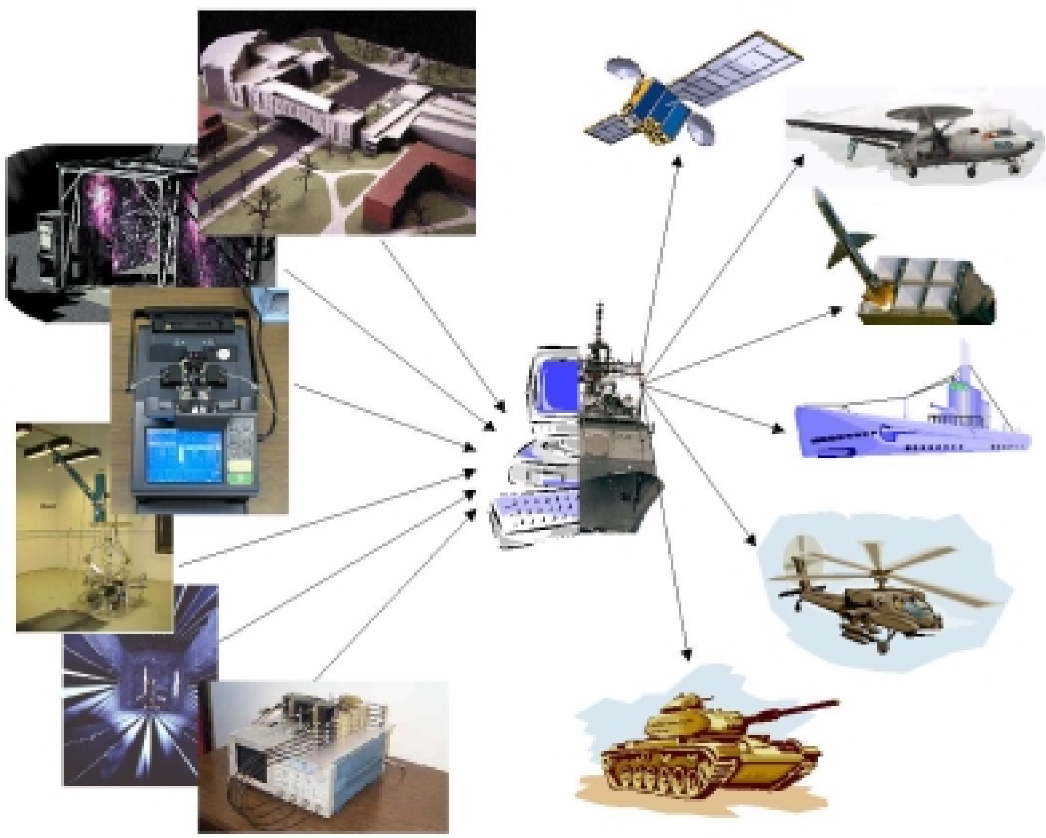

Navy Collaborative Integrated Information Technology Initiative

A Proposal to the Office of Naval Research in Response to BAA 00-007

From Virginia Polytechnic Institute and State University

Navy Collaborative Integrated Information Technology Initiative (NAVCIITI)

Proposal to Office of Naval Research in Response to BAA 00-007

VT Proposal No.:

Funding Requested:

Submitted by: Virginia Polytechnic Institute and State University
Office of Sponsored Programs
301 Burruss Hall
Blacksburg, VA 24061-0249

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Approval: ______________________________

H.T. Hurd, Director, Sponsored Programs

Date: ______________________________

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Access to the general public of the information enclosed herewith is prohibited until notice has been received of the name and affiliation of the requestor, and the purpose of the request. The investigator and Virginia Tech shall be allowed sufficient time to review the application and to redact those portions considered to be confidential. In the event that the funding agency disagrees with the request for redaction made by the investigator and/or Virginia Tech, investigator and/or Virginia Tech reserve the right of appeal prior to release of the enclosed confidential information.

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Navy Collaborative Integrated Information Technology Initiative (NAVCIITI)

Proposal in Response to BAA 00-007

Introduction

The Virginia Polytechnic and State University is pleased to submit this proposal in response to ONR BAA 00-007. The proposed program leverages funding of $2.71M from the Navy for the first year of effort to establish NAVCIITI, the Navy Collaborative Integrated Information Technology Initiative. This initial work was carried out under Grant Number N00014-99-1-0158 that was awarded on 14 November 1998 with a period of performance through 30 September 2000. This proposal provides a fully integrated program to address the Navy Requirements outlined in BAA 00-007:

1. Wireless Secure Communications;
2. Visualization, human computer interface and collaboration technologies;
3. Computer networking;
4. Real time interoperability

In addition, this proposal offers cost sharing, real and potential reductions in federal expenditures resulting from the research, and a unique group of activities that have been developed over the past year through close collaboration and discussions with ONR and other Navy organizations.

Cost Sharing

Virginia Tech is committed to $4M in auditable cost sharing over the two-year period of the proposed program. In addition, Virginia Tech will provide dedicated facilities for the conduct of the program totaling at least 30,000 square feet of space, which includes 360 square feet of office space for occupation by Navy personnel. The dedicated space will be fully configured, staffed, and equipped for the proposed program at the inception of the proposed effort.

Savings in Research and Other Federal Expenditures

The proposed program leverages funding of $2.71M from the Navy for the first year of effort to establish NAVCIITI, the Navy Collaborative Integrated Information Technology Initiative. Virginia Tech confirmed in a letter of 10 January 2000 to ONR that it provided $5.4M in cost sharing for the first year of effort. These investments reduce the expenditures needed to achieve the technical objectives proposed by the present team, and directly multiply the return on investment made in the proposed program. As a result of this prior investment, the Navy will not have to provide expenditures, for example, for a state of the art CAVE facility with ceiling and floor projections (as well as side projections) able to run 3D CAVE programs such as CAVE-5D. This CAVE also has as an integral part a moving platform that brings realism to the representation of the dynamic response of a ship in various sea states, which constitutes a key element in the formulation of a ship under attack. The CAVE will also be provided with a validated virtual capability of transferring cargo at sea, which is again a key element in replenishing the supplies. Moreover, the Navy will not have to proovide for an eight-processor SGI super computer and three SGI OCTANES to run and visualize ral-time parallel simulations of a ship under attack. Total equipment purchased during the first year of effort, to be used for years 2 and 3 in the proposed program, amounts to about $1.3M, a direct savings of expenditures for support of the second and third years of effort covered by the present proposed program that would likely have to be duplicated by other potential bidders. Also, the total cost of the equipment that is being purchases under DURIP program in support of the CAVE Ship and Crane Simualtor is approximately $500,000. Additional direct savings to the Navy will be realized by the fact that the University is providing a dedicated space for NAVCIITI in the new Advanced Communications and Information Technology Building, in the amount of 30,000 square feet. The general approach proposed will minimize the cost and risk of deployment of the products of the research. This discussion is highlighted below.

Proposal Summary

The proposal is structured for two years duration to ensure continuity and maintain the momentum of on going research areas in Advanced Command and Control technologies at Virginia Tech. The research thrust areas are wireless secure communication, visualization, human computer interface and collaboration technologies; computer networking, real time interoperability, information architecture and management, and ship performance processing.

Recognizing what experience has taught us, one of the most costly endeavors is deploying immature technologies. The cost of correcting the risk of introducing immature technology is much higher than the cost of developing and demonstrating technology prior to introducing it into the fleet. The first year effort emphasizes the individual technologies in accordance with the first year of coordinated effort, defined by discussions with the NAVY Points of Contact (POC). As a result of the interaction with the various Navy POCs, and based on the needs and advice from the user community, (e.g., NSWC PHD Dam Neck, NSWC Dahlgren, NSWC Carderock, NRL, NUWC, NAWC (WD), and SPAWAR), Virginia Tech will build a test bed to represent “ Digital Ship”.

The culmination of this research will be building a common Test Bed to integrate and demonstrate Command & Control technologies. The common test bed is based on the concept of the “Digital Ship” and the associated Three-Tier information technology architecture. The test bed will provide a leap forward towards the construction of the Synthetic Battle Space. This approach will yield a great deal of saving in cost and development time for advanced technologies. It is estimated that this approach will result in a pay-back ratio of several times the investment in this project. The saving is realized from reducing the risk of introducing new advanced technologies. The Digital Ship test bed will be an invaluable resource to integrate and validate technologies, and provide insights on many vexing operational challenges. The Digital Ship will give us the capability to emulate “ ship under fire,” “ship under attack,” “ ship in a self defense mode,” and other operationally meaningful demonstrations. Virginia Tech has the facilities, professional personnel and the tools to build the Digital Ship test bed. Additional information about the NAVCIITI collaboration can be found at http://www.rgs.vt.edu/navciiti.

Project 1.0 Wireless Secure Communications

Task 1.1 Smart Antennas

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Abstract

Our research program of Year One culminated in a measurement campaign that illustrated the astonishing gains achieved by employing smart antennas at the handset. The results show that two spatially separated antenna elements, separated by as little as one-fifth a wavelength, provide 3 to 10 dB of diversity gain (exceeded 99% of the time) in line-of-sight environments and 5 to 11 dB of diversity gain in non-line-of-sight environments. This implies that handheld smart antennas can reduce the fade margin or transmitter power by an amount equal to the diversity gain. Our results also show that polarization diversity and pattern diversity provide comparable diversity gains in non-line-of-sight paths. Furthermore, very small separations (e.g., around a fifth of a wavelength) are sufficient to provide large diversity gains. Our research efforts also demonstrate that handheld smart antennas can provide jamming protection of up to 40 dB. For Years Two and Three we propose to continue our channel measurement campaign and to develop hidden Markov Model (HMM) -based channel models for representing the smart antennas. We will also explore using smart antennas at the transmitter to reduce power consumption and improve LPI characteristics. Responding to ONR's Objectives

Relationship to Navy Needs

The overall goals of this work are to develop smart antenna techniques that (1) reduce power consumption (i.e. increase talk-time), (2) reduce the probability of intercept of a communications link, and (3) improve link reliability and range by reducing jamming and multipath distortion. This work will lead to new approaches to designing wireless systems that take advantage of spatial diversity at *both* the transmitter and at the receiver.

Background

The antenna and power amplifier are perhaps the weakest technologies in a communications link. While the performance of digital signal processing components in a radio has improved remarkably in power consumption and sophistication, the antenna and power amplifier have not improved significantly. For a given level of sophistication, the DSP is becoming a less important part of the overall power budget. For instance, in a commercial PCS or cellular phone, the talk time is approximately two hours, yet the standby time (requiring the receiver being on) is on the order of days. A smart antenna that can incorporate directionality can use the antenna gain to relax the requirements on the power amplifier. Thus a lower power signal with gain due to the directionality of the smart antenna can reduce power consumption and reduce the possibility of further interception. Range is extended by using both smart transmit and smart receive antennas to improve the signal gain. Additional reductions in power consumption can be achieved by switching between combinations of temporal processing and spatial processing, which requires understanding under what circumstances and with what combinations they are most effective. Our approach is to use digital signal processing to compensate for the inadequacies of conventional antennas and more evenly balance the weakness in the overall communications link.

Collaborative Efforts with Navy Programs

Virginia Tech has an ongoing Navy/DARPA program in the area of smart antennas and software radios. The Navy point of contact is SPAWAR in Charleston, South Carolina. During the past year we visited this group to bring them up to date on the technology and to discuss future cooperative efforts.

Leveraging Navy Support

Virginia Tech has had a record of leveraging Navy support to attract commercial contributions to the technology. Corporate funders attracted by our ongoing smart antenna activity under NAVCITT and Navy/DARPA efforts include Raytheon, ITT, LGIC, Metawave, and Texas Instruments. Contracts from these corporations, along with second-phase contracts expected within the month, total about $1.3M. Thus, Navy funding functions as seed money for research attracting additional investment in the technology. Further, the software radio work sponsored under the NAVCITT and Navy/DARPA efforts has created another set of potential commercial spin-off projects. Virginia Tech is negotiating with one company to commercialize the software radio intellectual property.

Statement of Work

To accomplish our goals and to meet the objectives of ONR in Year Two and Three, the following tasks are proposed.

1.1.1: Wideband Vector Channel Measurements

This first task, headed by Professor Reed with the cooperation of Professor Stutzman, will focus on the measurement of vector channels for wideband communication systems. These measurements will provide an important (and previously absent) knowledge base for the modeling of wideband communication channels and the design of wideband wireless systems that employ smart antennas. In turn, this knowledge base will stimulate research in innovative diversity-combining algorithms and adaptive filtering techniques, including space-time adaptive processing technique.

In this task, we will complement our ongoing measurement campaign by increasing the storage time for our 100 MHz 4 channel array, Figure 1[1]. We will measure a wide range of wideband channels and antenna configurations that are applicable to naval and marine operations. The wideband capability is essential for allowing us to understand the trade-offs in temporal and spatial diversity. This will provide insight into the relative merits and trade-offs associated with these diversity techniques. In turn, this will help engineers determine when the application of these techniques will achieve a given level of performance with minimal power consumption. The equipment will be built during the first three months and channel measurements will be performed in three stages. The first stage, ending in six months, will concentrate on measuring signal statistics for calculating diversity gain (especially for the indoor environment). Second phase measurements will focus on interference rejection capability and these measurements will last another three months. The last stage will focus on measurements for use in the Markov channel modeling and fast simulation efforts and this effort is expected to last three months.

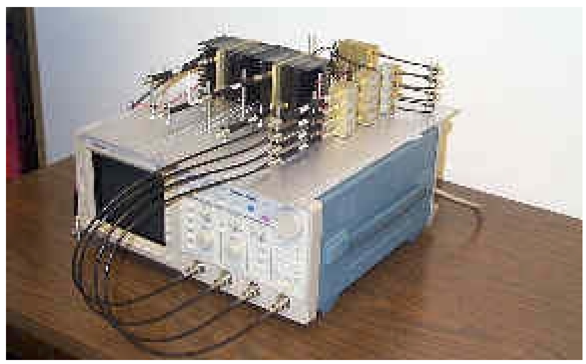

Figure 1. Four channel array developed with partial NAVCITTI support.

1.1.2: Examine Transmit Diversity Strategies

If radiated power can be reduced from a full hemisphere to a quarter hemisphere, talk time can increase by nearly a factor of four. This constitutes a huge saving in battery life. Our initial calculation shows that by simply pointing a cardioid antenna, pattern transmit power can be reduced by over 2 dB. It is likely that a more sophisticated technique, which utilizes a feedback signal from the receiver to the transmitter, would produce significantly more gain. Issues such as latency, complexity, and overhead of the feedback signal are fundamental limitations that need to be explored. We will develop the algorithms for steering antennas on the handset with minimal feedback overhead and complexity. These algorithms will be tested using laboratory experiments and computer simulation. Professors Reed and Stutzman will lead this effort. Algorithm development will be conducted during the first six months, followed by four months of hardware development for the test bed and simulation verification of the concept. During the final year, we will use the hardware test bed to validate performance and use the insight provided by these measurements to develop better signal processing algorithms.

1.1.3: Space-Time Coding

A special form of transmit diversity is space-time coding. Space-time coding integrates trellis codes, modulation design, and antenna array processing at both the transmitter and receiver to realize a space diversity gain in a non-selective fading channel. By employing multiple

[1] This unit was constructed with support of the first year NAVCITTI contract.

antennas at the base station and only one or two antennas at the wireless terminal, large gains in diversity can still be realized in both the up-link and down-link while complexity at the wireless terminal is minimized. We will conduct research on space-time coding that is robust to frequency- selective multipath and algorithms that address the overloaded array environment. We will confirm our findings with simulation and hardware experiments. This will involve the creation of a space-time coding test bed. Professor Reed will co-lead this task with Professor Woerner. Four months will be devoted to designing and build the test bed, six months to creating the algorithms, and four months for taking measurements.

1.1.4: Channel Modeling and Simulation

Modern communication systems are extremely complex, and both design and performance analyses require some level of computer-aided analysis. The complexity of these systems is driven by the difficult environments (noise, fading, multipath, and interference) in which these systems operate and the competing requirements for reliable communications with low power and high data rates. The incorporation of vector channels with smart antennas further complicates system models. The application of traditional waveform-level simulation techniques to these problems is a difficult task because of the computer runtime necessary to establish fundamental performance characteristics such as the system bit error rate. An alternative to the waveform-level simulation approach is the discrete symbol-level simulation model that incorporates the discrete vector channel, including the modulator, transmitter, waveform channel, and receiver, into a *hidden Markov Model* (HMM). We propose to use the wideband channel data collected with recently developed channel sounding hardware to develop both conventional waveform-based channel models and the computationally more attractive HMM-based channel models. The capabilities of the resulting waveform-based and HMM-based modeling techniques will be compared from both an accuracy and a numerical efficiency perspective. From these measurements and subsequent simulations, we will be able to develop relevant performance metrics and design rules for diversity systems in wideband environments. We will employ these models to show how the simulation of communication networks that employ smart antennas will greatly speed up network simulation involving multiple smart antennas.

Professors Tranter and Reed will jointly pursue this effort. Channel models will be developed in the first five months, parameterization of data collected from the measurements will be performed during the following three months, and measurement and simulation verification of the models will be performed for four months after that. The last six months of the project will focus on integrating Markov models into link and network simulation tools to greatly speed up network simulation and performance analysis.

1.1.5: Integrated Demonstration for the Digital Ship

The hardware and algorithms developed in this task will be applied to the wideband antennas developed in Task 1.2 in the demonstration of the Digital Ship concept. This task will extend over the duration of the contract. Professor Reed will be primarily responsible for this task.

Key Personnel

Professor Jeffery H. Reed. Professor Reed, Associate Director of Virginia Tech's Mobile and Portable Radio Research Group (MPRG), has extensive experience in smart antennas, spread spectrum, position location, digital signal processing, interference rejection, and software radios. He is also a member of the Center for Wireless Telecommunications, a Center for Innovative Technology sponsored by the Commonwealth of Virginia. Professor Reed, together with Professor Brain Woerner of the MPRG, is writing the first textbook on software radio design and analysis. He is also the co-editor of five books and has authored approximately 100 journal and conference papers.

Virginia Tech

Professor Warren Stutzman. Dr. Stutzman is Director of Virginia Tech's Antenna Group (VTAG), a capacity he has served in for 30 years. He co-authored the world's leading textbook on antennas, in addition to numerous journal articles on antennas and related topics. He has been responsible for over $10 million in sponsored research on antennas, propagation, and communications. Professor Stutzman is a Fellow of the IEEE.

Professor William H. Tranter. Professor Tranter is the Bradley Professor of Communications and Associate Director of Virginia Tech's Mobile and Portable Radio Research Group (MPRG). Professor Tranter is an active educator and researcher in the area of communication system design and analysis. Professor Tranter's primary research interest revolves around the application of DSP techniques to communication systems. He also has a strong interest in the development of computer-aided design and simulation methodologies for communication systems. Professor Tranter is an active participant in the IEEE and currently serves on the Board of Governors for the IEEE Communications Society. He is also the author of numerous journal papers and textbooks. Recently Professor Tranter was awarded the Millennium medal from IEEE for his technical and service contributions to the field of communications.

Professor Brian D. Woerner. Dr. Woerner received his B.S. degree in computer and electrical engineering from Purdue University in 1986, and his M.S. and Ph.D. degrees from the University of Michigan, in 1987 and 1991 respectively, where he was a Unisys Fellow. Professor Woerner has also earned a Master's degree in Public Policy from the University of Michigan with an emphasis on telecommunications policy. Professor Woerner has served on the faculty at Virginia Tech since 1991 and is currently an Associate Professor of Electrical Engineering. He has received a Research Initiation Award from the National Science Foundation and has been recognized for outstanding teaching. His research interests lie in the development of modulation, error correction and interference rejection techniques for CDMA systems. He is currently the *IEEE Transactions on Communications* editor for Spread Spectrum.

Task 1.2 Multifunctional Antennas

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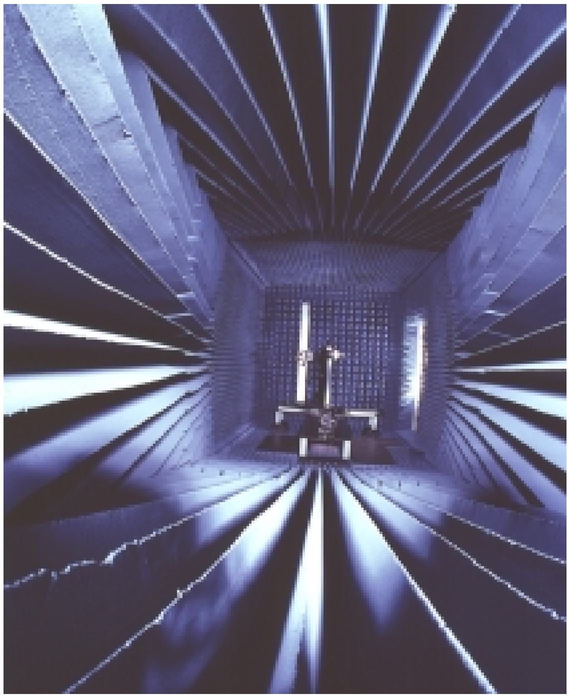
Abstract

Year 1 activities for multifunctional antennas included hardware and software acquisition, development of an in-house antenna code, construction of an anechoic chamber, and designs for future low profile wideband array antennas. Year 2 and 3 efforts will build on Year 1 accomplishments. Efforts in Years 2 and 3 will consist of two major tasks: completion of the test facility and investigations into new antenna element and array designs. Commercial and in-house computer codes developed in Year 1 will be used to simulate the antenna designs and optimize performance. The new antenna designs will find direct application to future Navy needs. The new anechoic chamber (figure below) and antenna test facility will be completed in Year 2 and will be used to measure prototype antenna designs. See the following web site for details on the indoor anechoic chamber: http://www.ee.vt.edu/antenna.



Relationship to Navy Needs

Navy vehicles have several RF functions, such as communications, radar, and intelligence gathering. In addition, each of these functions may be performed on several frequency bands. Conventional solutions require the use of many antennas deployed over the vehicle. This leads to significant RF interaction, increased radar cross section, and higher costs. The solution is to use wideband antennas that handle multiple functions. An example is the Navy's shipboard Advanced Multifunctional RF System (AMRFS). The antennas being investigated in Year 2 are useful in a wide variety of multifunctional RF systems. Unique features of the new designs are that they offer a low-profile solution suitable for ships and aircraft and the antenna can be conformed to vehicle surfaces.

Background

There is significant interest in wideband phased arrays for both military and commercial applications. Phased arrays offer great system flexibility through multiple target tracking, adaptive beamforming, and aperture sharing of functions. Wide bandwidth operation maximizes the benefits and minimizes the antenna size. However, array architecture and antenna element choice must be investigated thoroughly to meet system requirements. Virginia Tech has been involved in wideband array and element design for several years. Our research on innovative array designs for 4:1 bandwidth operation were published in [Shively and Stutzman, "Wideband Arrays with Variable Element Sizes," IEE Proc., Part H, vol. 137, pp. 238-140, Aug. 1990.] In a recent effort, we designed the Foursquare antenna element for the Navy's UAV program through a contract with ITT. This new element is of very small size, permitting broad scan over wide bandwidth.

Collaborative Efforts with Navy Programs

The Antenna Group is learning more about Navy needs in future programs involving wideband systems. Contacts that have been cultivated with Navy agencies including ONR, SPAWAR, and NSWC Dahlgren. In addition, the Antenna Group is working closely with Northrop Grumman to support them on antenna systems for the Navy.

Leveraging Navy Support

The Antenna Group has sponsored programs that augment the Navy's support, making possible many additional results. For example, Harris Corporation is sponsoring a research program to investigate the implementation of wideband antennas in very large phased arrays. The Antenna Group will perform computer simulations to examine the design issues of large phased arrays. At the same time Harris has a $750k program to investigate wideband phased arrays experimentally. This is an expensive effort that would not be possible to perform at Virginia Tech with current funding. However, we will benefit from Harris's results. These studies are directly applicable to future Navy systems.

In addition, this Multifunctional Antenna task complements the Smart Antenna task. The smart antenna effort has external funding to provide heavy leveraging of Navy sponsorship. The projects include: $2M SPAWAR and DARPA, $332k Texas Instruments, and $173k Metawave projects. The Antenna Group is involved in all these, providing antenna, propagation, and channel modeling research. Finally, there are two students working on these problems who are funded by endowed fellowships.

Statement of Work

1.2.1 Completion of the Test Facility

The spherical near field scanner and network analyzer equipment will arrived in October 1999. The near field antenna test facility will be assembled, calibrated, and tested for accuracy.

Personnel: Stutzman, Nealy, Takamizawa, Mescher

Schedule: To be completed in August 2000

Deliverables: A complete state-of-the-art antenna test facility available to support the Navy's needs.

1.2.2 Wideband Element Antenna Design

The Foursquare antenna element is currently being analyzed using an in-house FDTD code developed in Year 1. Sensitivity of the Foursquare impedance bandwidth to the height above the ground plane and the separation between the squares will be characterized using the FDTD code. This study will determine the optimum height that can be tolerated while maintaining the broadband impedance response. A study of the sensitivity to the separation between the square patches will yield the optimum configuration and the separation accuracy required during fabrication of the element. Both studies will also give insight into the operating principles of the Foursquare.

Personnel: Stutzman, Nealy, Suh

Schedule: To be completed in December 2000

Deliverables: A parametric approach to element design.

1.2.3 Wideband Element Antenna Measurements

Prototype wideband elements will be constructed and tested in the anechoic chamber. The new measurement facility will allow rapid and accurate measurements of wideband antennas. The planar scanner will be used to scan over the face of the array to probe the currents to understand how the array behaves. The spherical scanner will be used to measure the full patterns of elements and arrays.

Personnel: Stutzman, Nealy, Suh, Buxton, Mescher

Schedule: To be completed in March 2001

Deliverables: Demonstration antennas along with test data validating the antenna element design.

1.2.4 Extended Bandwidth Elements

The concept of the Foursquare antenna can be extended to form the Fourpoint antenna. This geometry has one more geometric parameter to vary for adjusting electrical performance. Preliminary results indicate that the Fourpoint antenna has broader bandwidth than the Foursquare antenna and can be dual banded. This antenna will be investigated.

Personnel: Stutzman, Nealy, Suh

Schedule: To be completed in August 01

Deliverables: Design information for the Fourpoint antenna.

1.2.5 New Approaches to Wideband Antennas

Future Navy communication systems will require multiple operating frequency bands. Innovative approaches are needed to develop multiband phased arrays in a single planar aperture. We will investigate a new type of antenna array consisting of sub-elements that are excited together to form the primary element. All of the sub-elements of the array are excited for the highest operating band. Only the primary elements are excited for the low frequency band. This array geometry can be viewed as a fractal, which is known to have potential for wideband operation. The advantage of this array is that the effective element spacing changes with the frequency band to maintain the required small electrical spacing over the operating band. Initial simulations of this dual band Foursquare have shown that it performs well and that the subdividing of each square does not degrade the low frequency behavior. Research areas include studies to determine how the element operates in order to exploit its geometry for optimum bandwidth.

Personnel: Stutzman, Nealy, Takamizawa

Schedule: To be completed in September 2001

Deliverables: Array design approaches

Task 1.2.6 Array Antenna Investigations

Arrays for Foursquare and dual band Foursquare antennas will be investigated, included electronic phase scan performance. Feeding is an important issue that needs to be addressed. Harris Corp. will be conducting an experimental program in cooperation with the Antenna Group; this will lead to considerable leverage of technical productivity.

Personnel: Stutzman, Takamizawa, Nealy

Schedule: To be completed in October 2001

Deliverables: Array design approaches

Task 1.2.7 Smart Antennas for the Digital Ship

This task complements the Smart Antenna task (Task 1.1 of NAVCIITI). These efforts will merge to produce a smart antenna to support the Digital Ship mission.

Personnel: Stutzman, Takamizawa, Suh, Mescher, Nealy, Reed

Schedule: To be completed in April 2002

Deliverables: Smart antenna concepts and demonstration for the digital ship

Key Personnel

Warren Stutzman is the PI for this task. He is the director of the Antenna Group and has 30 years experience in this position at Virginia Tech. He has co-authored the leading textbook on antennas in the world as well as many journal articles on antennas and related topics. He has been responsible for over $10 million in sponsored research on antennas, propagation, and communications. Dr. Stutzman is a Fellow of the IEEE.

Appendix: Research Progress For the First Year

Several activities were initiated or have been completed during Year 1 of the NAVCIITI effort. First, the Antenna Group completed detailed simulation runs of the Foursquare radiating element using an in-house computer code based on finite-difference time-domain (FDTD) techniques. The element was selected because of its low profile and wide bandwidth. It is ideal for use in phased arrays on ships and aircraft.

The FDTD code was used to calculate input impedance of a single Foursquare element. The FDTD code was also used to calculate the E- and H-plane far-field patterns of the Foursquare antenna. The calculated results compare well with the measured patterns. The Foursquare has similar far-field patterns in both the E- and H-planes. The gain loss is 5 dB or less for 45° of scan in any direction off broadside, making the element ideal for phased array applications. In addition, the far-field patterns are nearly constant in shape over the operating bandwidth of the Foursquare.

Software was purchased to simulate wideband antennas. Two large commercial packages (IE3D and Fidelity) will be used to simulate antennas. The software was evaluated by comparing to antennas that were constructed and measured by the Antenna Group; excellent results were obtained. In addition, an in-house custom FDTD code was written to provide high level investigation of antennas. Purchases of a near field scanner and associated equipment. This equipment will be used to measure wideband antennas designed using the software.

Task 1.3: A Secure Configurable Platform for Shipboard Information Processing Systems

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Abstract:

The purpose of this project is to demonstrate the viability of a potentially highly adaptable low-cost technology for naval information management and communications systems. It is the intent of this project to demonstrate an alternative means of collecting, processing, storing, and transmitting information securely throughout the next-generation seaborne naval platforms. The technology featured in this task has been chosen based upon the following criteria:

(1) The focus of this project is on information management. The processing power of the underlying platform should be sufficient to address a variety of demanding computational tasks.

(2) The processing platform should utilize commodity (high production volume) components. The intent here is to reduce per-unit costs, manufacturing cost and time-to-deployment as new devices become available.

(3) The hardware technology should be multifunctional, and be capable of fulfilling the operations of perhaps a variety of tasks with little or no modifications. The intent of this is to derive economy-in-scale by having one deliverable satisfy possibly several requirements.

The system should handle data in a secure manner. System resources should be protected from unintentional (friendly misuse of system resources) or intentional (protection of software and hardware against theft and reverse engineering) threats.

Relation of Work to ONR Objectives

This task addresses two issues of importance to the Navy. First, it demonstrates how COTS parts can be used to build a multifunctional platform capable of efficiently supporting a variety of tasks involving the collecting, processing, storing, and transmitting of information. Second, it demonstrates a flexible, tight integration of security techniques and configurable hardware.

Statement of Work

1.3.1 Athanas, Jones, and their students will acquire two configurable radio front-ends as well as a new generation configurable computing board. These will be integrated into a typical PC platform. This task will be completed by month three.

1.3.2 Athanas, Jones, and their students will work with TECSEC, Inc (Vienna, VA) to design a strategy for encrypting bitstreams (programs for configurable computing boards) using data-centric split-key cryptography. The strategy will be designed by the end of month three. By making use of TECSEC technology, the implementation of this strategy in software will be completed by the month six.

1.3.3 Athanas, Jones, and their students will implement at least two different radio functions integrating the radio front-end with the configurable computing board integrated in task (1). This task will be completed by month six.

1.3.4 Athanas, Jones, and their students in consultation with TECSEC will integrate the radio functions developed in task (3) with the bitstream security techniques developed in task (2). This result of this task is the demonstration of the secure, multifunctional platform. This task will be completed by the end of the contract.

1.3.5. Athanas, Jones and their students will design and implement a testbed appropriate for experimentation and evaluation of this technology for the Navy. The testbed will consist of ten configurable computing machines connected via high-speed networking with selected nodes augmented by configurable radio front-ends.

1.3.6. Athanas, Jones, and their students will implement a secure, network router on nodes of this testbed. The router will be based on the numerous configurable network router prototypes that the PIs have developed with their students. The focus of this particular router will be security with a focus on the prevention of intrusion.

1.3.7 Athanas, Jones, and their students will integrate the configurable radio and configurable router to demonstrate their functionality on this ten-node testbed.

Scientific Background and Technical Approach

Recent technology development has made configurable computers and configurable radios readily available. Configurable computers are flexible platforms, such as those available from Annapolis Micro Systems and Virtual Computer Corporation, that combine the flexibility of software with the speed of hardware. A configurable radio platform, such as the one available from Rockwell, allows flexible control over the frequency and power at which the radio operates. The combination of these two technologies allows for the construction of a multifunctional radio platform with significant digital signal processing capabilities as well as the capability to perform other computations such as encryption/decryption.

To be useful in a military environment such a multifunctional radio platform should be protected from unintentional (friendly misuse of system resources) or intentional (protection of software and hardware against theft and reverse engineering) threats. Friendly misuse would be, for example, the operation of the radio on unauthorized frequencies or power levels. Intentional misuse would include the capture and use of the radio by enemy forces to "listen" to encrypted communication. Such misuse would be difficult to prevent if all the radio functions are implemented in hardware. Fortunately, the signal processing and encryption on this platform is handled on a configurable computer, allowing for the integration of security software into the system. A particular configuration of the radio platform represents one function of the radio; such a configuration is represented in a bitstream file. We will protect these bitstreams using the split-key, data-centric technology of TECSEC, allowing a user to access only those functions for which they are authorized. Without the proper keys, no configurations are available to a user, leaving them with a useless collection of hardware.

In the second phase of the project, we intend to further exercise the multifunctional platform as well as build a testbed that allows for larger scale experiment and evaluation. The multifunctional platform will be further exercised by building a configurable, secure network router. Jones and Athanas have constructed several configurable network routers; these routers were able to change routing protocols as well as act as firewalls. A configurable network router can operate at speeds comparable to what is achievable with ASIC implementations, while providing the flexibility of CPU-based network routers. This configurability will be exploited to allow for more sophisticated security measures to be implemented as well as on-the-fly updates to the router functionality to respond to new threats.

A ten-node testbed will be built to allow for large-scale experimentation and evaluation of this multifunctional platform. This platform will be composed of ten configurable computing boards (each in its own host) connected by Myrinet high-speed networking with some nodes augmented by a configurable radio front-end. The configurable radio and the configurable router will be integrated on this testbed, allowing for a realistic test environment. Jones and Athanas will build on the infrastructure they have constructed as part of the DARPA SLAAC project as well as their prior experience with building such a testbed.

Key Personnel

Peter Athanas is interested in high-performance computing, configurable computing machinery, VLSI, and high-level synthesis. Dr. Athanas received his B.S. Degree in Electrical Engineering from the University of Toledo, his M.S. Degree in Electrical Engineering from Rensselaer Polytechnic Institute, and his Sc.M. Degree in Applied Mathematics and Ph.D. Degree in Electrical Engineering from Brown University. He also worked in industry as Senior Design Engineer in the Advanced Technologies Group for United Technologies/Hamilton Standard (Windsor Locks, CT). Dr. Athanas has been active in the configurable computing community for several years. He is serving on the organizing committees of the major configurable computing forums.

Mark Jones has research interests in high-performance computing, parallel computing, configurable computing, algorithm construction, data security, and quality high-performance software construction. He has published over 40 journal articles and conference proceedings on his research. Dr. Jones received his B.S. in Computer Science from Clemson University and his Ph.D. in Computer Science from Duke University in 1990. From 1990 to 1993, he was a member of the technical staff at Argonne National Laboratory where he worked on the development of algorithms and software for massively parallel computers. While at Argonne, he received the 1992 Gordon Bell Prize from the IEEE Computer Society. From 1993 to 1997 he was a member of the Computer Science faculty at the University of Tennessee.

While at UT, he received an NSF CAREER Award in 1995. He joined the Electrical and Computer Engineering faculty at Virginia Tech in August of 1997.

Project 2.0 Visualization, HCI and Collaboration

Task 2.1 Scientific Visualization

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Abstract:

Creating a detailed picture of a battlefield terrain, weather, and military resources is vital for the success of a military mission. In a virtual immersive environment, such as a CAVE or Immersive-Workbench, mission planners and command center (CC) personnel can gain a tactical advantage. Because of the inherent three-dimensional nature of immersive environments, CC personnel can better plan the distribution of military resources on land and at sea both above and below the surface. Much of the tactical information, which is lost in a traditional map, can be accessed and used for mission planning in an immersive three-dimensional environment. This same concept can be extended for C&C of digital ship under fire, where the CAVE can be used for real time damage assessment and damage control. With the aid of super-computers it is also possible to include discrete simulation models of tactical systems as well as physically realistic simulation models of other mission critical CC activities such as ship-to-ship and ship-to-shore material transfer, and underwater acoustic phenomena.

Visualization of Simulation Model Results—
Mission critical CC activities such as ship-to-shore and ship-to-ship material transfer can also benefit from the use of virtual immersive environments. Recently funded ONR DURIP project will simulate the active motion control of a ship-mounted crane in the CAVE. This DURIP project is an extension of a larger five-year ONR MURI project to study a variety of sea states and motion control problems (MCP) for the navy. Another mission critical CC activity is the interpretation of Under Water Acoustic (UWA) data and METOC data. Again virtual immersive environments can aid in creating necessary data displays for the interpretation of complex 3D acoustic structures and meteorological structures.

Description of Proposed Research:

The future CAVE location in the Advanced Communications and Information Technology Center (ACITC) building has a 12’x12’ opening in the floor. To move the CAVE to the

ACITC, the DURIP project will pay for the construction that must be completed with a floor mounted motion platform to the rear of the CAVE and glass floor panels in the front. A ceiling projection will also be required to view simulated crane operations.

Simulation models of ship and crane motions will be calculated on a remote site SGI Origin-2000 and linked to the CAVE computer and motion platform for “real-time” simulation & visualization of model results from the crane operators view point. With the CAVE floor projection in place the crane operator can experience a ship-to-ship material transfer simulations. Simulation model results will be compared will actual physical scale models experiments to confirm the validity of CAVE simulations.

We will develop relationships with the Navy organizations producing the data under investigation. Acoustic simulation models used by the Naval Under Water Warfare Center (NUWWC) and meteorological simulation models used by the Navy METOC Center will be identified and implemented on the CAVE computer. Simulation results will be visualized post-mortem in the CAVE. If simulation models are relatively fast, we will implement an existing web-based Java forms interface (or other interfaces available at Navy labs) that will allow researchers to selectively change physical parameters in the form, submit batch jobs and obtain numerical results with simple graphical representations in performer binary or VRML file formats. These file formats can then be quickly viewed in the CAVE. Although this process is not a “real-time” simulation/visualization interface, it will provide acoustic and meteorological researchers and opportunity to parametrically study their structure-property relationships interactively. In year 3 this concept will be extended to the “Digital Ship” project where the virtual environment of a CAVE can become the C&C center for simulation of a ship under attack. Simulations of shipboard damage detection, assessment, and damage control can be experienced through a model of distributed onboard sensors based on fiber-optic and wireless sensor arrays. Coordinating fire and damage control personnel, who are equipped with wearable computers, is possible with well designed collaborative awareness tools that link shipboard personnel with the CAVE C&C center.

With both ceiling and floor projections as well as front and side wall projections, it will be possible to extend the immersive capabilities of the present CAVE to view, not only crane operations, but also complex 3D structures predicted by under water acoustic models as well as 3D meteorological models. Existing 3D CAVE programs such as CAVE-5D and NUWC's CTISS (Command Technology Information Support System) will be modified as necessary to study and interpret simulation results.

Statement of Work:

2.1.1: CAVE motion platform (CMP) installed and operational, July 00

2.1.2: CMP controlled by remote computer simulation and operator controls, December 00

2.1.3: Demonstrate CAVE simulation of ship-to-ship materials transfer, April 01

2.1.4: Identify working simulation models used by NUWC, June 00

2.1.5: Design CAVE displays to interpret NUWC acoustic model results, December 00

2.1.6: Demonstrate CAVE displays to interpret NUWC acoustic model results, April 01

2.1.7: Evaluate and modify CAVE display interfaces for NUWC acoustic model, July 01

2.1.8: Demonstrate CAVE simulation of ship-to-ship material transfer, August 01

2.1.9: Evaluate human in the loop with the ship-to-shore simulation, December 01

2.1.10: Create training simulation models for ship-to-shore simulation, March 02

2.1.11 Final report on CMP with ship-to-shore simulation, April 02

2.1.12: Design Digital Ship CAVE interfaces (CSCI) for simulation of ship under fire, June 01

2.1.13: Complete DCSI working prototype and integrate with 3-tier test bed, September 01

2.1.14: Evaluate DCSI, recommend improvements, and modify, January 02

2.1.15: Modify DCSI to run on smaller hardware: HMDs, IWBs, and flat panels, April 02

2.1.16: Throughout DCSI development, create collaborative interfaces to work with HMDs, IWBs, and flat panels, April 02

2.1.17: Final report on DCSI, April 02

Note that the construction involved in moving the CAVE will not be paid from the NAVCIITI program.

Technical Approaches:

We will use existing simulation model programs on the remote site SGI Origin-2000 and existing Vega and Vega-Marine models on the CAVE computer. Linking these two computers together will possibly require dedicated OC-3 network links. If so, necessary high speed network hardware will need to be installed on both computers.

Simulation models of under water acoustic models used by the Naval Under Water Warfare Center (NUWC) and Navy METOC data will be implemented to run on the CAVE computer during off-hours and results archived. Results will be visually analyzed in the CAVE using existing CAVE programs and virtual environment interfaces such as NUWC's CTISS (Command Technology Information Support System).

The Digital Ship CAVE interface will be used as a development only platform. Since we anticipate that smaller hardware devices such as HMDs (Head Mounted Displays), IWBs (Immersive Work Benches) and flat panels will be the actual ship board devices used by ship personnel.

Key Personnel

Ronald D. Kriz is an associate professor with a joint appointment between the Departments of Engineering Science and Mechanics and Materials Science and Engineering. His research interests include modeling damage development in fiber-reinforced composites and nondestructive ultrasonic and optical methods for detection of damage and monitoring degradation of properties in composites. Dr. Kriz founded the laboratory for Scientific Visual Analysis in 1990 that is now the University Visualization and Animation Group, which is an NSF NCSA-PACI CAVE Alliance Partner. The alliance uses supercomputer resources across a national grid where CAVEs are used to interpret simulation results. His research is mostly wave propagation phenomena and he also supports other CAVE related educational and research activities across the campus as part of Virginia Tech's new Advanced Communication and Information Technology Center.

Ali H. Nayfeh is a University Distinguished Professor of Engineering in the Department of Engineering Science and Mechanics. His research interests include perturbation methods, nonlinear dynamics, linear and nonlinear control, dynamics and control of power systems including voltage instability and subsynchronous resonance, structural mechanics, ship and submarine motion, aero and underwater acoustics, hydrodynamic stability, aerodynamic, nonlinear waves and flight mechanics.

Task 2.2 Visualization and HCI: Description of Technical Effort for "Eye-Tracking in VEs"

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Background and Related Navy Collaboration:

Virginia Tech has a long-term collaboration with NRL (Dr. E. Swan, Dr. J. Templeman, et. al.) to research human-computer interaction (HCI) issues in virtual environments (VEs). Our recent work, funded by ONR and NRL and presented at the *VR'99 Conference* (the premiere international VR conference), was awarded "Best Technical Paper" of the conference by popular vote of conference attendees. Our work is conducting empirical studies to produce generalizable guidelines for designing VE user interfaces. The studies are using a map-based battlefield visualization VE called "Dragon", and include comparative evaluations of parameters for such critical VE design issues as stereopsis vs. non-stereopsis, ego-centric vs. exo-centric navigation, platform (Immersive Workbench vs. desktop vs. CAVE™), and head-tracked vs. non-head-tracked immersion. This prior and on-going work places us in an especially advantageous position to uniquely contribute to the proposed Digital Ship integrated testbed that is the "glue" for this proposal.

The work proposed herein expands and enhances this collaborative research between Virginia Tech and NRL. Further, with FY99 funds from NAVCIITI, Virginia Tech now has an Immersive Workbench (IWB). Prior ONR DURIP monies funded an IScan eye tracking system that currently is being installed in our CAVE.

Objective of Proposed Research

We propose to use the Dragon software to explore use of eye tracking in VEs, producing and expanding guidelines for VE user interface design. To our knowledge, eye tracking has not been incorporated into a CAVE or an IWB elsewhere, much less systematically studied within these VEs. These issues are especially critical for (human-centric) design and evaluation of our Digital Ship concept. The objective of our two-year proposed research is to concurrently explore two different facets of eye tracking:

(1) use of eye tracking for data collection for usability analyses of VEs and

(2) use of eye tracking as a multi-modal interaction technique in VEs.

While research exists in both these facets for eye tracking in 2D non-immersive GUIs (e.g., Jacob at NRL), this will be some of the first systematic eye tracking research performed in 3D immersive VEs.

Description of Proposed Research:

Use of eye tracking for data collection for usability analyses of VEs

In a Digital Ship, a highly usable user interaction design is essential. While the IWB and CAVE provide control over visual stimuli presented to a user, an eye tracker captures and records some of a user's actions and responses to such stimuli. Myriads of open research questions exist for which eye scanning data may offer answers, or at least heuristics. For example, unanswered questions critical to usability of VEs include: How does motion in a VE attract attention? How does color affect user response in a VE? How does grouping of objects influence usability in a VE? What do users look at when driving a vehicle in a VE or when maneuvering through a VE or when manipulating objects in a VE? Our eye tracking system can capture data such as response times, dwell times, location, direction, and so on, that facilitate, for example, cognitive load, attentional, and perceptual analyses, to help answer these kinds of questions.

Use of eye tracking as a multi-modal interaction technique in VEs

A Digital Ship has the potential to include different modes of user interaction with the myriad of systems that will be integrated through our concept. Various multi-modal interaction techniques based on eye tracking can be studied in VEs, potentially extending the user interface. Again, numerous questions arise, for example: What is the optimum user interface design for eye-based interaction techniques? Can eye-based interaction techniques enhance or take advantage of the natural use of eye movement with other modes of interaction in VEs? What is the effect of dwell time on objects in VEs? Are there user actions (e.g., selecting, dragging objects) that logically map to eye-based interaction techniques? How do two users in two geographically different, but networked, VEs (e.g., a CAVE at Virginia Tech and a Workbench at NRL) interact with each others' avatars; how do they "look at" each other? Again, data from our eye tracking system can help answer such questions.

Technical Approach to Proposed Research:

Initially we will use the Dragon application, which will greatly expedite our work; we are already familiar with the domain, content, and software, and from our prior work (e.g., *VR'99 Conference* paper mentioned above) know that the user interface has high usability. This familiarity will allow us to efficiently modify the software as needed for this proposed work. It also amortizes and ensures our continued interaction with NRL, and provides a common thread for exploring potential collaborations with other researchers (see below). As the Digital Ship testbed is developed and becomes available during Year 3, we will migrate our work into that domain as appropriate.

Three main tasks to accomplish our proposed research will be performed over Years 2 and 3:

2.2.1: Get eye tracker fully functional and integrate into Dragon software on multiple hardware platforms

Year 2: Our eye tracking system is installed in the CAVE, but has not been tried with our recently-acquired IWB. In Year 2, we will instrument Dragon with eye tracking on both the IWB and in the CAVE, as appropriate. The eye tracker currently can translate eye motion data into a three-dimensional line segment that is used for intersection testing with objects in the VE. A known technical issue with serial communication still needs to be solved with the eye tracker, but we expect to fix this quickly. Because of the highly novel aspects of this proposed research, we may encounter unexpected technical issues; we will deal with these as/if they arise, making decisions that will maintain the intent of our research as proposed herein. We expect to mostly complete this aspect of the research in Year 2.

2.2.2: Explore use of eye tracking for data collection for usability analyses

Year 2: In Year 2, we will collect raw eye tracking data of subjects using Dragon. Then we will explore ways to determine what those data reveal in terms of usability of a VE user interface design. A simple and obvious situation, in which a CAVE user repeatedly looks from one wall to another while performing a task, could suggest that objects on the two walls should be closer together to make the task easier and faster. Eye tracking data could reveal this repeated movement and thereby indicate a potential usability problem. Eye tracking may be especially useful for several parameters in current Dragon studies (e.g., 2D vs. 3D; stereopsis vs. non-stereopsis), so this proposed research can further enhance those efforts. Further, we will interact with Dr. Sandra Marshall at San Diego State, who has collected eye tracking data from flat panel applications to study decision-making and what a user is looking at just prior to making a decision. This concept fits very well with determining usability of a decision support system, for example. We will also explore two other possible collaborations: Dr. Tom Tullis at Fidelity Investments has expressed interest in possible joint collaboration on use of eye tracking data for usability evaluation; we will further explore this opportunity. And we will also investigate possibilities for integrating our eye tracking studies with the auditory research currently underway at NRL by Dr. James Ballas.

Year 3: In Year 3, we will explore two issues of particular interest to design of user interfaces in our Digital Ship:

1. *How use of eye tracking data can be automatically analyzed (e.g., looking for repeating patterns in the raw eye tracking data file).* -- Based on results of Year 2, in which we expect to find usability issues that can be indicated by eye tracking patterns, we will investigate how to automate analysis of raw eye tracking data to reveal the most efficacious usability issues in a specific user interface design for the Digital Ship testbed. This work will not only reveal potentially new and novel methods for usability engineering, but will also ensure that the Digital Ship user interfaces developed by our entire NAVCIITI team are highly usable.

2. How usability issues indicated by eye tracking data compare to usability issues discovered through formative usability evaluations -- We will design and perform one or more feasibility studies to compare usability findings from our automated analyses to those that are determined by traditional user-based evaluations of an interaction design. This will help determine what types of usability problems are best found by which usability evaluation methods; whether these types of problems complement, compete, or overlap; and help determine what method(s) for usability evaluation give the greatest cost/benefit for design of VE applications such as the Digital Ship testbed.

2.2.3: Explore use of eye tracking as a multi-modal interaction technique in VEs

Year 2: In Year 2, we will invent, design, and implement one or more metaphors for interacting with the Dragon VE application via eye gaze, focusing most on those metaphors that are most likely to transfer effectively to the Digital Ship testbed. We do not expect metaphors used in GUI applications, such as selection of an object based on dwell time as a user gazes at that object, to be any more effective in VEs than they are in GUIs. Thus, we will not explore eye gaze specifically as a control technique. Rather, we will explore whether natural use of the eyes while using other VE interaction modes (e.g., with glove, wand, voice) can enhance user interaction, and we will seek metaphors that help understand perceptual issues in multi-modal VEs. Hix is a co-organizer of a Workshop at VR2000, in March 2000, to explore and brain-storm some of these issues; that Workshop should provide very helpful ideas for this proposed research, in a very timely fashion. Also during Year 2, as we develop eye-gaze-based interaction techniques, we will design preliminary evaluation studies to be performed in Year 3.

Year 3: In Year 3, we will transition our interaction metaphors (eye-gaze-based designs) from Year 2 into the Digital Ship user interfaces. Then we will empirically assess these eye-gaze-based designs to determine their usability and effectiveness as interaction techniques in the context of the Digital Ship testbed, especially in combination with other modes of user interaction. For instance, we might assess how eye gaze in the natural course of moving a wand might (e.g., through user "look ahead" and prior user actions) indicate the object most likely to be selected, or the information most likely to be requested. Eye gaze techniques, coupled with voice, wands, laser pointers, gestures, and even head-tracking -- interaction techniques already found in many IWB and CAVE applications -- provide a rich and challenging VE for conducting empirical studies to assess multi-modality in VE user interfaces. These findings will be extrapolated into guidelines for designing effective multi-modal user interfaces in VEs.

We will also explore possible interaction with Dr. Phil Cohen at Oregon Graduate Institute's Center for Human-Computer Communication, performing research on integrated spoken language and gesture using a 2D pen/voice multi-modal interface called QuickSet. Like Dragon, QuickSet is also a map-based application and thus may fit particularly well with our on-going work with Dragon. And Dr. Rob Jacob at Tufts University has also expressed interest in exploring collaborative research possibilities.

Expected Results/Deliverables:

The following results will be delivered in the form of appropriate reports, briefings, and published papers:

Year 2:

• Discussion of technical issues involved in installing an eye tracking system into VEs (per Task 1)

• An in-depth assessment of the efficacy of eye tracking to assess usability of VEs, including presentation of any methods we discover for eye tracking data analyses (per Task 2)

• Presentation of eye-gaze-based interaction techniques that we invent, design, and implement, as well as studies designed for Year 3 to evaluate these techniques (per Task 3), as well as suggestions for techniques to integrate into the Digital Ship testbed (in Year 3)

Year 3:

• Automation of any methods (from Year 2) for analysis of eye tracking data for use in usability evaluation, within the Digital Ship testbed (per Task 2)

• Comprehensive results of comparisons of eye tracking data for usability evaluation with findings of other usability evaluation techniques, again within the context of the Digital Ship testbed (per Task 2)

• An in-depth assessment of the effectiveness of eye gaze as a multi-modal interaction technique in VEs, including combination with other appropriate VE interaction techniques integrated into the Digital Ship testbed (per Task 3)

• Guidelines for design of VE user interfaces based on information from usability assessments of raw eye tracking data, as well as from eye gaze techniques themselves, with emphasis on those that are most relevant to design of a Digital Ship and other Naval software applications (per Task 3)

Key Personnel

Deborah Hix has nearly 20 years of pioneering research and development specifically in the area of usability engineering. She has worked closely with the Naval Research Laboratory in the past six years. During the first three of these years, she worked at NRL more than half time so has a broad knowledge of Navy systems. Recent work has focused on development of the user interface as an integral part of overall software engineering process, usability engineering and formative evaluation, especially for virtual environments.

Task 2.3 Command and Control: Collaboration and Coordination of NAVCIITI

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Abstract

The object of this project is to formulate a digital representation of platforms, e.g., ships in the network centric environment. This task has three elements: (1) administer and manage the NAVCIITI program by using collaboration software tools, (2) determine command and control metrics to evaluate connectivity to warfare, (3) construct and evaluate a ship information management system (SIMS) in a ship under fire scenario. These tasks will provide the basis for the digital ship. The digital ship will be used to evaluate the contribution of such a system to command and control in warfare. The SIMS will provide the linkage to the network centric environment of the other projects under the NAVCIITI program. During the first year of work, the present task addressed two aspects of command and control. The first was the definition of a state space for command in a littoral battle theater. This is a collaborative activity. The second aspect had to do with determining the benefit of real-time information inputs to an interpretive/predictive model that constructs the expected consequences of inputs, in terms of accuracy of expected results compared to eventual outcomes for specific event sequences. This task was completed successfully, and the results of the effort have been submitted for publication. The work included the following general features.

- a highly repeatable physical event sequence was established and fully characterized

- a mechanistic model was constructed that predicted the average behavior of the event sequence based on the nature of all inputs
- specific input information for one of the input types was monitored in real time for a specific event sequence and used to update predicted results from the model for that case
- the accuracy of the predicted results for average behavior (based on initial inputs) was compared to the accuracy of predicted results for a specific event sequence from the model with one real-time input update from that sequence

The results were striking. The improvement in accuracy was more than one order of magnitude for all cases and more than two orders of magnitude in some cases. As a result, it has been concluded that real time input updates must be used whenever possible to increase the accuracy of predictive models in any state space used for command and control. Latency, in any form, greatly degrades the fidelity of the representation and the quality of the information.

The first progress report dealt with the results of the effort to establish the value of real-time situation assessment on expected outcome for a situation response situation that involved complex interacting processes. During the second year of effort, the following objectives will build on that work and the results of the experiments completed.

Statement of Work

The subtasks to be undertaken include the following:

2.3.1 Collaboration workspace – The US Defense Advanced Research Projects Office (DARPA)/Defense Information Systems Agency (DISA) Joint Projects Office (JPO) is defining a core set of Department of Defense (DoD) collaboration tools. Among those tools are Odyssey and Collaborator, systems that provide place-based chat, shared presentations and a live multimedia multi-privileged white board. Virginia Tech has not been involved in the development efforts of Odyssey or Collaborator, but will participate in the testing and enhancement of these systems. Deliverables under this task will upgrade and improve the usability of Odyssey and Collaborator for ship-to-ship, ship-to-shore, and land-based collaboration by Navy, Marine Corps and other DoD components and partners. Additional collaborative components will be developed for integration with these tools and architectural enhancements will be made to improve reliability, scalability, and security. Multi-faceted evaluation techniques will be employed to study the complex usability issues of these collaborative systems

2.3.2 Define metrics for shipboard command and control system. –The command and control functionalities that will be investigated are the integration of data and information from organic and non-organic sensors and the timely distribution of the information to the various nodes within the command and control network. The two year effort will concentrate on deriving the mathematical model of combat effectiveness and relating the contribution of Command and Control to the model. The year three task will concentrate on exercising the model and demonstrating the criticality of the C&C as the force multiplier. A report will be prepared to define the design basis for the testbed.

2.3.3 Design and implement a ship information management system (SIMS) testbed – using the metrics defined in subtask 2, an integrated information management system will be designed, constructed and installed in the new Advanced Communications and Information Technology Building which will house the NAVCIITI program in the spring of 2000. This will become a centerpiece of NAVCIITI and will provide a prototyping methodology for the technology being developed in the program. The second year effort will concentrate on determining and selecting the optimal architecture of the digital ship. The third year task will address the implementation of the digital ship testbed. A report will summarize the design configuration and the analysis of data collected.

Technical Approach

2.3.1 Collaboration workspace: Evaluate, plan, and implement Collaborator enhancements. Virginia Tech will establish a testbed for evaluation, planning, and testing of enhancements to the ONR Collaborator whiteboard system. During year 2 Virginia Tech will:

1. Develop Java classes that allow a client-side application to query an SQL database via a middleware component. Communication between client-side classes and middle tier will be implemented with sockets, RMI, or CORBA, depending on platform constraints, and will be abstracted to allow evolution to new communication layers. Communication between middle tier and database will be implemented using JDBC for SQL access.

2. Develop Java classes to support archiving and printing of ONR Collaborator whiteboard content by creating images from arbitrary JDK 1.1 (or higher) user interface components, as supported by the JDK (Java Development Kit).

3. Develop basic collaborative text editor and notebook shell, based on Virginia Tech's Virtual School collaborative notebook, for use on the Collaborator whiteboard. This component will initially support collaborative editing of text and will be used to test integration issues between Virginia Tech and ONR components.

4. Investigate options for integration of video and audio conferencing and playback functionality within ONR and Virginia Tech components. A detailed workplan will be developed following this analysis.

5. Investigate options for notebook-based presentation authoring and viewing. Options based on ONR and Virginia Tech components will be evaluated to plan implementation of a collaborative presentation system.

Integration of a simplified version of Virginia Tech's collaborative notebook with the ONR Collaborator system along with investigation of conferencing and presentation options will result in detailed requirements and workplan for the following in year 3:

1. Implementation and integration of audio and video conferencing tools

2. Implementation and integration of presentation authoring and viewing tools

3. Additional collaborative editor implementations for the collaborative notebook. These will likely include adaptations of existing page types (e.g., for planning and drawing), as well as new page types to handle custom data and presentation construction.

4. Extensions to the underlying collaboration architecture used by the collaborative notebook and other Virginia Tech collaborative components ("CORK", the Content Object Replication Kit, developed by Virginia Tech) to support more flexible security by supporting the Bell-LaPadula security model (clearances and classifications) at the collaboration architecture level.

Further extensions to CORK will support greater scalability and recovery from node and communication failures.

The result of this effort for year 3 will be a model implementation of a suite of collaborative components. These components can be directly incorporated by the Navy into the ONR collaboration tools. They can also be used to drive network infrastructure testing in the NAVCIITI Digital Ship testbed. Based on our own testing, and the experiences of Navy and NAVCIITI collaborators, we expect the suite of components to evolve through the latter portion of year 3. During year 3, we will also plan further development work, including the investigation of extensions to the CORK architecture and collaborative components to support handheld and mobile devices.

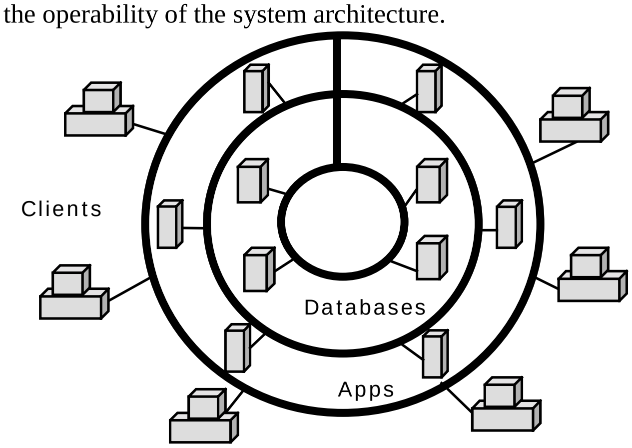
Collaborative software presents challenging usability issues. For example, support for awareness of the past and present status and activities of collaborators is a critical issue for collaborative systems. Virginia Tech has developed multi-faceted evaluation techniques for studying use of collaborative software where users are distributed across both time and space. These techniques involve collating a range of event streams and other types of user information (including session logs, files created or changed, user comments, in situ observer reports, transcribed and annotated video). A key strength of this approach is that it supports cross-correlation of many different kinds of data, providing a broader and stronger analysis of user behavior and experience. Multifaceted evaluation will be employed and refined in the NAVCIITI testbed to study awareness and other usability issues for collaboration support in the Digital Ship.

2.3.2 Define metrics for shipboard command and control system: In the derivation of the laws of combat, the attributes of command and control are assumed to be ideal. The oversimplification of the contribution of command and control causes confusion in the minds of strategists and tacticians when the issue of quantity versus quality arises. This is because the command and control force multiplier is a key parameter for winning in warfare. The oversimplification of the contribution of command and control is due to the difficulty in determining and quantifying the metrics associated with the effectiveness of command and control. In the real world, the contributions of command and control vary significantly and contribute visibly to the outcome of battle. This subtask will focus on capturing the attributes and contributions of command and control to the warfighter in combat. The contributions of command and control functionalities will be evaluated through mathematical modeling, visualization, communication and collaboration. The digital ship testbed will be used to demonstrate the sensitivity of combat effectiveness to the contributions of Command and Control functionalities. The outcome of this effort will be a design for a new concept in shipboard information systems that will optimize the collection and use of data in meeting ship mission requirements.

2.3.3 Design and implement a ship information management system (SIMS) testbed: Platforms are key and critical nodes of the warfighting network. An effectively integrated information platform provides on-demand, correct and timely information about every aspect of the warfighting platform. Systems engineering principles are used to determine the range of capabilities and functionalities of the ship and its building blocks. From an information engineering perspective, the ship is structured into interconnected clusters of workcells. A ship information management system is needed to optimally tie the ship's systems together. Using LANs, servers, clients, databases, middleware and displays, the SIMS interconnects the operators of every cluster of workcells. Many organizations and businesses are converting their information infrastructure to the three-tier architecture. This trend is occurring because they are realizing that access to updated mission critical information is giving them the ability to make responsive, informed decisions, and at the same time improve the processing efficiencies. Since data are normally located in a variety of systems, transparent access to data from anywhere in the business enterprise is needed. The three-tier architecture is the architecture of choice because it supports the transparent retrieving, manipulating and sharing of data. Also, the three-tier architecture has the advantage of separating the user processing, business logic, and processing functionality, which allows for easier and lower cost of maintenance and component upgrades. Hardware and software in each tier can be easily replaced with other products without affecting the other tiers. This transparency minimizes disruptions to system users, allows for easy migration to advanced technologies, as they become available, and promotes system flexibility, scalability, and growth.

A three-tier architecture (see figure) is proposed to provide connectivity, scalability, interoperability, and flexibility of the ship information management system. The approach to the optimization of the information flow and distribution in a ship is to construct a prototype and perform experiments to evaluate the metrics on the operation of this unique information architecture. One of the nodes of the 3-tier architecture is a virtual mission prototype which can respond to a dial-in capability. The virtual mission prototype node will provide the hooks to the Navy's Intranet and VON. Parameters to be studied include response times (latency) of the information system and scalability of the architecture. Navy data and models will be used to the extent possible to simulate the operability of the system architecture.

Figure 1 Diagram of 3-tier SIMS architecture



An application of this architecture in this task was developed in coordination with Gene Camponeschi (Carderock) in association with their Code 60 work on Survivability and Damage Control for a ship on fire. It will focus on Command and Control issues associated with fire tolerance and will use the Digital Ship test bed to simulate a ship on fire.

The NAVCIITI team has visited the Carderock team on several occasions, and several representatives of Carderock have visited Virginia Tech, including Dick Metrey the technical director. As a result of these extensive interactions and presentations, we have constructed a detailed MOU that specifies how the two teams will work together on several projects. For the NAVCIITI program, we will focus on fire tolerance on board ship, and on the C&C issues associated with damage control and survivability. The specific plan of action that has been worked out will combine the extensive modeling capability of the Carderock team, which creates a simulation of the progressive damage associated with various fires on board, with structural material degradation simulation models from Virginia Tech (using the widely acclaimed MRLife code published by our team), and communication and intelligence models generated under Tasks 3.1, 3.2, and 4.0 of our NAVCIITI program to achieve the first comprehensive model of a ship on fire. This model will use both simulation and stimulation from physical data. The stimulation data will be generated (much is already available) by the unique facilities for fire studies at Carderock. Those data, unique in the Navy and unique in the world, will provide representations of progressive damage in a variety of situations for which no models are presently available, and will ensure that the resulting Digital Ship on Fire (DSF) model has direct and immediate applicability to Navy needs.

The foundation for this task is firmly founded. Teams from both organizations have been meeting since July of 1999. Subsequent meetings and correspondence have formulated a variety of directions and made the essential connections between specific personnel at Carderock and at Virginia Tech. Survivability and Damage Control are major Command and Control issues. The Digital Ship test bed will provide an efficient and economical method of addressing those issues with comprehensive and realistic inputs from Navy situations and personnel. All coordination with Carderock will be through the POC for this task, Gene Camponeschi (Code 6501, Program Office, Structures and Marine Composites) and Mr. Usman Sorathia (Fire Protection & Sea Survivial Branch).

Key Personnel

Kenneth Reifsnider is an internationally recognized expert in the durability and damage tolerance of material systems. He has given invited keynote, plenary and guest lectures on those and related subjects in 19 countries, and has twice served as a NATO consultant. He is a member of the National Materials Advisory Board, and serves as Editor in Chief of the International Journal of Fatigue. Dr. Reifsnider is the originator of the MRLife performance simulation code that predicts the remaining strength and life of composite materials and systems, in the presence of complex combinations of mechanical, thermal, and chemical applied environments. The code series is the most widely used methodology in the U.S. to predict the damage tolerance of composites in the applications community. The structure and operation of the code is also a developmental starting point for some of the project/battle management software to be developed on the present program. Dr. Reifsnider will serve as the Principal Investigator for the NAVCIITI program.

John M. Carroll has researched human learning and problem solving in human-computer interaction contexts for two decades. This proposal integrates four of his long-term research interests: user-centered design methods, formative evaluation, science-based design, and project-oriented construction.

Abdul R. Habayeb has 30 years of experience with the Navy, most recently as weapons command and control technology administrator for the Naval Air Systems Command. He is recognized in the industry for his work in systems integration and systems effectiveness. His engineering background includes design of logic circuits and control systems, performance reliability assessments, and analysis and quantification of weapons systems effectiveness. Dr. Habayeb has published several papers, reports, and a book entitled, ***System Effectiveness***. Dr. Habayeb previously served as dean of the faculty of engineering and chairman of the electrical engineering department at Yarmouk University in Jordan. He holds patents in the field of switching circuits and data communication.

Task 2.4 Mechanically-Flexible, Visual Displays and Optical Interconnects for Digital Ship Simulation

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Abstract

The overall objective of this work is to contribute to interactive optical visualization and high speed optical interconnection for the real-time simulation of battle scenarios for Digital Ship systems.

This work would extend research performed during the first year of the NAVCIITI program, and would focus work performed by individuals in the Fiber & Electro-Optics Research Center at Virginia Tech into this single area. It would further leverage basic research in optical display materials science, electroluminescent polymer chemistry, and thin film light emitting devices that has been supported by the National Science Foundation and DARPA programs. Finally, it would directly support battlespace visualization as part of simulations to be performed in the new ACITC building on the Virginia Tech campus.

An additional objective is to design, procure and install optical high speed robust optical fiber-based LAN interconnects between computers, visualization displays including the CAVE, and human operators as part of digital ship operational simulations within the ACITC building.

Science and Technology Objectives

The science and technology objectives of our contribution to Project 2 are to develop and demonstrate engineering prototypes of fully addressable multielement optical displays having the following characteristics.

1. emission brightness of 100 cd/m^2 or more (brightness of normal CRT)
2. two-dimensional size up to approximately 96” x 96”
3. lifetime (time over which emission drops by 3 dB) of 10,000 hours or more
4. multiple color output, including white light
5. mechanical flexibility to permit rolling and unrolling the display
6. additional functionalities, such as local sensing of finger pressure or laser pointer light
7. ability to integrate some level of electronic functionality into the flexible display package

The science and technology objectives of our contribution to task 3.1 are to investigate robust methods for optical interconnect operation and survivability as part of dynamic high-speed digital ship systems.

Approach and Related Science and Engineering Contributions

Multifunctional Visualization Displays

The proposed development work will be based on the use of electrostatic self-assembly (ESA) methods for the formation of thin film materials and devices. The ESA process uses the alternate adsorption of anionic and cationic molecules and materials from water solutions onto electrically charged substrates to form multilayer thin films. The properties of the molecules and the stacking order of the layers in the complete film determine its electronic, optical, mechanical and other functionalities. We have demonstrated the ability to form green light emitting thin film devices by ESA processing through prior basic science programs. In these devices, the electroluminescent materials used to emit light are conjugated polymers, and the adjacent hole and electron transport materials in the device structure are also polymer based, so the entire device is mechanically thin and flexible. We have formed such basic devices on very thin polyester, Kapton and other low-temperature polymer-based substrates that may be rolled or folded without being creased.

During the proposed NAVCIITI program effort, we will build on this prior work to move the technology from the state of current devices (emission brightness on the order of 75 cd/m^2, size on the order of 6” x 6”, lifetime on the order of 1000 hours, a single color, and pixel count of 128 elements) to devices having the specifications indicated above. This will be accomplished primarily by increasing the emission efficiency of the electron and hole recombination process using the ESA process advantage of control of the molecular level surface characteristics of adsorbed thin film materials, and through modifications in our current device processing laboratory system. Methods to incorporate red-green-blue pixels and two-dimensional passive transmission filters to realize effective white light pixel-based displays will be demonstrated.

We will also study and demonstrate how additional functionalities, such as the ability of the display to sense and respond to external stimuli such as finger surface pressure, laser light pointer radiation, or voice commands, may be possible. Our approach here will be to use related properties that may be incorporated into such thin film devices, such as light detection and piezoelectric behavior, to create detector elements within and/or physically below the outermost optical display layers in the thin film. The underlying physics of the operation of the thin film devices here is also based on molecular-level self-assembly. Optical detector element, and arrays of such elements, may be fabricated using the same general approach used to form light emitting devices. By varying the properties of the polymers used in the active layers in the detector devices, the wavelength range of the detector devices may be varied. FEORC has demonstrated initial laboratory bench prototypes of such self-assembled thin film detectors, and would further develop them by increasing their sensitivity, and integrate them with light emitting display elements.

Pressure sensitive piezoelectric thin film devices may be formed by creating multilayered media having net macroscopic polarization. FEORC has demonstrated that such films may be formed using a variety of polymer materials, and used to form piezoelectric thin films with d_{33} coefficients on the order of 1000 pC/N, or greater than that of PVDF and some types of PZT materials. Here we will investigate how such elements may be incorporated into the back of light emitting displays and interconnected to serve as spatially sensitive pressure detectors or distributed acoustic microphones. It should be noted that the same process used to form piezoelectric materials by self-assembly may be applied to the formation of optical nonlinear optical materials used in optical modulators and switches used in communication and signal processing networks.

Finally, the goal of interconnecting the sensor elements through signal processing and control electronics to the display, to achieve control of display format, local display color, local display symbols and other properties is possible using ESA-processed optoelectronic devices. The same ESA method may be used to create pn semiconductor junction devices and systems formed from such devices.

Survivable Optical Interconnect Networks

The Digital Ship concept puts tremendous bandwidth requirements on the communications network backbone through multiple digital services such as integrated voice, data and video applications. Optical fiber is almost an ideal medium, as its transmission capabilities can completely answer the bandwidth demands in addition to offering a very important immunity to electromagnetic interference (EMI). EMI immunity is crucial against enemy's jamming, strong magnetic fields caused by radar and communication antennas, as well as against natural phenomena such as lightning, increased sun activity, etc.

However, in order for a communication network to be fully robust for applications such as the digital ship, the transmission system needs to be placed in a well-engineered and optimized topology, which would survive single and multiple link and/or node failures. In addition to these hard failures, the network performance needs to be guaranteed under soft failures, where issues of interoperability, protocol functionality, traffic load balancing, and rerouting of information become very important. Ultimately the network needs to be able to offer quality of service (QoS) to mission-critical data at all times and under various conditions that may be encountered during an actual battle.

The Fiber & Electro-Optics Research Center (FEORC) intends to study the crucial network parameters such as throughput, transaction rates, response times, survivability, and self-healing capabilities, and then offer optimal solutions based on the network's performance under various conditions. Toward this goal, FEORC intends to obtain and setup the necessary hardware and software which would be necessary for transmission, switching and routing, and performance monitoring of the network. Initially the network can be altered to mimic various failure scenarios, and its performance can then be monitored while the ship simulation program of Nayfeh *et. al*, is in progress.

Even though the field of optical communications changes rapidly, the testbed will be built with some forethought to satisfy current needs for high bandwidth demand, standardized transmission rates and formats, and provisions for QoS. At the same time it will be flexible enough to offer a foundation for future upgrades and novel research. Specifically, it is our intent to begin with multiple ATM switches which could initially be connected in a highly survivable network topology (such as a meshed-ring topology) where each node would be of degree four or higher (each node connected to four other nodes). Furthermore, switch modules used as the Network-to Network Interfaces (NNI) would operate at OC-12 (SONET's standard speed of 2.5 Gbps) while individual computers would be connected via the Network Interface Cards (NICs) which serve as the User-to-Network Interfaces (UNI) and operate at OC-3 rates (SONET's standard rate of 155 Mbps). The main advantage of such a setup is that it can offer a guaranteed QoS for mission-critical applications while allowing network performance testing under various operating conditions.

Furthermore, operating such a network by setting up multiple ATM Virtual Paths (VP), where each VP can represent a different wavelength, and by using VP identifiers, this network can serve as a great research testbed for simulating multiple wavelengths. This approach would obtain invaluable test results for an all-optical cross-connect WDM meshed-ring communications network under the very desired conditions of simulating a ship in a battlefield maneuver, with tremendous time and cost savings. Ultimately the existing ATM network could be aided and expanded to include the wavelength channels in addition to the ATM VPs, thus furthermore expanding the capacity of the network. The results of testing the network by using VP identifiers can also offer valuable insights into the behavior of IP networks using IP flow labels. However, IP does not currently offer guaranteed QoS, which is a significant drawback for an application such as this.

Finally, in addition to the mentioned ATM switches, NNIs, UNIs, and PCs, FEORC plans to obtain various software and hardware tools for monitoring and analyzing network performance, such as the Network Associates Sniffer Pro LAN network analyzer or the Netcom Systems award-winning SmartBits system.

Anticipated Outcomes and Deliverables

Deliverables for Year 2 and 3 are anticipated for both subtasks.

First, we will deliver a large mechanically flexible optoelectronic array device having integrated sensing capabilities at the end of Year 2. These first generation prototype device size will be approximately 24" x 24". Pixels will be multicolored. Integrated sensors will be able to respond to incident light and mechanical pressure and produce output signals that are a function of either. By the end of Year 3, the device will be packaged so it may be mechanically bent and rolled up for storage, and will be connected to a simple electronics header for interconnection to off-board hardware and software. Deliverables for Year 2 will include demonstration of prototype displays, and for Year 3 will include displays interconnected into Digital Ship simulation systems.

Second, we will deliver a design for the robust optical interconnect system by the end of Year 2. This system design will incorporate requirements for bandwidth, system architecture and adaptability and robustness to system, software and environmental parameters, as defined by all cognizant Digital Ship system research team members. By the end of Year 3, we will deliver and demonstrate a working prototype fiber LAN interconnect system based on this design.

Contributions to Navy and Other DoD Programs

The ability to visually sense, transmit and represent information, imagery and data is important to all Navy and other DoD operations. The proposed research has near-term applications to the Digital Ship simulator system to be housed in the ACITC building on campus at Virginia Tech. Additionally, this work contributes to basic science and technology (S&T) efforts of the Office of Naval Research, the Naval Research Laboratory, DARPA, as well as Air Force and Army programs.

Interactions with Navy Laboratories and Navy Prime Contractors

FEORC has established direct or indirect relationships with the following primary organizations concerning this work.

Naval Research Laboratory, Optical Sciences Division, Dr. E. J. Frieble, friebele@nrl.navy

NAWC China Lake, Dr. J. Roberts, RobertsMJ@navair.navy.mil

DARPA DSO, Synthetic Multifunctional Materials Program, Electro-active Polymers Program

DARPA ITO, Battlefield Awareness and Data Dissemination (BADD) program

Lockheed-Martin Advanced Technology Center, Palo Alto

Lockheed-Martin Astronautics, Denver

Northrop-Grumman, Hawthorne and Pico Rivera

Litton-Ingalls Shipbuilding, Pascagoula

Facilities

FEORC was founded in 1985 and currently houses more than 50 research staff, faculty and students in two dedicated research buildings totaling 18,000 square feet of space near the main Virginia Tech campus. Facilities include equipment for the synthesis and characterization of optical materials, devices and systems, and has been supported on more than 450 separate programs totaling more than $33 million.

The first year of the NAVCIITI program provided additional specialized equipment for the research and development of both display and fiber interconnect devices and systems. Figure 7-1 shows a femtosecond laser system used for the characterization of display elements and materials, and an automated optical fiber fusion splicer to be used to fabricate test interconnect systems for Digital Ship simulation studies.

Femtosecond Laser and Automated Fiber Fusion Splicer Equipment Provided by NAVCIITI Year 1 Program Would Be Available to Support Additional Research.

Virginia Tech

Principal Investigator

Dr. Richard O. Claus received B.E.S. and Ph.D. degrees in electrical engineering from the Johns Hopkins University in 1973 and 1977, respectively. Since 1977 he has served as a member of the engineering faculty at Virginia Tech where he is now a named professor in the College of Engineering and director of the Fiber & Electro-Optic Research Center. He has authored or co-authored more than 800 journal and conference papers and holds more than 20 issued patents. He has also served as a PI or co-PI on research programs totaling more than $30 million. He has received awards from the IEEE, OSA, SPIE, ASME and ASCE.

Project 3.0 Computer Network Interoperability

Task 3.1 Network Hardware Interoperability

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Abstract

The Computer Network Interoperability task area focuses on enabling interoperability between heterogeneous networks which may belong to and be managed by different organizations, including allies and coalition partners. The proposed research addresses four specific problem areas directly related to the network infrastructure needed for the Navy's Virtual Operations Network (VON) initiative: (i) wireless-wireline interoperability, including mobility; (ii) quality of service (QoS) across heterogeneous networks; (iii) network management in shared heterogeneous networks; and (iv) security, especially in wireless systems. We will investigate these problem areas, investigate and propose solutions based on commercial equipment and commercial standards, and demonstrate and evaluate solutions with respect to both functionality and performance using a distributed network interoperability test bed. The test bed will initially include 10/100-Mbps Ethernet, IEEE 802.11 wireless local area network (LAN), and ATM technology. Host environments will include both UNIX and Windows NT. We will emphasize use of the TCP/IP protocol suite and network infrastructure support for delay sensitive applications, bandwidth-on-demand, and security. Our first year's focus is on deploying the test bed and developing and evaluating specific interoperability solutions. Our second year's activities will continue the interoperability focus, including an emphasis on tracking and contributing to new standardization activities, and will leverage and expand the test bed to investigate solutions to other networking challenges of importance to the Navy.

Responding to the Objectives of the Office of Naval Research

Computer network interoperability is an important aspect of the Navy's need for information technology interoperability as defined in a Naval Research Advisory Committee (NRAC) report issued in November 1998.[2] The VON architecture is envisioned to realize interoperability both for heterogeneous information and network systems and for heterogeneous ownership and administrative responsibility. An effective network infrastructure is required for the VON to function properly and to provide a rich set of interoperable capabilities. The VON strategy calls for using existing infrastructure, but the right common system is unknown and the existing infrastructure is not necessarily uniform. Network infrastructure problems that must be addressed include bandwidth management, network management, and security, with emphasis on operation in a wireless-wireline environment and interactions between systems and protocols.

Both years of this proposed research program will address issues that are critical to the network infrastructure for the VON. We emphasize capabilities cited for their importance in the NRAC report, including TCP/IP, video teleconferencing, bandwidth-on-demand, and security. We will provide results from test bed experiments and other investigations to indicate the functionality and performance of network interoperability solutions that address VON requirements of scalability, use of wireless data links, inter-platform bandwidth allocation, and authentication and confidentiality. We will examine networking issues including virtual private networks (VPNs), routing, multicast communications, quality of service, security, network management, and policy mechanization for both security and network management. We will consider applications that are critical to the VON, including electronic mail with attachments, video teleconferencing, collaborative applications, technical picture exchange, and World-Wide Web applications.

In the second year of the proposed research, our primary focus will continue to be networking infrastructure for the VON. We will also apply our effort and leverage the capabilities of our test bed to benefit other programs and activities. For example, there is the strong potential for synergy with other Office of Naval Research Science and Technology activities, including the Naval Combat Systems Interoperability (CSI), Interoperable Networks for Secure Communications (INSC), and Extending the Littoral Battlespace programs. We will explore and pursue opportunities for integration of our work in the wireless environment with secure radio research pursued in Task 1.4 of this proposed NAVCIITI program. We will also provide results for use in modeling activities within the proposed NAVCIITI program, specifically for Task 2.3 and Task 3.2. We will also integrate portions of the network interoperability test bed with other efforts to provide hybrid model and system in-the-loop capabilities for networking components of the "Digital Ship" model of Task 2.3.

Statement of Work, Schedule, and Deliverables

The proposed research consists of six tasks related to networking technology for a VON. Each of the tasks will culminate in demonstrations using a common network interoperability test bed. Tasks 1 through 4 are the core of the proposed activity and will be pursued for both years of the proposed two-year program. Task 5 will be performed primarily in the first year of the proposed program. Task 6 will be pursued primarily during the second year.

3.1.1 Interoperability of wireless and wireline networks.
We will demonstrate controlled mobility supported by a shared backbone network and, in conjunction with other tasks, security and network management for wireless LANs. We will also investigate issues

[2] "Information Technology Interoperability," Naval Research Advisory Committee Report, NRAC 98-2, November 1998.

related to broadband wireless access technologies and satellite communications, although demonstrations are not planned. (Lead investigator: Scott F. Midkiff)

3.1.2 Interoperable quality of service across heterogeneous network infrastructures based on IP differentiated services (DiffServ) for delay-sensitive applications.

We will demonstrate methods to provide capabilities for bandwidth-on-demand and video teleconferencing, for example, across different types of networks that may be managed and provisioned by different organizations. (Lead investigator: Luiz A. DaSilva)

3.1.3 Network security over heterogeneous wireless and wireline networks.

We will emphasize security problems related to wireless networks and will demonstrate and evaluate IPSec capabilities in a heterogeneous wired-wireline environment. (Lead investigator: Nathaniel J. Davis, IV)

3.1.4 Network management in environments where different physical networks and network services are managed and provisioned by different entities.

We will demonstrate management techniques for a rapidly assembled network that consists of geographically distributed LANs interconnected by a separately controlled backbone network. (Lead investigators: Scott F. Midkiff and Clark K. Gaylord)

3.1.5 Deployment of the network interoperability test bed.

This test bed will support the other sub-tasks. The distributed test bed will be located at both the Advanced Communications and Information Technology Center at Virginia Tech's main campus in Blacksburg and Virginia Tech's Alexandria Research Institute. (Coordinators: Scott F. Midkiff and Luiz A. DaSilva.)

3.1.6 Integration of interoperability research with other NAVCIITI program activities.

We will explore and pursue the integration of this network-level research with secure link-level capabilities being developed in Task 1.4. We will provide model results and capabilities for "in-the-loop" inclusion of test bed resources in simulation and hybrid simulation models being developed for the VON and "Digital Ship" concept in Task 3.2 and Task 2.3, respectively. (Lead investigator: Scott F. Midkiff)

Major milestones and associated completion dates are listed below.

First Year

- First-year demonstrations to support VON defined in consultation with Navy point-of-contact (7/15/00)
- Test bed operational (8/15/00)
- Interim report available (9/15/00)
- Initial demonstrations completed for each task (3/31/01)
- Final report available with results for all first-year demonstrations (4/30/01)

Second Year

- Second-year demonstrations to support VON defined in consultation with Navy point of contact (6/15/01)
- Interim report available (8/15/01)

- Initial integration with appropriate other NAVCIITI tasks demonstrated (12/31/01)
- Initial demonstrations completed for each task (2/28/02)
- Full integration with appropriate other NAVCIITI tasks demonstrated (3/31/02)
- Final report available with results for all first-year demonstrations (4/30/02)

Deliverables during each year include an interim report and a final report for the overall thrust area with sections for each sub-task. The interim report for each year will define specific approaches and demonstration plans for the year. The final report will indicate and evaluate candidate solutions to interoperability problems. The final report will also provide details of demonstration results.

Scientific Background, Objectives, and Technical Approach

All tasks will investigate and demonstrate novel approaches to the integration and management of commercial equipment and protocols using industry standards. An emphasis will be placed on rapid configuration with an effort to minimize *a priori* assumptions about connected networks and capabilities. We will also track and offer input to relevant standardization and related activities, especially through the Internet Engineering Task Force (IETF), using both electronic interaction and attendance at key meetings. In the following, we discuss the four core research areas, directly supporting sub-tasks 1 through 4 as defined above.

Interoperability of Wireless LANs with Wireline Networks. Wireless links and networks are important components in a network infrastructure because they enable mobility, at-sea access (to a backbone via a satellite link or to shore or other ships via terrestrial wireless), and rapid deployment and configuration. Key differences between wireless and wireline networks are the opportunity for mobility, typically lower data rates, the broadcast nature of the link, and the potential for dynamic link conditions, e.g. due to fading. We will investigate and demonstrate mobility support based on Mobile IP[3] or IPv6[4] mobility support that allows roaming across wireless LANs connected in a shared internetwork. We will also examine security and network management issues precipitated by the remaining differences cited above. We will also consider broadband wireless access, especially Local Multipoint Distribution Service (LMDS), although demonstrations are not planned.

Interoperable Quality of Service Based on IP DiffServ. The diverse QoS requirements of applications, such as video teleconferencing or real-time imagery, can be met by offering different grades of service according to users' needs and to the importance (priority) of the application. QoS architectures define a set of configurable interfaces that formalize QoS in the end-system and network, providing a framework for the integration of QoS control and management mechanisms[5]. IP DiffServ[6] holds the promise of allowing dynamic management of the diverse types of traffic flowing over a heterogeneous environment according to their performance requirements (throughput, delay, loss rates). We will investigate and demonstrate the effectiveness of IP DiffServ in meeting QoS objectives across a wide-area

[3] C. Perkins, "IP Mobility Support," IETF RFC 2002, October 1996.
[4] S. Deering and R. Hinden, "Internet Protocol, Version 6 Specification," IETF RFC 2460, December 1998.
[5] C. Aurrecoechea, A. T. Campbell and L. Hauw, "A Survey of QoS Architectures," *Multimedia Systems* (1998) 6:138-151.
[6] S. Blake *et al.*, "An Architecture for Differentiated Services," IETF RFC 2475, December 1998.

internetwork. Specific objectives include determination of the appropriate mapping between DiffServ categories and ATM service classes and negotiation of QoS, assessment of the level of control that can be exercised over end-to-end QoS in a heterogeneous environment and demonstration of control of QoS using IP DiffServ.

Network Security over Heterogeneous Wireless and Wireline Networks. Wireless systems introduce security risks because the transmission channel is inherently unsecured. Wireless transmissions are subject to interception, disruption, and information substitution. Unauthorized stations may also attempt to join the network and inject fraudulent information or utilize services improperly. We will identify networking security problems and address how protocols (wireless or otherwise) can be deployed to deal with security issues. We will focus, in particular, on IPSec.[7] We will apply general protocol principles and taxonomies to a demonstration of IPSec in a mixed wireless-wireline network.

Interoperable Network Management in Heterogeneous Environments. This task will attempt to identify and clarify some of the network management issues associated with heterogeneous networks using both wireless and wireline network technologies. It will also address the problem of shared network infrastructure when some organizations require visibility of certain network features and other organizations require protected configuration access to the network. The study will demonstrate network management interoperability between IEEE 802.11 wireless LAN, Ethernet, and IP over ATM technologies. Performance comparisons between the different technologies will be performed using various performance measurement tools, including TTCP and Ganymede Software's Chariot. A comparison of network management interfaces will also be made, with emphasis on how these may be unified.

Key Personnel

Scott F. Midkiff (midkiff@vt.edu) joined Virginia Tech in 1986 where he is presently an Associate Professor. Previously, he was a Member of Technical Staff at AT&T Bell Laboratories (1979-1982) and a Visiting Research Associate at Carnegie Mellon University (1985-1986). Midkiff received the B.S.E. degree, *summa cum laude*, in Electrical Engineering and Computer Science from Duke University in 1979, the M.S. degree in Electrical Engineering from Stanford University in 1980, and the Ph.D. degree in Electrical Engineering from Duke in 1985. Midkiff's research includes wireless networks, broadband network management, and network applications. He conducts wireless networking research within the Center for Wireless Telecommunications (CWT) and is part of the Virginia Tech team funded by DARPA's Global Mobile Information Systems (GloMo) program. He is a member of the Governing Board of the Internet Technology Innovation Center, a four-university partnership funded by Virginia's Center for Innovative Technology. He is a past recipient of an IBM University Partnership Program grant and a Digital Equipment Corporation Faculty Program/Incentives for Excellence grant.

Luiz A. DaSilva (ldasilva@vt.edu) joined the Bradley Department of Electrical and Computer Engineering at Virginia Tech's Alexandria Research Institute as an Assistant Professor in the fall of 1998. Previously, he held research assistantships at the Information and Telecommunication Technology Center (1995-1998) and at the Telecommunication and Information Sciences Laboratory (1987-1988), both affiliated with the University of Kansas. He also worked at IBM Brazil from 1989 to 1995 in various technical and market development capacities. DaSilva completed his B.S., M.S. and Ph.D. in Electrical Engineering in 1986, 1988 and 1998, respectively, all at the University of Kansas. For his Master's thesis, he designed and evaluated a class-oriented communication system for packet speech; his Ph.D. work was on game-theoretic analysis of pricing schemes for networks that

[7] S. Kent and R. Atkinson, "Security Architecture for the Internet Protocol," IETF RFC 2401, November 1988.

offer multiple service classes. DaSilva's primary research interests are in quality of service issues in broadband integrated networks.

Nathaniel J. Davis, IV (ndavis@vt.edu) is an Associate Professor in the Bradley Department of Electrical and Computer Engineering at Virginia Polytechnic Institute and State University, Blacksburg, VA. Dr. Davis' research is centered on the design and the use of advanced parallel and distributed computing systems. Ongoing research efforts include parallel processing network design, design of fault tolerant and reconfigurable computing structures, communications network performance modeling, and the application of wireless communications technology to computer communication networks. Davis received the B. S. degree in 1976 and the M. S. degree in 1977, both in electrical engineering, from Virginia Polytechnic Institute and State University. He received his Ph.D. degree in electrical engineering in 1985 from Purdue University. Prior to joining Virginia Tech's faculty in 1989, Dr. Davis spent 12 years on active duty with the United States Army Signal Corps. His duty assignments included various communications-electronics staff officer positions with the XVIII Corps (Airborne) at Fort Bragg, NC and two assignments with the faculty of the Air Force Institute of Technology, Wright-Patterson AFB, OH. Davis is a member of Virginia Tech's Center for Wireless Telecommunications.

Clark K. Gaylord (cgaylord@cns.vt.edu) received a Bachelor of Science degree in Mathematics from the University of North Carolina at Charlotte in 1986 and a Master's degree in Mathematics with Statistics Concentration from the University of Virginia in 1988. Clark joined the Research and Development group of Virginia Tech's Communications Network Services department in February 1997. Since 1989, Clark has worked as a research statistician, statistical consultant, instructor, and computer systems engineer and network engineer at Virginia Tech. His diverse interests include network management methodologies, mathematical modeling of network performance and utilization, and the role of computing in education.

Task 3.2 Network System Interoperability

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Abstract

The work proposed by the Virginia Tech Systems Research Center (VT-SRC) for the period 1 May 2000 to 30 April 2002 is in direct support of the Virtual Operations Network (VON) Project, led by CDR Dave Jakoubek of the Office of Naval Research (ONR). The primary points of contact are David Marlow of the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) and Russell Eyres of the Space and Naval Warfare Systems Command-San Diego (SSC-SD). The VON concept has materialized from recommendations of the Naval Research Advisory Committee (NRAC) and from increased emphasis on interoperability among systems used on a doctrinal level and for training.

A virtual private network in concept, VON serves two major functional roles: (1) operational support in the form of planning, informing, etc. in a non-real-time mode, and (2) tactical communications in a real-time or quasi-real-time mode. Indicative of the heterogeneous nature of consortia members executing a VON-supported mission is that the participation and role of a member can be more important than the C^4I capabilities of that member.

The effort in the second year is focused on a collaborative effort with NSWCDD and SSC-SD. The Navy participants are developing a shipboard demonstration of concept in the November-December 2000 timeframe. The VT-SRC will develop analytical models to represent the topological layout envisioned for the demonstration and characterize the information flow to assess both processing and bandwidth capacity required among the participants. The details of protocol specification are not intended, and the models are to be expanded and refined based on results of the demonstration. Experiments with the models are intended to address the requirements for initial force network configuration aids and the added requirements as the deployed network configuration reacts and responds to changing conditions. The experience in the shipboard demonstrations should facilitate model extension and parameter estimation.

The third year effort includes further extensions of the analytic models and the definition of simulation modeling objectives. The installation of the High Level Architecture (HLA) Run-Time Infrastructure (RTI) tools, mandated by the Defense Modeling and Simulation Office (DMSO), must precede the simulation model definition. A general simulation model that permits flexible representation of topological connections, routing capabilities, bandwidth, informational flows, and processing power is to be specified for experimentation in the Distributed Systems Laboratory (DSL) established with first year funding. The modeling objectives for the DSL experiments are to test tools, procedures and protocols *prior to* operational exposure. Prototypes can be examined and subjected to verification so that shipboard testing can be reduced. Moreover, the prototypes can be subjected to stressful behavior not possible in the shipboard testing. In the following years, linking of the DSL with the VT-CAVE could permit the experimentation with human interface issues so vital in the success of a coalition-supported mission.

Response to ONR Objectives

This task responds to ONR objectives with regard to network system interoperability in general and for the VON Project specifically. The requirements based on the NRAC 1998 report mandate the use of model-based experiments coupled with shipboard exercises to assess: (1) the degree of interoperability possible with varying consortia of naval assets, (2) the scalability of prototypical network designs, (3) the advantages and limitations of multiple levels of security versus a single level, and (4) the degree to which existing computing and network infrastructure can be employed.

Creation of the simulation environment within DSL offers potential major savings in testing and evaluation of ideas without extensive shipboard exercises. As noted above, such an environment permits evaluation under extenuating and stressful conditions that might not be possible aboard ship.

Statement of Work: Task Definition

3.2.1. Analytical Modeling Efforts to Characterize the VON

Working jointly with the Information Technology Interoperability Task $(IT)^2$ group that includes SPAWAR, NSWCDD and ONR, develop a characterization of the VON communication and computing architecture that expresses the bandwidth and processing capabilities and is amenable to analytical modeling. In collaboration with the $(IT)^2$ group, identify the parameters and the means for estimating values that are needed. Define objectives that can be achieved to support the US/UK shipboard demonstration planned for fall 2000. Define objectives that can be realized by analytical models and begin to note those that require more in-depth simulation modeling. Completion: 30 April 2001. Deliverables: Interim Report and briefing for results needed to support shipboard demonstration by 1

September 2000. Draft report describing analytical models in progress and proposed experimentation period by 30 April 2001.

3.2.2. Extensions to and Experiments with the Analytical Models

Based on the objectives defined in the first year effort, conduct preliminary tests and perform the required V&V to produce credible results. Carry out experiments supporting the VON Project. Completion: 30 April 2002. Deliverables: Report describing results of the V&V and an assessment of needs for further analytical model extensions and the expected benefits of further analytical investigation.

3.2.3. Initial Efforts in Defining Simulation Requirements

Install and test the HLA-RTI tools. Completion: 31 October 2001. Deliverables: Report describing the DSL capabilities for supporting a laboratory for initial assessment of technology proposed for VON. Develop general simulation model requirements permitting objectives defined for VON experimentation. Establish feasibility and develop schedule for development of a distributed simulation that links DSL and the VT-CAVE. Completion: 30 April 2002.

Planned Effort from 1 May 2002 to 30 April 2003

Equipment support for the DSL should be upgraded as the simulation environment becomes the standard basis for evaluation of network design changes and technology insertion for the VON Project. The methodology for screening shipboard experiments based on DSL simulation results should be formalized. Linking the DSL and the VT-CAVE provides an environment for representation and evaluation of concepts supporting the Digital Ship concept and the communications requirements in coalition missions. Structuring feedback from shipboard exercises to refine and extend the simulations must be incorporated in this methodology. More in-depth evaluations of human-computer interface issues will be enabled as the representation of communications support for coalition operations improves in fidelity.

Key Personnel

Richard E. Nance is the RADM John Adolphus Dahlgren Professor of Computer Science and the Director, Systems Research Center. Dr. Nance has served as PI or Co-PI on 33 projects supported by Navy agencies over the past 25 years. He was the Staff Computer Scientist for the Combat Systems Department at NSWCDD during a sabbatical leave in 1979-80. He served as a special liaison to the Royal Navy from May to September of 1980 while on an appointment as a Science Research Council Senior Research Fellow at Imperial College, London. Dr. Nance is the Founding Editor-in-Chief of the *ACM Transactions on Modeling and Computer Simulation*, and is a Fellow of the Association for Computing Machinery.

James D. Arthur is widely recognized for his expertise in verification and validation methodology, distributed systems language support and software engineering (particularly software quality assessment and prediction). He has served as PI or Co-PI on over a dozen Navy-sponsored projects since coming to Virginia Tech in 1983. Dr. Arthur received the university Alumni Outstanding Teacher Award in 1990.

Project 4.0 Real Time Interoperability

Task 4.1 Scheduling and Resource Management in Distributed, Asynchronous Real-Time Systems

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Abstract

Our research effort in the last three years has resulted in adaptive resource management middleware algorithms that achieve the desired timeliness and survivability requirements of periodic, variable data stream computations in distributed, asynchronous real-time combat systems. The effort that was performed as part of DARPA's Quorum program has resulted in technology demonstrations and transitions to the Naval Surface Warfare Center's HiPer-D test-bed.

The purpose of this research is twofold: (1) to develop *application-profiling mechanisms* that enable resource management techniques to optimize application timeliness in distributed, asynchronous, real-time systems and (2) to develop *feedback control scheduling and resource management algorithms* for distributed, asynchronous real-time systems. We propose to develop application-profiling mechanisms during Year 2 and feedback control algorithms during Year 3 of the project. The proposed techniques will be researched, developed and demonstrated on the Digital Ship test-bed to be constructed at Virginia Tech. The test-bed will consists of COTS host machines, network technologies, shipboard combat system (benchmark) applications, and resource management middleware components that have resulted from our prior work.

Description of Proposed Research

Application Profiling Mechanisms for Resource Management

We propose to investigate application-profiling mechanisms that enable resource management strategies to use application profile data and thereby optimize application timeliness in distributed, asynchronous real-time systems. The proposed research will investigate techniques to profile performance characteristics of shipboard, combat system applications. The project will develop mechanisms that estimate application timeliness at different system loads. Further, the project will develop resource allocation strategies that use the profiling mechanisms during resource allocation to optimize application timeliness. This work will extend our prior effort on reactive, resource availability-based, resource management middleware strategies that was performed as part of DARPA's Quorum program.

We intend to perform profiling of application components under different scenarios that are characterized by parameters such as data stream sizes (number of sensor reports per cycle), host utilization, and network utilization. The scenarios will be constructed by configuring benchmark applications to generate varying data stream sizes and program-to-host assignments. Profiling will be done under isolated conditions e.g., executing each benchmark program at different data stream sizes on each host type. It will also be performed under different program-to-host mappings, resource utilizations, and data stream sizes. Middleware components such as QoS managers and hardware monitors will be used for performing profiling.

The project will use statistical techniques such as regression models and their variants to develop metrics that estimate application timeliness at different system loads. Resource allocation algorithms that use the metrics to evaluate the timeliness of the application for a given resource allocation will be developed. The algorithms will optimize application timeliness by comparing the estimated timeliness under each allocation and selecting the allocation that gives the optimal timeliness. The resource allocation algorithms will be implemented as part of the resource manager middleware component. The quality of the timeliness estimation metrics will be experimentally evaluated. We will study the influence of the metric parameters on the application timeliness by evaluating the application timeliness after resource reallocations are produced and enacted by the metrics-driven allocation algorithms. Metric parameters such as data stream sizes and resource utilization levels (hosts and network) will be experimentally studied to determine their influence on the application timeliness. The metrics will also be experimentally studied to evaluate the influence of the size of the profiled data of the metric parameters on the application timeliness. The experiments will be performed under varying frequencies of data collection and profiling, and evaluating the resulting application timeliness.

(Lead Investigator: Binoy Ravindran)

Feedback Control Scheduling and Resource Management

The objective of this effort is to develop a theory of feedback control scheduling and resource management for distributed, asynchronous real-time systems. Feedback control real-time scheduling has been originally proposed by [SLST99] for real-time systems that have workloads that cannot be accurately characterized.[8] The algorithm proposed by the authors—PID feedback control with EDF—has been used without any theoretical guarantees of performance. The proposed research will investigate how feedback control theory and methodology can be used to systematically design scheduling and resource management algorithms that can achieve the timeliness requirements in distributed, asynchronous real-time systems.

In our past work on *DeSiDeRaTa*,[9] we had developed heuristic algorithms for performing resource management. The algorithms also perform feedback control in the sense that they "adjust" application characteristics at run-time through program replication and migration based on (asynchronous) feedback to achieve the desired timeliness requirements. However, the behavior of the algorithms is unknown beyond a set of experimental conditions under which they have been studied. It is not known under what conditions of external system load and resource availability do the resource allocations performed by the algorithms achieve the desired application timeliness. Furthermore, the algorithms were not formally studied and in general, nothing could be said about their feasibility conditions. We believe that this is an

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[8] J. A. Stankovic, C. Lu, S. Son, and G. Tao, "The Case for Feedback Control Real-Time Scheduling," *Proceedings of the EuroMicro Conference on Real-Time Systems*, June 1999.
[9] B. Ravindran, L. R. Welch, and B. Shirazi, "Resource Management Middleware for Dynamic, Dependable, Real-Time Systems," *Journal of Real-Time Systems*, To appear.

important issue that needs to be addressed before such algorithms can be deployed on shipboard systems.

Real-time scheduling and resource management based on feedback control theory appear to be promising. This is because feedback control provides a mechanism for (analytically) modeling the system and designing control functions that continuously measure a system variable and take corrective actions when the variable offsets from a desired value. However, most of the control systems that have been traditionally studied are Linear Time Invariant (LTI) systems in continuous and discrete times. Real-time computer systems that perform distributed mission management such as collaborative direction within a team of autonomous entities conducting combat do not fall into these system models. The modeling paradigm that closely matches distributed, asynchronous real-time systems belong to the category of "hybrid systems." Hybrid systems have multiple elements that have different types of modeling designs. For distributed, asynchronous real-time systems, the overall (proposed) model will contain elements of automata theory as well as continuous and discrete systems. The models therefore, will inherently be nonlinear. Dr. Kachroo has been working on designing hybrid control systems for queuing systems that have properties very similar to real-time scheduling systems. The hybrid control techniques will be extended to provide the mathematical foundation for developing feedback control theory for scheduling and resource management in distributed, asynchronous real-time systems.

In this research, we propose to investigate scheduling and resource management algorithms that are based on control theory for distributed, asynchronous real-time systems. We propose to develop control algorithms to perform feedback control scheduling and resource management. The objective of the control algorithms will be to maintain the application in a state of acceptable timeliness. The control functions will be designed through analytical modeling in the hybrid design formulation.

We will develop mathematical models that are representative of the system for designing the feedback control functions. Developing an analytical model of the system for the design of the control functions is an important issue. If the model of the system is complex, the design of control functions that provide performance guarantees can become very difficult. The design of the functions, in fact, does not require an extensive model of the system. We only need a nominal system model that is representative of the essential dynamics of the system for designing the functions. The un-modeled dynamics can be bundled as external disturbance. We will design feedback control functions that give stability and transient performance guarantees for the nominal model and also for the entire system that includes the disturbances and uncertainties. We will design and choose the most appropriate mathematical models for the system that express the essential dynamics and at the same time, allow the design of the control functions.

We will use properties of shipboard combat system applications as the basis of the computation model for the feedback control scheduling and resource management techniques. Some of the features of the computation model will include application program components that are replicable and migrate-able at run-time to adapt the system to changes in workloads. The performance of the control algorithms will be studied analytically and tested through simulations to determine their feasibility conditions. Further, the control algorithms will be implemented and demonstrated on the Digital Ship test-bed to be constructed at Virginia Tech.

(Lead Investigators: Binoy Ravindran and Pushkin Kachroo)

Relation to ONR Objectives

The proposed research aims to develop application profiling mechanisms and feedback control scheduling and resource management algorithms that achieve the desired operational (timeliness) requirements of distributed real-time systems that are "asynchronous." The term asynchronous is used here in the sense that processing and communication latencies do not necessarily have known upper bounds, and in the sense that event and task arrivals are non-deterministically distributed. Examples of such systems include the emerging generation of Navy surface combatants that must process data sets (radar tracks) and respond to event (threat) arrivals that have neither known upper bounds nor deterministic distributions, respectively. The proposed work thus addresses the Command and Control mission of ONR by seeking

1. to develop techniques that effectively use application information for optimizing resource allocations and thus efficiently contributing to mission success, and

2. to solve a fundamental problem in resource allocation: determining feasibility conditions of dynamic resource allocation strategies for asynchronous systems.

Statement of Work

The proposed tasks are summarized as follows.

Application Profiling

4.1.1. Profiling of Application and System Resource. Test bed to be operational by month one. Extend the QoS managers and hardware monitor components of the middleware to perform profiling and data collection. Construct different scenarios of data stream sizes, resource utilization, and program-to-host assignments by configuring the benchmark and perform application profiling. <u>Completion:</u> end of month 3.

4.1.2. Metrics for Estimating Application QoS. Develop metrics for estimating application timeliness at different system loads and implement them as part of the QoS managers and hardware monitor components. <u>Completion:</u> end of month 5.

4.1.3. Resource Allocation Techniques. Develop resource allocation techniques that use metrics developed in 4.1.2 to optimize timeliness. Implement the strategies as part of the resource manager. <u>Completion:</u> end of month 7.

4.1.4. Experimental Evaluation. Experimentally evaluate the metrics in 4.1.2 to study (1) the relative influence of profile data such as data stream sizes, and resource utilization on the application timeliness, and (2) the influence of the size of the profiled data on the application timeliness. <u>Completion:</u> end of month 12.

The deliverables include an interim report and final report. The interim report will describe the specific approaches (metrics and algorithms) and plans for experimental evaluation. Final report will describe profiling strategies, metrics for estimating application QoS, resource allocation algorithms, and experimental results.

Feedback Control and Scheduling

4.1.5 Mathematical Models: Develop mathematical models of the system to design feedback control functions. <u>Completion:</u> end of month three.

4.1.6 Problem Sub-division: Subdivide the overall scheduling and resource management control problem into a set of basic mathematical control sub-problems. Completion: end of month four.

4.1.7 Problem Solution: For each of the sub-problems identified in task (2), perform mathematical analysis for control function design. Completion: end of month six.

4.1.8 Implementation of the Simulation Platform: A simulation platform is already being developed for this problem in preparation for this research work. We will complete the platform that will provide us with an easy to use and flexible means of testing the effectiveness of the control algorithms. Completion: end of month seven.

4.1.9 Simulation: Perform simulations using the simulation platform and test the control functions using appropriate problem scenarios with chosen inputs. Completion: end of month eight.

4.1.10 Implementation of Control Algorithms on the Digital Ship Test-bed: Implement the control algorithms on the Digital Ship test-bed. Completion: end of month twelve.

Deliverables: The deliverables include an interim report and final report. The interim report will describe the mathematical models, subdivision of control problems, their analysis, and plans for simulation and implementation on the test-bed. Final report will describe the feedback control algorithms, analytical and simulation results, and implementation results on the test-bed.

Principal Investigator

Binoy Ravindran is an Assistant Professor in the Bradley Department of Electrical and Computer Engineering at Virginia Tech. He received his Bachelor's degree in Mechanical Engineering from the University of Kerala, India in 1991, Master's degree in Computer Science from New Jersey Institute of Technology (NJIT) in 1994, and Ph.D. in Computer Science and Engineering from the University of Texas at Arlington (UT Arlington) in 1998. His current principal research focus is on distributed asynchronous real-time systems having custom, application-level, end-to-end quality of services (e.g., timeliness, survivability). While at NJIT and UT Arlington, he conducted research in software engineering and distributed real-time systems for the U.S. Navy. He received two "Student Achievement Awards" from NJIT for outstanding research by a graduate student (1994,1995), and a "Doctoral Dissertation Award" from UT Arlington for outstanding doctoral research (1998). During 1997, Dr. Ravindran served as Staff Researcher at Los Alamos National Laboratory where he designed and prototyped network architectures for data mining applications. During 1999, Dr. Ravindran was an invited speaker at INRIA, France, and at the ARTES (Swedish National Strategic Research Initiative in Real-Time Systems) Real-Time Week, Sweden. He also served as the Program Chair of the 1999 IEEE International Workshop on Parallel and Distributed Real-Time Systems.

Pushkin Kachroo, Ph.D., P.E., is an Assistant Professor in the Bradley Department of Electrical and Computer Engineering at Virginia Tech. He has been a Research Scientist at the Virginia Tech Transportation Institute for about four years. He worked in the R&D robotics laboratory of the Lincoln Electric Co. for two years in a team that developed the first automatic laser vision based welding robot for the company. He received his Ph.D. from University of California at Berkeley in 1993, M.S. from Rice University in 1990, and B.Tech from I.I.T Bombay in 1988. He has a P.E. in Electrical Engineering from the state of Ohio. He has authored two books in 1999: Feedback Control Theory for Dynamic Traffic Assignment, Springer Verlag , and Incident Management for Intelligent Transportation Systems, Artech House. He also has co-authored four edited volumes. He has authored about 50 journal and conference publications.

Budget

The summary request for funding is depicted in the table below. Budget breakdowns and justifications are presented after the summary.

1. Wireless Secure Communications		**$511,636**
1.1 Smart Antennas	$120,386	
1.2 ..deleted..	$0	
1.3 Multifunctional Antennas	$135,000	
1.4 Secure Configurable Platform	$256,250	
2. Visualization, HCI and Collaboration		**$996,383**
2.1 Scientific Visualization	$311,410	
2.2 HCI	$174,200	
2.3 Command and Control: Collaboration and Coordination	$400,772	
2.4 Multifunctional Optical Displays	$110,001	
3. Computer Network Interoperability		**$372,333**
3.1 Network Test Bed	$252,330	
3.2 Network Analysis	$120,003	
4. Real Time Interoperability and Combat Systems		**$85,433**
4.1 Distributed Asynchronous Real Time System	$85,433	
Total Requested Funding		**$1,965,785**

Virginia Tech

Project 1.0 Wireless Secure Communication Budget

	First Year	Second Year	Total Project 1
Personnel			
Faculty	$21,501	$44,034	$65,535
GRA	$130,113	$168,733	$298,846
Wage	$5,280	$25,363	$30,643
Undergraduate Student	$15,600	$15,600	$31,200
Total Personnel Salaries	$172,494	$253,730	**$426,224**
Fringe Benefits	$6,171	$16,214	**$22,385**
Tuition	$29,520	$38,289	**$67,809**
Equipment	$71,510	$157,286	**$228,796**
Supplies	$13,570	$24,445	**$38,015**
Travel	$6,000	$12,500	**$18,500**
Contractual Services	$0	$0	**$0**
Sub--TECSEC	$100,000	$100,000	**$200,000**
Total Direct Costs	$399,265	$602,464	**$1,001,729**
Indirect Costs	$99,510	$140,913	**$240,423**
Total Costs	**$498,775**	**$743,377**	**$1,242,152**

Budget Justification

The supplies and equipment costs are for the purchase of necessary hardware to execute the project. A subcontract to TECSEC ($200,000) is included for the security software work. The travel budget is for travel to/from Navy sites as well as the presentation of this work at relevant conferences.

Project 1 Equipment List

Item	Value	Justification
Rockwell RF front-ends (2)	$15,000	Needed to complete test bed for task 1.1--Space-time coding test bed
Laptop computer with external DSP co-processor	$10,000	Needed for interfacing to the array collection system and for processing data for task 1.1
Rockwell miniature radio codex (2)	$18,000	Construct secure platforms for task 1.4--Configurable front-end for software radio
Myrinet LAN cards (10)	$14,000	High-speed networking in the testbed for task 1.4
Myrinet switch	$6,000	Connecting Myrinet cards to provide high speed networking in the testbed for task 1.4
SLAAC configurable	$118,685	Part of testbed to demonstrate the

computing board (8)		utility of secure, configurable software radios and secure configurable network routers for task 1.4
SLAAC Configurable computer boards augmented with boards to connect to radio (2)	$38,510	Construct secure platforms for task 1.4--Computational platform for software radio
Total for Project 1	**$ 220,195**	

Project 2.0 Visualization, HCI and Collaboration Budget

Personnel		
Habayeb	$68,750	
Post Doc	$25,000	
Murtafa, 100%, 7.5 months	$22,500	
Kelso, 69%, 7.5 months	$34,417	
Arsenault, 72%, 7.5 months	$39,602	
Hix, 100%, 2 months	$15,077	
System Admin, 25%, 7.5 months	$9,375	
Holton	$4,600	
Zhao	$14,500	
GRA (C,1), 7.5 months	$10,388	
GRA (C,2), 7.5 months	$20,776	
GRA (C,3)--9, 7.5 months	$98,525	
Total Personnel Salaries		**$363,510**
Fringe Benefits		**$56,956**
Tuition		**$44,817**
Equipment		**$212,397**
Supplies		**$10,500**
CAVE Usage		**$23,450**
Travel		**$38,000**
Contractual Services		**$17,355**
Total Direct Costs		**$766,985**
Indirect Costs		**$229,398**
Total Costs		**$996,383**

Budget Justification

Contractual services include memory upgrades for the immersive workbench computer and maintenance agreements for the workbench and computer. A server and 2 PCs are needed to establish the collaborative workspace. Servers, LAN hardware and software are required to assemble the SIMS. Water filters, a lock-in amplifier, an optical source and a photolithography system are requested because they are not available within the Fiber & Electro-Optic Research Center and because they are needed to fabricate displays. Small chemical, mechanical and optical materials and supplies are requested to support the proposed work.

Project 2 Equipment List

Item	Value	Justification
195MHz R10K CPU board for Onyx computer	$16,547	Needed to upgrade computer to power immersive workbench for task 2.2
1-64MB Texture memory raster manager for Onyx computer	$35,750	Needed to upgrade computer to power immersive workbench for task 2.2
Water filters for ESA lab	$3,500	Needed to upgrade laboratory for optical display development in task 2.4
Lock-in amplifier	$4,200	Needed to upgrade laboratory for optical display development in task 2 2.4
Photolithography layout system	$10,900	Needed to upgrade laboratory for optical display development in task 2.4
Optical source reference and detectors for Digital Ship simulator system	$6,200	Needed to upgrade laboratory for optical display development in task 2.4
Impedance analyzer	$30,150	Needed to upgrade laboratory for optical display development in task 2.4
PC workstations (3)	$9,000	Needed to build collaborative workspace for task 2.3
PC workstations with software (6)	$35,400	Needed to develop prototype of SIMS for task 2.3
10/100 ethernet (12)	$15,000	Needed to develop prototype of SIMS for task 2.3
Servers (5)	$45,000	Needed to develop prototype of SIMS for task 2.3
Databases (3)	$15,000	Needed to develop prototype of SIMS for task 2.3
Lab benches/shelves	$10,000	Needed to develop prototype of SIMS for task 2.3
LAN monitoring software (3)	$9,000	Needed to develop prototype of SIMS for task 2.3
Total for Project 2	**$212,397**	

Virginia Tech

Project 3.0 Computer Network Interoperability Budget

Personnel		
Nance, 10%, 7.5 mon	$9,475	
Arthur, 10%, 7.5 mo	$5,116	
GRA (C,1)-- 7.5 months	$10,388	
GRA (C,2)--4, 7.5 months	$45,000	
GRA (C,3)-- 7.5 months	$21,750	
Total Personnel Salaries		**$91,729**
Fringe Benefits		**$3,648**
Tuition		**$24,045**
Equipment		**$162,287**
Supplies		**$5,600**
Travel		**$15,300**
Contractual Services		**$12,000**
Total Direct Costs		**$314,609**
Indirect Costs		**$57,724**
Total Costs		**$372,333**

Budget Justification

We will deploy a common test bed to support these research tasks and, in particular, to enable demonstrations of candidate solutions to network interoperability problems. The test bed will consist of commercial ATM switches, commercial IP routers, 100-Mbps Ethernet switches, IEEE 802.11 wireless local area network access points, and personal computers. The different network technologies offer a variety of capacities and capabilities to provide a heterogeneous testing environment. The personal computers will be capable of running either Windows NT or UNIX (Linux or FreeBSD) and will act as specialized routers, gateways and firewalls and 10/100-Mbps Ethernet and IEEE 802.11 hosts. To facilitate investigation of wide area networking issues, the test bed will be distributed between Virginia Tech's Blacksburg, Virginia campus and Virginia Tech's Alexandria Research Institute in Alexandria, Virginia. The two sites will be connected via at least DS1 (1.5 Mbps) connectivity using the statewide NET.WORK.VIRGINIA ATM network. Equipment, supplies, DS1 service, software, and laboratory furnishings will be used to implement the network interoperability test bed.

Project 3 Equipment List

Item	Value	Justification
Multi-protocol routers (3)	$18,000	Needed to develop test bed for task 3.1
ATM edge switches (2)	$50,000	Needed to develop test bed for task 3.1
10/100 ethernet switches (4)	$4,800	Needed to develop test bed for task 3.1
Wireless LAN access point (3)	$3,300	Needed to develop test bed for task 3.1
Wireless LAN adapters (12)	$3,600	Needed to develop test bed for task 3.1
Wireless LAN PC card adapters (6)	$480	Needed to develop test bed for task 3.1
Linux/NT PCs (9)	$27,000	Needed to develop test bed for task 3.1
Linux/NT Notebooks (6)	$18,600	Needed to develop test bed for task 3.1
LAN monitoring software (2)	$6,000	Needed to develop test bed for task 3.1
Lab benches/shelves	$ 13,710	Needed to develop test bed for task 3.1 & 3.2
Plain paper copy board	$3,000	Needed to develop test bed for task 3.2
LCD projector	$7,800	Needed to develop test bed for task 3.2
HP 2100TN printer	$967	Needed to develop test bed for task 3.2
HP 4500 laserjet printer	$2,200	Needed to develop test bed for task 3.2
Trinitron 500PS display	$1,120	Needed to develop test bed for task 3.2
Trinitron 200PS displays (3)	$1,710	Needed to develop test bed for task 3.2
Total for Project 3	**$162,287**	

Project 4.0 Real Time Operability and Combat Systems Budget

	First Year	Second Year	Total Project 4
Personnel			
Faculty		$16,028	**$0**
GRA	$17,091	$53,325	**$16,028**
Wage	$8,145		**$70,416**
Total Personnel Salaries	$25,236	$69,353	**$94,589**
Fringe Benefits	$0	$1,443	**$1,443**
Tuition	$4,373	$13,514	**$17,887**
Equipment	$0	$5,000	**$5,000**
Supplies	$0	$340	**$340**
Travel	$2,000	$4,000	**$6,000**
Contractual Services	$0		**$0**
Total Direct Costs	$31,609	$93,650	**$125,259**
Indirect Costs	$12,371	$34,500	**$46,871**
Total Costs	**$43,980**	**$128,150**	**$172,130**

Budget Justification

Two PCs and associated software are requested for the real time operability study.

Project 4 Equipment List

Item	Value	Justification
PC workstations with software (2)	$5,000	Needed to develop scheduling and resource management algorithms for task 4.1
Total for Project 4	**$5,000**	

Contract Data Requirements List