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NPSNET and the Naval Postgraduate School Graphics and Video Laboratory

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A report developed as a guide to work
carried out over the last year by the
NPSNET Research Group in the
Graphics and Video Laboratory

Abstract

The Naval Postgraduate School Networked Vehicle Simulator IV (NPSNET-IV) is a low-cost, student written, real-time networked vehicle simulator that runs on commercial, off-the-shelf workstations (the Silicon Graphics IRIS family of computers). NPSNET-IV has been developed at the Naval Postgraduate School's (NPS) Department of Computer Science in the Graphics and Video Laboratory. It utilizes Simulation Network (SIMNET) databases and SIMNET and Distributed Interactive Simulation (DIS) networking formats. The DIS networking format is flexible enough to allow multiple players to game over the Internet. The availability of NPSNET-IV lowers the entry costs of researchers wanting to work with SIMNET, DIS and follow-on systems. Without the contributions of the department's MS and Ph.D. candidates, the NPSNET project would be impossible to maintain and continue. The diversity of their interests accounts for the broad range of research areas within the project.

1.0 Introduction

NPSNET-IV is the newest incarnation of the three-dimensional visual simulator developed at the Naval Postgraduate School's Computer Science Department in the Graphics and Video Laboratory. The project centers on the development of graphics simulation software, and has expanded to include many facets of virtual reality. NPSNET-IV is a low-cost, student written, vehicle simulator that runs on commercial, off-the-shelf workstations (the Silicon Graphics IRIS family of computers).

The Naval Postgraduate School was established in 1909 to meet the advanced educational needs of the Navy. The school provides advanced professional studies for military officers of all services and of foreign nations, as well as civilian employees of the U.S. government. It also supports the Navy and Department of Defense through continuing programs of research and maintenance of expert faculty.

NPSNET Research is being conducted entirely within the Department of Computer Science at NPS as part of the MS and Ph.D. programs. The research is directly supported by the teaching efforts of the Computer Graphics and Visual Simulation track. This track (one of six in the department) has a real-time, interactive, three dimensional slant that is particularly conducive to work in the virtual worlds field.

In addition to the general requirements of the department, the track offers five classes designed to give the MS candidates an understanding of real-time, interactive three-dimensional graphics and visual simulation. The courses are:

1. Computer Graphics - An introduction to the principles of the hardware and software used in the production of computer generated images. The focus of this course is a major software design project utilizing the departmental computer graphics facilities. The course is intended for Computer Science students proficient in the development of software systems (proficiency developed by previous departmental courses common to all tracks).

2. Image Synthesis - This course covers advanced topics in computer image generation with the focus on quality and realism in computer image synthesis.

3. Computer Animation - Presents the history of conventional and computer 2D/3D animation and state-of-the-art animation of 3D computer models. Students present paper/topic reviews and animation projects. The projects include real time computer animation and computer-generated animation videos utilizing the Graphics and Video Laboratory facilities.

4. Physically-Based Modeling - A physically-based model is a mathematical representation of an object (or its behavior) which

incorporates forces, torques, energies and other attributes of Newtonian physics. The goal of this course is to use such modeling to simulate, and graphically depict, the realistic behavior of flexible and rigid 3D objects.

5. Virtual Worlds and Simulation Systems - We cover the design and implementation of real-time, visual simulation systems for animating and interacting with virtual environments in this course. We pay special attention to practical issues involving performance/realism trade-offs; experience with computer/human interaction, especially novel input devices and paradigms; and simulating kinematic and dynamic behaviors in real-time.

With the knowledge obtained in these courses, the candidates are singularly prepared to design and work with computer graphics simulations. These officers, having graduated, are a valuable resource to their future stations as Simulation Engineers, having a firm grasp on state-of-the-art computer and simulation technology and software.

At the school, many computer science students choose to work on theses related to NPSNET. Without the contributions made by these students, the NPSNET project would be impossible to maintain and continue. The diversity of their interests accounts for the broad range of research areas within the project.

Research and courses are supported by the Graphics and Video Laboratory. During the course of a year, we have up to 35 students utilizing the laboratory completing class and thesis research requirements. The lab currently has the following equipment and software:

1. Silicon Graphics, Inc. (SGI) IRIS workstations. We currently have: Powervision IRISEs (340 VGX and 240 VGX models), 4D/35 Elan, 4D/30 Elan, ten Indigo Elan, four Indigo 2

Extremes, five Indigo XS, two Reality Engine, and two four-processor Onyx RE2.

2. Two Hewlett-Packard 9000 Series 700.
3. Sound support: Macintosh IIfx, EMAX-II sampler, Ensonics special effects processors, RAMSA rack and speakers.
4. Two VPL Head Mounted Displays (HMD).
5. StereoGraphics CrystalEyes stereoscopic display system.
5. Pioneer VDR-V1000 Video Laser Disk Recorder.
6. Galileo and Avanzar video boards.
7. Three large-screen monitors (two 55 inch and one 70 inch)
8. Wavefront's Advanced Visualizer (with Kinemation and Dynamation when released/received).
9. Performer and MultiGen.

The NPSNET Research Group has recently begun a joint project with the Air Force Institute of Technology (AFIT) under Advanced Research Project Agency (ARPA) sponsorship. AFIT and NPS are separately developing two advanced simulators in support of Warbreaker efforts. Warbreaker, a series of simulation exercises, brings together previously separate research and development efforts using the Defense Simulation Internet (DSI). The joint program between NPS and AFIT is the first academic cooperation program between the two schools.

The original thrust of the NPSNET project was to create a low-cost, government owned, workstation based visual simulator that utilizes Simulation Network (SIMNET) databases and SIMNET and DIS (Distributed Interactive Simu-

lation) networking formats. Since the accomplishment of these goals, the research group has been fine-tuning the simulator, while also building an extension to the original NPSNET that would lower the entry costs of researchers wanting to work with SIMNET and follow-on systems, so that NPSNET functions as a core linking newer simulators to the older code.

1.1 The Virtual World

While NPSNET is a visual simulator, it can also be categorized as a virtual world system. What is a virtual world system? Research in this area is still at an early stage, and no one is sure how broad a spectrum of programs the field may incorporate. Virtual world systems are the focus of much research and public attention, but many other researchers focus on very narrow technological aspects of virtual world development (i.e., DataGloves, and Head Mounted Displays). The image conjured by the phrase "virtual reality" is that of frivolous applications and expensive gear. However, there are a myriad other aspects to virtual world research ranging from arcade games to medical imaging. In an attempt to include both ends of this broad spectrum, we define "virtual world systems" as any system that allows the user to interact with a three-dimensional computer-graphics generated environment. There are two kinds of virtual environment: a simulation of a real environment that may be too expensive, too dangerous or too frivolous to interact with in reality (virtual worlds), and a totally artificial environment created for specialized applications (cyberspace). As NPSNET stands currently, it is a large scale virtual world, created to explore and interact with 3D terrain, structures and players on that terrain.

The NPSNET project focuses on the application of virtual world systems in an attempt to find useful, cost-efficient uses for this new technology. Because of the nature of this focus, the

emphasis of the project is on software development. While many researchers work with the hardware of virtual reality, the NPSNET project is developing the software to go with the technology. This software includes hardware drivers, interfaces, networking Application Programmer Interfaces (APIs), graphics, and functions determined by the particular use of the simulation. Thus, our goal is to build worlds that are useful to inhabit instead of building the hardware to enter them.

1.2 Immersion

One of the long-term goals of NPSNET is total immersion. This phrase has two distinct meanings. The first is that the graphics representing the virtual world respond to the actions and movements of the user via input devices. The other meaning is that the system convinces the user that they really are in the environment represented by the system. At present, while the NPSNET graphics do respond to the movements of the user via input devices, Head Mounted Displays (HMDs) are not utilized. We have received two VPL HMDs and expect to integrate them into NPSNET over the next year.

2.0 Current Projects

The NPSNET project has a history of diverse research, all of which can be attributed to the many students who choose to write their theses on the project, and who then research a subject that most closely suits their interests. In the past year, many projects have been completed, enhanced or begun, all with the goal of developing a fully-interactive, believable environment and/or making the simulation available and useful.

2.1 The Object-Oriented Programming Paradigm

The object-oriented programming paradigm is an approach to programming that places emphasis on the objects in a simulation. Instead of starting from the functions in a program and then finding the appropriate data, object-oriented programming starts from the data and then applies functions. In this paradigm, everything is either an “object” or a “class.” Each object is encapsulated with all the functions it can perform, so that an object is responsible for running all the routines that apply to it, from calculations to animation. It also makes programming new objects quicker by making it possible for a new object to “inherit” characteristics from other objects. By defining the new object in a certain category, it will then inherit the qualities associated with that category.

In the last year, the entire NPSNET program was rewritten to adhere to the object-oriented programming paradigm. The new program (NPSNET-IV), written in AT&T C++, uses a vehicles and weapons hierarchy to take advantage of inheritance so that certain classes of object, a plane, for instance, will automatically have certain properties (it can fly, it can land, it needs to be controlled, etc.). The code that describes a flight routine only needs to be written once, thus simplifying programming. This hierarchical approach is also being applied to objects other than vehicles and weapons, though these appear to be the most useful application in our program.

2.2 Real-Time Scene Management

One of the most important aspects of visual simulation is real-time scene management. It is difficult to update the scene in real-time because of the high computational demands involved in graphics. Keeping a complex scene running in

real-time means keeping the frames per second ratio high. In order to keep that number high, it is crucial to keep the number of polygons on the screen low. Graphics displays are made of polygons, and it is the moving and filling of them that takes such huge amounts of computation. The reduction of polygon flow to the special hardware comprising the graphics pipeline has been a continual topic of research. We are currently running with a floating frame rate that is dependent on scene complexity. The program can run as fast as sixty frames per second, or as slow as ten or less in a very complex scene. The average is between twenty and thirty frames per second.

When we translated NPSNET into the object-oriented programming paradigm, we also decided that the best answer to simplifying and quickening our scene management was to use a Silicon Graphics, Inc. API called Performer. Performer was written to most deftly utilize the Silicon Graphics Inc. IRIS family of computers. It enables the user to run the same program on any of the several types of IRIS at optimal speed, without having to modify the application software. Performer runs in the background of the computer and handles many of the general-purpose processes necessary in a visual simulator, such as hidden surface elimination and culling. Thus, by using Performer, we have eliminated the need to write NPSNET-specific code for these mundane processes.

2.3 Physically-Based Modeling

Physically-based modeling applies the laws of the physical world to the virtual world. This year, an accurate, quaternion-based flight dynamics model was written for the system that is capable of modeling any jet or turbo-prop aircraft and producing relatively believable vehicle dynamics. New aircraft enter the system by the addition of their flight characteristics into an editable file. We have also continued to develop

our real-time collision detection and response for NPSNET.

While it is not truly “physically based,” the smoke and dust trails we have added to NPSNET-IV were developed from physically based models. Unfortunately, real-time modeling and rendering of physically based environmental effects is usually impossible for today’s graphics workstations. Instead, we have taken the physically based models for each effect and simplified them so that they run in real-time. The smoke is realistic in appearance, as are the dust trails, though they do not follow all the physical rules of their real counterparts. In addition to smoke plumes and vehicle dust trails, we have also written a number of effects in IRIS GL. To integrate these effects (which include flames, lightning, sun and moon position and simulated night observation devices) is not a difficult task, in that they must only be translated into Performer. However, it is a slightly time-consuming effort, one we expect to finish soon. This environmental effects library will render our virtual world more believable, and thus more immersive.

2.4 Dynamic Terrain

Another aspect of NPSNET’s physically based modeling being developed is dynamic terrain. The idea behind dynamic terrain is that the battle affects the environment. These changes must be sent out across the network and reflected in each player’s world view, even if that player joined the game after the tree was knocked down. If a player knocks down a tree, the tree is represented throughout the network knocked down. In addition to trees, we also have berms, buildings, craters and bridges that respond to dynamic changes. Craters can be driven over, affecting the vehicle’s motion. The same was done with berms, which were constructed on top of the existing terrain, while bridges can be

driven over and under. Such changes must be recorded so that the exercise can be resumed later should a hiatus occur. Physically-based modeling treats such graphics problems as products of physical interactions. The information generated by these interactions is saved and sent over the network so that each player sees the same state of the world. We are active in the development of Distributed Interactive Simulation (DIS) Protocol Data Units (PDUs) to represent dynamic changes to the terrain. Currently, all static objects can be destroyed, so that a new "killed" icon appears. However, a recording and transmission process for state-of-the-world has yet to be implemented.

2.5 Autonomous Forces and Expert Systems

The addition of autonomous forces into NPSNET is critical to the realism of the simulation. When sufficient numbers of actual live players are unavailable or unaffordable, the simulation must provide interactive players. Previous versions of NPSNET used a harnessing program that listened to the network, grabbed unmanned vehicles, and gave them a simplistic behavior. In NPSNET-IV, we have replaced this program with a more flexible "tool box" that serves the same purpose as the harness program. The noise entities of previous incarnations, who had purely reactive behavior options, have been replaced by players that have a history, mission, goal and overall increased intelligence.

These players consist of a drone aircraft that follows a pre-scripted path, four sailboats capable of collision avoidance with each other and the shore, four trucks that follow the roads of the virtual world, and the Loch Ness Monster, which we are using as a simplistic rule-based model that chases planes that fly close to it. Nussy was originally built as a proof-of-concept to assure that we can create autonomous agents that sense when an entity enters a particular area, track that

entity's movements, and intercept the entity. Since the completion of Nussy, we used her code to create a Surface-to-Air Missile Site which can track and intercept SCUD missiles. We also based an Aegis cruiser on her reactive behavioral paradigms.

These forces are all controlled remotely, meaning that they are run from a workstation separate from the rest of NPSNET-IV. The workstation, like any other "player" on the system, sends its PDUs over the network, to be read by the rest of the players. This new paradigm makes autonomous force and autonomous agent behaviors easily modifiable. It also increases the speed of the program by bringing more computing power to bear on the autonomous force issues while freeing up CPU time on the main NPSNET-IV workstation.

2.6 Human-Computer Interface

Part of our work with human-computer interface involves a human factors evaluation of the Head-Mounted Display (HMD). Having received two HMDs, we are examining their usefulness in various applications. Unfortunately, we have found many shortcomings in this interface, including disorientation, poor resolution and eye strain. This informal evaluation has, in fact, spurred us to research other forms of stereoscopic display, including active and passive glasses.

One of the major additions to NPSNET-IV is that of stereoscopic display, utilizing the StereoGraphics CrystalEyes system, to enable the user to perceive true 3D depth in a scene. Stereo presents a separate view of the scene to each eye. These two perspective views are computed from eye points slightly offset in the horizontal direction. The views are then alternately displayed on the monitor screen at a typical rate of 120 times per second. The CrystalEyes eyewear, synchro-

nized with this display rate using IR technology, precludes the right eye from seeing the left eye's view and vice versa by utilizing an active LCD shutter placed in front of each eye. The difference between an object's horizontal position in the two scenes (parallax) when fused by the human visual system enables the perception of depth of that object.

NPSNET-IV has the capability to adjust the horizontal difference between the eyepoints to create more or less depth in the scene as desired. The system is also capable of switching between stereoscopic and monoscopic modes seamlessly by a single key press. This capability is important since about ten percent of the population is "stereo-deficient," meaning their visual system does not properly fuse the two images thus causing a single blurred image. The ability to operate in monoscopic mode is also important since the generation and display of two stereoscopic views for a complex scene can cause the system to drop below the perceivable smooth motion rate.

A related capability of NPSNET-IV is to widen and narrow the field-of-view for a given eyepoint. This feature yields similar results to changing a lens on a camera. By narrowing the field-of-view, a zoom is accomplished. By widening the field of view to the maximum, a fish-eye view is achieved. Both changes to the field-of-view can be easily made with single key presses. It is widely accepted that both stereopsis and a wide field-of-view contribute to the perception of immersion and thus play an important role in virtual reality research.

Another improvement in our human-computer interface has been the integration of flight sticks. Used with simulations for years, we have purchased several flight sticks, as well as several joysticks, to replace the input devices currently in use. The SpaceBall, designed by Spatial Sys-

tems, is less than ideal as a vehicle control device. It is a spherical knob affording the user six degrees of freedom. Unfortunately, due to its construction, the SpaceBall makes it difficult to isolate the several rotations, which users frequently find confusing and difficult to use. The more intuitive the interface, the more immersive a given simulation will be. The joystick and the flight stick were chosen because they would be familiar not only to pilots, but to most people having played video-games. The sticks are also more quickly learned, and make people more comfortable than the generally unintuitive SpaceBall. We found the SpaceBall to be very distracting, and our aim in replacing it was to allow the user to focus more on the game itself rather than on the interface. We are now using the flight stick and throttle made available by Kinney Aero. This device, more durable than other joysticks we have tried, is nearly identical to an actual flight control apparatus.

Currently, there are three input options: the two listed above and the keyboard. These options will facilitate switching between vehicles once we have constructed a seamless environment. Just as SpaceBalls are less than ideal for flying, joysticks are less than ideal for driving a tank. Thus, if a player switches vehicles, they will be able to switch input devices as well. Also, as we frequently give the code to other organizations who lack specialized input devices, the toggle option allows them to use whatever device is available to them.

Sound is another form of human-computer interface that increases the sense of immersion, especially when aural cues are spatialized. In the last year, we pursued both synthesizer-generated and computer-generated sound. While many of our computers are already sound-capable, the top of the line RealityEngines are not equipped with a sound board. We have recently received

the necessary boards, and plan to install them so that each workstation is sound-capable. However, our major thrust in aural cues has been in exploration of spatialized or “3D” sound.

Spatialized sound depends on direction and volume to indicate location and distance of the source of the sound in the virtual world. NPS Spatialized Sound Server (NPSSSS) relies on an Emax II digital synthesizer, six speakers and two subwoofers to generate and play sounds activated by interaction with the virtual world. The program generates three types of sound: continuous sounds, triggered sounds and triggered-spatialized sounds. Continuous sounds include the player’s vehicle, whose volume remains constant, and environmental noises, like the waterfall, whose volume decreases as the player moves away from it in the virtual world. Triggered sounds are played at a constant volume and are “triggered” by events in the virtual world. For instance, if a missile gets within range of the player, a warning alarm is played. Triggered-spatialized sounds are the most complicated to generate. NPSSSS must first read the PDUs off the network that trigger such a sound (e.g. a detonation) and decide if the sound is within “earshot” of the player. If so, NPSSSS sends a command to the Emax to play the sound at the correct volume through the specified speakers. Thus, if a missile impacts a building one hundred yards in front of the player’s vehicle, NPSSSS tells the Emax to play an explosion through the left-front and right-front speakers at the correct volume. Sound has become an important tool through which information about the virtual world can be imparted to the player.

2.7 DIS Integration

The Distributive Interactive Simulation (DIS) Standard, which is an IEEE standard protocol for simulation information packaging, has been integrated into NPSNET. DIS is the

replacement for the SIMNET protocol in Department of Defense simulators. With a library that reads DIS packets in place, NPSNET is able to handle information from any other Department of Defense simulator source. It also means that NPSNET information will be readable by all DIS-compliant simulations, military or otherwise.

In the last year, we upgraded our DIS capabilities, and were one of the first sites to comply with the DIS 2.0.3 standards. Since DIS does not require root privileges to implement or alter (as SIMNET does), DIS safeguards against accidental and potentially catastrophic changes to the operating system. Also, since DIS does not require root privileges, the number of programmers able to participate in DIS integration is greatly increased.

Currently, NPSNET-IV reads Entity State PDUs, Fire PDUs and Detonation PDUs. We are currently implementing the other twenty-four types of PDU, as well as additional aspects of the DIS standards, including fidelity, exercise control and feedback and security standards. Another change we are currently implementing is to change our world coordinate system from a flat world to an orbital (i.e. round) world. While this is an important difference in the functioning of a virtual world, it is also a rather massive undertaking, one that we hope to finish in the coming year.

In order to test our DIS code, and in order to participate in large area networked simulations, we installed a T-1 link into our lab. The T-1 connects us to DSI, and we have used it to test our networking code with AFIT and other DSI participants.

2.8 Constructive Combat Model Integration

This year has also seen the development of a proof-of-concept concerning the feasibility of

integrating DIS standards into JANUS, the Army's two-dimensional battle simulator. JANUS simulates a battle from a higher level than NPSNET, and so is designed not as a complex visualizer, but as a stochastic scenario model. JANUS, a low resolution model, has poor display capabilities, and does not run in real-time.

Our proof-of-concept allows JANUS to send and receive DIS Entity State PDUs. JANUS can also accept an NPSNET-IV Stealth entity, so that JANUS may be observed in a three-dimensional context using NPSNET-IV as the interface. Of course, this is merely the tip of the iceberg, and to fulfill our overall purpose, JANUS must be able to send and receive many types of PDU. We are currently building a fieldable version of the code, based on our proof-of-concept.

We are also developing a proof-of-concept regarding the possibility of a three-dimensional scripting system for JANUS. This system would read JANUS scripts, and modify them for better route planning. Because of the two-dimensional nature of the JANUS display, it has always been difficult to be certain that tanks were being deployed "covertly," i.e., that the "enemy" forces could not see the tanks. A three-dimensional interface to JANUS will facilitate more efficient covert route planning.

We hope to complete this work in the next year. The goal of this project will be to extend the life of JANUS, a model that the government has invested in heavily. Also, by interfacing JANUS with NPSNET, we are aiding the transition from older technology into virtual simulators that we feel are the future of combat simulations.

2.9 Terrain Database Evaluation

Combat modeling requires terrain databases upon which an engagement is played. The devel-

opment of these databases tends to be inconsistent, and there is no strong standard to guide research. Since these databases are very expensive to create, reusing databases already in existence is far more efficient than rewriting each database for every system with which it may be used.

Terrain database evaluation, testing and conversion are a permanent part of the NPSNET efforts. In fact, the NPSNET Group began as an attempt to provide one location in the US Government where many visual simulation databases were understood, and where public domain software and assistance were available. The focus of the NPSNET Group has been to learn how to read the "latest" terrain databases and convert them for use with the NPSNET system. With this in mind, we have been beta-testing databases and writing conversion routines. We are also providing three-dimensional visualization capabilities for the US Army Test and Experimentation Command so they can examine their databases more thoroughly.

2.10 Hyper-NPSNET

The Hyper-NPSNET project has truly expanded in the last year, and already contains many of the aspects originally envisioned. The concept of hypermedia is that media, be it video, text or audio, does not have to be stored sequentially. A hypermedia book contains all the chapters of the book, but one can access them in any order. Each chapter is a "node," and it is accessible from all other chapters related to it by subject.

The Hyper-NPSNET effort is parallel to the core NPSNET efforts. The goal of the Hyper-NPSNET system is to integrate into the 3D virtual world hypermedia data. The efforts in the last year have produced a modified version of NPSNET-1 with a Motif user interface. In the

current version of Hyper-NPSNET, stored video clips (in Moviemaker format on disk) and audio samples (in AIFC format on disk) are attached to information anchors placed on the terrain. The replay of the multimedia data is possible via direct selection with a mouse or via audio/video landmine mode. This mode triggers audio or video samples, depending on what is available, when the player approaches within a certain distance of the node.

The addition of hypermedia to NPSNET may seem strange until one considers the practical uses of such a device. If we embed a node into a particular building, the node can be accessed and text or video containing vital information about the layout, design, or purpose of that building can be displayed, along with historical battle and intelligence information. This information could be crucial to planning and analysis on the virtual battlefield. These nodes will also allow the user to make a search of all other nodes and find related objects elsewhere in the virtual world.

2.11 Major Demonstrations

While the NPSNET Research Group gives minor demonstrations within our lab at least once a week, in the last year, we participated in two larger demonstrations: the Warbreaker exercises and the Association for Computing Machinery, Special Interest Group in Graphics annual conference (SIGGRAPH '93).

Warbreaker, a series of simulation exercises, brings together previously separate research and development efforts using the DSI. Last year saw the successful completion of the first phase of the project, Zealous Pursuit. NPSNET played a vital role in these exercises by providing for them a stealth entity version of NPSNET. Stealth mode, which specifically gives the user a non-interactive view of the battlefield, allows the

user to watch a battle ("live" or "recorded"), either from the ground or from a "God's Eye" view. The Stealth mode can be used to watch replays of battles and learn from them. For instance, we can watch a battle where there were many instances of casualties caused by friendly fire, and assess why it happened and what can be done in the future to avoid it. In preparation for this exercise we have developed a simulator downlink for the Unmanned Air Vehicle (UAV). Used to view targets and terrain, the simulator downlink provides visual light and infrared visualization of the virtual video collected by the UAV.

NPSStealth was used in the Warbreaker demonstrations (specifically, Zealous Pursuit) as a "silver standard", i.e. a system that could be used to verify other systems' participation in the SIMNET environment. A visual simulator shell and a SIMNET network code interface were developed for the NPSStealth system. That software was distributed to over fifty sites in fiscal year 1993 (see Appendix A), and allowed the rapid and low-cost entry of other simulators into the Warbreaker efforts.

Our work with Warbreaker also includes database and model traversal and manipulation. Basically, we have aided Warbreaker participants in their efforts to implement their databases and models by making recommendations about how to cut the databases down to usable size, how to match together differing pieces, and more detailed work, such as how to embed roads into terrain. We have provided them with networking code compatible with SIMNET 6.6.1, as well as providing program monitors and diagnostic code. In these ways, we have assisted the Warbreaker efforts through consultation and distribution of source code.

In August, the NPSNET Research Group attended SIGGRAPH '93 in order to demon-

strate the latest version of our virtual world simulator in conjunction with AFIT and ARPA. In the Tomorrow's Realities Gallery of the conference, the two schools maintained two booths consisting of several Silicon Graphics workstations, an HMD, a BOOM mounted display, a workstation equipped with 3D sound, and a monitor running in stereo mode, complete with LCD shutter glasses. Along with these computers upon which the conference attendees were encouraged to play, were two workstations devoted to autonomous forces and networking, a T-1 link to the DSI, and a live video link to ARPA's Warbreaker facility. Both autonomous and live players were piped in over the DSI from San Diego, Arlington, Dayton and Monterey. At our busiest point, we had 50 players (counting the autonomous players) participating simultaneously. This was the first time the general public has been able to participate in a wide area networked visual simulation, and our exhibit was in fact the only military demonstration at the conference. We estimate that at least 10,000 people came through our booths at the Tomorrow's Realities Gallery during the five-day conference. We feel that this demonstration is an important synthesis of our efforts, and feel we have learned as much from this year's participation as we did from our exhibition at SIGGRAPH '91.

3.0 Future Projects

Future projects includes both long- and short-term efforts, some of which were mentioned in the last section. Our future direction will be guided, at least in part, by the needs of the Warbreaker participants. Many of our projects are already funded, and have a successful proof-of-concept behind them. Some are farther away than this, though there are none that are strictly "future" as we have made initial forays into all of them.

3.1 Continuation of Current Projects

While we have made great progress with many of our projects, there is still much to be accomplished. Some of our projects, such as terrain database evaluation, will continue basically as they are, remaining a resource for the Department of Defense. Others will continue to develop, such as physically based modeling, in whatever direction proves most pressing. Many of our projects will be expanded and improved in the next year, and we feel it is important to discuss the direction of each.

3.1.1 Autonomous Forces

Autonomous agent behaviors are taking on a new dimension in the next year. Collaborative behaviors will be written and incorporated into NPSNET-IV using Modular Semi-Automated Forces (MODSAF) as an API. Multiple vehicles, be they ships, planes or helicopters, will be able to cooperate to fulfill a goal, thus making them more like human players. NPS is one of seven sponsored sites developing autonomous force behaviors with STRICOM's MODSAF program, and we hope to be the first to have complex collaborative behaviors implemented.

3.1.2 Human-Computer Interface

As was mentioned before, we are looking into immersive interfaces that are not based on the HMD. This includes the use of passive glasses with an LCD shutter that fits over the computer screen. The code we wrote for the LCD shutter glasses can be used with the screen shutter without modification, as the screen works on the same principal and timing as Crystal Eyes.

Another immersion possibility lies in our recent acquisition of SCRAMNet, a reflective memory networking program. SCRAMNet will allow us to harness together multiple workstations, so that we can create the equivalent of a

twenty CPU, five graphics pipeline computer. We will then be able to render multiple views from the same point in three-space. By displaying these views on monitors placed around a player, and using our eight-speaker three-dimensional sound system, we will create a non-HMD immersive environment with very high resolution and frame rate. This project will be completed in the next year, taking us yet another step closer to the immersive seamless environment that is our goal.

Of course, HMDs cannot be ruled out. With every new generation, they become lighter, with higher resolution and quicker frame-rates. We are currently integrating our HMDs into the NPSNET system, and hope to purchase the next top-of-the-line model. We also plan to purchase a BOOM mounted display for command and visualization of an entity.

3.1.3 JANUS

Having developed a proof-of-concept for the integration of DIS into JANUS, we hope to write a fully DIS-compliant version of JANUS. Once this is accomplished, we plan to distribute the code so that physically separated units can train together in the virtual environment, thus creating a single cohesive fighting force. This goal is by no means distant, though it could easily take another two years of development before there is a deliverable product.

3.1.4 Networking

Networking is one of the most complex problems facing the virtual reality community, but despite this, it remains an almost ignored issue. Many assume that networking will be easy once all the other problems are solved, even though history tells us that without standards, networking is impossible. Our networking work has mostly revolved around keeping abreast of the latest version of DIS. The next focus of our

networking efforts will be the exploration of alternative methods of carrying network information.

One such alternative method we are experimenting with is the Internet. We have recently built NPSNET-IV on top of IP Multicast to provide dynamic group communication services and internetworking to the application. Through the use of multicast gateways, groups can communicate across an internet. The Multicast Backbone (MBONE) is an experimental internet serving as a virtual network which is layered on top of portions of the physical Internet to support routing of IP multicast packets. This virtual network is composed of islands that can directly support IP multicast, such as multicast LANs (like Ethernet), linked by virtual point-to-point links called "tunnels". The tunnel endpoints are typically workstation-class machines having operating system support for IP multicast and running the "mrouter" multicast routing daemon.

We have used MBONE to demonstrate the feasibility of IP Multicast for distributed simulations over a wide area network using DIS packets. In the past, gaming with other sites required prior coordination for reserving bandwidth on DSI. With the inclusion of IP Multicast, sites connected via the MBONE can immediately participate in a simulation. Furthermore, we have integrated other multicast services such as video with NPSNET-IV; for example, allowing participants to view each others simulation with a derivative of a video tool, nv, developed by Ron Fredrickson at Xerox Parc and Stephen Lau at SRI.

While our research of Wide Area Network methods is limited by the direction the DSI and ARPA take, our Local Area Networking efforts lean towards high speed networks. Considering the state of development of Asynchronous

Transfer Mode (ATM) protocol, we have chosen the Fiber Distributed Data Interface (FDDI) in our local area networking for now. We hope that this fiber optic technology will aid in our development of both shared virtual simulations and networked hypermedia.

3.1.5 Hyper-NPSNET

Network speed is of key importance in the development of Hyper-NPSNET. The nature of this project requires a network (as NPSNET is predominantly a networking program) capable of sending audio, video and text (as Hyper-NPSNET is a multimedia program). The use of video over a network is in its infancy, and network speed becomes a major issue when working with such a time-critical medium. We plan to examine the transmission issues surrounding real-time video clips sent out over a network. In particular, we hope in the next two years to build a small ATM test network.

3.2 Urban Terrain

To expand the training usefulness of NPSNET, the addition of "urban terrain" is being considered. Urban terrain consists of modeling cities or other populated areas, and would entail the ability to exit the virtual vehicle and enter virtual buildings. The software problems surrounding such a "seamless environment" are daunting, beginning with the question of how one controls multiple modes of transportation (including walking) with a limited number of input devices. But the problems of quantity of detail, size of the datasets, and scene complexity also enter into the picture. In the end, we would like the urban terrain mode to enable the user to drive a vehicle through the streets, stop at a building, exit the vehicle, enter the building and interact with the objects in the building. We would like the world to be so complete that the user could look out the window and see what is

actually going on outside. The technical difficulties underlying this goal are of great interest to many researchers in the field of virtual worlds.

3.3 Virtual Sand Table

A sand table is a device used during battles, simulations, and tactical planning sessions to help visualize the terrain and troop movements. Usually, a sand table is just that: a sand-box on stilts where the sand has been sculpted to represent specific terrain. Models are then placed on the sand table, and route planning lines are drawn.

One of our goals is to build a virtual sand table using the NPSNET code. With a terrain database and a "God's Eye View," we hope to create a new tool for planning and visualization. While we have not worked out the details yet, we hope to display the world in stereo (either through the new BOOM mounted display, or through LCD shutter glasses), thus allowing the user a more immersive and interactive experience, as happens with real sand tables.

3.4 Meteorological and Atmospheric Effects

We not only plan to incorporate the atmospheric effects already written for NPSNET, we also plan to increase their number and realism. We feel that it is details such as these that make an application truly immersive, and we plan on including numerous effects. Some that we feel are extremely important are wind, snow and rain.

3.5 Instrumented Test Range Integration

The first simulations involved soldiers on bases with blanks pretending to kill one another. Today, this remains an important aspect of simulations, though our ability to "fake" battles has expanded astronomically. Instrumented test ranges use special sensors throughout the battlefield that relay information about vehicle and

personnel location back to a command center. We plan to work with one such instrumented test range at Fort Hunter Liggett within the next year. NPSNET will operate as a visualization interface to broadcast the maneuvers planned for December 1993. We will watch the exercise in the virtual world as the information is sent to us over telephone lines, allowing us to see the battle from multiple positions and angles. This gives the user a better overall understanding of the maneuver. It also allows the user to watch invisibly, so that the watched units do not know they are being monitored. Thus, the observer does not affect the performance of the unit. This option allows command and staff to understand the actual workings of units in combat.

3.6 Underwater Virtual World Integration

The development of an underwater virtual world has been underway at NPS for quite some time. The world is being used to test an Autonomous Underwater Vehicle (AUV) without actually submerging the robot. Just as a human might wear an HMD to be "fooled," the AUV is hooked up to workstations that simulate its environment. Basically, it is an immersive virtual world for a robot.

Once the AUV's world is a complete model, we plan to add graphics so that there will be a window into the AUV's virtual world. This window will then be integrated into NPSNET, so that we can have virtual submarines capable of accessing hypermedia nodes (from Hyper-NPSNET) equipped with video. Thus, a user can request more detail of a certain location, and be provided with actual video of the real world simulated by the virtual world. Video is already available from the Monterey Bay Aquarium Research Institute over the MBONE, and it is only a matter of faster networks to increase the frame rate. Of course, full implementation of both Hyper-NPSNET and the underwater virtual

world into NPSNET are relatively long-term goals.

4.0 Conclusion

A fully interactive version of NPSNET is a continuing developmental effort. Despite promises by the media, virtual worlds are still in their infancy, and there is no assurance that the technology will develop as quickly as publicists claim. Nevertheless, NPSNET functions as a study in three-dimensional visual simulation and virtual worlds. The very problems we face are examples of why virtual worlds are slow to emerge.

However distant the NPSNET final product is, we are still making valuable contributions to the research field, and to the Department of Defense. We are a useful resource for other organizations and government contractors. We hope that our work in commercial technology-based three-dimensional simulations will both hasten the arrival of fully-interactive virtual worlds and demonstrate the existence of useful, cost effective virtual reality applications.

5.0 Acknowledgments

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Members of the NPSNET Research Group

- Michael J. Zyda, Professor of Computer Science (Co-Principal Investigator).
- David R. Pratt, Assistant Professor of Computer Science (Co-Principal Investigator).
- LCDR John S. Falby, USN, Military Instructor (Organization).
- Robert McGhee, Professor of Computer Science (Investigator- autonomous players).
- Sehung Kwak, Adjunct Instructor of Computer Science (Investigator- autonomous players).
- Hemant Bhargava, Assistant Professor of Administrative Sciences (Investigator- autonomous players).
- Paul Barham, member of research staff (stereo & user interface).
- John Locke, member of technical staff (SIMNET & DIS networking software support).
- Chuck Lombardo, member of technical staff (Hyper-NPSNET prototype).
- Suzanne Bloch, Summer Technical Staff (MIDI and network sound manager).
- Kristen Kelleher, Summer Technical Staff (technical writer).
- Jenny Stevens, administrative assistant to the NPSNET Research Group.

Appendix A: Partial List of Organizations Possessing NPSNET Code

- [1] Department of Electrical and Computer Engineering, Air Force Institute of Technology
- [2] Institute for Defense Analysis
- [3] Topographic Engineer Center, Ft. Belvoir
- [4] Command, Control and Computer Technology Group, Guidance and Control Directorate, Research, Development & Engineering Center, US Army Missile Command (AMSMI-RD-GC-S)
- [5] Line of Sight Anti-Tank Project Office (SFAE-ASM-LS-E)
- [6] Information Systems Engineering, Jet Propulsion Laboratory
- [7] Submarine Technology Department, Applied Physics Laboratory, The Johns Hopkins University
- [8] Conflict Simulation Laboratory, Lawrence Livermore National Laboratory
- [9] Strategic & Information Systems, Logicon
- [10] ENEWS Project, Naval Research Laboratory
- [11] GreyStone Defense Systems Division
- [12] TRAC, Los Alamos
- [13] Simgraphics Engineering Corporation
- [14] Research & Development Division, Lockheed Missile & Space Company, Inc.
- [15] Extravehicular Systems Branch, Ames Research Center, NASA
- [16] TOMAHAWK Mission Planning Branch, Naval Surface Warfare Center, Dahlgren
- [17] Hughes STX Corporation
- [18] Hughes Research Laboratories
- [19] Air Force Human Resources Laboratory, Williams Air Force Base
- [20] Ball Systems Engineering
- [21] Merit Technology Incorporated
- [22] Lincoln Laboratory, Massachusetts Institute of Technology
- [23] Information Systems Division, Lockheed Sanders, Inc.
- [24] MARS Project, Naval Surface Warfare Center, White Oak
- [25] SOAR Project, University of Michigan
- [26] Eagle Project, TRAC-OAC, Ft. Leavenworth
- [27] Institute for Simulation and Training, University of Central Florida
- [28] UAV Project, Joint Development Facility, Department Of Aeronautical Engineering, Naval Postgraduate School
- [29] Advanced Marine Enterprises, Inc.
- [30] Aegis Research Corporation
- [31] Alliant Techsystems
- [32] Amherst Systems, Inc.
- [33] Bolt Beranek and Newman, Inc.
- [34] CAE-Link Corporation
- [35] Cameron University
- [36] Computer Sciences Corporation
- [37] Division Information Technology and System Development, The Netherlands

- [38] Dynetics, Inc.
- [39] GE - Advanced Technology Laboratories
- [40] Jade Simulations
- [41] Loral Electro-Optical Systems
- [42] Loral Vought Systems
- [43] Martin Marietta Information Systems
- [44] Merit Technology, Inc.
- [45] Mitre Corp. Joint Warfare Center
- [46] NRaD
- [47] Naval Air Warfare Center
- [48] Naval Undersea Warfare Center
- [49] Photon Research Associates
- [50] Raytheon Company
- [51] Rice University
- [52] SAIC
- [53] Silicon Graphics, Inc.
- [54] SRI
- [55] San Diego Supercomputer Center
- [56] Stanford University
- [57] Systran Corp.
- [58] Technical Solutions, Inc.
- [59] U.S. Army Ballistic Research Laboratory
- [60] U.S. Army Research Laboratory
- [61] U.S. Army Tactical Simulation Project Office
- [62] Universite Paul Sabatier, France

Appendix B: NPSNET Publications List

Refereed Journals: Accepted Papers/Published Papers/Book Chapters

- [1] Bhargava, Hemant and Branley, William, "Simulating Belief Systems of Autonomous Agents," accepted *Decision Support Systems*, pending final versions, 1994.
- [2] Zyda, Michael J., Pratt, David R., Falby, John S., Lombardo, Chuck and Kelleher, Kristen M. "The Software Required for the Computer Generation of Virtual Environments," accepted by *Presence*, 7 June 93 for Vol. 2, No. 2.

[3] Cooke, Joseph M., Zyda, Michael J., Pratt, David R. and McGhee, Robert B. "NPSNET: Flight Simulation Dynamic Modeling Using Quaternions," *Presence*, Vol. 1, No. 4, pp 404-420.

[4] Zyda, Michael J., Wilson, Kalin P., Pratt, David R., Monahan, James G. and Falby, John S. "NPSOFF: An Object Description Language for Supporting Virtual World Construction," *Computers & Graphics*, Vol. 17, No. 4, pp 457-464.

[5] Zyda, Michael J., Pratt, David R., Falby, John S. and Mackey, Randy L. "NPSNET: Hierarchical Data Structures for Real-Time Three-Dimensional Visual Simulation," *Computers & Graphics*, Vol. 17, No. 1, 1993, pp. 65-69.

[6] Zyda, Michael J., Osborne, William D., Monahan, James G. and Pratt, David R. "NPSNET: Real-Time Collision Detection and Response," *The Journal of Visualization and Computer Animation*, special issue on Simulation and Motion Control, Vol. 4, No. 1, January - March 1993, pp.13-24.

[7] Zyda, Michael J., Monahan, James G. and Pratt, David R. "NPSNET: Physically-Based Modeling Enhancements to an Object File Format," chapter in *Creating and Animating the Virtual World*, Editors: Nadia Magnenat Thalmann and Daniel Thalmann, Publisher: Springer-Verlag Tokyo, 1992, pp. 35-52.

[8] DeHaemer, Michael J. and Zyda, Michael J. "Simplification of Objects Rendered by Polygonal Approximations," *Computers & Graphics*, Vol. 15, No. 2, 1991, Great Britain: Pergamon Press, pp. 175-184. Paper received "Best Paper 1991" award from an international selection committee appointed by the editor of *Computers & Graphics*, 29 Sep 92.

Appearances/Participation in/on Videotape & Live Demonstrations

- [9] "NPSNET and AFIT-HOTAS: Interconnecting Heterogeneously Developed Virtual Environments," demonstrated in the Tomorrow's Realities Gallery, SIGGRAPH '93, Anaheim, California, Aug. 2-6. The presentation at SIGGRAPH was a live demonstration showing the NPSNET system running networked over several IRIS workstations, and the DSI.

[10] Zyda, Michael J. and Pratt, David R. "NPSNET: LHD-1 Landing Script," on ACM SIGGRAPH Video Review, Vol. 70, July 1992, entitled "Visualization Software: The State of the Art." The video segment shows a brief clip of NPSNET animating the landing of an LHD-1.

Conferences: Accepted Papers/Published Papers

[11] Pratt, D., Zyda, M., Falby, J., Amburn, P., Stytz, M., "NPSNET and AFIT-HOTAS: Interconnecting Heterogeneously Developed Virtual Environments," in "Tomorrow's Realities Gallery," *Computer Graphics Visual Proceedings, ACM SIGGRAPH '93*, 1993.

[12] Zyda, Michael J., Lombardo, Chuck, and Pratt, David R. "Hypermedia and Networking in the Development of Large-Scale Virtual Environments," in the *Proceedings of the International Conference on Artificial Reality and Tele-Existence*, Tokyo, Japan, 6-8 July 1993.

[13] Wilson, Kalin P., Zyda, Michael J., and Pratt, David R. "NPSGDL: An Object Oriented Graphics Description Language for Virtual World Application Support," in the *Proceedings of the Third Eurographics Workshop on Object-Oriented Graphics*, Champéry, Switzerland, 28 - 30 October 1992.

[14] Pratt, David R., Zyda, Michael J., Mackey, Randy L., and Falby, John S. "NPSNET: A Networked Vehicle Simulator with Hierarchical Data Structures," in the *Proceedings of the IMAGE VI Conference*, Scottsdale, Arizona, 14 - 17 July 1992.

[15] Zyda, Michael J., Pratt, David R., Monahan, James G. and Wilson, Kalin P. "NPSNET: Constructing a 3D Virtual World," in *Computer Graphics, Special Issue on the 1992 Symposium on Interactive 3D Graphics*, MIT Media Laboratory, 29 March - 1 April 1992, pp. 147-156.

[16] Brutzman, Donald P., Kanayama, Yutaka and Zyda, Michael J. "Integrated Simulation for Rapid Development of Autonomous Underwater Vehicles," *Proceedings of the 1992 Symposium on Autonomous Underwater Vehicle Technology*, Washington, DC, June 2-3, 1992, pp 3-10.

Invited Papers

[17] Zyda, Michael J. "The Software Required for the Computer Generation of Virtual Environments," abstract in *The Journal of the Acoustical Society of America*, Vol. 92, No. 4, Pt. 2, October 1992, pp. 2345-2346.

[18] Falby, John S., Zyda, Michael J., Pratt, David R. and Wilson, Kalin P. "Educational and Technological Foundations for the Construction of a 3D Virtual World," in the *Proceedings of Virtual Reality '92*, San Jose, 23 - 25 September 1992.

[19] Zyda, Michael J., and Pratt, David R. "NPSNET Digest: A Look at a 3D Visual Simulator for Virtual World Exploration and Experimentation," in the *Proceedings of the 1992 EFDPA Conference on Virtual Reality*, Washington, DC, June 1-2, 1992, pp. 190-208.

Significant Mentions of Our Research

[20] Temin, Thomas R. "DoD Trains Soldiers with Virtual Battlefield," *Government Computer News*, 30 August 1993, pp. 68 - 70.

[21] Kelleher, Kristen "In the Belly of the Entertainment Beast," *Mondo 2000*, Issue 8, October 1992.

[22] Marsan, Carolyn Duffy "Navy School Makes Virtual Reality Fly," *Federal Computer Week*, Vol. 5, No. 24, August 12, 1991, pp. 3, 8, 11.

Technical Memoranda and Working Papers

[23] Locke, John, Pratt, David R., and Zyda, Michael J. "Integrating SIMNET with NPSNET Using a Mix of Silicon Graphics and Sun Workstations," working paper to conference on the Interoperability of Defense Simulators, Orlando, Florida, 17 - 19 March 1992.

Appendix C: NPSNET Theses

MS Theses

[1] Covington, James, "Implementation of Surface/Sub-Surface Operations on NPSNET," Masters Thesis, Naval Postgraduate School, Monterey, California, anticipated date of completion March 1994.

[2] Elkern, Kenneth, Jr., "NPSNET: Multi-Channel Display of a Real-Time Virtual World Battlefield Simulator," Masters Thesis, Naval Postgraduate School, Monterey, California, anticipated date of completion September 1994.

[3] Johnson, Matthew, "World Modeler: A System to Allow JANUS Combat Simulations to Interoperate with DIS-Compliant Combat Simulations," Masters Thesis, Naval Postgraduate School, Monterey, California, anticipated date of completion September 1994.

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- [4] McMahan, Chris, "NPSNET: Implementation of a Control Panel User Interface for Navigation of a Three-Dimensional Virtual World," Masters Thesis, Naval Postgraduate School, Monterey, California, anticipated date of completion September 1994.
- [5] Mohn, Howard, "NPSNET: Implementation of a Two-Dimensional Overlay and Mission Planning Tool for Command and Control of Autonomous Forces," Masters Thesis, Naval Postgraduate School, Monterey, California, anticipated date of completion September 1994.
- [6] Roesli, John, "NPSNET: Spatialized Audio and Data Sonification in a Virtual World," Masters Thesis, Naval Postgraduate School, Monterey, California, anticipated date of completion September 1994.
- [7] Tipton, Frank, "Distributing Live Video from an Unmanned Aerial Vehicle Across a Local Area Network in Real-Time," Masters Thesis, Naval Postgraduate School, Monterey, California, anticipated date of completion September 1994.
- [8] Upson, Christopher, "Design and Implementation of a Wide Area Network Protocol for the JANUS(A) Combat Simulation Model," Masters Thesis, Naval Postgraduate School, Monterey, California, anticipated date of completion September 1994.
- [9] Vaglia, James, "Creating a Real-Time Three-Dimensional Display of the JANUS(A) Combat Modeler," Masters Thesis, Naval Postgraduate School, Monterey, California, anticipated date of completion September 1994.
- [10] Watt, Anne, "NPSNET: Meteorological Effects for a Real-Time Virtual World Battlefield Simulator," Masters Thesis, Naval Postgraduate School, Monterey, California, anticipated date of completion September 1994.
- [11] Corbin, Daniel, "NPSNET: Environmental Effects for a Real-Time Virtual World Battlefield Simulator," Master's Thesis, Naval Postgraduate School, September 1993.
- [12] Hearne, John, "NPSNET: Physically Based, Autonomous Naval Surface Agents," Master's Thesis, Naval Postgraduate School, Monterey, California, September 1993.
- [13] Lombardo, Charles, "Hyper-NPSNET: Imbedded Multimedia in a Three-Dimensional Virtual World," Master's Thesis, Naval Postgraduate School, Monterey, California, expected date of completion September 1993.
- [14] Smith, Richard S., "NPSNET: Scripting of Three-Dimensional Interactive Vehicles for Use in the JANUS Combat Simulation," Master's Thesis, Naval Postgraduate School, Monterey, California, September 1993.
- [15] Steiner, John and Jacobs, Robert, "Improvements to Autonomous Forces through the use of Genetic Algorithms and Rule-Base Enhancement," joint Master's Thesis, Naval Postgraduate School, Monterey, California, September 1993.
- [16] Young, R. David., "NPSNET IV: A Real-Time, 3D, Distributed, Interactive Virtual World," Master's Thesis, Naval Postgraduate School, Monterey, California, September 1993.
- [17] Zeswitz, Steven, "NPSNET: Integration of Distributed Interactive Simulation (DIS) Protocol for Communication Architecture and Information Interchange," Master's Thesis, Naval Postgraduate School, Monterey, California, September 1993.
- [18] Schmidt, Dennis A., "NPSNET: A Graphical Based Expert System to Model P-3 Aircraft Interaction with Submarines and Ships," Master's Thesis, Naval Postgraduate School, Monterey, California, June, 1993.
- [19] Boone, Mark, "NPSNET: Real-Time Walkthrough and Rendering of Urban Terrain," Master's Thesis, Naval Postgraduate School, Monterey, California, December 1992.
- [20] Dahl, Leif, "NPSNET: Aural Cues for Virtual World Immersion," Master's Thesis, Naval Postgraduate School, Monterey, California, September 1992.
- [21] Nash, Dave, "NPSNET: Modeling the In-Flight and Terminal Properties of Ballistic Munitions," Master's Thesis, Naval Postgraduate School, Monterey, California, September 1992.
- [22] Warren, Pat and Walter, Jon, "NPSNET: JANUS-3D - Providing a 3D Display for a Traditional Combat Model," joint Master's Thesis, Naval Postgraduate School, Monterey, California, September 1992.
- [23] Walters, Alan, "NPSNET: Dynamic Terrain & Cultural Features," Master's Thesis, Naval Postgraduate School, Monterey, California, September 1992.
- [24] Weigeshoff, William, "NPSNET-SAF: Automated Terrain Analysis for Route Planning and Fields of Fire," Master's Thesis, Naval Postgraduate School, Monterey, California, September 1992.

[25] Wilson, Kalin P., "NPSGDL: An Object Oriented Graphics Description Language for Virtual World Application Support," Master's Thesis, Naval Postgraduate School, Monterey, California, September 1992.

[26] Brutzman, Donald P., "NPS AUV Integrated Simulator," Master's Thesis, Naval Postgraduate School, Monterey, California, March 1992.

[27] Cooke, Joseph M., "NPSNET: Flight Simulation Dynamic Modeling Using Quaternions," Master's Thesis, Naval Postgraduate School, Monterey, California, March 1992.

[28] Daley, John A., "HYPER-NPSNET: A Virtual World with An Integrated 3D Hypertext," Master's Thesis, Naval Postgraduate School, Monterey, California, March 1992.

[29] Park, Hyun Kyoo, "NPSNET: Real-Time 3-D Ground-Based Vehicle Dynamics," Master's Thesis, Naval Postgraduate School, Monterey, California, March 1992.

Ph.D. Theses

[30] Brutzman, Donald, "Underwater Virtual World for the Autonomous Underwater Vehicle," Ph.D. Thesis, Naval Postgraduate School, Monterey, California, expected date of completion September 1994.

[31] Pratt, David "A Characterization of Virtual World and Artificial Reality Systems", Ph.D. Thesis, Naval Postgraduate School, Monterey, California, June, 1993.

[32] Amburn, Phil "System Development and Evaluation of an Air to Air Debriefing System Using a Head-Mounted Display," Ph.D. Thesis, University of North Carolina, Chapel Hill. The chair of the Ph.D. committee is Frederick P. Brooks, Jr. of UNC. Dr. Zyda is a member of the committee.