditions for the RLS estimator to have acceptable operation under dynamic interference from the LQ regulator, that is concurrently operated within the same closed loop system, are demonstrated and adapted to support our stability conclusion. These main results just conclude stability robustness of local dynamics of the adaptive manipulator system. The effects of the nominal dynamics are still left to be suppressed along the desired trajectory. This part of control work belongs to the nominal dynamic compensator which stems from the use of the identified nonlinear model to calculate the nominal torque along the commanded trajectory to compensate for the large nonlinear dynamics.