NAVAL POSTGRADUATE SCHOOL
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DISSERTATION

A VIRTUAL WORLD
FOR AN
AUTONOMOUS UNDERWATER VEHICLE

Donald P. Brutzman

December 1994

Dissertation Supervisor: Michael J. Zyda

A VIRTUAL WORLD FOR AN AUTONOMOUS UNDERWATER VEHICLE

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B.S.E.E., U.S. Naval Academy, 1978
M.S., Naval Postgraduate School, 1992

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.

An underwater virtual world can comprehensively model all salient functional characteristics of the real world in real time. This virtual world is designed from the perspective of the robot, enabling realistic AUV evaluation and testing in the laboratory. Three-dimensional real-time computer graphics are our window into that virtual world.

Visualization of robot 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. Extending the theoretical derivation of a set of six-degree-of-freedom hydrodynamics equations has provided a fully general physics-based model capable of producing highly non-linear yet experimentally-verifiable response in real time.

Distribution of underwater virtual world components enables scalability and real-time response. The IEEE Distributed Interactive Simulation (DIS) protocol is used for compatible live interaction with other virtual worlds. Network connections allow remote access, demonstrated via Multicast Backbone (MBone) audio and video collaboration with researchers at remote locations. Integrating the World-Wide Web allows rapid access to resources distributed across the Internet.

This dissertation presents the frontier of 3D real-time graphics to support underwater robotics, scientific ocean exploration, sonar visualization and worldwide collaboration.

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A. INTRODUCTION

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. 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, enabling realistic AUV evaluation and testing in the laboratory. 3D 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. This architecture was first proposed in (Brutzman 92d).

This dissertation develops and describes the software architecture of an underwater virtual world for an autonomous underwater robot. Multiple component models provide interactive real-time response for robot and human users. Theoretical development stresses a scalable distributed network approach, interoperability between models, physics-based reproduction of real-world response, and compatibility with open systems approaches. Implementation of the underwater virtual world and autonomous underwater robot are documented in a companion software reference (Brutzman 94e).

B. MOTIVATION

Underwater robots are normally called Autonomous Underwater Vehicles (AUVs), not because they are intended to carry people but rather because they are designed to intelligently and independently convey sensors and payloads. AUVs must accomplish complex tasks and diverse missions while maintaining stable physical control with six spatial degrees of freedom. Little or no communication with distant human supervisors is possible. When compared to indoor, ground, airborne or space environments, the underwater domain typically imposes the most restrictive physical control and sensor limitations upon a robot. Underwater robot design requirements therefore motivate this examination. Considerations and conclusions remain pertinent as worst-case examples relative to other environments.

A large gap exists between the projections of theory and the actual practice of underwater robot design. Despite a large number of remotely operated submersibles and a rich field of autonomous robot research results (Iyengar 90a, 90b), few AUVs exist and their capabilities are limited. Cost, inaccessibility and scope of AUV design restrict the number and reach of players involved. Interactions and interdependencies between hardware and software component problems are poorly understood. Testing is difficult, tedious, infrequent and potentially hazardous. Meaningful evaluation of results is hampered by overall problem complexity, sensor inadequacies and human inability to directly observe the robot *in situ*. Potential loss of an autonomous underwater robot is generally intolerable due to tremendous investment in time and resources, likelihood that any failure will become catastrophic and difficulty of recovery.

Underwater robot progress has been slow and painstaking for many reasons. By necessity most research is performed piecemeal and incrementally. For example, a narrow problem might be identified as suitable for solution by a particular artificial intelligence (AI) paradigm and then examined in great detail. Conjectures and theories are used to create an implementation which is tested by building a model or simulation specifically suited to the problem in question. Test success or failure is used to interpret validity of conclusions. Unfortunately, integration of the design process or even final results into a working robot is often difficult or impossible. Lack of integrated testing prevents complete verification of conclusions.

AUV design must provide autonomy, stability and reliability with little tolerance for error. Control systems require particular attention since closed-form solutions for many hydrodynamics control issues are unknown. In addition, AI methodologies are essential for many critical robot software components, but the interaction complexity and emergent behavior of multiple interacting AI processes is poorly understood, rarely tested and impossible to formally specify (Shank 91). Better approaches are needed to support coordinated research, design and implementation of underwater robots.

Despite these many handicaps, the numerous challenges of operating in the underwater environment force designers to build robots that are truly robust, autonomous, mobile and stable. This fits well with a motivating philosophy of Hans Moravec (Moravec 83, 88):

> .. solving the day to day problems of developing a mobile organism steers one in the direction of general intelligence... Mobile robotics may or may not be the fastest way to arrive at general human competence in machines, but I believe it is one of the surest roads. (Moravec 83)

C. OBJECTIVES

This dissertation addresses the following research questions:

- What is the software architecture required to build an underwater virtual world for an autonomous underwater vehicle?
- How can an underwater robot be connected to a virtual world so seamlessly that operation in the real world or a virtual world is transparent to the robot?
- What previous work in robotics, simulation, 3D interactive computer graphics, hydrodynamics, networking and sonar visualization are pertinent to construction of an underwater virtual world?
- What are the functional specifications of a prototypical AUV, and what are the functional specifications of robot interactions with the surrounding environment?
- How can 3D real-time interactive computer graphics support wide-scale general access to virtual worlds? Specifically, how can computer graphics be used to build windows into an underwater virtual world that are responsive, accurate, distributable, represent objects in openly standardized formats, and provide portability to multiple computer architectures?
- What is the structure and derivation for an accurate six degree-of-freedom underwater rigid body hydrodynamics model? The model must precisely reproduce vehicle physical response in real time, while responding to modeled ocean currents and control orders from the vehicle itself. The hydrodynamics model must be general, verifiable, parameterizable for other vehicles, and suitable for distributed simulation. Such a model is highly complex due to multiple interacting effects coupled between all six degrees of freedom.
- What are the principal network software components needed to build a virtual world that can scale up to very large numbers of interacting models, datasets, information streams and users? How can these network components provide interactive real-time response for multiple low- and high-bandwidth information streams over local and global communications networks?
- Sonar is the most effective detection sensor used by underwater vehicles. Sonar parameters pertinent to visualization and rendering include sound speed profile (SSP), highly-variable sound wave path propagation, and sound pressure level (SPL) attenuation. How can a general sonar model be networked to provide real-time response despite high computational complexity? How can scientific visualization techniques be applied to outputs of the sonar model to render numerous interacting physical effects varying in three spatial dimensions and time?
- How can these concepts be implemented in a working system?

D. DISSERTATION ORGANIZATION

The real world is a big place. Virtual worlds must also be comprehensive and diverse if they are to permit credible reproductions of real world behavior. A variety of architectural components are described in this dissertation. Ways to scale up and arbitrarily extend the underwater virtual world to include very large numbers of users, models and information resources are included throughout.

Chapter II reviews related work in underwater robotics, robotics simulation, underwater vehicle hydrodynamics, robot simulation, computer networking, and scientific visualization of sonar models. Chapter III provides precise problem statements and solution overviews, both for the general dissertation topic as well as individual virtual world components. Chapter IV presents the functional characteristics of the NPS AUV, the underwater robot which has been networked with the underwater virtual world. Chapter V describes the requirements and design decisions made in building an object-oriented real-time interactive 3D computer graphics viewer. Chapter VI derives novel extensions to an underwater vehicle hydrodynamics model which permit real-time networked response, standardized nomenclature, suitability for parameterized use by other underwater vehicles, and correctness both in cruise and hover modes. Chapter VII identifies and examines the four network capabilities necessary for scalable and globally distributable virtual worlds. Network considerations include both tight and loose temporal coupling, low-bandwidth and high-bandwidth information streams, audio, video, graphics, multimedia, posture updates using the Distributed Interactive Simulation (DIS) protocol, and very large numbers of connecting models and users. Chapter VIII outlines a general sonar model, presents an example geometric sonar model, and describes how scientific visualization techniques might be applied to render the large set of important characteristic values which describe sonar behavior. Chapter IX presents experimental results for the hydrodynamics model and network performance during distributed exercises. Chapter X summarizes the many dissertation conclusions identified in preceding chapters. An acronym appendix is provided for reader convenience. Finally an accompanying video appendix documents performance of the NPS AUV operating in the underwater virtual world and presents a variety of exercise scenarios.

The structure of the accompanying software reference (Brutzman 94e) parallels the organization of this dissertation. All source code, support files and compiled executable programs are also freely available via Internet access using anonymous file transfer protocol (ftp) access. The software reference includes help files and source code for archive installation, the NPS AUV robot execution level, 3D computer graphics viewer, hydrodynamics, sonar modeling, networking, and use of the World-Wide Web (WWW) and Multicast Backbone (MBone).