CHAPTER V

Conclusions and Suggestions for Further Improvement

5.1 Conclusions

The thesis represents an attempt to find practical value of one of the most promising control strategy among adaptive manipulator control, which is believed to possesses much control potential in dealing with dynamical complexity of a robot manipulator. The certainty equivalence control law for a manipulator proposed in (6) is extensively studied. The control law is composed of three functional parts: the nominal dynamic compensator, the linearized perturbed dynamic identifier and the one-step-ahead LQ optimal regulator. The idea underlining this integration is that when we command a manipulator to follow a desired trajectory, we may think of the trajectory to be achieved as a summation between the nominal trajectory that represents the result of the manipulator nominal dynamics taken into account along the desired trajectory, and the local perturbed trajectory that is resulted from all other dynamic effects neglected in the nominal dynamic discussion. Based on this separation, one can use general dynamic equations of a manipulator obtainable from various methods and principles to compute the nominal torque corresponding to each point in the desired trajectory to compensate for large nonlinear dynamics. The local perturbed dynamics left can be linearly expanded in the vicinity of a trajectory point to obtain linear model of the perturbed dynamics. The RLS identification methodology is inserted into the control scheme at this point to serve the need to identify the local linearized model in terms of a set of model parameters. The LQ optimal control design is then utilized to synthesis a stable regulator tending to regulate the state of the identified model to zero. This means that the situation is corresponding to force the nominal trajectory to track the desired trajectory. The process of the linearization and the regulator redesign occurs recursively with different time scale with the nominal torque computation that is carried out at every trajectory point update. The time scale implementation of the linearization and the regulator redesign relies upon the bandwidth of the closed loop dynamics.

The above concept is somewhat intuitive, inspired from success of the certainty equivalence control scheme in other area of applications. Theoretical discussion to certify applicability of the scheme achieves acceptable results only when a controlled plant can be considered to behave like a linear system. Robot manipulators, however, represent complicated, highly-nonlinear, and time-varying dynamical systems. To apply the indirect adaptive control to a manipulator, there are so many problems left to be clarified before we can proceed to test the scheme with actual hardware. The work (6) proposed the scheme and presented computer simulation results using the simulation model for PUMA - 560 without any rigorous study of relevant theoretical support. Despite, the results insist that the resulting adaptive manipulator system tracks the commanded trajectory, there is no confidence that actual hardware experiments will follow the simulation results.

Our study commences with the depth of physical knowledge of a robot manipulator via the detailed derivation of its mathematical model. The derivation follows the Lagrangian energy concept resulting in a very systematic method to obtain the equations of motion. The results come out as a set of symbolic closed-form formula ready to use to derive the equations for a sequential linkage of n-degree-of-freedom. The derivation is done on the basis of some necessary assumptions.
The importances are that all mechanical imperfection is neglected, all frictional forces that may reside in the mechanism are not taken into account, and vibrational effects are considered beyond our interest. Detailed discussion to extract physical insight of dynamical behaviors of a manipulator is also made.

Theoretical development is presented to increase mathematical validity of the control scheme. In fact, the extreme theoretical justification should take the complete nonlinear equations of motion into account directly combining the identifier and the regulator dynamics in stability and robustness considerations, but, for a manipulator control system the combined dynamics will possess a huge and complex structure so that with available mathematical tools and techniques at present, the direct analysis is not yet feasible. Our tack follows the concept of time scale separation between the RLS identifier dynamics and the combined-state dynamics of the whole control system excluding that of the RLS identifier to avoid the above problem. By appealing to the generally-known integral manifold theory on the basis of slow parameter adaptation with respect to the closed loop dynamics, we can really draw stability conclusion of the whole adaptive control system. In our presentation of theoretical background, asymptotic stability of the one-step-ahead optimal regulator can be drawn and demonstrated by using the Lyapunov's second method. Thereafter, the fundamental Robustness results for an LQ regulator are presented to extend the previous stability results to cover the applications on the practical systems. Based on the recent work (7) , some necessary and sufficient conditions can be elaborated to guarantee convergence of least square parameter estimation working in a closed loop system with a LQ optimal regulator. In the final, the integral manifold theory with slow adaptation help us to extend the convergence to include the RLS on-line estimation, and the total result we can infer is that stable cooperation between the RLS identifier and the LQ optimal regulator is feasible, if some smoothness conditions and restriction on the amount of the regressor and unmodeled dynamics are satisfied and persistency of plant excitation is maintained.

The Chula 2 manipulator system built at the time of this thesis creation is used to base our experimental evaluation. The manipulator represents a three-degree-of-freedom mechanism having SCARA configuration. Two couple of a DC motor and a 1:160 harmonic drive are used to compose transmission systems of the first two joints of the manipulator. The third joint is prismatic, configured to perform vertical translation by through a mechanical combination of a DC motor and a ball-screw package to convert motor rotation into linear distance. Each joint axis is equipped with a high resolution optical encoder to accurately sense the angle of the joint, the high-resolution of the encoders used permits us to refine speed of rotation directly from the encoder pulse train without too much significance of error. All control electronic is intentionally designed to serve digital control needs. The total computing throughput of the complete control system is delivered from the cooperation of the three computing modules working in parallel to each other. The lowest level calculation occurs in the SDP, a data acquisition and processing system, its operation is to serve as a storage of joint position data after the data is interpreted into radian unit from pulse train of the joint encoders. Apart from this, the velocity capture circuits installed in the SDP function continuously to measure the encoder pulse period whose value indicates speed of shaft rotation, when this speed implication is available, the processor equipped with the SDP will translate this information into joint speed in rad/sec. As a result, the servo acquisition loop can be taken place every 2 msec. period yeilding the maximum sampling rate of more than 500 H . Concurrently with the data acquisition task, the SCS is free to run the servo as fast as the software implemented on it can offer, while leaving algorithm-level, real-time computational burden, if necessary, to the ECS. With the PD implementation, the resulting computing capability of the total controller emerges at 400 Hz., without joint of the ECS, since it is not necessary the PD. The performance of the sensing system is quite satisfactory. Tracking data reported is of very high resolution. The resulting resolution of the joint sensors are 1.5 microradians/step, 2 microradians/step and 0.5 microns/step for join 1, 2 and 3 respectively.

The experiments were planed to run under three different conditions to examine the applicability of the certainty equivalence control law in many different points of view. Comparison with the PD control was made in each experimental run. The results can be concluded that there exists some potential of the adaptive control to track the desired trajectory, but less smoothness of tracking occurred with respect to the PD. In conclusion, the adaptive control is proved to outperform the PD in two aspects. In adaptive case, speed of response exhibits automatic adjustment to match current situation. This stems from the virtue of the adaptive mechanism that can realize control situation through the model identification and reflects the realization in the adjustment of the control parameters. The idea to replace the nonlinear fixed model of the nominal dynamics with the identified model is proved to offer significant advantages. As it was evident in the experiments with the loaded system, after the transients originated from perturbing the mass of link 3 had died out, the adaptive control was able to suppress this disturbance and turn the deteriorated system to continue to track the desired trajectory leaving less trajectory tracking difference in the final, whereas a large final error occurred under the PD control.

5.2 Improvement

5.2.1 Control Scheme

1. **Improved Nonlinear Nominal Model**: The parameterized model of the nominal dynamics proposed in (6) just represents the first step towards the development of more effective identification of the nonlinear manipulator dynamics. The major drawback of the method comes from the parameterized structure which needs to incorporate joint acceleration into the augmented joint coordinate vector. Since acceleration sensors are not available at present, numerical differentiation method must be used to compute joint acceleration from velocity information. This method offers inaccuracy of the differentiation that should be avoided in real-time computation. An alternate is that an appropriate filtering technique should be implemented to reduce the order of the model so that joint acceleration will diminish from the parameterization of the filtered model.

2. **RLS Algorithm with Exponential Forgetting**: The standard least square estimation exhibits good robustness with respect to noise and disturbance, but poor ability in tracking time-varying parameters. The reason for the good noise-rejection property is easy to understand: noise , particularly high-frequency noise, is averaged out. The estimator's inability in tracking time-varying parameters can be inferred from that the least square estimate attempts to fit all the data up to the current time, while, in reality, the old data is generated by old parameters. To compensate for this effect, exponential forgetting technique should be used to improve estimation accuracy in tracking time-varying plant information.

3. **Ad-hoc Techniques**: In order to improve robustness of the adaptive control system, one of many existing ad-hoc techniques may be used. The main objective is to reduce sensitivity of the adaptation to measurement noise and small fluctuation in the quantities that are used to drive the adaptation.

5.2.2 Hardware

1. **Velocity Filters** : The method of measuring pulse period to indicate rotational shaft speed, in spite of yielding a high sampling rate and being appropriate when the encoders used possess high encoding resolution as in our case, leads to quite noisy velocity data like tachometer sensing. This represents an important difficulty in an attempt to construct a robust adaptive control system, since adaptation mechanism is driven by quantities acquired from measurement . We suggest that an appropriate type of digital filters should be selected to incorporate into the velocity capture modules of the SDP to filter measurement noise at an appropriate bandwidth. Before we can do this, the study of frequency characteristics of velocity signal must be carried out.

2. **Motor and Amplifier Gain Correction**: In the absence of a direct joint torque sensor, no attempt has been made to correct the gains of the motors and the amplifiers. In the experiments, we directly used the gains specified by the manufacturers. It is assumed that a composition of a current amplifier and a DC servo motor has zero-order dynamics characterized by a constant gain, while in fact, it actually possesses higher-order dynamics of their own. This causes a certain amount of error in commanding proper actuating torque to drive the manipulator linkage, that is the basic need of any adaptive implementation. Hence, with the presence of direct joint torque sensors, accurate calibration to obtain more correct gains can be possible.

3. **Higher Speed Digital Gating**: We have found that at some instance, when spike in velocity occurs during motor intermittent operation, the decoder circuits fails to transmit the decoded

pulses through the velocity measurement system. It is believed that, at that situation, frequency of the decoded pulses exceeds the specifications of the digital gates used causing an amount of measurement error in velocity data, hence, without changing the circuit schematic, higher speed digital logic gates should be used to replace the old gates.

5.2.3 Software

1. **Efficiency of the Software Codes** : It is the fact that software implementation in our experiments are not optimized for computing speed and arithmetic precision. Careful checking and reconsideration of the codes should improve computational efficiency and result in a higher servo rate.

2. **More Effective Compilation**: Our software implementation do not make use of full computing power of 80386 CPU of the ECS microcomputer. Because the compiler we have used is based on limited arithmetic of the 80386's predecessor, 80286, hence, arithmetic performance may be advanced with the replacement of a more efficient compiler which should be a truly 80386-based compiler.