CHAPTER IX

Summary and Conclusions

9.1 Summary

In this dissertation, efficient dynamic simulation of simple closed chain mechanisms on land and under water has been investigated. These systems are characterized by a single reference member supported by a number of serial (actuated) chains. The development of efficient dynamics algorithms is motivated by the need for real-time and even super-real-time computational rates for advanced applications in design, development and operation of these systems. Based on new efficient transformation techniques and single chain dynamics algorithms reported in the appendices, more efficient multiple chain algorithms have been developed in this work. With these results, a new comparison between algorithms based on the Composite Rigid Body (CRB) and Articulated Body (AB) methods for the various systems considered here has been made.

In Part I, typical multiple chain, land-based systems are examined. The first system consists of multiple manipulators cooperating to lift a large load. Hard constraints are set by the grasps on the load and thus a closed chain algorithm results. The most efficient algorithm developed is based on one by Lilly and Orin [24] and uses the CRB approach to compute some of the required dynamic quantities. The resulting method has a computational complexity of $O(mN^3)$ for an m manipulator system with N degrees of freedom each, and it is more efficient than $O(mN)$ AB-based algorithms for $N \leq 21$.

Parallelism of the resulting algorithm was examined to increase the computational rates obtainable by the simulation. Two forms of parallelism, spatial (structural) and temporal, were investigated and could also be combined for further increases in speedup. The algorithm was implemented on an eight processor Cray Y-MP supercomputer, and the simulation of a four PUMA system was performed. Speedups as high as 3.1 were achieved on four processors using spatial parallelism, and 3.97 on eight processors using combined parallelism. These algorithms break down in the presence of manipulator singularities; therefore, a new algorithm to handle this case was also developed. The increase to the computational requirements is

minimal. This also led to the development of a new algorithm for dual arm systems, which requires *less* computation for cases with and without singularities.

Also studied in Part I was the simulation of multilegged vehicles. Although hard constraints at the contacts between the feet and ground have been considered in the past, it is more realistic to model these with compliance. Called the decoupled tree-structure (DTS) approach [7], this approach breaks the closed loops in the system, and open loop algorithms can be applied to the problem. For the resulting system, Freeman and Orin [7] developed an efficient algorithm based on the AB method. In this dissertation, a new algorithm is developed, referred to as the CRB/DTS method, which extends the CRB algorithm to multiple chains. This algorithm is found to be more efficient than the AB approach for typical legged vehicles with three degree-of-freedom legs.

In Part II, simulation of underwater robotic vehicle (URV) systems is covered. Typical URV systems consist of a mobile base, such as a submarine, and a number of robotic manipulators. Also considered is a multilegged robot for underwater operation. In either case, the DTS approach can be used. Additional development to obtain the equations for hydrodynamics forces and investigation of efficient incorporation of these into existing land-based algorithms was performed. For these systems in an underwater environment, an AB-based algorithm was found to be the most efficient, and the method for incorporating the hydrodynamic effects and deriving the new algorithm have been presented.

As part of the development of a real-time graphical simulation system at the Naval Postgraduate School, an investigation into the implementation of the resulting hydrodynamic simulation algorithm using object oriented design (OOD) techniques was undertaken. The goal was to develop a software package in C++ that is capable of simulating a large class of tree-structured robotic systems having star topologies (when using DTS), and yet maintain the high level of efficiency achieved with the algorithms developed here. Success was achieved through the use of OOD mechanisms including object hierarchies, encapsulation, inheritance, and polymorphism. In addition, the resulting software package is also easily expandable and maintainable.

9.2 Future Work

This dissertation presents the development of computationally efficient algorithms for the simulation of simple closed chain mechanisms on land and under water. In particular, efficient, parallel and robust algorithms for multiple manipulator systems have been developed and implemented; legged vehicle simulation algorithms on land and under water have been derived; and a software package for dynamic simulation

of a large class of robotic systems has been created. Although the contributions of this work are broad, considerable work still remains:

1. The simple closed chain mechanisms considered in this work contain serial chains. This may be extended to more general systems which contain chains with internal kinematic loops or the complete class of tree-structured topologies.

2. With DTS approaches, compliant contacts must be modeled. This requires further study to determine appropriate models (rather than the simple spring and damper systems) and the various parameters required for different surfaces. In addition, the effects of stiff surfaces on the numerical stability of the simulation algorithm should be studied.

3. Experimental validation has been performed for the code executed in the simulation of a single chain system with a fixed base. It was verified against the Composite Rigid Body method implemented in C for the simulation of a PUMA manipulator in [68]. Beyond this, there has been no experimental validation of the correctness of the algorithms or software developed for systems with mobile bases. All that has been done is to demonstrate that the *Tiburon* and *Aquarobot* simulations seem qualitatively correct to a number of observers acquainted with dynamics and control of the real vehicles. Although the effort would be very time consuming and expensive, the ultimate validation of a simulation can result only by comparison with a physical system and this should be done.

4. Partial validation is possible with linearization and vibrational mode analysis. This has been done for massless-leg, walking machine models and previously unexpected errors in nonlinear simulations were detected [69]. This work needs to be extended to the more realistic models developed in this dissertation. Such models would also be useful for control system design [69].

5. Computation of fluid dynamics generally requires the solution of the Navier-Stokes equations which are extremely complex. The approach taken in this work is a simplification and computes lumped approximations of the hydrodynamic effects. Although research has been performed with single rigid bodies with simple shapes to determine the accuracy of this approach, experimental validation should be carried out for more complex systems.

6. The development of the **DynaMechs** software package is part of a project at the Naval Postgraduate School (NPS) to develop a real-time graphical simulation system for URV systems to aid in the development of new control

algorithms for an underwater legged vehicle. A number of additional suggestions can be made for the extension of the package to satisfy NPS's goal which include the addition of actuator models (DC and hydraulic). Real-time graphical user interfaces (GUIs) must also be developed for the simulator both for configuration input and operator interfaces which would lead to a number of virtual reality applications especially in the area of physically-based modeling.

7. The parallelism examined in Chapter 3 for multiple manipulator systems, can also be applied to the algorithm developed for this package to increase computational rates. Implementation of this on the new parallel SGI platforms could be undertaken.

8. Additional extensions for the software package include allowing for simulation of closed chain mechanisms with hard contacts such as the multiple manipulator system in Part I. These systems are also characterized by changing topological structures which require additional research to perform modeling of impacts when hard contacts are initiated.

9. To simulate typical space-based robotic systems, an additional `Link` subclass should be developed which models flexibility.

In conclusion, it is believed that the simulation algorithms presented here represent the most efficient ones developed to date for multiple-chain systems. The dissertation also contains a complete and accurate comparison of the two competing approaches, CRB and AB, in developing these algorithms. This dissertation has also laid the groundwork for the development of a dynamic simulation software tool for multiple-chain robotic systems which, with real-time and super real-time rates, could be used in a number of different applications.