X. CONCLUSIONS AND RECOMMENDATIONS

A. PRINCIPAL DISSERTATION CONCLUSIONS

Construction of an underwater virtual world is feasible. Using 3D real-time computer graphics in an underwater virtual world enables effective AUV development. Visualization of robot interactions in an underwater virtual world improves our perceptual ability to evaluate robot performance. A networked robot and virtual world enables researchers to "scale up" to extremely high degrees of complexity, and makes robotics research and collaboration accessible worldwide.

A comprehensive software-hardware architecture for a general AUV underwater virtual world demonstrates the feasibility of these concepts. Several components make up this virtual world. A complete underwater vehicle dynamics model suitable for physics-based real-time simulation is developed. Real-time visualization of AUV and sensors interacting with a realistic environment is achieved by decoupling robot-virtual world interactions from graphics by the use of the Distributed Interactive Simulation (DIS) protocol. World-wide accessibility is provided using the World-Wide Web (WWW) for software archive retrieval and the Multicast Backbone (MBone) for live streams. Convenient and comprehensive network connectivity enables effective scientific collaboration among researchers and robots.

B. SPECIFIC CONCLUSIONS, RESULTS AND RECOMMENDATIONS FOR FUTURE WORK

Additional detailed conclusions appear at the end of each chapter.

1. Underwater Robotics

A large gap between theory and practice has resulted in relatively few underwater robots. The difficulties of the underwater environment are as severe as any other, making any AUV failure potentially fatal. AUV software and hardware solutions are available but many problems remain due to difficulty integrating component solutions. Real-time control under complex dynamic and temporal constraints is essential. Stability and reliability are paramount but testing is difficult. Virtual worlds may help break the AUV development bottleneck.

A large number of open tasks await underwater robot designers. Insistence on in-water testing following laboratory simulation is needed to ensure that progress is cumulative and grounded in reality. AUVs are beginning to perform important tasks that cannot be done effectively by other platforms. Both NPS and the AUV community is poised for significant real world accomplishments such as effective minefield search.

2. Object-Oriented Real-Time Graphics

Interactive 3D graphics are used as our window into virtual worlds. Graphics are completely decoupled from robot-virtual world interaction in order to permit real-time performance for robot and world models. Graphics viewers can be effectively networked to use the global Internet as an input/output device, i.e. as a source or target for any information stream desired. Object-oriented graphics models supported by scene description languages are essential for scaling up virtual worlds. Rendering and network compatibility across multiple platforms is highly desirable. *Open Inventor* and the proposed Virtual Reality Modeling Language (VRML) are well suited for virtual world construction and rendering. Future work includes increasing the number of objects populating the virtual world, adding hooks to objects on remote servers via URL definitions, and porting to other architectures to encourage widespread use of the underwater virtual world. Since the physical size and scope of an underwater virtual world is very large, it is a good candidate for a large immersive environment such as a CAVE (Cruz-Neira 93).

3. Underwater Vehicle Hydrodynamics Models

No hydrodynamics model was previously available which was suitable for real-time simulation performance in hover and cruise modes. A general standardized and parameterized hydrodynamics model is presented based on numerous preceding models, rigorous physical derivations and empirical testing. The model is computationally efficient, capable of running at short intervals (10 Hz) and networked using the DIS protocol. Future work includes implementation of the hydrodynamics model for other vehicles, extension to include special effects such as tethers and wave motion, connection to a large-scale world collision detection model, and possible porting into vehicle software as a predictive "world in the loop" for intelligent control and machine learning supervision.

4. Networking

The key considerations in networking virtual worlds concern compatibility, bandwidth and scalability. The Internet Protocol (IP) suite is essential for global compatibility. Point-to-point sockets are capable of supporting tightly-coupled world models interacting with a robot. The IEEE DIS protocol permits entities to compatibly communicate and interact at the entity/application level. Multicast protocols allow bandwidth reduction for both transmission and reception, a necessary step for scaling beyond limited numbers (hundreds) of interacting entities. Scalability is also supported through the use of World-Wide Web compatibility which provides flexible and well-defined communications mechanisms for information retrieval. Future work includes continuing to scale up using DIS, multicast and the World-Wide Web, and also building a persistent underwater virtual world server for continuous availability to humans and robots using the Internet.

5. Sonar Modeling and Visualization

Many sonar models are available but most are highly specialized and none appear to be suited for general use. Based on initial testing and validation, the Recursive Ray Acoustics (RRA) Algorithm sonar model (Ziomek 93) holds exceptional promise due to computational efficiency, frequency constraint independence, sound speed profile (SSP) constraint independence and bathymetry constraint independence. Sonar visualization is the application of scientific visualization techniques to enable effective analysis of high-dimensionality sonar data.

Sonar visualization also holds great promise as a means of effectively interpreting robot sensor interactions in a counterintuitive environment. Future work starts with porting the RRA ***C***-translation offline model to become an online model, possibly by adding hooks to the original RRA FORTRAN source code. Visualization tools will be used to experiment with effective matches between the high dimensionality of sonar parameters and the high dimensionality of graphics rendering techniques. The most promising visualization results will be used for real-time rendering of sonar transmissions in the underwater virtual world.

C. NEXT STEP: BUILDING A LARGE-SCALE UNDERWATER VIRTUAL WORLD

Results in this dissertation have stressed the possibilities of scalability to arbitrarily large levels. Having shown that comprehensive real-time robot operation is possible in a virtual world, it is now appears possible to scale up while including numerous independently acting human and robot entities. Scientific rigor can be provided by examining inputs, outputs and constraints on various world models and defining ways for these models to interact in theoretically correct ways. The exponential and open growth of the World-Wide Web has been possible due to the open capabilities of the Hypertext Markup Language, providing an excellent exemplar for sustained exponential growth. It is likely that VRML or related efforts will enable similar growth of virtual worlds and virtual world components.

Virtual worlds have the potential to completely change the current paradigms of how people use information. This work points out promising directions for connecting information, robots and people in ways that provide context, meaning and substance. The real world is the best model for a virtual world. When our virtual constructs cumulatively approach realistic levels of depth and sophistication, our understanding of the real world will deepen correspondingly.