Chapter 8: Conclusions and Recommendations

This dissertation has presented the theoretical development of a new parallel-architecture robotic wrist. The goal of the theoretical modeling has been to create the tools necessary to form the Carpal Wrist concept into a working model for application. The primary areas of model development are:

- Positional Kinematic Analysis
  - Forward kinematic solutions
  - Inverse kinematic solutions
- Instantaneous Kinematic Analysis
  - Velocity rate control
  - Singularity and Dexterity Analysis
- Dynamic Analysis
  - Inverse dynamics, solving dynamic actuator torques
  - Forward dynamics, time response simulation environment
- Application Issues
  - Full orientational Control
  - Redundancy Resolution
  - Path Planning / Trajectory Synthesis
  - Optimal Trajectory Synthesis
- Prototype Design, Implementation and Testing

These issues have been addressed, validated, and presented in this work. Closed-form positional kinematic solutions have been developed allowing real-time manipulator control (Chap. 3). The instantaneous kinematic analysis has been performed and demonstrated the Wrist to be free of singularities (Chap. 4), and to have a high degree of dexterity when compared to other conventional robotic wrists (Canfield et al., 1997). The dynamic model of the Wrist was developed providing a design tool for actuator selection under high-speed operation (Chap. 5), and a simulation environment to design high-level control systems (Chap 6). Several details in implementation were addressed (Chap. 7). The kinematic issues of incorporating the Wrist with current robotic arms was addressed to satisfy task requirements with the manipulator system mobility. A design for a fully orientational Wrist was presented. Three methods of redundancy resolution were developed. These demonstrate several approaches to improve manipulator performance based on kinematic or dynamic criteria, while simultaneously eliminating redundant manipulator freedom. Path planning and optimal trajectory synthesis methods were presented that are necessary to achieve a high state of manipulator performance. The application issues discussed in Chap. 7 not only illustrate solutions necessary for manipulator implementation, but also demonstrate application of the kinematic and dynamic Wrist model. This makes value of a complete model and closed-form solutions evident.

8.1 Recommendations, Future Work

The theoretical model of the Carpal Wrist has been developed consisting of several parts: kinematic position analysis, velocity analysis, and dynamic analysis. The kinematic position and velocity analyses have resulted in exact solutions for the Wrist model, and have been applied in control of the prototype Wrist and in comparing the dexterity of the Carpal Wrist to other mechanical pointing devices. The dynamic model of the Wrist included several assumptions, including neglected friction forces and assumptions on mass of the leg elements. The dynamic model was compared with experimental dynamic results, helping to verify the analytical dynamics but also indicating possible improvement in the model. Continued work on the dynamic model is suggested to include friction forces as well as mass of the leg elements. Friction forces can be introduced into the model as velocity-dependent energy loss terms with empirical friction coefficients. Leg mass may be included as instantaneous lumped-mass elements sharing the motion of the distal plate and tool.

Continued development of the time response dynamic model is also recommended and planned. The time response model is intended as a simulation tool that can be used in designing control systems as well as in task simulation. Elements of improving the forward dynamic model include accounting for the friction and neglected mass parameters as suggested in the inverse dynamic model. Additionally, considerations of integration methods to be used on the time response problem need to be made.

Applying the kinematic and dynamic model to the design of a production model Wrist has been performed to a small degree in the development of the prototype Wrist, demonstrated in Appendix A and Ganino (1996). However, design for industrial application and meeting specific performance goals is one of the most important areas of future work necessary to find large-scale commercial application of this device. In the mechanical design of a production wrist, there are three critical elements: midjoint bearing design, methods of actuation, and working volume requirements. The midjoint bearings are the critical load bearing elements in the Wrist device. These elements must provide a large range of motion and remain small to avoid interference, all while supporting the load in each leg branch. Because of the critical nature of these midjoints, a majority of the design effort will go into these elements. The kinematic and dynamic models developed have provided the tools necessary to determine the force state of the midjoints. Therefore, continued work will require finding satisfactory bearing members to meet the demands place on these elements. For example, investigating ceramic or high-precision needle roller element bearings will be part of this research. Methods of actuation is a second area of future work for industrial application. Actuation methods will depend on a variety of issues, including type of application, operating environment, available power supplies, and required speed and payload performance. Third, working volume requirements must be examined. While Chaps. 3 and 4 have developed the tools to design for range of motion and have demonstrated a large workspace, meeting operating volume requirements in necessary in many applications and must be addressed.

Finally, continued research in advanced application of the kinematic and dynamic models are planned. In particular, areas of optimal trajectory synthesis (path planning), as well as redundancy resolution form an area of new technology and interest. Optimal trajectory synthesis becomes an area of concern in application of the device where a high level of control accuracy and control authority is desired, for example when performing high-speed and/or high precision tasks such as orienting devices for aiming lasers, mirrors, etc., or in machining operations, controlling tool cutters or manipulating the work-piece. In these applications, the dynamics of the actuators, Wrist device, and payload all play essential parts in the overall response of the system. Therefore, models to meet high levels of performance must consider the interaction of these elements.

Continuing the work that has been started in this dissertation is planned as demonstrated in these specific examples. This work has been divided into two areas, addressing application issues necessary to achieve commercial application of this device, and continued theoretical development on this specific device and in general parallel-architecture manipulators. Future work in both areas is necessary. Application issues must be addressed in the short term, to meet specific performance goals to begin industrial application. Development of the theoretical model will become more important in the future as application of this device to higher performance tasks demands better simulation and control models.