III. PROBLEM STATEMENT AND SOLUTION OVERVIEW

A. PROBLEM STATEMENT

A critical bottleneck exists in Autonomous Underwater Vehicle (AUV) design and development. It is tremendously difficult to observe, communicate with and test underwater robots, because they operate in a remote and hazardous environment where physical dynamics and sensing modalities are counterintuitive.

B. PROPOSED SOLUTION

An underwater virtual world can comprehensively model all necessary functional characteristics of the real world in real time. This virtual world is designed from the perspective of the robot controller, enabling realistic AUV evaluation and testing in the laboratory. Three-dimensional real-time graphics are our window into the virtual world. A networked architecture enables multiple world components to operate collectively in real time, and also permits world-wide observation and collaboration with other scientists interested in the robot and virtual world.

C. AUV DEVELOPMENT DIFFICULTIES

The primary difficulty facing AUV developers is a challenging physical environment: an operating AUV is inaccessible, remote, and unattended. It is subjected to extremes of pressure, temperature, corrosion. Communications are intermittent or nonexistent. Sonar sensing is physically slower and very much different from vision. Vehicle deployment, operation and recovery are time-consuming and expensive. Vehicle physical dynamic control is very challenging. There are six spatial degrees of freedom (three dimensions each for position and rotation), not all physical control issues are solved, and there may be an unpredictable influence by ocean currents. Propulsion is costly, slow and limited. A typical vehicle only has a few hours endurance.

There is clear empirical evidence of a severe bottleneck in underwater robotics. There are thousands of indoor and outdoor land-based mobile robots, many hundreds of airborne and space-based autonomous robots, and many hundreds of underwater remotely operated vehicles (ROVs). In contrast there are perhaps a dozen working AUVs in existence, each with limited functionality. A harsh working environment and susceptibility to physical failure are among the major reasons for this scarcity. AUV failure in the ocean is unacceptable for several reasons: any failure may become catastrophic, recovery may be difficult or pointless, and replacement costs in time and money are prohibitive. We can conclude the following about AUV design: reliability, stability and autonomy are paramount, AUV constraints are often worst-case for any type of robot due to challenges inherent in the underwater environment, and many theoretical and engineering problems remain open.

D. WHY AN UNDERWATER VIRTUAL WORLD?

The broad requirements of underwater robot design provide a strong argument against piecemeal design verification. Individual component simulations are not adequate to develop effective intelligent systems or evaluate overall robot performance. A precise definition of a virtual world follows to eliminate any possible ambiguity in this term.

> Virtual world system..characteristics are seeing and interacting with distant, expensive, hazardous, or non-existent 3D environments. The technology for "seeing" is real-time, interactive 3D computer graphics and the technology for "interacting" is evolving and varied. (Zyda 92b)

An underwater virtual world for an autonomous underwater vehicle is intended to provide complete functionality of a submerged environment in the laboratory. A virtual world can provide adequate simulation scope and interaction capability to overcome the inherent design handicaps imposed when building a remote robot to operate in a hazardous environment. Construction of a virtual world for robot development and evaluation is hereby proposed as a necessary prerequisite for successful design of a complex robot which operates in a hazardous environment, such as an AUV.

A virtual world used to recreate every aspect of the environment external to the robot must also include robot sensors and analog devices (such as thrusters and rudders) which are impossible to realistically operate in a laboratory. Interactions between software processes, vehicle hardware and the real world must all be comprehensively modeled and mutually consistent. Robot physical behavior and sensor interactions must be modeled and simulated exactly. The robot controller itself is directly plugged into the virtual world using normal sensor and actuator connections, either physically or logically. The difference between operation in a virtual world or an actual environment must be transparent to robot software in order to be effective.

The current underwater robot development paradigm is inadequate and costly. Piecemeal design verification and individual component simulations are not adequate to develop and evaluate sophisticated artificial intelligence (AI)-based robot systems. Virtual world systems provide a capability for robots and people to see and interact within synthetic environments. The research goal of this dissertation is to provide complete functionality of the target environment in the lab, providing adequate simulation scope and interaction capability to overcome the inherent design handicaps of classical simulation approaches. AUV underwater virtual worlds may break the AUV development bottleneck.

E. AUV UNDERWATER VIRTUAL WORLD CHARACTERISTICS

The underwater virtual world must recreate the complete environment external to the robot. Robot physical dynamics behavior must be correctly reproduced, since underwater vehicles are prone to nonlinear dynamic instabilities and unpredicted physical responses may result in vehicle loss. Robot sensors and analog devices must be also modeled accurately. To minimize sources of simulation error, an exact copy of robot hardware and software is plugged into the virtual world using physical or logical sensor and actuator connections. The difference between operation in a virtual world or an actual environment must be transparent to the robot software. Finally, successful implementation of a virtual world can be quantitatively validated by identical robot performance in each domain. This is a type of Turing test from the robot's perspective: if robot performance is identical in each domain, then the virtual world is functionally equivalent to the real world.

Numerous component models make up the virtual world. Principal among them are a six degree-of-freedom hydrodynamics model and geometric sonar model. All models must interact with the robot in real time. Additionally, to be fully effective, the virtual world needs to provide connectivity to viewers at any location for remote observation and participation. A carefully constructed set of network connections enables all of these goals to be met simultaneously.

The overall structure of the AUV underwater virtual world software architecture is illustrated in Figure 3.1. This architectural structure diagram is very broad and is intended to show how many component models can work together. Most virtual world components have been implemented in this dissertation, demonstrating the soundness, validity and scalability of the resulting virtual world.

F. NETWORKING

Distribution of underwater virtual world components enables scalability and real-time response. A distributed approach also minimizes dependence on unique (or hard-to-replace) hardware and software. A standard point-to-point socket connects the robot and the virtual world allowing rapid and direct two-way interaction. The IEEE Distributed Interactive Simulation (DIS) protocol (NPS implementation version 2.0.3) is also used for compatible interaction with other virtual worlds and users listening on the Internet (IEEE 93) (Zeswitz 93).

This project is an excellent application to take advantage of a high-bandwidth Internet, further extending the capabilities of multiple researchers. The network approach allows many individuals dynamic remote access, which is demonstrated by Multicast Backbone (MBone) transmission of video, graphics, sound and DIS reports

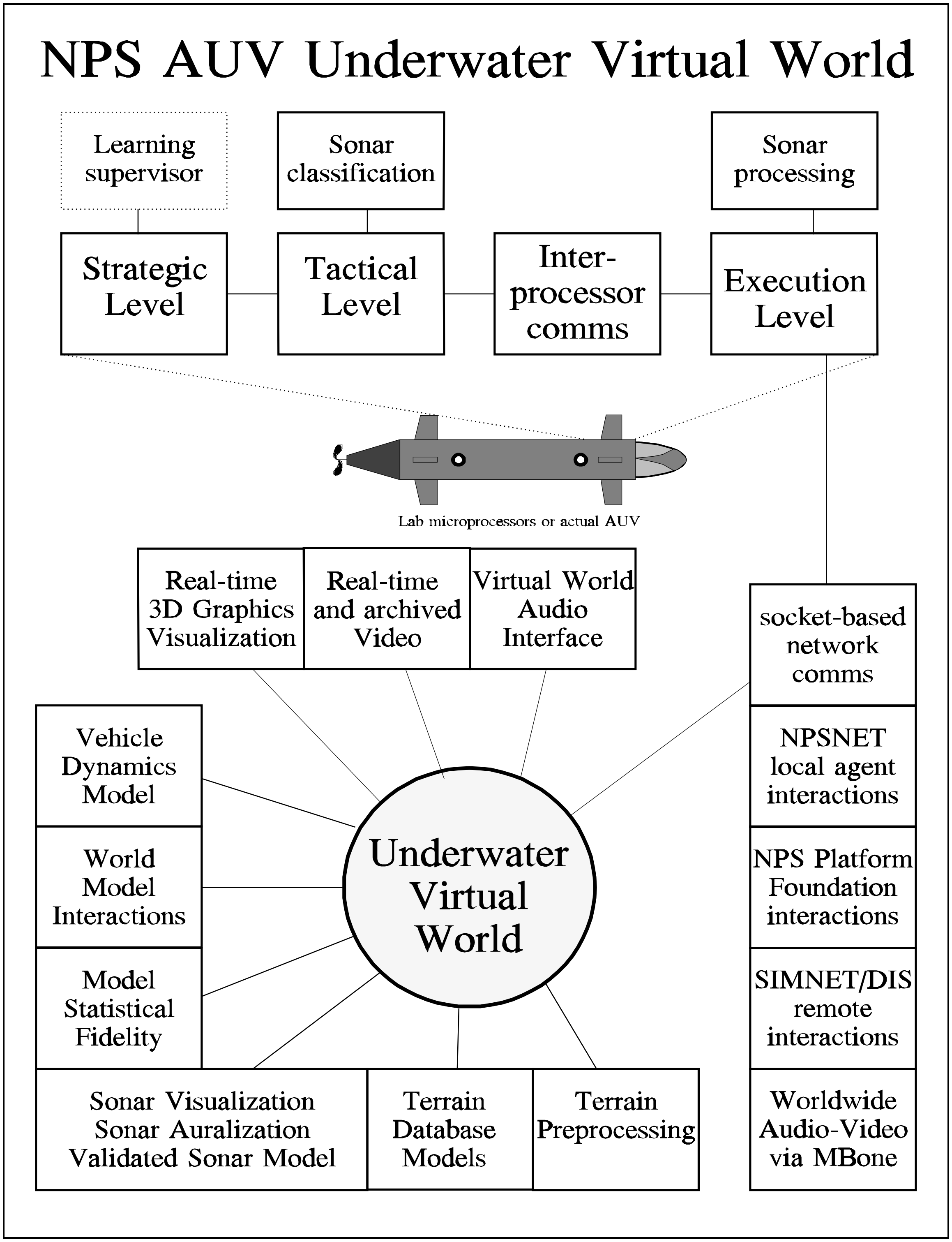

Figure 3.1. NPS AUV underwater virtual world software architecture.

for collaboration with other participants outside the site where the robot and virtual world are operating. Providing hypermedia access via publicly available World-Wide Web (WWW) network browsers such as *Mosaic* makes a complete variety of pertinent archived information available to anyone. Retrievable information resources include images, papers, datasets, software, sound clips, text, speech, source code, executable programs, live or archived video, and any other computer-storable media. Together MBone and the World-Wide Web provide the infrastructure of the information superhighway, letting anyone listen in and watch your work. Addition of multicast networked DIS packets and publicly available software lets people observe an identical interactive virtual world from any location with minimum burden on the global Internet. Remote interaction by numerous players within the virtual world of robot and environment becomes feasible and even convenient.

G. IMPORTANCE OF SENSORS

Design of autonomous underwater robots is particularly difficult due to the physical and sensing challenges of the underwater environment. Robot performance is often very tightly coupled to sensor accuracy and interpretation. Emergent behavior from interaction between robot processes and the environment can only be determined through experimentation. Having valid sonar and terrain models is very valuable for robot design and testing, since sensor interactions can be repeated indefinitely. Many new research projects become possible. Machine learning based on massive repetitive training is feasible, such as the design and implementation of trainable genetic algorithms or neural networks. Potentially fatal scenarios can be attempted repeatedly until success is reliably achieved, without risk to robot, human or environment.

H. SONAR VISUALIZATION

Visualization of robot sensor interactions within a virtual world permits sophisticated analyses of robot performance that are otherwise unavailable. Sonar visualization permits researchers to accurately "look" over the robot’s shoulder or even "see" through the robot’s eyes to intuitively understand sensor-environment interactions. Similar in-depth analysis is not possible using traditional test methods such as individual software module evaluation, direct robot observation or post-mission scenario reconstruction. In particular, the overwhelming size and information content of ocean-related and robot-related datasets means that visualization is essential to extract meaning from numerous simultaneous quantitative relationships. Visualization of the robot in its surroundings greatly improves human understanding.

An initial geometric sonar model implementation demonstrates how larger-scale sonar and terrain models can fit into the underwater virtual world architecture. More detailed visualizations of environmental datasets and a general sonar model have been implemented offline. They are included to show how additional sonar visualization capabilities can extend even further the functionality of the implemented underwater virtual world. Future work in sonar and terrain includes scaling up these models for interaction using world spaces of arbitrary sizes.

I. PARADIGM SHIFTS: CONTENT, CONTEXT, AND WORLD IN THE LOOP

Within two lifetimes we have seen several paradigm shifts in the ways that people record and exchange information. Handwriting gave way to typing, and then typing to word processing. It was only a short while afterwards that preparing text with graphic images was easily accessible, enabling individuals to perform desktop publishing. Currently people can use 3D real-time interactive graphics simulations and dynamic "documents" with multimedia hooks to record and communicate information. Furthermore such documents can be directly distributed on demand to anyone connected to the Internet. In this project we see a further paradigm shift becoming possible. The long-term potential of virtual worlds is to serve as an archive and interaction medium, combining massive and dissimilar data sets and data streams of every conceivable type. Virtual worlds will then enable comprehensive and consistent interaction by humans, robots and software agents within those massive data sets, data streams and models that recreate reality. Virtual worlds can provide meaningful context to the mountains of content which currently exist in isolation without roads, links or order.

As networked virtual worlds mature they will become more robust, efficient and portable. Going past the logical conclusion of "hardware in the loop" use of robots within a virtual world, as is presented in this dissertation, eventually virtual world models will be embeddable back into the robots. Having a "world in the loop" as an embeddable component in this manner will extend the capabilities of robots to sense, interpret and interact with the real world around them. The fidelity and scope of virtual world models and representations will improve steadily as robots and humans operate interchangeably in virtual worlds and the real world.