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Payoffs and Challenges of Human Systems Integration (HSI) Modeling and Simulations in a Virtual Environment

ABSTRACT To ensure that the human component is adequately addressed in system design, requirements for human performance, manning levels, training, and safety, the elements of human systems integration (HSI) must be considered early in the design process. HSI requirements are integrated through implementation of HSI modeling and simulation (M&S). Objectives of HSI M&S are to: (1) assess alternative concepts in terms of human performance, productivity, workload, and; (2) provide human performance inputs to system level simulation, and determine the impact of system design and organization on human performance and safety; (3) quantify relationships between human capabilities and system characteristics; and (4) visualize and quantify spatial relationships between humans and system elements.

Payoffs of HSI M&S are the ability to: (1) acquire data on human performance, skills, and safety provisions in advance of system construction; (2) model human performance in system concept alternatives; (3) assess human performance as a function of human machine interface (HMI) design concepts; and (4) assess team performance as a function of HMI design, communications design, and collaborative problem solving.

Challenges of HSI M&S in a virtual environment include problems associated with: (1) virtual interfaces (of the simulated system); (2) human perception and cognition in virtual environments; (3) virtual object manipulation; and (4) quality of data acquired during simulation.

INTRODUCTION

Human systems integration (HSI) is the systems engineering discipline which combines the principles, methods and data of engineering with behavioral science to address the requirements of humans in complex systems. As a systems engineering discipline, HSI incorporates (1) a systems domain—the human element of the system; (2) a set of objectives directed at optimizing the integration of the human into the system, (3) methods and tools directed at: identification, analysis and integration of requirements; design of system elements (human machine interfaces) to meet these requirements; and evaluation of the adequacy of the design in terms of the requirements, (4) databases of design principles, standards and human performance data, and (5) measures of effectiveness.

HSI modeling and simulation (M&S) is an experimental or analytical evaluation designed to satisfy unresolved issues or problems with human integration into the system. Its objective is the collection of data on defined aspects of human performance or behavior, under controlled conditions, and using a representation or model of relevant system characteristics. HSI modeling and simulation represent an experiment (a controlled assessment of independent variables in terms of dependent measures) or an analysis (examination of human and/or system characteristics at greater levels of detail). Its purpose is to critically evaluate some aspect of the system, and human involvement in that system aspect. It is concerned with acquisition, collection, analysis, and interpretation of experimental or analytical data. Finally, HSI M&S employs a representation or model of relevant system and/or human characteristics, performance, or behavior. It is this representational aspect that distinguishes a simulation from other methods of experimentation and analysis. To be a simulation, a study must employ a representation of a real world entity. The representation may be logical (a computer model), physical (a mock-up, physical model, breadboard, or prototype), or virtual. It is the requirements for HSI simulation using a virtual representation of the system and/or human attributes that comprise the thrust of this paper.

HSI MODELING AND SIMULATION

A major concern of HSI simulation regards the characteristics of the data used and collected. The primary issue for data collection in HSI simulation is the concern for data quality. Simulation data quality is a direct function of data reliability, data validity, data accuracy, and data relevance.

- *Data reliability* is an index of the extent to which spurious factors influence the simulation data. Data reliability requirements indicate the need for precision in the data as a function of the adequacy of the experimental controls applied in the acquisition of data. Data reliability is a measure of the amount of measurement error in the data and data reliability is maximized (measurement error minimized) through strict control of data acquisition conditions.

- *Data validity* is an indication that the simulation data measure what they were intended to measure. Data validity is also an indication of the amount of sampling error in the data.
- *Sampling* addresses the requirement that simulated conditions are representative of conditions in the real world being simulated. A sample is a subset of a population selected to ensure simulation data will be generalizable to the population.
- *Fidelity* on the other hand is concerned with the extent to which the simulated representation reflects some aspect of the real world.
- *Data accuracy* requirements indicate the extent to which inaccuracies will be accepted in test data. Accuracy of acquired data depends on the precision of the data acquisition and recording provisions in the simulation.
- *Data relevance* is an indication of the extent to which simulation data are pertinent to the issue at hand. HSI simulation is usually concerned with some aspect of human performance, behavior, response, safety, workload, adaptation, limitations, and interaction with machines and other humans.

Another significant area of simulation is the concern for supporting modeling and evaluating human behavior, human performance, and human involvement in the system. In all HSI simulation it is the human, human functions and tasks, human performance capability, or aspects of the system with which the human interacts, that is being simulated. The representation of the system (including the mission and environment) can include the human but always includes interfaces between the human and other components of the system. These interfaces can be functional (operations and tasks), environmental (physical environment and tactical environment), informational (information sensed and processed by the machine to be provided to the human), organizational (hierarchy of workstations, organization of data), operational (workloads, missions, time constraints), cooperational (communications, collaboration in team performance), cognitive (decision rules, diagnostics, discriminations), and physical (actual system elements such as controls, displays, workspace, etc.).

OBJECTIVES

The objectives of HSI modeling and simulation are to:

1) assess alternative system design concepts in terms of human performance, productivity, workload, and safety using a logical, physical or virtual representation of the system, equipment, and environment before finalizing design decisions and directions;
2) provide human performance inputs to system level modeling and simulation, and determine the impact of system design and organization on human performance and safety;
3) quantify relationships between human capabilities, operational variables, and design concepts for workload, visual fields, arrangements, traffic patterns, personnel interactions, display, maintenance access, etc.;
4) visualize and quantify spatial relationships between humans and workstations, worksites, spaces, equipment, and environments;
5) engage in realistic, high fidelity training of Navy personnel;
6) provide means to effectively engage in war gaming and mission rehearsal that is both low cost and effective.

CLASSES OF HSI SIMULATION

The classes of HSI modeling and simulation are:

- computer models of human interactions with system operations, equipment and conditions.
- warfighter-in-the-loop modeling and simulation.
- HSI CAD modeling and simulation.

Computer models of human interaction with systems elements are of three basic types: (1) task network modeling and simulation (for workload assessment and quantification), (2) human performance models (for inclusion into system level simulations), and (3) problem solving/planning simulation (diagnostic problem solving—reduction of uncertainty, rehearsal—playout of expected scenarios, mission planning, predictive "what-if" simulation, and war gaming).

Warfighter-in-the-loop simulation involves the simulation situation where one or more human participants interacts with synthetic system elements (including other crew) using a representation of the system aspects of interest. This simulation is of three types:

1) a single human warfighter-in-the-loop actually performing tasks with a virtual representation of system human interfaces—controls, displays, workstation elements, information, environments, or maintenance workspace. The results of these simulations are concepts and criteria for: human performance as a function of human machine interface (HMI) design concepts; human interaction with automation—decision support; teleoperation—telemaintenance; workload measurement—dynamic allocation of functions; and information management.
2) multiple human warfighters-in-the-loop performing mission tasks as in the single warfighter class. Results of these simulations include concepts and criteria for: team performance as a function of HMI design; communications design and protocols; collaborative/coop-

erative problem solving; and investigations of the impact of stress on human performance.

3) mixed real and synthetic warfighter-in-the-loop incorporating a combination of several human operators and several simulated operators performing tasks involving real and simulated systems and platforms, under real and simulated environmental conditions, conditions of readiness, and threat conditions. The results of these simulations include: full mission simulations; total ship training simulation; and battle force tactical training.

HSI CAD simulation includes the simulation setup where a representation of one or more synthetic warfighters interacts with synthetic elements of the system for purposes of visualization of workstation or ship space arrangements and demonstration of operational requirements, traffic patterns, and resource allocations. The two types of simulation in this class are:

1) single human model or mannequin observed to perform tasks at a workstation or worksite with emphasis on visualization of reach envelope, field of view or visual envelope, control and display placement, workstation anthropometrics, etc. The results of these simulations are: design concepts and criteria for physical interactions with arrangements; visual—reach envelopes; maintenance access; emergency egress; and watchstation arrangement and orientation.
2) multi-human models or mannequins (physical or virtual) observed to perform tasks in a simulated environment where the emphasis is on visualization of arrangements, layouts, queuing, and interactions. Results of these simulations include concepts and criteria for: aircraft servicing; multi-person maintenance activities; deck operations; space arrangements—multi watchstations; and traffic patterns—cargo transfer.

HSI M&S virtual environment applications can be defined for classes and types of HSI M&S. These are presented in Table 1.

TABLE 1. HSI M&S CLASSES

M&S Types	Computer Model	Warfighter-in-the-loop	HSI CAD
Analysis	Visualization of function allocations and task parameters	Task Performance	Visualization of comm links, information flow, OSDs
Diagnostics		Virtual display of decision support for diagnostics	
Engineering Simulation	Visualization of task network simulation for workload & perform assessment, and human performance modeling	Virtual workstation for assessing human performance for function allocation strategies	Visualization of arrangements, queuing, traffic patterns, cargo handling, damage control.
Training	Visualization of training needs, terminal objectives	Conduct of skills training using virtual representations	Conduct of training for comms, management organization, and supply support using visualization
Test and Demo	Visualization of HSI test requirements and procedures	Review of workstation consolidation using virtual representations	Review of arrangements using virtual displays
Planing/Gaming	Symbolic visualization of resource allocations, mission planning and gaming	Mission rehearsal	

TYPES OF HSI SIMULATION

The types of HSI modeling and simulation, defined by the purpose of each, are as follows:

- *Analytical M&S*—for mission, function, task, workload, timeline analyses; tradeoff analysis; and design requirements integration.
- *Diagnostic M&S*—playout of alternate scenarios for purposes of supporting decision making and diagnostics.
- *Engineering simulation*—to support development and evaluation of design concepts and approaches.
- *Training simulation*—to support training delivery, rehearsal of learned skills, and interactive gaming.
- *Test and demonstration simulation*—visualization of concepts to test and demonstrate feasibility and risk reduction.
- *Planning/gaming simulation*—force level war gaming.

M&S IN VIRTUAL ENVIRONMENTS

While there is an enormous benefit that can be accrued by modeling and simulation endeavors using virtual environment (VE) technology, there are also significant challenges and risks that must be addressed. It is one thing to put a human in a digitally created, synthetic environment and expect him or her to enjoy this new experience for a few moments. It is quite another to expect humans to perform productive work (e.g., training, equipment operation, decision rendering and execution, design development, and so forth) within that environment for protracted periods of time. Our sensory experiences, expectations, reasoning facilities, memories, and so on have developed within the context of sensing, reasoning, and behaving in an extremely reliable and constant *literal* world.

Unless we are willing to take enormous risks associated with human safety and performance in *virtual* environments we must carefully examine the nature of humans and the synthetic environments in which we will be placing them.

There is vast research literature related to components of VE. Many of these were performed well before the notion of VE was put forth, but are nonetheless apropos to the topic. These research areas include: stereopsis (capabilities of vision given two eyes with slightly different world views), audition, depth perception cues and integration of those cues, stimulus orientation, biomechanics (ranges, speeds and forces of body motion), kinesthesis (sensing of musculosleketon system attitudes), proprioception (sense of accelerating forces, generally gravity), human motor control, human anthropometrics, haptics (touch), olfaction (smell), and the gustatory senses (senses of the mouth and palette). The research literature related to 3-dimensional viewing alone numbers in the tens of thousands of articles (stereopsis, for example, has its own professional society).

Bringing all the accumulated HSI/human factors knowledge to the design of VE will be an enormous task, to say the least. What seems to be happening is 1) VE developers are establishing de facto standards for interfaces based on experiences during VE interface design efforts, and 2) new research is being performed which specifically addresses the VE interface and its components in the context of a VE system (as opposed to examining stereopsis alone, for example). This type of research is required since the convergence of VE technologies in establishing virtual worlds is new, and many issues are completely unstudied. For example, means to achieve a sense of realness in virtual scene exploration (that integrates object acuity, visual contrast, permanence, and persistence), are not well known. The use of anecdotes and phenomenal impressions by VE developers, in concert with a growing body of VE interface research, will probably form (at least in the near term) the basis for VE interface design.

What follows is a summary of human related issues that need to be recognized and addressed as VE technology is employed by the Navy. The issues are presented in three general Categories, as follows:

- Safety and health
- Sensation, perception, and motor control
- Cognition and Task Performance

SAFETY AND HEALTH

There are a number of safety and health concerns associated with VEs, these include: flicker induced disorientation, potential hearing loss from high volume audio, repetitive stress disorders and syndromes, and "simulator sickness," a condition peculiar to artificial sensory environments such as wide field of view simulators and virtual environments (Kennedy et al, 1989). Simulator sickness is generally characterized by the following symptoms:

- eyestrain, blurred vision and fatigue
- disorientation, loss of balance
- nausea

In some cases, simulator sickness can be completely debilitating, with sufferers unable to remain standing or seated without assistance, and experiencing excessive nausea and gastric discomfort (Kolasinski et al., 1995).

Vection is involved with simulator sickness. Vection is a condition where two or more sensory mechanisms are in perceptual disagreement about movement within a space. Vection occurs when a visually based perception of motion is not synchronized with other sensory modes perceiving motion. For example, when visual input indicates that one is accelerating forward, but at the same time there is no (or a contrary) kinesthetic sensation of forward acceleration, vection can result. Vection can also be induced by somatosensory mechanisms, for example when walking in the dark, or in the opposite direction of a rotating platform (Boff and Lincoln, 1988). Displays which produce strong vestibular effects are likely to produce the most simulator sickness (Kennedy et al., 1988).

Simulator sickness occurs more frequently in immersive VE than in simulators with wide field of views that fill the users visual field (Kennedy et al, 1995).

Disorientation and nausea in VEs are similar to the symptoms of motion sickness and both are considered to be caused by sensory conflict as stated by Reason and Brand (1975) and as cited in Kolasinski et al. (1995): "all situations which provoke motion sickness are characterized by a condition of sensory rearrangement in which the motion signals transmitted by the eyes, the vestibular system and the non-vestibular proprioceptors are at variance either with one another or with what is expected from previous experience." In other words, sense of motion and position is achieved through an integration of:

- the visual scene
- vestibular receptors (semi-circular canals and the otoliths)
- other somatosensory systems such as the proprioceptors
- perceived self-motion (a cognitive integration of the above)

When any of these are in disagreement (in terms of their "reporting" the state of the environment) then motion sickness can occur. The greater the disparity of reporting, the greater the likelihood and magnitude of illness.

Factors Influencing Simulator Sickness

Factors associated with simulator sickness in VEs are shown in Table 2 (adapted from Kolasinski et al. (1995)).

Individual differences (among humans) in susceptibility to simulator sickness are quite varied. Some notable individual factors are as follows (Kolasinski et al., 1995):

- Motion sickness susceptibility is greatest between ages of 2 and 12 years. Susceptibility tends to decrease rap-

TABLE 2. POTENTIAL FACTORS ASSOCIATED WITH SIMULATOR SICKNESS IN VIRTUAL ENVIRONMENTS (adapted from Kolasinski, et. al., 1995).

Individual Differences	Simulator Factors	Task Factors
Age	Binocular viewing	Altitude above terrain
Concentration level	Calibration	Degree of control
Ethnicity	Color	Duration
Real-world task experience	Contrast	Global visual flow
Simulator adaptation	Field of view	Head movements
Flicker fusion tolerance	Flicker	Luminance level
Gender	Inter-pupillary separation	Unusual maneuvers
Illness	Platform motion	Method of movement
Mental rotation ability	Phosphor lag	Posture (Sitting, sanding)
Postural stability	Tracking error	Self-movement speed
Perceptual style (sensory channel emphasis)	Viewing region (size of simulated visual field)	Linear or angular acceleration forces
	Scene content	Vection
	Time lag (transport delay)	Type of application
	Update rate (frame rate)	
	Refresh rate	

idly from 12 to 21 years, then more slowly through the remainder of life (Reason and Brand, 1975).
- Females tend to be more susceptible than males.
- Chinese women may be more susceptible than European-American or African-American women.
- Posturally less stable individuals may be more susceptible to simulator sickness.
- The state of health of an individual (presence of flu, ear infection, hangover, sleep loss or when taking certain medications).
- The incidence of sickness has been shown to decline with increasing experience in both simulators and VEs.
- Individuals' perceptual styles differ in terms of how sensory channels are used and integrated in interpreting the state of the literal world.

Hardware Characteristics play a crucial role in invoking (or not) simulator sickness. Some of these factors include:
- The luminance, contrast and resolution of displays.
- Display Flicker, when readily perceived, can have a powerful influence on the onset of illness.
- Optical factors contributing to occulomotor symptoms are related to motion and simulator illness.
- Temporal correlations of simulated events and virtual displays are not well correlated. System lags of less than 300 ms are necessary to maintain an association of an individuals movements with associated (virtual) image motions.
- Attitudinal correlation's (body position sensing) are off. For example, in head trackers, if the human's proprioceptive sense of head position differs from a head tracker's sense (which drives display generation), then visual images and proprioceptive expectations become disassociated.

Task variables and simulator sickness factors include the following:
- Degree of control over the motion affects simulator sickness. For example, the incidence of simulator sickness among air-crew has been reported to be lower in pilots than in co-pilots or other crew members.
- The speed of global visual flow (i.e. the rate at which objects flow through the visual scene).
- A wide Field-of-view requirement may enhance performance in a simulator but it also increases incidence of simulator sickness.
- Requirements for head movement and visual tracking increases illness since conflicts between visual and vestibular motion cues increase sensory variance.

SENSATION, PERCEPTION, AND MOTOR CONTROL

Depth Cues. Effective depth cues in VE include; interposition (nearer objects masking view of more distant objects), height in the picture plane, object size, stereopsis, motion parallax, and accommodation (focus) to name a few. In addition, other sensory modes can influence perception of depth (sound volume, for example). Depth cues can operate alone and in combination. Depth cues also can conflict with one another. For example, when a stereoptic cue tells us that an object is off in the distance, while the objects known size (a car for example) tells us the object is close, perceptual variance is induced. When such variances occur, very odd perceptual experiences result (to test this, view a cross-polarized or red/blue lens 3-D system with the lenses reversed). VE systems must therefore accommodate numerous depth cues, and provide adequate integration among the cues provided. Three-dimensional auditory displays can enhance and convey meaning about the direction and distance of virtual objects in virtual environments (www.ehto.be/ht_projects/vrepar/hfact.htm).

Pupillary Separation. This can be a significant issue when a VE user has an inter-pupillary separation (separation distance between the pupils of an individuals eyes) which is greater or smaller than that for which visual images are configured. Where this is the case, potential eyestrain, headaches, and associated visual system problems may result. The empirical evidence suggests that for individuals whose inter-ocular separation is smaller than that for which the system is configured may experienced ocular problems such as eyestrain and fatigue. In addition, virtual scenes, as presented to each eye, can exaggerate or reduce (virtual) pupillary separation distance. This will have a significant effect on the perception of depth that is derived from bifoveal disparity. Where eye separation is exaggerated, the sensation will be that one is looking at the world through a wide angle lens. Where minimized, the effect is as though looking at the world through a telephoto lens (depth compression without magnification—everything looks as though it were painted on a distant wall).

Depth of Focus Effects. A difficult problem with screen based VE systems is the lack of focus effects. The fixed focal distance of the virtual screen causes a focal conflict that can induce eyestrain and contributes to perceptual variance. This is a conflict of extent of accommodation (focus) of the lens and extent of binocular convergence. There is significant efferent control of the muscles of the eye due to the extent of contortion of the lens of the eye. When the lens is relaxed (an object is in close to the eye) the eyes converge at a point in front of the face (because the object is in close). Lack of focus effects confuses this visual mechanism.

Exploratory Viewing. This viewing involves users orienting to VE scenes in order to gain perspective and orientation, for example, rocking ones head to gain a slightly different perspective of a scene. Brooks states that the ability to move the viewpoint needs to be a separate control in most interfaces and that rocking is much better than rotation. He also states that user-positioned light sources and user-controlled camera zoom substantially enhance the perception of structure in the exploration of a passive virtual scene (Brooks, 1988).

Touch (Haptics). The area of touch has been broken down into two different areas. *Force feedback* deals with how the virtual environment affects a users sense in interacting with solid virtual objects. For examples, walls that stop someone instead of letting them pass through, and sensing the strength of ones grasp on a hand held object. *Tactile feedback* deals with how a virtual object feels. Temperature, size, shape, firmness, and texture are some of the bits of information gained through the sense of touch. The texture of a surface is an extremely difficult feature to simulate.

Object Manipulation. The virtual handling of objects poses a significant challenge to developers of virtual environments. If you were handling a virtual egg, for example, how would one know whether they are squeezing it so hard that it may break, or not hard enough to keep hold? Object behavior can also be a problem in simulation ("Did I press that virtual button?"). There are several different types of devices that allow a user to "feel" certain aspects of force application. Force feedback gloves, exoskeletons, and butlers (a robot that basically gets in the way whenever you try to move through an object) are all forms of force feedback mechanisms that can aid greatly in simulating the control and manipulation of objects in virtual spaces.

Virtual Space Occupancy and Bump Detection. Much is sacrificed in terms of realness when two presumably solid objects apparently occupy the same space. This problem has been reported numerous times. Shared occupancy of solid objects in space and user observation of the collision of virtual objects that don't behave as expected significantly reduces the sensation of virtual realness. Means to enhance virtual realness and virtual world predictability is to incorporate other senses, such as audition, in VE world object manipulation. For example, provision of a "bump" or scraping sound when object collide or are placed on surfaces.

COGNITION AND TASK PERFORMANCE

Scene Fidelity. VE systems need extensive computing power and tradeoffs have to be made among the VE components competing for processing cycles (scene generators, 3-D sound generation, etc.). Scenes do not generally afford a level of fidelity to the literal world along even one sensory modality, let along an integrated VE encompassing vision, audition, acceleration, etc.

Effects of Lags on Performance. The effects of lags on the performance of tasks is dependent on the frequency and magnitude of head movements, the field of view of the display, and depth cues provided by the display. Lags show up sharply when one is trying to hold a virtual object still in space as one moves the head about it. (Puttre, 1991).

Progressive Refinement. This addresses perceptions of movement and perspective within a virtual environment, and preservation of the sensation of reality. According to Brooks, real-time motion, complex world-models, and high-quality images overwhelm the ability of current hardware to provide a high fidelity and smooth motion effect. Brooks recommends dynamic techniques to address the problem, which include:

- Moving objects realistically, no matter what else suffers.
- Sacrificing image resolution or model complexity or image quality while the user is moving objects.
- When objects stop moving, automatically invoke progressive image-refinement, resolution improvement, progressive detailing, or other means to immediately improve image quality.
- Avoiding jumping or moving images discontinuously.
- Provide a realistic illusion of motion by providing rapid update rates (20 to 30 updates/second) and very short lag between the action of a dynamic device and its effect on the view.

Immersive VE Understanding. According to Brooks (1988), virtual world understanding is difficult and results from the fact that humans have rather precise world-models of our literal world and can navigate in the dark and reach for objects without looking at them. These models are based on years of experience in dealing with a literal environment, and with consistent and reliable cues as to depth and the physics of human interaction. Forming similarly accurate mental models of virtual worlds (with fewer and less reliable cues and stimuli) requires hours of exposure to virtual worlds. To facilitate this, every feasible cue of the real world should be embodied in virtual worlds, so that virtual experiences (and hence models) can be generalized from real world experiences.

Use of Metaphors. The explicit selection of a metaphor for interface components helps in defining issues and making consistent interface design decisions. As stated by Brooks, "Different metaphors demand, or are permitted by, different classes of display devices and input devices."

Uncertainty Reduction. Uncertainty can be defined as ambiguities in our perceptions of the world stemming from lack of (or conflicting) information. For example, when viewing a small animal at a distance and at night, we may be able to discern that it is some creature, but what creature it may be is uncertain. Adding information reduces uncertainty. Adding the information that it has hair, a tail, and runs quickly, for example, reduces uncertainty a great deal. Addition of more information can eliminate uncertainty—we identify the creature as a cat. Uncertainty occurs in the literal world on a constant basis. Cognitive (or better, information) uncertainty is reduced typically by getting more information from (and about) the environment. In the virtual environment, uncertainty increases simply because there is less information available to its occupants, e.g., a needed display is not available virtually, a procedure is absent, or hypotheses formed ("is it a cat?"), while valid, may not be testable.

The following discussion demonstrates requirements for, and application of, HSI Modeling and Simulation in US Navy ship acquisition programs.

REQUIREMENTS FOR SIMULATION IN SHIP ACQUISITION

Ship acquisition simulation programs should contain the 6 basic objectives delineated in DOD 5000.59-P, the Modeling and Simulation Master Plan (October 1995):

- A common technical framework,
- timely and authoritative representations of the natural environment,
- authoritative representations of systems,
- authoritative representations of humans and human behavior,
- an infrastructure which meets developer and user needs,
- shareable benefits.

The common technical framework will enable the user/decision maker to (1) freely access, manipulate and utilize required information through well-defined data standards and protocols, and (2) augment the simulation when and if the need arises when the framework employs a good architectural structure and mission space concept models. As Figure 1 depicts, the simulated environment, the systems under consideration, and people representations comprise a ship simulation program's core.

The marine environment represents the natural environment for ship acquisition programs; however, ship acquisition programs must also represent the design and development environment. Once modeled with time considerations, the product becomes the synthetic environment. Key acquisition disciplines and the design and development environment make up the technical framework. The design and development environment should contain the tools, systems and personnel needed to adequately assess system performance and fieldability. Properly staffed Integrated Product Teams (IPTs) fill the requirement to make performance decisions.

A Modeling and Simulation IPT should, at a minimum, have the user, the system designer, the human systems integration expert, the prospective builder, the logistics expert, and the M&S team member collaborate to determine system performance parameters. This collaboration, effectively applied, will lower life cycle costs, avoid costly rework, allow wide-ranging theory exploration, and enable the user to preview the system before the builder commits the design to production.

The Naval Sea Systems Command has fielded M&S programs in a few surface ship acquisition programs, LPD 17, DDG 51 Flight IIA Aviation Facility and Sealift, while the CVX and DD 21 M&S programs still require further development. Due to an M&S program's enormity (including cost), most ship acquisitions do not adequately achieve all six objectives listed above.

M&S programs encounter another pitfall when personnel involved fail to sufficiently incorporate either the synthetic environment, the human perspective or the system representation. System representation usually suffers less in M&S programs than does the attempt at representing the natural environment and modeling humans and human behavior. The LPD 17 program concentrated more on key systems addressing the ship's major mission area and problems with hardware and software required to effect a robust M&S product than on representing the marine environment, humans and human behavior (Gauthier, Mc-

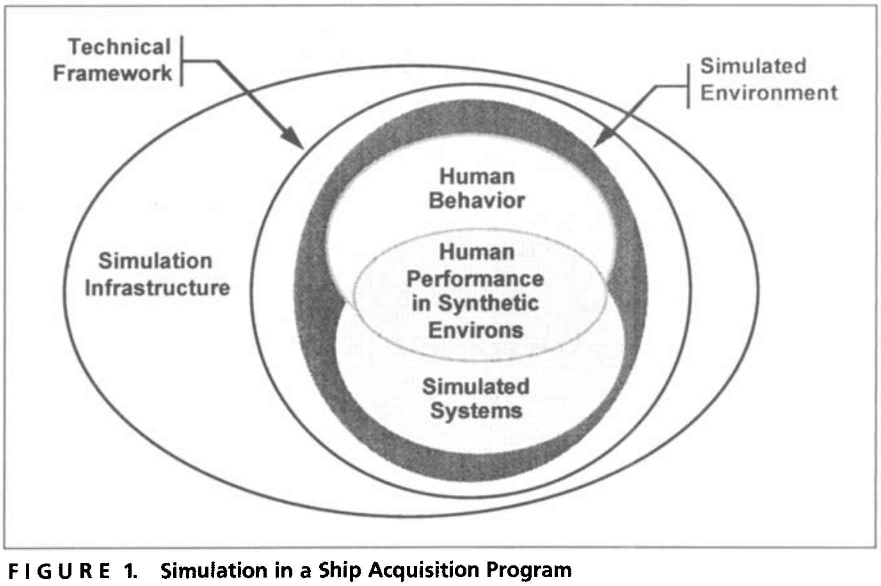

FIGURE 1. Simulation in a Ship Acquisition Program

Intire and Nutting, 1996). Visualization served as their key human engineering parameter. As described herein, however, visualization comprises only a small part of human interactions in the M&S environment.

The Sealift program attempted to address both ship motion and wind effects in addition to modeling key ship systems. In one lessons learned, the authors (Edinburgh, Back and McVeigh, 1996) discuss the sea state statistics and operational impacts on ramp motions: "It was not doubted whether the ramp motion could pendulate the predicted amounts if left to do so [they held the ramp in different critical positions for lengthy time periods to get a good sea state representation]. The question remained whether this was a reasonable approach since a crane operator would not allow these kinds of motions to build up." Modeling typical crane operators and their behaviors in this condition may have provided more insight into this aspect of the Sealift ramp design. The DD 21 and CVX M&S programs, while still in the developmental stage, have an opportunity to incorporate the lessons learned from the LPD and Sealift M&S efforts.

To maximize an M&S program's benefits, a program manager should insist on the system's ability to manage data on a very large scale and precise data coordination to represent all affected system characteristics. It should also include those emerging technologies which not only contain the latest state-of the-art developments, but enhance an M&S's utility. Those aspects include test conditions which reflect the system's expected operating modes and environments. They must also insist on knowledgeable user input and that the developers include all human dimensions, including traditional and cognitive dimensions. The organization's program infrastructures must insist on a common technical framework to enable shared benefits from the M&S effort. Most importantly, the M&S program must consider the user first; this means incorporating human characteristics as integral parts of the design. Those human characteristics require detailed modeling projects which simulate not only emulated motions and abilities, but thought processes of humans which determine decisions an operator makes under the environment in which one works. The discussion now turns to how U.S. Navy Modeling and Simulation technology has been used to enhance human performance characteristics.

APPLICATIONS OF M&S IN ADVANCED MANNING ANALYSIS

This section presents three examples of how the application of M&S technology to Navy system design efforts have resulted in big benefits in terms of enhancing human performance, reducing workload and manning, and providing a significant potential for life cycle cost reductions.

Navy Advanced Information Management Evaluation System

As an example of an inside-out simulation, the US Navy Research and Development Center (NRaD) has developed and applied the Navy Advanced Information Management Evaluation System (NAIMES) to investigate shipboard operator performance using various advanced computer interface designs. NAIMES was used to empirically evaluate alternative tactical symbology sets employing icon shape coding and symbol color coding in a project conducted by the Navy Space and Naval Warfare Systems Command (SPAWAR) (STANAG 4420, 1991). A sample display is shown in Figure 2. The NAIMES simulation assumed that future Navy tactical consoles will be UNIX or POSIX workstations and that OSF Motif compliant graphical user interfaces will be generated using the X Window system. Inside-out simulation techniques focus on cognitive, information processing and decision making aspects of human performance. If a simulation test subject receives specified information via a monitor, reaches a decision and then makes a response via a data entry device, the response time and accuracy of the response can be determined. Over a number of trials, statistical data can be obtained on probability of qualitative error, magnitude of quantitative error and response time. Human behavior in the simulated tasks may or may not be amenable to direct observation. Frequently, it is necessary to save response inputs during trials and score the accuracy of the responses off-line.

In other kinds of tasks, there is overt and observable behavior. Where operators must travel to a worksite, obtain access subject to physical limitations and exert force on manual controls or other components, observable behavior is produced. It is certainly possible to conduct tests and data collection trials in such cases using human subjects and equipment mockups. This classical approach can be expensive, however, due to the cost of constructing mockups in advance of final design data and labor costs of data collection. Outside-in simulations as defined for purposes of this paper involve computer modeling of physical spaces, human anthropometry and operator actions using CAD/CAM computer functionality such as the Deneb Ergo application, discussed later. Essentially, digitally created mannequins having specified anthropmetric dimensions are maneuvered within modeled physical space constraints and the data are used to identify ergonomics problems, access problems, excessive task times, and limits on the percent of the population accommodated by the design in terms of the distributions of anthropometric quantities.

While it would be an expensive undertaking to attempt to develop operator-in-the-loop or outside-in simulations of every manned station and operator action aboard a ship, it should be noted that, increasingly, operators interact with computers to perform shipboard tasks. This trend suggests that low cost simulation of advanced modes of

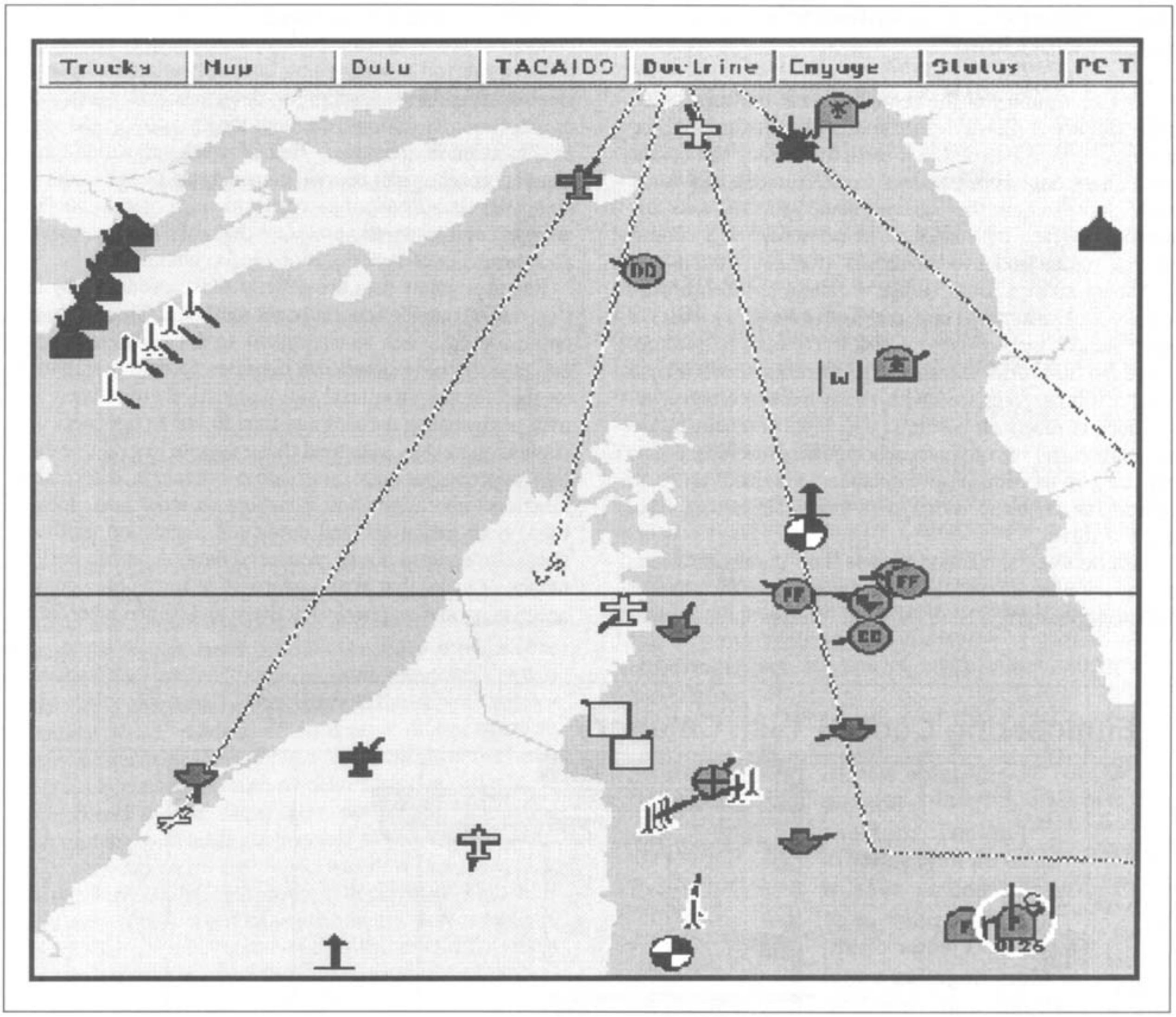

FIGURE 2. Evaluation of Tactical Symbology Using the Navy Advanced Information Management Evaluation System

user-computer interaction for shipboard tasks will become increasingly feasible from both the technical and economic standpoints. Simulating a conceptual shipboard workstation will be much easier and cheaper than simulating direct hardware interaction via functional mockups.

Further, it may not be necessary to conduct inside-out or outside-in simulation for a large number of concepts variants or scenarios that affect crew size, allocation of functions, location of manned stations, travel to local equipment sites, etc. Many of these effects can be investigated using task network simulation tools. Task network simulation involves modeling the operation of a man-machine system as a network of tasks. Tasks are assigned in a fixed or variable manner to selected operators which often represent humans but can also represent machines or other resources. The time taken to perform each task in one or more sequence(s) is modeled as a random variable having a specified probability distribution. Task sequence relationships can be probabilistic so that various contingencies can be represented as occurring with specified probabilities. Task network simulation tools such as SAINT, MicroSaint or SIMWAM (Kirkpatrick et al., 1984) use Monte Carlo methods to sample probabilistic task sequencing and distributions of task time. The man-machine system models that result can have considerable flexibility and can represent real-world scenarios of considerable complexity. When the model is run, the program records statistical data such as the numbers of completions of tasks, the time spent per task per operator and total busy/idle time per operator.

Engineering Control Automation and Human Workload

As another example of the results of task network simulation, Figure 3 shows a distribution of task workload for an Engineering Control watch aboard a surface combatant ship. These data were obtained from a run of a SIMWAM model representing the baseline manpower and task assignments which consist of three personnel in a central control station and five personnel in engine rooms and machinery spaces. Data on the duration and frequencies of individual tasks were obtained from interviews with US Navy subject matter experts and were used to parameterize the SIMWAM baseline (e.g. current) model. These results will be compared with those from alternative allocations of functions based on assumptions about future automation and remote control of auxiliary machinery. The objective is to reduce watchstander workload so as to reduce the required watch personnel complement from eight to three.

Task network simulation models have parameters such as the number of operators and the task qualifications of selected operators. These can be set to appropriate values to represent variant manpower and/or functional allocation concepts. For example, Kirkpatrick, Malone and Kopp (1984) reported a study using task network simulation of shipboard tracking operations to determine how resistance to saturation resulting from high target loads would vary as a function of crew size. Task network simulation modeling approaches can provide considerable power in developing the data needed as inputs to manpower/capability analyses and tradeoffs, provided that valid data on means and variability of task duration can be obtained.

Required input data are exactly those produced by inside-out or outside-in simulation methods. Therefore, an optimized approach would appear to be to utilize inside-out or outside-in simulation methods to obtain statistics on the minimum required set of objectively measured human performance metrics and then to utilize task network simulation models to extend these results to evaluate system concept variants, alternative scenarios, alternative functional allocations and variations in input load. Ideally then, both inside-out and outside-in simulation methods should be used to obtain measured data on human performance of tasks that are 1) intensive in terms of cognitive processing and/or physical activity and 2) are inherent in

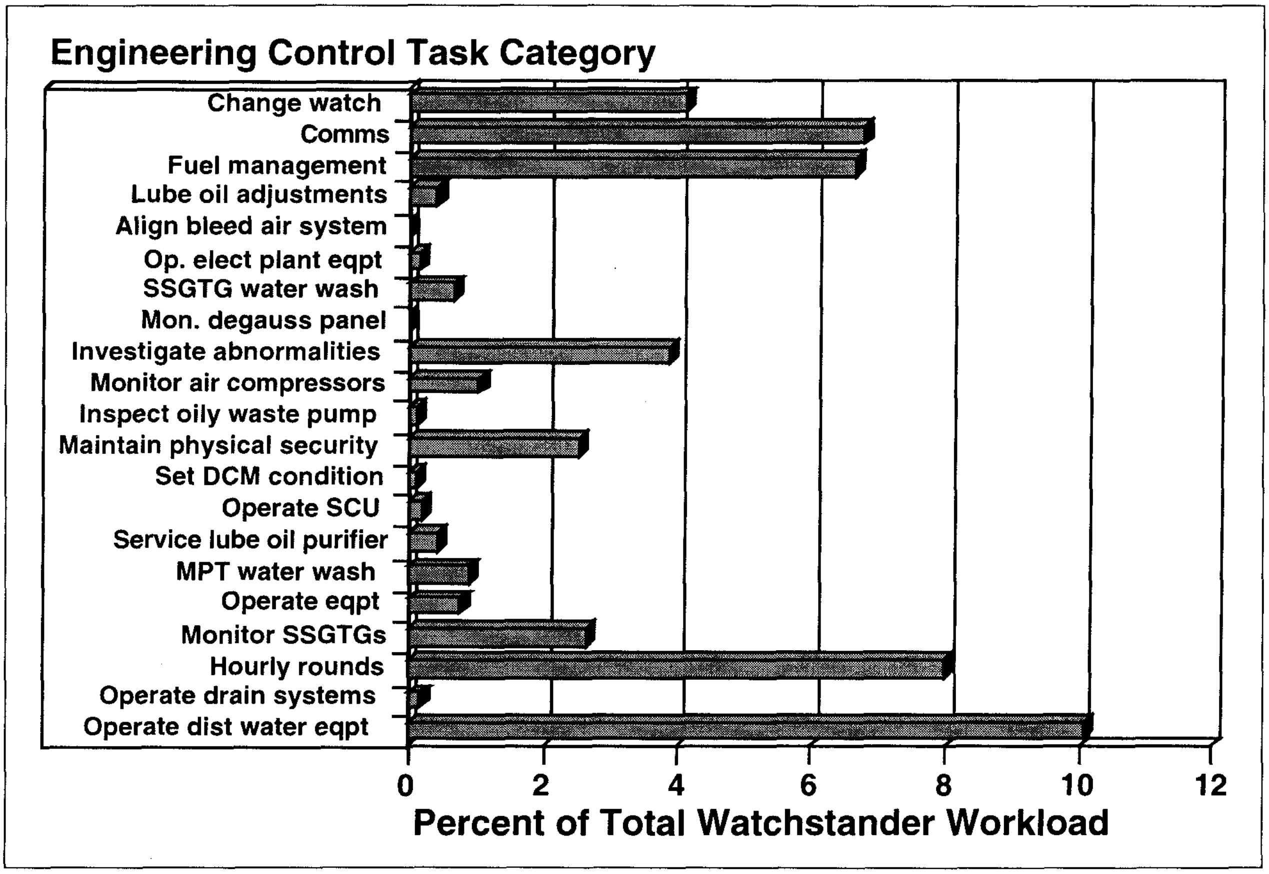

FIGURE 3. Example Task Network Simulation Output—SIMWAM Baseline Engineering Control Model

a given system concept or inherent in predecessor systems similar to the system in question. Statistics calculated from this data set, such as probability of error, mean response time or variance of response time, should be used to parameterize task network simulation models and these models should then be exercised dynamically to conduct "what if" analyses to evaluate alternative function allocations, crew sizes, effects of alternative design factors and effects of scenario variations such as input load.

Assessment of Conventional vs. Integrated Bridge Designs

In order for the reader to better visualize the full capabilities of HSI modeling and simulation, an example of such use is presented, in which several of the techniques outlined in this paper were employed. Inside-out, outside-in and task network M&S approaches were all utilized in assessing manning and HSI requirements.

The scope of this simulation based design effort was to demonstrate the capability of the ERGO[1] software module of Deneb Robotics' IGRIP software for use in advanced manning and human systems integration (HSI) analyses, through the design, development and comparison of a conventional DDG 51 bridge model to an integrated bridge model. This simulation effort involved the design and development of 3-D models, determination of a scenario to employ, performing a functional decomposition of the tasks to be accomplished for both models, scripting tasks to be accomplished by the ships crew, developing the motion programming within the models and assessing results.

The conventional bridge model was developed using the *Arleigh Burke* (DDG 51) design, depicted in Figure 4. This figure shows the normal steaming watch stations of OOD, JOOD, Quartermaster-of-the-Watch (QMOW), Ship Control Console Operator (SCCO), Boatswain's Mate-of-the-Watch (BMOW) and Surface Detector Tracker (SDT). The major items of equipment include two radar repeaters (surface and navigation), chart table, CIC console and ship control console. The integrated bridge design was based on the general configuration and capabilities of state-of-the-art integrated bridges developed by a variety of manufacturers. (Grabowski and George, 1996).

Figure 5 depicts a nominal integrated bridge arrangement, with components of the conventional bridge, such as chart table, being retained. However, the capabilities assumed for this "generic" IBS bridge included full electronic charting and navigation, ship control and decision aids for voyage planning, safe navigation/piloting, collision avoidance and video sensor integration. (e.g., The Sperry Vision 2100M Command & Control System, July 31, 1996). Based on the enhanced capabilities and function integration provided by the integrated bridge, the BMOW SDT, and helmsman have been omitted and their tasks either eliminated or shifted to other watches. For example, the reduced navigation workload allows the QMOW to assume reduced duties of the BMOW.

A "maneuvering in littoral waters" scenario was selected, as it is manpower intensive and would be an expected scenario for the 21st Century Surface Combatant in a littoral warfare role. The real-time situational scenario developed for testing operations in both the integrated and conventional bridge arrangements is represented by the DDG 51 patrolling the mouth of a harbor (Figure 6), while maneuvering past a small off-shore island and several transiting ships.

A functional decomposition of the scenario for each bridge model was accomplished to determine the tasks (and times spent on each task) required for each watchstander. The task network simulation tool, SIMWAM, was used to determine cognitive processes used in the models. The times required for watchstanders' movements were directly determined by ERGO. The motion programming involved creating a master time line, a time line for each ship's track, modeling bridge watchstanders' task movements and cognitive process time (keyed to the master time line). This was done for each simulation, and takes into account the simultaneous activities of the various operators. It also involved the development of pop-up windows (Figure 7) showing the task being performed, the times for each watchstander, a summary window showing the total motion time, and the overall time for each watchstander. Detailed ergonomic data for each operator can also be shown. The desired actions were to compare the times spent on each task between the two models, summarize and compare the total time each watchstander spent during the entire scenario for each model, compare watchstander requirements to accomplish the scenario, determine human factors deficiencies within the two designs, as well as assessing ERGO as an advanced manning analysis tool.

Tables 3, 4 and 5 provide examples of the kinds of comparisons that can be produced as an automatic output.

The detailed results of these simulations can be viewed by designers and integrators in real-time, directly from the computer modeling monitor. As an example of what

[1]The ERGO programming module from Deneb Robotics, Inc., provides anthropometrically correct human models of the 5th, 50th and 95th percentile male and female. Human factors can be evaluated and ergonomic issues can be resolved by both engineer and the system integrator early in the design process. It allows users to rapidly prototype and analyze human motion, including;

- reachability
- interferences
- field of view
- posture analysis
- lifting guidelines
- energy expenditure, and
- accurate activity timing.

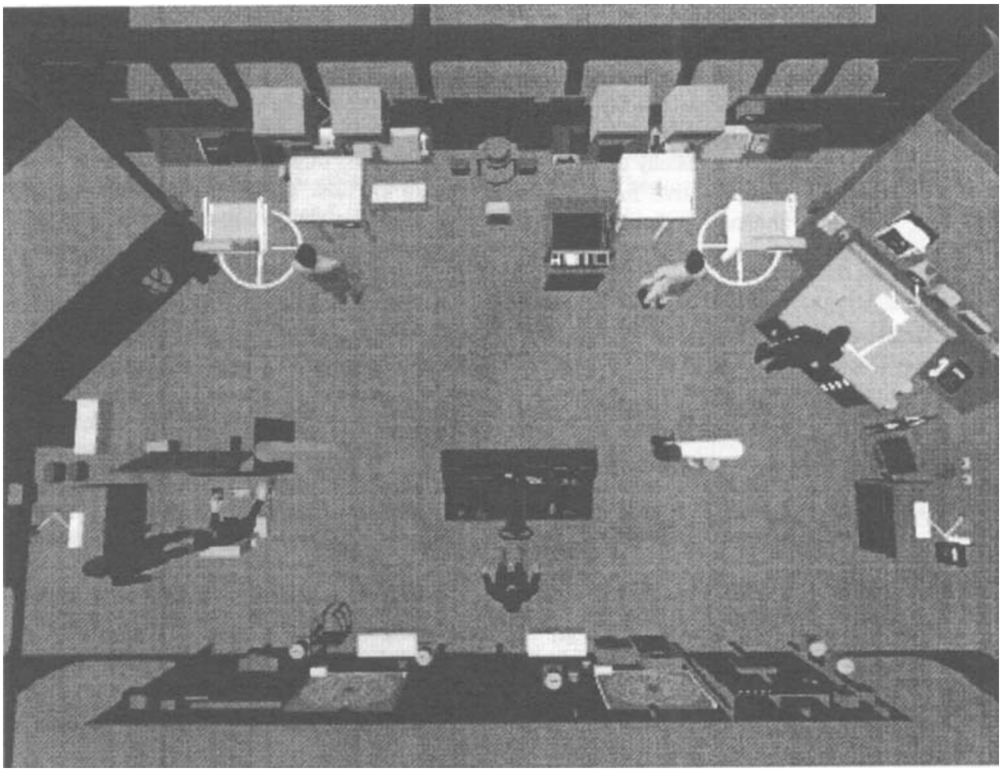

FIGURE 4. View of Conventional Bridge

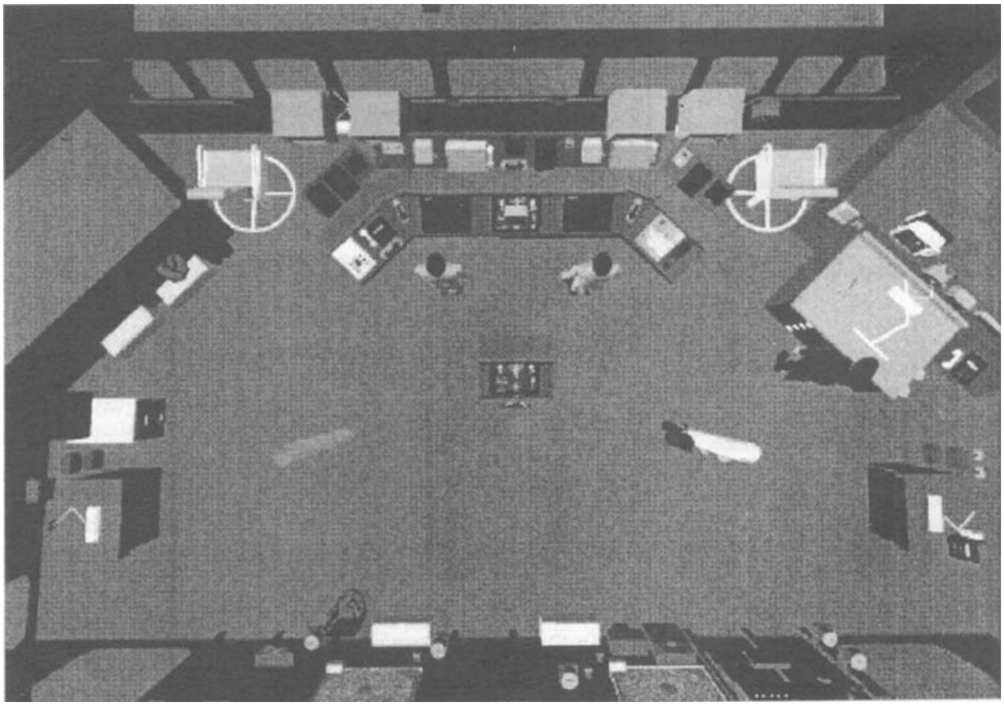

FIGURE 5. Plan View of Integrated Bridge Arrangement

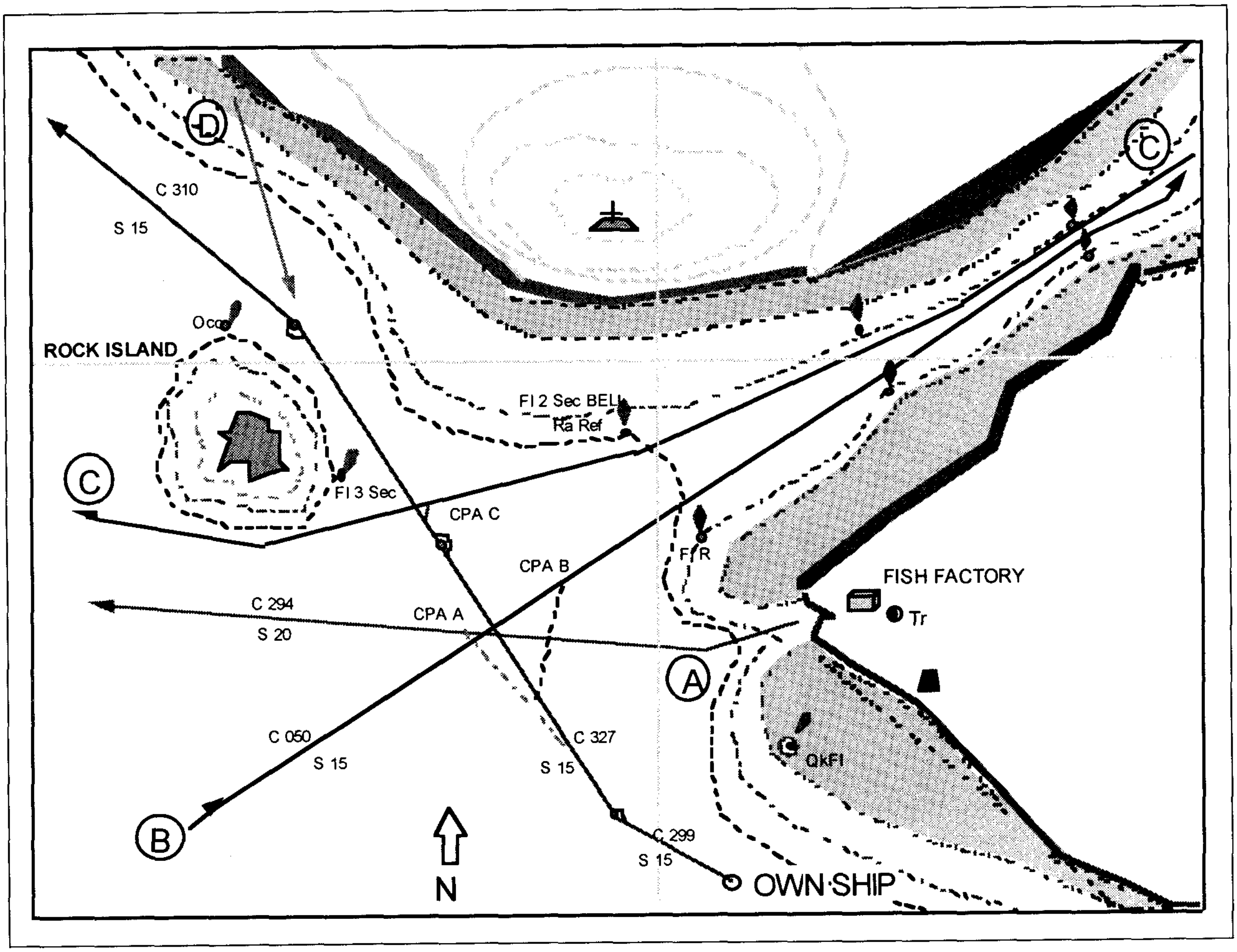

FIGURE 6. Coastal/Harbor Entrance Scenario Situation

TABLE 3. CONVENTIONAL BRIDGE SCENARIO - EVENT TIME & TASK EXAMPLES					
EVENT TIME	QMOW	SDT	OOD	JOOD	BMOW
1 min 25 sec - 1 min 45 sec	Walking back to chart table, plot-ting radar range 1	Reporting "skunk A" to OOD	Walking to chart table, examining chart		
12 min 10 sec - 12 min 40 sec	Plotting bearings	Reporting CPA of "skunk A" at 327 deg, 2300 yds	Check tactical display, CO calls to direct launch of helo, directing JOOD to set flight quarters	Directing BMOW to pass word	Walking to 1MC, passes word of flight quarters

TABLE 4. CONVENTIONAL BRIDGE SCENARIO - TIME UTILIZATION				
Time Utilization	QMOW	OOD	JOOD	BMOW
Time on Task	942.85	170.72	22.52	28.22
Moving	298.42	46.93	6.14	13.72
Idle time	0.00	772.13	920.33	914.63
Percent Utilization	100%	18%	2%	3%

TABLE 5. INTEGRATED BRIDGE SCENARIO - TIME UTILIZATION			
Time Utilization	QMOW	OOD	JOOD
Time on Task	109.48	95.32	46.32
Moving	28.65	13.35	7.41
Idle time	833.37	847.53	896.53
Percent Utilization	12%	10%	5%

can be shown by these simulations, Figure 8 presents a view of the QMOW trying to reach for the GPS, across the chart table. As indicated in the figure, IGRIP confirmed that for a 50th percentile male, the GPS is unreachable from this position. This "reach test" capability is useful to determine proper arrangements before a design is built. Figure 9 presents a "camera" view from the position of the OOD (50 percentile male height of eye) showing the actual view the OOD would have of contact "A."

CONCLUSIONS AND RECOMMENDATIONS

While there are numerous issues regarding the application of virtual environment technology to Navy modeling and simulation, there also is the potential benefit of very high payoffs that can be accrued by the Navy. The timing is entirely apropos: VE technology is becoming available just at the time when the Navy is in dire need of new tools and approaches to support ship design. Radical changes in the

FIGURE 7. Example of Pop-up Windows

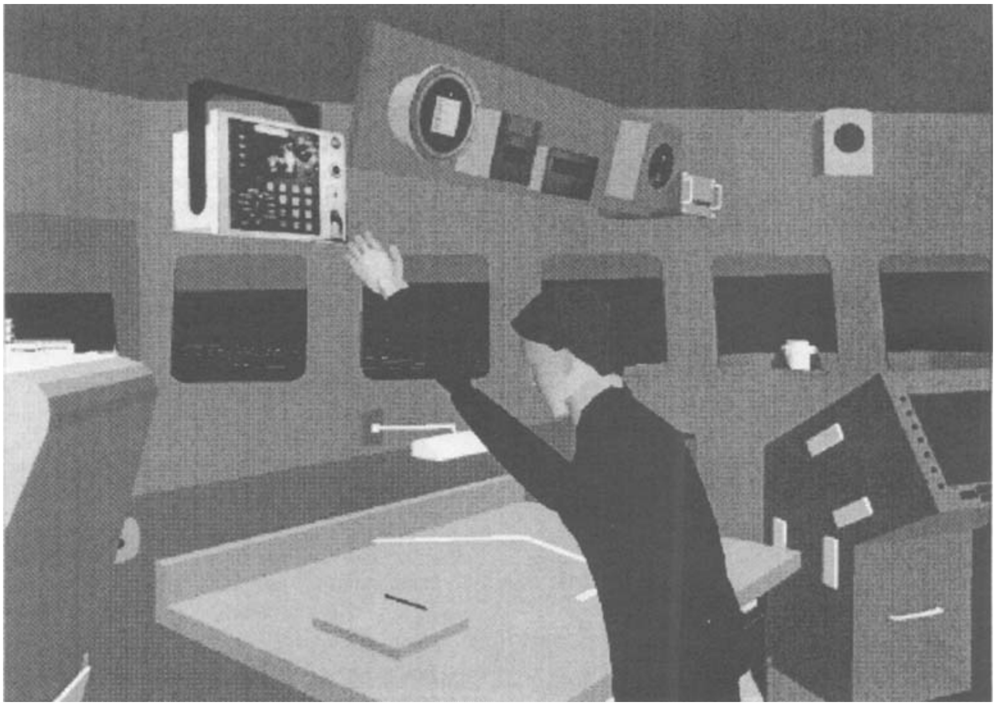

FIGURE 8. QMOW Reaching for GPS—Conventional Bridge

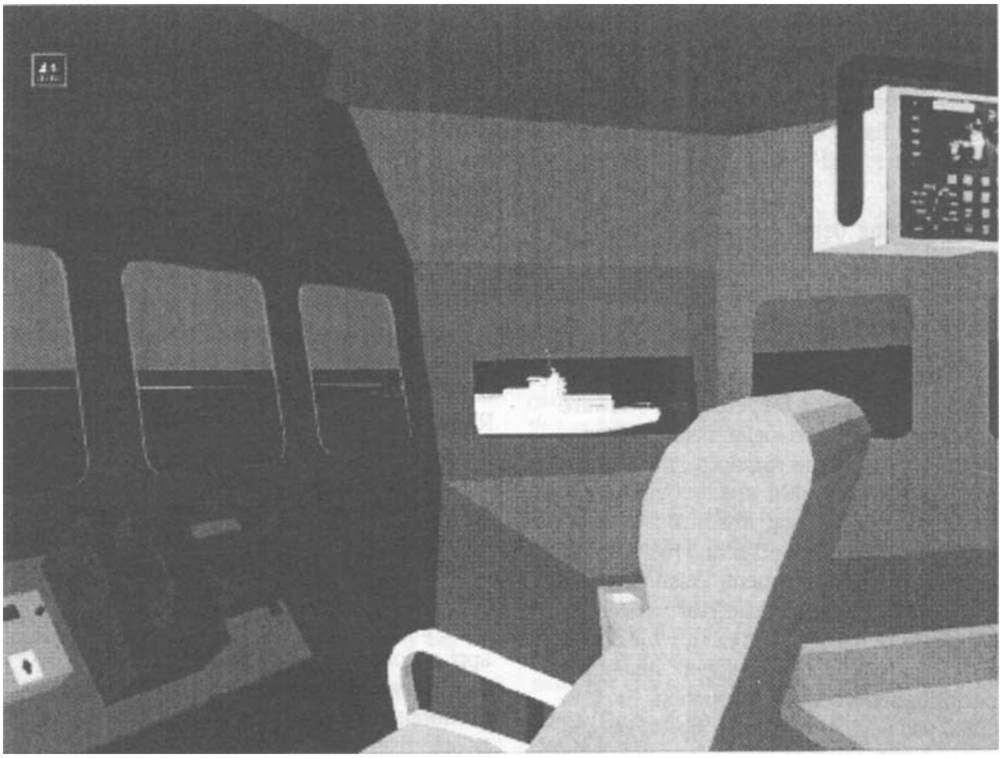

FIGURE 9. Inside-Out View—from OOD Station

environment in which the Navy operates (costs, threats, people) is necessitating revolutionary changes in the way the Navy conducts its business and designs its ships. Mandates and policy that are being handed down are requiring that manning, for example, be reduced by some 50 to 70 percent, compared to current levels. New propulsion and auxiliary systems are being proposed (electric drives), radical new ship designs are being proposed (Arsenal ship, new aircraft carriers), and new approaches to maintaining and supporting the fleet are on the horizon (Smart Base). How effective traditional approaches to ship design will be under this environment is unclear. What is clear is that new tools are needed to pragmatically develop, validate, and test designs that meet these new requirements.

Timely and effective human operator performance is critical to the proper functioning of shipboard systems. At the same time costs associated with manpower, personnel and training (MPT) constitute a major element and, in some cases, the largest element in ship life cycle costs. Thus, manpower cost reduction is currently a leading initiative in US Navy ship acquisition. While manpower reduction aboard ships can considerably lower the cost of ownership, this approach cannot simply be applied wholesale and arbitrarily because of the risk of losing ship functionality if critical human capabilities are discarded. These considerations suggest a tradeoff between manpower level and total system performance assuming that human input is essential to the latter. It has also been suggested that an optimum level of manning will emerge if analysis includes the marginal cost of increased automation to achieve manpower reduction.

It is easy to announce that "We must design for reduced manpower." What is not so obvious is how to obtain reliable data on human performance and its effects on total system or total ship capability that can be used in manpower/capability tradeoffs. This paper suggests that application of the discipline of HSI in general, and simulation techniques in particular, early in the design process are the means for meeting the above data requirements. The primary payoff of the use of HSI simulation methodology throughout the ship or ship system acquisition cycle is that a rational and data-driven approach can be taken to the admirable goal of "design for reduced manpower."

The recommended approach of applying HSI methods throughout the acquisition cycle differs considerably from past practices where human factors engineering, MPT, system safety and other HSI disciplines were applied, if at all, as an add-on following completion of design in the engineering and manufacturing development phase. In fact, the payoffs of HSI simulation techniques can only be obtained if this takes place starting in the concept exploration and definition phase. It is in the concept phase, where alternatives are evaluated, that the opportunity arises to apply HSI simulation and tradeoff methodology to the question of capability versus life cycle cost. Unless valid measurements of operator performance can be obtained for use as inputs to tradeoffs, concept evaluation and concept definition, there will be no rational basis for later design decisions that will fix or drive manning levels, operator-machine interfaces, skill level requirements and other HSI factors.

The practice of rendering design decisions without a basis for estimating the manpower and operator performance costs associated with these have, in the past, led to substantial unintended and unanticipated system life cycle cost increases above the planned baseline. In the field of software life cycle costs, for example, Karat (1992) has reviewed studies showing that 80 percent of software life-cycle costs are incurred due to maintenance following release and that 80 percent of the required maintenance effort is due to unforeseen or unmet user requirements. Karat has correctly pointed out that much of this effort could be rendered unnecessary by better and more extensive usability testing during development. Assuming that HSI simulation methodology will be applied throughout the system acquisition cycle, a number of benefits will accrue as the forthcoming data are used to support manpower versus human performance tradeoffs throughout the concept, demonstration and engineering development phases. This paper discussed utilization of inside-out, outside-in and task network simulation approaches.

The payoff that will accrue from application of HSI simulation methods early in and throughout the acquisition process is the availability of valid human performance data for input to manpower/capability tradeoffs and capability/cost tradeoffs, as well as to evaluation of design alternatives to optimize manning level and its contribution to system life cycle cost. The utilization of a mix of inside-out, outside-in and task network simulation methodologies can be maximally effective in obtaining valid human performance data to input to tradeoffs and design decisions in areas including the following:

- Availability of human operator performance data for concept and design tradeoffs in advance of detail design and construction,
- Models of human interactions in system functions for analysis of workload, manpower requirements, effectiveness of alternative manning levels, and effects of scenario variables,
- Assessments of human skill requirements and implications for training and cross-training,
- Assessment of human performance as a function of human machine interface (HMI) design characteristics, levels of automation, machine aiding, remote control and teleoperation,
- Assessment of systems safety and system level performance as functions of human operator performance,
- Assessment of effectiveness of team and collaborative performance, communications and problem solving.

Specific examples of areas in which M&S in virtual contexts can benefit the Navy include the following:

Systems design and prototyping. VE can provide design assistance in system design and prototyping via application to configuration control for shuttle deployed satellites and instruments. For example, virtual representations, based on CAD/CAM renderings of spaces, can be used to develop and verify form and fit of the payload to the platform, in terms of access, clearance, and in-space deployment. Other elements of system design that can be aided by 3-D human visualization and virtual prototyping include visualization and design of construction and maintenance access, workspace layouts, internal hardware configuration, and visualization of dynamic operations such as UNREP and carrier air operations mission rehearsal and training.

Hypermedia front end. VE systems could serve as navigational and display front ends to information systems employing hypermedia. VE/Hypermedia applications addressing areas such as operations training, component and hardware visualization, equipment design and configuration, and systems operations may be appropriate Navy applications.

Telecommunications and Tele-collaboration. In this application, VE would be used to enable the meeting of people from diverse locations. In terms of telecommunications, the need for immersive VE is difficult to demonstrate, since video teleconferencing can accomplish the same goal much more pragmatically. Tele-collaboration, on the other hand, could be quite beneficial to system design efforts. In this case, immersive or desktop VE would enable design efforts, meetings and reviews to be conducted using a common reference point, e.g., a virtual representation of the system under design. In this case, VE supported by CAD/CAM devices could enable real-time design modification, and hence visualization, of that system. Since all participants would be viewing the same system representation (from distal locations), such concurrent engineering and decision making could significantly reduce systems design and acquisition time.

Simulation and Training. VE (desktop, immersive, or 3-Dimensional viewing) can be applied where spatial aspects of simulation and training are important. These would include visual tasks (inspection, tracking and pursuit control), motor tasks (maintenance, access, calibration, transportation), and dynamic tasks (tracking, deployment, targeting and engagement, fire control). Virtual walk-downs of tasks/procedures to be trained obviates much of the requirement for models, prototypes, and functioning hardware on which to be trained.

While this paper has explored the daunting challenges of applying virtual environment technology and human systems integration to Navy modeling and simulation, the ultimate benefits will be more efficient and effective weapon systems and more manageable total ownership costs. ✣

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