provided for remote networked collaboration. Overall, the ARPA/Navy UUV hybrid simulator is one of the best of all "hardware in the loop" simulations, where computer simulation and target system are closely coupled in isolation from any other interaction methods. The ARPA UUV Hybrid Simulator constitutes a tremendous accomplishment which provided inspiration and points of comparison for several parts of this work.

3.   **NASA Ames Intelligent Machines Group (IMG):**
       Telepresence Remotely Operated Vehicle (*TROV*)

The NASA Ames Intelligent Machines Group (IMG) has worked on a variety of robots and human-computer interface devices with the long-term objective
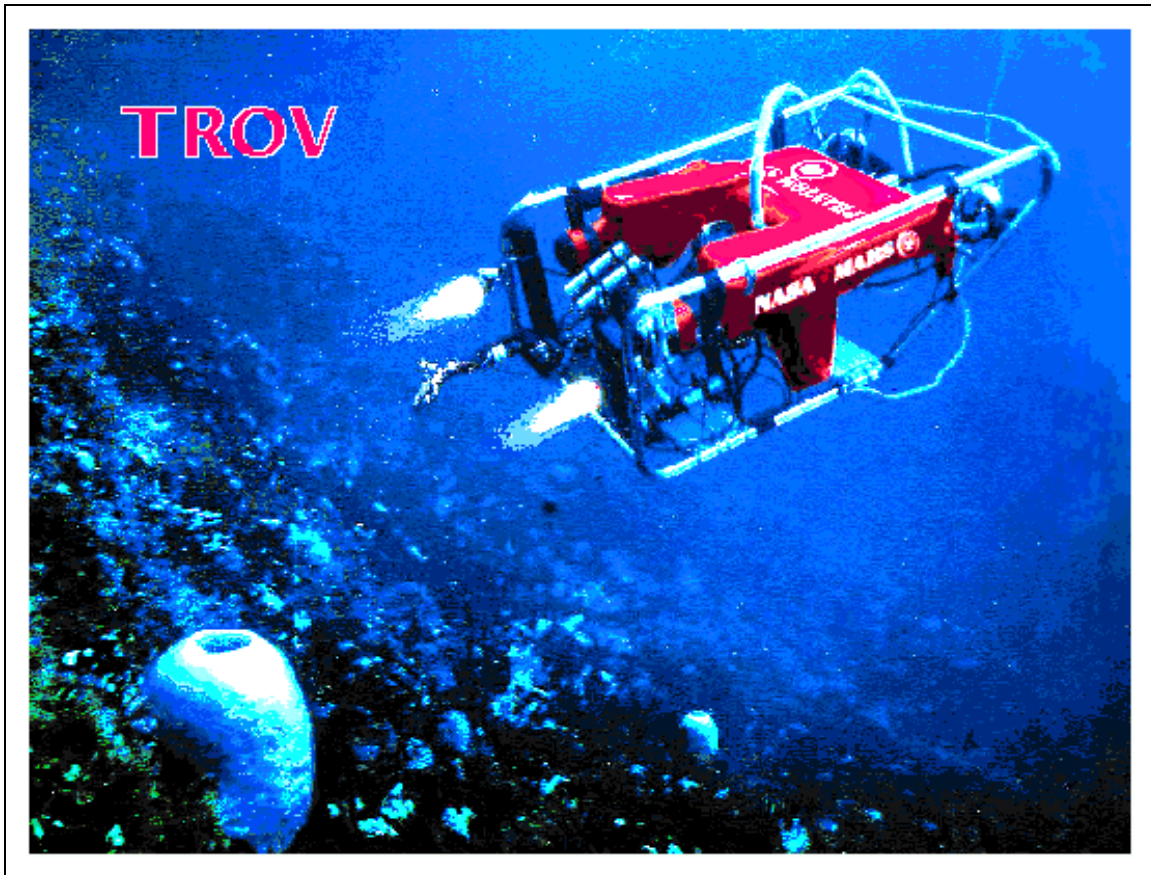

Figure 2.11.   NASA Ames Intelligent Machines Group (IMG)
                       Telepresence Remote Operated Vehicle (*TROV*) (Hine 94).

of providing effective telepresence for scientific exploration of other planetary surfaces, such as on Mars (Hine 94). Telepresence is defined as the projection of human senses into remote locations, and its effectiveness is measured by the usefulness of telepresence robotics in conducting actual scientific investigations. Human sense of presence can be enhanced by virtual reality input/output devices (such as headset and data glove) together with virtual world representations combining interactive 3D graphics with low-bandwidth high-latency network links to remote robots. In 1993 NASA Ames deployed the Telepresence Remotely Operated Vehicle (*TROV*) under Ross Sea ice near McMurdo Science Station, Antarctica. The underwater vehicle was an open-frame Phantom S2 ROV with four thrusters, stereo video cameras, a gripper manipulator, oceanographic sensors, acoustic transponder navigation, four commandable degrees of freedom and 1000 ft depth capability. Communication with the *TROV* was via a twisted-pair umbilical tether to the *TROV* controller topside and then using Internet Protocol (IP) packets over infrared (IR) laser, microwave and intercontinental satellite links. This varied communications path induced significant latencies, albeit still less than those experienced at interplanetary distances. The Virtual Environment Vehicle Interface (VEVI) modular operator interface for direct teleoperation and supervisory (task-level) control integrated all inputs and outputs, including a head device for steering the viewing cameras and incrementally updated graphics models for terrain and other pertinent physical objects. Science teams running the two-month mission focused on marine biology, chemical oceanography and benthic ecology. Science objectives were met and teleoperation was proven feasible from a variety of locations around the globe. Stereo displays provided excellent depth perception, and controller time-delay modifications for task-level control and predictive teleoperation response proved successful. Related work includes the DANTE robot exploration of the Alaskan volcano Mt. Spurr and possible regional collaboration in deep AUV exploration of Monterey Bay. *TROV* is representative of the most sophisticated teleoperated robots.

A survey and analysis of telerobotics capabilities and trends appears in (Durlach 94). Principal reference in the telerobotics field remains (Sheridan 92).

4.   University of Hawaii: Omni-Directional Intelligent Navigator (*ODIN*)

The University of Hawaii Omni-Directional Intelligent Navigator (*ODIN*) project combines an AUV with an integrated graphics simulation for development of adaptive dynamics control algorithms (Choi 94). *ODIN* is a small spherical AUV with
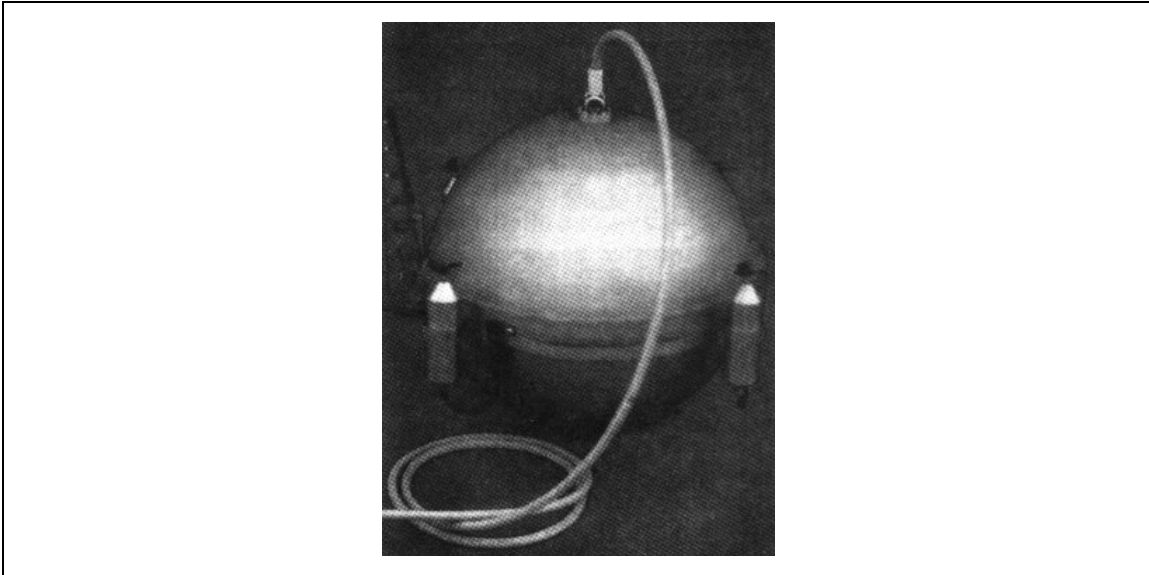
Figure 2.12.   University of Hawaii Omni-Directional Intelligent Navigator (*ODIN*) (Choi 94).

a single manipulator and four steerable vertical thrusters, capable of posture control in six degrees of freedom. Primary research conducted using *ODIN* concerns determination of hydrodynamics coefficients, linear controllers, nonlinear controllers, and adaptive controllers utilizing fault detection and automatic reconfiguration using neural networks. Integration of a single graphics workstation with *ODIN* demonstrates the functionality independently described in the NPS AUV Integrated Simulator (Brutzman 92a, 92c).

5. Tuohy: "Simulation Model for AUV Navigation"

(Tuohy 94) developed a simulation model to test AUV navigation applications. An object-oriented approach organized the overall simulation model into environmental models (consisting of terrain and water column maps) and physical object models (consisting of sensor, command/program and dynamics models). Contributions of this work include a proposed general model partitioning suitable for vessels and static structures, emphasis on map decomposition using spatial data structures, and model integration with 3D graphics.

6. Chen: "Simulation and Animation of Sensor-Driven Robots"

(Chen 94) describe how most robotics simulations include robot and environment while excluding sensors, and identify the creation of realistic simulation and animation software as an important robotics research issue. They present a system for simulation and animation of sensor-driven robot manipulators and indoor mobile robots. The system hierarchy includes models for robot, tool in work cell, sensors and physical objects. Physically-based models for proximity, point laser range, laser range depth imagery and vision intensity sensors are included, with research continuing on force/torque and tactile sensors. Three-dimensional interactive graphics are used for robot and sensor visualization, although real-time performance is not guaranteed. Robots can be integrated into the simulation system to permit running in real mode or virtual mode, either interactively or through recording playback. In real mode, robot controller subsystem electronics are physically connected to ports on the simulating workstation for two-way communication of command and sensor information. In virtual mode, robot software is run on the same workstation as the computer graphics, independently of robot hardware. Primary conclusion of this work is that a simulator for an integrated sensor-driven robotic system must incorporate simulation of sensory information feedback. Planned future work includes incorporation of a voice-recognition module in the robot and adding dynamic models to other objects in the simulation environment.

7. Yale University: Ars Magna Abstract Robot Simulator

The **Ars Magna** mobile robot simulator provides an abstract planar world in which a AI planner is able to control the movement of a mobile robot (Engelson 92). The objective of the simulator is to provide a more challenging and realistic environment for developing and evaluating planning systems than was previously available. Vehicle motion is purely kinematic and is based on a single point. Simulated manipulators are included. Sensor values are provided by geometric range models with adjustable noise distributions. Robot planning programs are written in a variant of the *Lisp* programming language. The useful but limited capabilities of the **Ars Magna** are representative of most other robot simulators currently in use.

D. UNDERWATER VEHICLE DYNAMICS

The study of dynamics and physics-based motion has long been recognized as a necessary prerequisite for realistic computer graphics rendering and valid robotics performance modeling. Although numerous articles pertaining to underwater hydrodynamics exist, almost without exception they focus on some small aspect of hydrodynamics performance. A complete hydrodynamic model suitable for real-time simulation response has not been available prior to this dissertation. An overview comparison of dynamics models in different environments appears in the hydrodynamics chapter. In this section key references preceding the new hydrodynamics model are identified.

1. Healey: Underwater Vehicle Dynamics Model

An earlier underwater vehicle hydrodynamics model presented in (Healey 92c, 93) provided the fundamental basis for the general hydrodynamics model. Strengths of the model included theoretical rigor, completeness for cruise operations using propellers/rudders/plane surfaces, and several years of empirical testing which produced an initial working set of hydrodynamics coefficients. Limitations include missing terms for thruster forces and moments, missing terms for low-speed hovering drags, extraneous terms corresponding to an unusual vehicle configuration, and an

arrangement of multiple differential equations not easily adapted to real-time temporal integration. Further details are provided in Chapter VI. Of all dynamics models examined, this was by far the best. Work presented in this dissertation extends and generalizes that fundamental contribution.

2. Fossen: *Guidance and Control of Ocean Vehicles*

Numerous texts exist on marine vehicle dynamics, most notably (Lewis 88), but their focus is almost exclusively on surface ships. (Fossen 94) provides a thorough treatise on both surfaced and submerged vehicle dynamics and control. He also examines stability, ocean modeling of wind and waves, and advanced control techniques. Theoretic derivations and explanations are provided throughout. Of relevance is that (Fossen 94) includes a total of three example underwater vehicle hydrodynamic models: two simplified linearized models (each by Healey) and the verbatim original six-degree-of-freedom model of (Healey 93).

3. ARPA/Navy UUV Hydrodynamics Simulation

The Navy/ARPA UUV design and development team has reported using a full six-degree-of-freedom hydrodynamics model for development and testing of sophisticated vehicle controllers (Pappas 91) (Brancart 94). Further details have not been published publicly.

4. Yuh: "Modeling and Control of Underwater Robotic Vehicles"

(Yuh 90) provided an important contribution to the underwater vehicle hydrodynamics literature. Although presented as an remotely-operated vehicle (ROV) model, it is pertinent to any type of underwater vehicle. He describes "added mass" and most other relevant terms. Nomenclature and algebraic differences make this model different but still close to the (Healey 93) model described earlier.

5. U.S. Navy Submarine Hydrodynamics

The subject of U.S. naval submarine dynamics is classified and was not considered during this work. Some open literature exists. (Jackson 92) provides an overview of the basic submarine design process, examining general requirements and

how design tradeoffs must be weighed. (Gertler 67) and (Feldman 79) present the general form of dynamics equations and coefficient nomenclature, closely conforming to the standard mechanical engineering reference (Lewis 88). No claims or suppositions regarding any classified work are made, implied or conjectured in this dissertation.

E.   NETWORKED COMMUNICATIONS FOR VIRTUAL WORLDS

Networking considerations in the construction of virtual worlds have gained increasing importance in recent years. As virtual worlds grow in complexity and quantity of information represented, the ability to scale up and accommodate arbitrarily large numbers of information sources and interacting entities becomes a crucial requirement. Currently there are many bottlenecks preventing unlimited and seamless virtual world communications. Research in this area is very active (Zyda 95). Multicast network protocols are a fundamental development in this regard and are examined further in Chapter VII. This section examines recent work in networking virtual worlds with an emphasis on scalability considerations.

1.   SIMulation NETworking (SIMNET) Architecture

SIMNET was the first architecture that permitted large numbers of simulated entities to interact together in real time, using heterogenous hosts and distributed communications over a network (Calvin 93). With over ten years of development and operation, SIMNET is a proven system. Key design principles are that objects interact in the virtual world by communicating events, all objects must relay valid data, network bandwidth is reduced by only transmitting state changes, and dead reckoning algorithms are used to predict intermediate postures. Enabling technologies for SIMNET were real-time computer graphics (image generators), distributed dynamic and static virtual world databases, semi-automated forces (SAF) which provide realistic entity or aggregate force behaviors, high speed local area networks (LANs) coupled with an interaction protocol, and free choice of human-computer interfaces. SIMNET effectiveness in Army tactical team training for

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combat has been documented on many occasions, such as the Battle of 73 Easting during the Iraq war (Calvin 93). The biggest theoretical success of SIMNET has been implementation of the interaction protocols, which became the foundation for the DIS protocol (IEEE 94a, 94b). As might be expected with any first-generation system there are some problems with the SIMNET architecture concerning scalability, many of which are addressed by ongoing DIS protocol development efforts. SIMNET protocols do not use Internet Protocol services, but instead require root superuser permissions for execution since they access hardware interfaces at the data link layer directly. In practice SIMNET capacity is limited to 300 simultaneous players (Durlach 94).

2.   Distributed Interactive Simulation (DIS) Protocol

The DIS protocol is an approved IEEE standard for communications between entities in small or large scale virtual environments (IEEE 93). From the recent proposed DIS standard revision:

> "Distributed Interactive Simulation (DIS) is a government/industry initiative to define an infrastructure for linking simulations of various types at multiple locations to create realistic, complex, virtual 'worlds' for the simulation of highly interactive activities. This infrastructure brings together systems built for separate purposes, technologies from different eras, products from various vendors, and platforms from various services and permits them to interoperate. DIS exercises are intended to support a mixture of virtual entities (human-in-the-loop simulators), live entities (operational platforms and test and evaluation systems), and constructive entities (wargames and other automated simulations)." (IEEE 94a, 94b)

The principal type of interaction in DIS is transmission of entity state information via Protocol Data Units (PDUs) which include position, orientation, time and (optional) velocity and acceleration values. A variety of standardized dead reckoning algorithms are available to maximize positional information transfer while minimizing bandwidth consumed. Numerous other PDU types are included which relate to exercise management, collisions, sensor emissions, and entity interactions

such as weapons fire and logistic support. Free and commercial DIS software libraries are available. The DIS protocol development community is very active and DIS continues to evolve. Current efforts are focused primarily on supporting larger numbers of simultaneous entities, and also on extending DIS functionality to support additional world information such as environmental effects and distributed terrain databases (IEEE 94a, 94b).

3. NPSNET

NPSNET is a networked virtual environment for battlefield simulation. Key strengths are high performance, a distributed software architecture, ability to

Figure 2.13.   NPSNET-IV virtual battlefield showing multiple active DIS-based entities, textured terrain and atmospheric effects running at high frame rates in real time (Pratt 93, 94b) (Zyda 93b).

handle large numbers (hundreds) of interacting human and autonomous entities in real time, initial implementation of multicast DIS libraries, public distribution, and insertion of remotely-controlled synthetic human models in virtual environments. NPSNET has over one hundred institutional users and has been a key component in numerous large-scale Army simulation exercises. NPSNET is likely the broadest and highest-performance virtual environment software that currently exists. Software distributions are free to registering users. Ongoing research efforts include object-oriented techniques for virtual environment construction, application level and network level communication protocols, hardware and operating system optimization, real-time physically-based modeling (e.g. smoke, dynamic terrain and weather), integration of multimedia, AI for autonomous agents, integration of analytic models such as JANUS, and human interface design (e.g. stereo vision and system controls) (Pratt 93, 94a, 94b) (Macedonia 95b) (Zyda 93a, 93b).

4. Macedonia: "Exploiting Reality with Multicast Groups"

Although DIS can scale to permit simulation exercises with several hundred interacting entities, several bottlenecks constrain current DIS network implementations from going much higher. This is a problem since distributed simulations accommodating tens of thousands of active entities are needed. One key difficulty is that participating hosts must listen to every DIS report, a requirement that eventually consumes all host processing cycles. (Macedonia 95a, 95b, 95c) proposes partitioning the communications space into more manageable streams through the considered use of multicast channels. Since multicast packets can be collected or discarded using network interface hardware at the data link layer, hosts need only process DIS traffic corresponding to subscribed multicast channels. Large-scale virtual worlds can thus be partitioned according to geographic space subdivisions, functional classes (such as radio frequencies), and temporal classes (such as normally static buildings or highly dynamic jet aircraft). Development of area of interest management protocols thus becomes necessary for retaining complete state corresponding to a given channel, providing a state snapshot to newly joining entities, and handing off control

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