TECHNICAL PAPER

This paper was presented at the HSI Symposium 2001.

Human Systems Integration and Advanced Technology in Engineering Department Workload and Manpower Reduction

■ Kenneth A. Lively, Anthony J. Seman, Dr. Mark Kirkpatrick

Abstract

Aboard current ships, such as the DDG 51, engineering control and damage control activities are manpower intensive. It is anticipated that, for future combatants, the workload demand arising from operation of systems under conditions of normal steaming and during casualty response will need to be markedly reduced via automated monitoring, autonomous control, and other technology initiatives.

Current DDG 51 class ships can be considered as a manpower baseline and under Condition III typical engineering control involves seven to eight watchstanders at manned stations in the Central Control Station, the engine rooms and other machinery spaces. In contrast to this manning level, initiatives such as DD 21 and the integrated engineering plant (IEP) envision a partnership between the operator and the automation system, with more and more of the operator's functions being shifted to the automation system as manning levels decrease. This paper describes some human systems integration studies of workload demand reduction and, consequently, manning reduction that can be achieved due to application of several advanced technology concepts. Advanced system concept studies in relation to workload demand are described and reviewed including:

- *Piecemeal applications of diverse automation and remote control technology concepts to selected high driver tasks in current DDG 51 activities.*
- *Development of the reduced ship's crew by virtual presence system that will provide automated monitoring and display to operators of machinery health, compartment conditions, and personnel health.*
- *The IEP envisions the machinery control system as a provider of resources that are used by various consumers around the ship. Resource needs and consumer priorities are at all times dependent upon the ship's current mission and the availability of equipment.pawnbrokers.*

Introduction

Considering current ships, such as the DDG 51, as a workload/manpower baseline, engineering department workload will have to be considerably reduced to meet the requirements of future combatants. This will be achieved through automated monitoring, autonomous control and other technology initiatives. It should be noted that workload/manpower reduction is generally regarded as a human systems integration (HSI) activity but, in fact, system operator workload demands are largely fixed by decisions made during development in the systems engineering domain.

To achieve the level of workload reduction contemplated, trade studies aimed at selection from alternative equipment items or design concepts will need to incorporate criteria that address the frequencies of occurrence, time durations, and skill levels of operator tasks that result from operating and maintenance requirements of the alternative candidates. Since it is not the intent of sharply reduced manning to result in fewer, but much more highly trained operators, the traditional mindset of having the operator oversee the automation system will have to be abandoned in favor of an operator-automation system partnership. The operator and the automation system will share the responsibility for monitoring and controlling the ship's systems, including the responsibility for the automation system to initiate a dialogue with the operator (or vice versa) when events dictate. This paper presents a discussion of some current combined systems engineering and HSI initiatives directed toward workload/manpower reduction.

The Naval Sea Systems Command (NAVSEA) process for HSI and optimized manning is intended for application both early in and throughout the system acquisition process. Analysis of alternative function allocations that vary in level of automation and, consequently, acquisition cost is the mechanism for achieving optimized manning. This process calls out the following steps during system development:

- Analyze mission requirements and define mission scenarios
- Analyze functional requirements and identify HSI high drivers
- Allocate functions, re-engineer and define roles of humans
- Allocate functions, re-engineer and define roles of the automation system
- Develop alternate workload/manning concepts
- Conduct task network simulations or other workload and performance analyses
- Conduct tradeoffs and assess human performance, safety, and workload
- Define task networks and analyze task requirements
- Design operator-machine interfaces (OMI) and develop training programs

The R&D efforts discussed in this paper exemplify many of the steps in the NAVSEA HSI process; point out the necessary interaction between systems engineering, HSI and fleet operators and indicate progress to date in reduction of workload/manpower demand in shipboard engineering departments.

HSI Analysis and Design Support for Automated Shipboard Auxiliary Systems

Kirkpatrick (1998) reported on a study carried out for NAVSEA in which engineering control activities aboard DDG 51 class ships constituted a workload baseline and analyses were conducted of the potential workload reduction associated with automation concepts. HSI methods were applied to modeling and analysis of watchstander workload of engineering control personnel aboard current DDG 51 ships. Task analysis methodology was used to define the current baseline tasks and workload. Engineering control tasks were identified using ship manpower documents and inputs from experienced subject matter experts.

The task list was reviewed and corrected as necessary by engineering control personnel during ship visits aboard the USS *Arleigh Burke*. Estimates of the frequency of performance of tasks and task duration were obtained from experienced watchstanders. Workload analyses were conducted using task network models developed under Simulation for Workload Analysis and Modeling (SIMWAM) software and by means of average workload calculations built into task databases. Similar models were developed for workload under alternative concepts for increased automation and remote control of propulsion and auxiliary machinery.

Under Condition III, the following stations are manned aboard the USS *Arleigh Burke*:

- Central Control Station (CCS)
  - Engineering Officer of the Watch (EOOW)

– Propulsion and Auxiliary Control Console Operator (PACCO)
– Electric Plant Control Console Operator (EPCC Op)

- Engineering Spaces
  – Engine Room Operator 1 (ERO 1)
  – Engine Room Operator 2 (ERO 2)
  – Propulsion Systems Monitor (PSM)
  – Auxiliary Systems Monitor (ASM)
  – Oil King

Up to 23 persons may be required to man-up engineering control depending on readiness conditions and on the evolution being performed. The workload analyses being conducted in this project address Condition III (deployed or wartime steaming). While this condition is not as manpower intensive as Condition I, the need to have multiple watch sections (usually 3) causes Condition III to drive total shipboard manpower. Under Condition I, all personnel man stations and the condition can only be maintained for a limited number of hours. The analyses also addressed normal operating conditions without equipment failures, damage, or other emergencies. As under Condition I, personnel other than the engineering control watchstanders would perform additional workload associated with abnormal events.

Results of the runs of the SIMWAM baseline model were entered into the average workload fields of the baseline task analysis database. **Table 1** shows average workload in man-hours per watch for the seven manned stations.

In the course of a four hour watch, the total workload for the baseline model in Table 1 is 17.690 man hours and the equivalent number of withstanders is 17.690 man hours/4.0 man hours per withstander = 4.423 withstanders.

Figure 1 shows functions that may be regarded as categories of engineering control withstander tasks and the percent of total workload accounted for by these categories in the baseline model.

Table 1:

Engineering Control Workload per Watch by Manned Station for the Baseline Model

MANNED STATION	MAN HOURS PER WATCH
EOOW	0.733
PACCO	0.984
EPCC Op	0.338
ERO 1	2.798
ASM	4.382
ERO 2	3.234
PSM	3.346
Oil King	1.875
TOTAL	**17.690**

Among the high driver task categories are the following:

- Change of watch
- Communications between personnel
- Fuel management
- Investigation of abnormalities
- Maintenance of physical security
- Monitoring of SSGTGs
- Hourly rounds by the PSM and ASM
- Operation of chill water and potable water systems
- Turbine water wash tasks with propulsion turbines and SSGTGs combined

Analyses were conducted of the potential for workload/manpower reduction of increased capability for remote machinery control from the CCS and of increased automation and autonomous control. In Phase I of the project, the goal was to examine reduction of the need for personnel in the machinery rooms. Technology assessments were made with regard to eliminating tasks currently performed in the engineering spaces and transferring these to the CCS where they would be accomplished by means of remote sensing and control. In Phase I very little was done in the way of total workload reduction. Rather, tasks could be regarded as moving from the machinery spaces but still

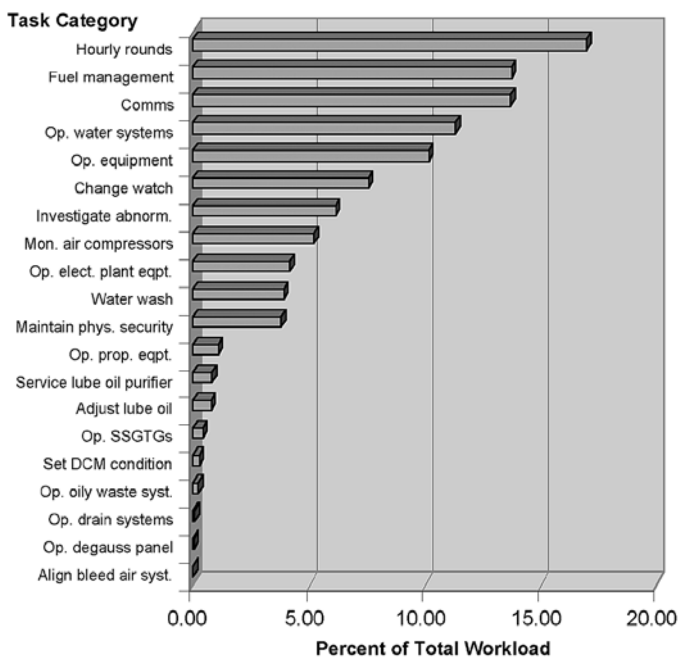


FIGURE 1: *Distribution of Baseline Workload by Task Category*

having the same workload demands. **Table 2** shows the results of this analysis in the column titled Phase I Alternative. Reduction of total workload in this column is largely because of the reduced need to communicate between spaces. Aboard the DDG 51, CCS operators can generally receive sufficient information from displays to make decisions about machine control. Implementing these decisions, however, often requires that they use ship voice communications equipment to direct machinery space operators to take action locally. Therefore, the workload associated with voice communications amounts to about 13 percent of the total in Figure 1.

In Phase II all operator tasks were reviewed to determine how automation, autonomous control and other technology capabilities could eliminate or reduce their workload demands. The results are shown in Table 2 in the column labeled Phase II alternative. The technology assumptions underlying the Phase II alternative concept resulted in a workload reduction of about 63 percent.

Table 2:

Engineering Control Workload per Watch by Manned Station for the Baseline and Alternative Models

MANNED STATION	MAN HOURS PER WATCH		
	Phase 1 Baseline	*Phase 1 Alternative*	*Phase II Alternative*
EOOW	0.733	1.876	0.675
PACCO	0.984	2.634	1.667
EPCC Op	0.338	1.404	1.291
ERO 1	2.798	—	—
ASM	4.382	4.391	1.687
ERO 2	3.234	—	—
PSM	3.346	3.457	1.274
Oil King	1.875	—	—
Central Control Station	2.055	5.915	3.633
Equivalent Watchstanders	0.514	1.479	0.908
Machinery Spaces	15.635	7.848	2.961
Equivalent Watchstanders	3.909	1.962	0.740
Total Man Hours	17.690	13.763	6.594
Equivalent Watchstanders	4.423	3.441	1.649

Reduced Ship Crew by Virtual Presence (RSVP)

The reduced ship crew by virtual presence (RSVP) system employs state-of-the-art and developing technologies to provide extensive shipboard monitoring and display. RSVP presents information concerning compartment environments, systems and machinery status and health, structural integrity, and personnel status. The overall objective of RSVP is to rapidly provide ship engineering department personnel with well-defined information and knowledge that summarizes the readiness of the ship to meet mission requirements. In other words, RSVP is a tool that (1) supports situation awareness and decision making for ship managers and (2) presents this information with a minimum of human work and information processing. RSVP collects extensive amounts of ship data and consolidates the data into information and knowledge structures. Sensor data are transmitted in a wireless fashion within compartments and are processed via a fault tolerant network to be saved and displayed at a workstation intended to be used by watchstanders. **Figure 2** shows some of the elements of the RSVP system.

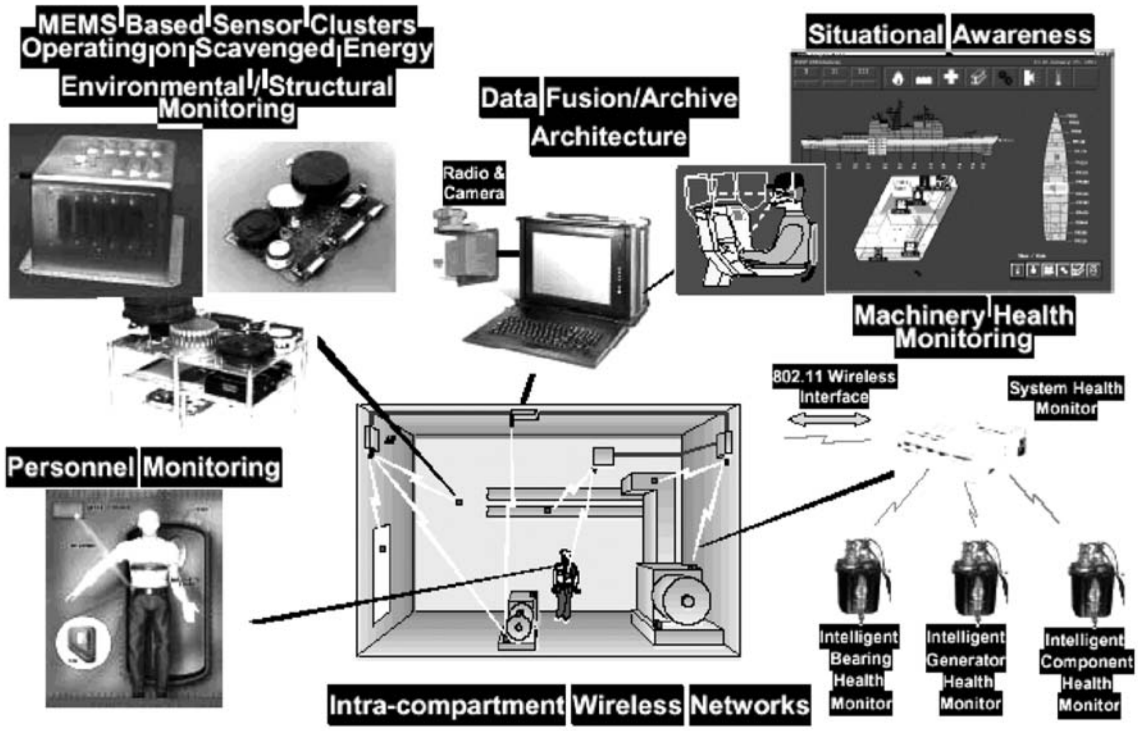


FIGURE 2:
RSVP System Elements

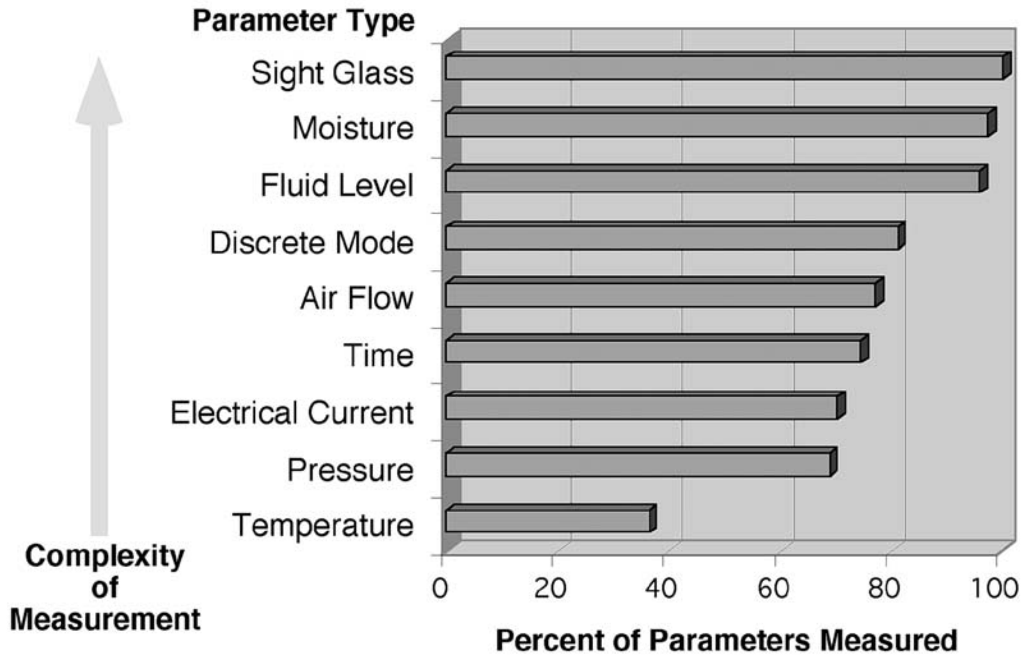
RSVP sensor clusters capture information in ships spaces including:

- Structure
- Machinery health
- Environment
- Crew status and health
- RSVP system health

In the Kirkpatrick (1998) study discussed previously, there was no development of the technology capabilities assumed in the Phase I and Phase II alternative concepts. Technology capabilities were reviewed in order to formulate assumptions about how these could impact workload demand. In the RSVP project a prototype system was developed and demonstrated in an Office of Naval Research advanced technology demonstration program. Many of the remote sensing capability assumptions made in the automated auxiliaries project were given substance by RSVP. The automated auxiliaries effort dealt only with tasks performed by the engineering control watch under Condition III normal steaming. Data sensed and displayed by RSVP, on the other hand, would be utilized not only for engineering control but also for damage control as well as for machinery health, personnel health, and environmental monitoring.

Baker and Kirkpatrick (2000) documented the results of an effort to estimate the extent of human work reduction that may be realized by provision of the RSVP system to existing ship work requirements. The analysis was performed for two areas aboard the DDG 51: (1) workload of engineering control personnel and (2) a fire and flood damage control scenario. In both cases, previous analyses of workload associated with the existing designs were reviewed and work load redistributed according to the functionality of RSVP and its ability to perform extensive ship monitoring, data analysis and fusion.

FIGURE 3:
Cumulative Frequency Distribution by Type of Parameter Recorded by Roving Monitors



Results of the study included estimated workload reductions of:

- 73% for the damage control administrator/DC team located in Damage Control Central for a fire and flood scenario aboard the DDG 51
- 47% for personnel tasks performed in the machinery spaces aboard DDG 51 for each four-hour watch under condition III steaming.

In connection with RSVP usability testing aboard the USS *Monterey* (CG 61), copies were obtained of data collection sheets used by the roving monitors to record machinery parameters during rounds in the engineering spaces (Kirkpatrick and Malone 2001). These manned stations are similar to the propulsion monitor and auxiliary systems monitor aboard the DDG 51. The parameters recorded by roving monitors were classified as follows:

- Visual observation of fluid level or condition using a sight glass
- Moisture
- Fluid level
- Discrete mode (e.g., identification of the pump currently on line where more than one is available)
- Air flow
- Time (e.g., cumulative run time for a component)
- Electrical current
- Pressure
- Temperature

Figure 3 shows the cumulative frequencies of the parameter types in ascending order of the estimated complexity of automatically measuring the parameter via sensors. Most of the parameter types present no problem and, in fact, are currently measured by the prototype RSVP system. Fluid level measurements in general are somewhat more complicated than are temperature, pressure, etc. Moisture determination would require assessment of water content. Measurements that currently use human observation of a sight glass would require analysis of the exact target property. Such observations often involve fluid level or fluid quality (e.g., contaminants in fuel or lubricating oil) and might be obtained by level or chemical analysis methods already discussed.

Figure 3 indicates the cumulative percent of all parameters that could be accommodated if the type in question and all less complex types could be measured. Measurements of temperature alone would accommodate about 35 percent of all parameters. Measurements of temperature and pressure would accommodate about 67 percent of all parameters. Measurements of parameters up and including fluid level would accommodate over 90 percent of all parameters and would very nearly obviate the need for hourly rounds by roving monitors.

The objection may be made that roving monitors do not just record specific parameters but also look and listen for problems or abnormal conditions while making rounds. RSVP addresses this issue by providing audio and steerable video inputs from compartments to the watchstander console. If a watchstander is needed to constantly monitor compartments remotely then the apparent workload reduction potential of RSVP may be over estimated. The argument here is that the intent of RSVP is to provide automatic monitoring of sufficient parameters that abnormal conditions in a compartment will be detected automatically and one or more event alarm(s) will be presented to direct the central operator's attention to the compartment, machine, structure, or person in question. Although technology exists that would permit autonomous monitoring of video and audio information from a compartment, it remains to be seen if intelligent pattern recognition will permit identification of sufficient events to obviate the need for a watchstander (local or remote).

HSI for the Integrated Engineering Plant

The IEP is being developed to provide a radical increase in the level of automation for propulsion and auxiliary machinery aboard future Navy ships. A commensurate reduction in engineering control workload/manning and cost of ownership associated with manning will also be achieved. The IEP is notionally a three-tier architecture with local or subsystem control at the lowest tier, system interaction and tactical decision making at the intermediate level, and strategic decision making and operator interaction at the highest level. By knowing the ship's current mission or mix of missions, a plan can be developed which provides an optimal response to the mission using combat systems equipment, weapons launchers, and propulsion requirements. Knowing which equipment needs to be operated, and at what level, the plan can then be broken down into a set of resource requirements. The various degrees of importance for each of the elements of the plan determine subsystem configuration and load priorities. The result constitutes an execution or implementation plan that can be used by subsystem controllers to perform distributed control over their respective subsystem. Equipment malfunction or damage will result in new goals and/or replanning as necessary. The IEP watchstander will assist in mission determination and in decision making.

The objective of a study reported by Kirkpatrick, Malone and Heasly (2000) was to perform a top down function analysis (TDFA) for IEP. This involved identification and decomposition of engineering control functions based on current Navy surface ships to support function allocation and determination of human roles so as to achieve workload/manning reduction aboard future ships using IEP. The goal is to reduce engineering control manning to one watchstander located at the Multi Modal Watch Station (MMWS) under normal operating conditions with, perhaps, a second person available to go into the engineering spaces on an as-required basis.

It was assumed that the machinery systems to be incorporated into future Navy ships will be largely those currently on board DDG 51 class destroyers. The primary exception to the above was the assumption that the "more electric ship" concept will be applied to future ships in the form of the integrated power System (IPS). Current DDG 51 class ships use gas turbines, reduction gear sets and shafts to provide propulsion. Ship's electrical power is produced by means of ship service gas turbine generators (SSGTGs) that are independent gas turbine generator sets. In contrast, the IPS concept calls for the main power turbines to drive generators and function so as to provide electrical power. Electric propulsion motors will constitute one of the ship electrical systems drawing from the outputs of the generators that will also supply electrical power for other ship systems. A representative IPS control architecture described by Hegner, Desai, and Lively (2001) shows how the mission context can be used to determine resource requirements and load priorities.

The TDFA produced by this effort consists of a decomposition of IEP functions down to the fifth level. For each function the following functional requirements were identified:

- *Information:* the information required to perform the function
- *Decision:* the decision and selection from among alternative actions required to perform the function
- *Performance:* the action required to perform and verify the function
- *Local:* requirements (if any) for human presence at the machine or component involved in the function.

In principle, a TDFA is completed when the analyst must state a means of performing the function to proceed farther with function decomposition. At this point, the TDFA is regarded as finished and the next step is function allocation. In practice, the Local function property was also included because of the assumption that the physical machinery to be controlled would be similar to that onboard DDG 51 class ships. Local requirements often arose because the component in question was an off-the-shelf item and operator activation, maintenance, monitoring, etc. was inherent in the design.

The IEP TDFA addresses the first two steps in the NAVSEA HSI and manpower optimization process. The data will be employed in future phases to support function allocation, modeling, and simulation to analyze workload requirements and development of operator-machine interactions and interfaces.

Conclusions

The current manning for an engineering control watch aboard DDG 51 class ships is eight watchstanders. The automated auxiliaries study discussed here suggested that this could be reduced to one watchstander plus a fraction of a watchstander who could, presumably perform other duties as required. This notion was based only on characteristics of the operator tasks currently performed and assessments of applicable automation and remote control technology. The goal of the IEP program is to accomplish engineering control functions using one watchstander. Depending on how the compartment and machine local access requirements are resolved, this might rise slightly and be consistent with the automated auxiliaries study results. The RSVP program provides a valuable verification of the technical feasibility of highly automated monitoring and demonstrates specifically how this capability can significantly reduce engineering control workload and manning. It also goes beyond the engineering control domain to show a benefit in the areas of personnel health and damage assessment and control. Considered in total, this body of work provides a good indication of the future workload/manpower reduction that can be obtained for surface combatants and supports the contention that this objective can best be achieved through a cooperative effort by systems engineering, HSI, and the Fleet. ■

REFERENCES

Baker, C. and M. Kirkpatrick, "Manning and Human Systems Integration for RSVP: Workload Reduction Estimations for Engineering Operations and Fire and Flood Damage Control Scenarios,", Phase II Technical Report, Carlow International, Falls Church, VA. 2000

Kirkpatrick, M. and T. Malone, "Human Systems Integration Verification and Demonstration of RSVP Human Interface and Usability,", Phase III Technical Report, Carlow International, Falls Church, VA. 2001

Kirkpatrick, M. "Human Systems Integration for Shipboard Automated Auxiliary Systems. Phase II" Technical Report, Carlow International, Falls Church, VA. 1998

Kirkpatrick, M., T. Malone, and C. Heasly, "Top Down Function Analysis for the Integrated Engineering Plant," Technical Report, Carlow International, Falls Church, VA. 2000

Desai, B., K. Lively, and H. Hegner, "How Much Autonomy? IPS Control System - A Case Study," International Federation on Automatic Controls Symposium on Control Applications in Marine Systems, Glasgow, Scotland, UK. 2001.

KENNETH A. LIVELY *graduated from the University of Colorado with a BS in applied mathematics and an MS in mathematics in 1976, and from the Massachusetts Institute of Technology with an MS in electrical engineering and the degree ocean engineer in naval architecture and marine engineering in 1984. He retired from the U.S. Navy in 1989 after 23 years of service. Assignments included electrical officer on the USS* Constellation *(CV 64), project engineer for the DDG 51 machinery control system (NAVSEA), and DDG 51 Technical Director (NAVSEA). He was vice president of the PDI Division of Bird-Johnson Company from July 1989 to November 1998, where he managed various gas turbine and machinery controls related development projects. He joined Anteon Corporation's Systems Engineering Group as senior controls engineer in December 1998, where he provided technical support to the integrated power systems program (NAVSEA PMS 510) and managed the Office of Naval Research Afloat Laboratory.*

DR. MARK KIRKPATRICK *is currently an independent consultant in human factors and workload/manning analysis and modeling. He holds a Ph.D. degree in experimental psychology from The Ohio State University and has 34 years of experience in applied human factors. From 1982 through 2000, Dr. Kirkpatrick served as the senior vice president of Carlow International. Prior to joining Carlow in 1982, Dr. Kirkpatrick served as a member of the technical staff at North American Rockwell's Missiles Division and as a project director and vice president for Essex Corporation. His areas of expertise include workload simulation, task analysis, operator-in-the-loop simulation, human performance experimentation, statistical analysis and human factors T&E. He has directed and/or participated in human factors projects for the U.S. Navy, U.S. Army, NASA, Department of Transportation, the U.S. Nuclear Regulatory Commission and private industry.*

ANTHONY J. SEMAN III *is the technical manager for the reduced ship's crew by virtual presence (RSVP) advanced technology demonstration (ATD), Naval Surface Warfare Center (NSWC), Carderock Division, Code 9113, Program Development and RDT&E Section. Mr. Seman received his bachelor of science degree in electrical engineering from Drexel University in 1989. He is currently completing graduate course work for a masters degree in computer science at American University. Mr. Seman has authored three technical papers on advanced, automated monitoring systems for Navy ships. Mr. Seman has received numerous performance and achievement awards, including a 1998 Meritorious Unit Commendation from PEO SC and a 2002 Gold Medal for Technical Accomplishment from the Philadelphia Federal Executive Board for RSVP. Mr. Seman is a member of the Institute of Electrical and Electronics Engineers (IEEE), and the American Society of Naval Engineers (ASNE).*

Calendar of Major Meetings

ASNE

2003

APRIL 22-23
Anti-Terrorism/Force Protection Workshop; *ASNE Flagship Section, Sheraton National Hotel, Arlington, Virginia (with exhibits)*

MAY 12-14
Intelligent Ships Symposium V; *ASNE Delaware Valley Section; Adam's Mark Hotel, Philadelphia, Pennsylvania (with exhibits)*

JUNE 23-25
Human Systems Integration Symposium 2003; ASNE Flagship Section, Sheraton Premier Tysons Corner, Vienna, Virginia (with exhibits)

JULY 21-24
Workshop for Battery Development; *Renaissance Portsmouth, Portsmouth, Virginia (no exhibits)*

AUGUST 14-15
Design for Zero Maintenance Workshop, *northern New England Section, Yoken's Restaurant & Comfort Inn, Portsmouth, New Hampshire (with exhibits)*

AUGUST 21-22
Marine Environmental Engineering Technology Symposium 2003; *ASNE/SNAME local Sections and ASNE/SNAME Joint Environmental Engineering Committee; Sheraton National Hotel, Arlington, Virginia (with exhibits)*

SEPTEMBER 16-18
Harnessing the Power of Technology for the Warfighter Symposium; *ASNE Southern Indiana, Bloomington/Monroe County Convention Center, Bloomington, Indiana (with exhibits)*

NOVEMBER 18-19
Fleet Maintenance Symposium 2003; *ASNE Tidewater Section; Virginia Beach Pavilion, Virginia Beach, Virginia (with exhibits)*

DECEMBER 9-10
ASNE Combat Symposium (Classified); *ASNE Combat Systems Committee and Flagship Section; Kossiakoff Center, JHU/APL, Laurel, Maryland (no exhibits)*

2004

JANUARY 27-29
Electric Machines Technical Conference (ETMC 2003); *ASNE Delaware Valley Section, Philadelphia, location TBD (with exhibits)*

MARCH 16-18
Engineering the Total Ship 2004 (Classified), *ASNE Flagship Section, NIST, Gaithersburg, Maryland (no exhibits)*

JUNE 28-29
ASNE Day 2004; *Hyatt Regency Crystal City, Arlington, Virginia (with exhibits)*

If you are interested in receiving information on exhibiting at one of our symposia, please contact Megan Sinesiou by phone at 703-836-6727 or via e-mail at meetings@navalengineers.org. For questions regarding registration, please contact our Meetings Assistant, Nikki Johnson, at the same number or via email at registrations@navalengineers.org.