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Ship Systems Automation Technology

Automation: The Use of Automated Ship Control Systems Technology to Reduce the Cost of Ships and Submarines

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ABSTRACT

The escalating costs of U.S. technology used to field U.S. winning capabilities in regional conflicts, such as the Persian Gulf War, come at a time when drastic reductions are projected for out-year defense budgets. The dilemma is how to meet current and future requirements for naval force structure and capability, and sustain the U.S. industrial base personnel resources necessary to build and man ships and submarines in the face of declining budgets. Expected costs saving technology improvements to date have added to life cycle costs due to increased systems performance and complexity, and an increase in the training requirements. This paper describes how advanced digital ship control technologies currently at sea in allied navies and in the U.S. Navy, upgraded with ship systems automation technologies being considered by ARPA and NAVSEA will be able to provide the intelligent ship (automation) technologies that may reverse the cost escalation trends while enhancing performance. The major challenge, however, may be more cultural than technical.

INTRODUCTION

The operational requirement for multi-mission naval capabilities remains vitally important whether the role is related to major power or regional conflicts. Too small a naval force guarantees an inability to act in the national interest. It also reduces the industrial base below a sustenance level with resulting cost escalation. The U.S. Navy must be able to build 2-3 submarines[1] and 6-10 ships per year to maintain force structure. At the same time, since SCN budgets can be expected to remain constant or decline, we must build less costly submarines and ships that can maintain the required warfare effectiveness.

Technology advances have been expected to play a role in lowering costs, especially in the areas of acquisition and life cycle costs. This has not been the case to date for the U.S. Navy. Instead, higher costs have been experienced due to increased performance requirements, and increased system and component complexity have canceled out expected savings.[2] In areas of training, new technology that was to improve operational capability and reduce training costs has brought instead a forty percent growth in new Navy Education Codes (NECs) and additional training infrastructure with its associated cost increases.[3]

The difficulties experienced in achieving cost reduction through the application of new technology are not unique to the U.S. Navy. Other free world navies have had to adjust to lowered budgets earlier than has been the case in the U.S., and they have done so over the years. Their experience in coping with both personnel shortages and fiscal reductions can provide examples for the U. S. Navy in the use of new design concepts, systems specifications, acquisition planning, operations and maintenance, personnel staffing and training, and the use of automation to reduce manpower requirements and improve affordability.

In addition to technical change, it is the opinion of many naval officers and shipbuilding professionals that cultural change may be the largest block to the introduction of manpower reducing automation technologies. This is not without reason. Many Navy regulations and doctrines are written in blood. But, if we are going to have a navy sufficient to serve in the national interest of presence, deterrence, and warfighting, we must reduce personnel aboard ships. This reduces the acquisition and life cycle costs, and more importantly, reduces the human risk in combat operations.

This paper will focus on the application automation technology to support manpower reduction, while achieving acquisition and life cycle for affordability. Manpower reduction will also reduce the human risk in combat. The discussion will include the following topics by Section:

1.0 Evolution of Control Systems for Ships
2.0 Warfare Requirements that Drive Ship Control Systems Design
3.0 Automating Ship Control Systems for Performance, Affordability, and Human Risk Mitigation.

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[1] VADM Roger F. Bacon, ACNO. Undersea Warfare, Sea Power, pg. 9 (July 1991)
[2] Richard F. Hogland, "The Challenge in Attack Submarines," Submarine Review, pg. 7, (July 1991)
[3] Meeting at Bureau of Naval Personnel to discuss the impact of emerging ship control technologies on training costs: Joseph Famme and RADM R. Oliver, et.al., (March 1991)

1.0 EVOLUTION OF CONTROL SYSTEMS FOR SHIPS

The evolution of control systems for ship combat systems and platform systems (hull, mechanical and electrical (HM&E), have evolved on different time lines over the past 60 years. The introduction of new naval warfare technologies, such as radar for combat systems and gas turbine engines for machinery systems, has generally introduced a new era of systems controls technologies to help the operator more efficiently and safely operate and maintain the ship systems.

Figure 1 provides a summary timeline of naval ship control systems technology development so that the reader can appreciate how enabling technology has led the way to new control systems (analog to digital) and control doctrine (manual to automatic). The timeline can be used to compare the history of combat and platform control systems development.

The timeline for control systems development is expressed as an estimated percentage availability of remote and automatic control systems for use by the operator, in addition to usual manual control. The graph shows that platform control systems technology has lagged combat control systems technology development by about 20 years, over a timeline from the 1930s to the present.

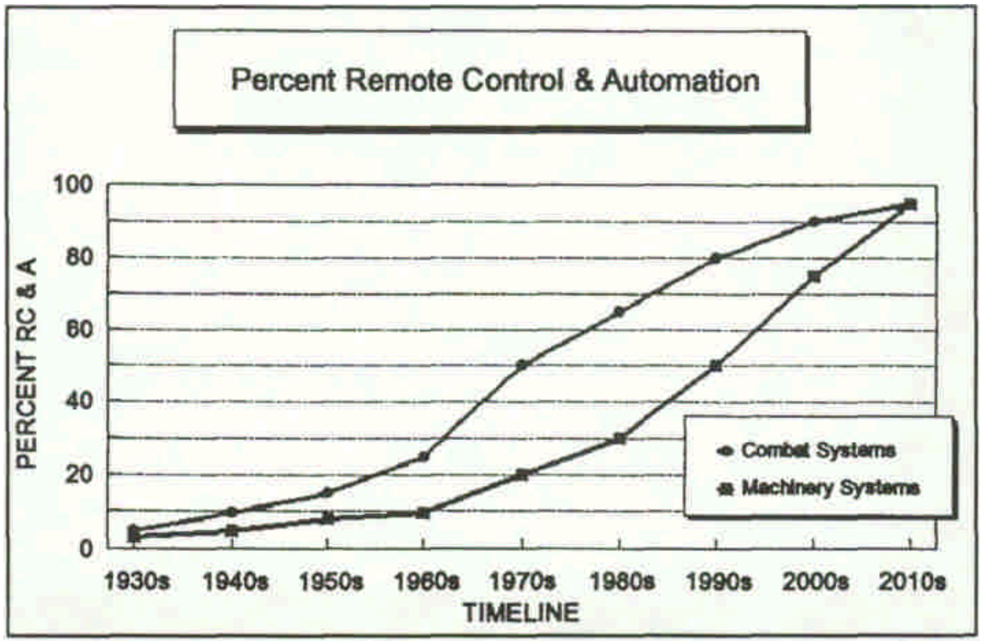

Figure1. Estimated Percent [of Applied] Remote Control & Automation , 1930 to 2020

The judgment as to the degree of remote control and automation technology expected to be introduced beyond the year 1995 depends on sponsor funding, solving technical challenge and cultural acceptance of ship systems automation programs now in progress and pending at ARPA, NAVSEA and the marine industry. These are the subjects discussed at forums such as the ASNE Intelligent Ship Symposium.

Combat Systems Controls Development Timeline

For combat systems, increased use of remote control and automated control followed the development of key naval technologies such as 2D radar in the 1930s, fire control tracking systems in the 1940s and 1950s, 3D radar and Naval Tactical Data Systems (NTDS) to control surface to air missiles in the 1960s, advanced ECM, sonar and AEGIS integrated combat systems in the 1980s, continuing into the 1990s.

The key to the success of modern combat systems control was the development in the late 1950s of NTDS. Based on the introduction of then powerful central data processing systems being developed for commercial uses, *NTDS introduced the technology of providing a common digital, graphical man-machine interface (MMI) between the system operator and the combat system being controlled.*

Remote control of combat systems from CIC became institutionalized, never to revert back to the manpower intensive and inaccurate grease pencil target tracking and ring sites that many readers may remember from an earlier tour of naval duty.

Because modern combat systems controls technologies used at sea lead significantly the use of modern platform control systems at sea, this paper will focus its attention on platform control systems technologies.

Platform Systems Controls Development Timeline

Platform hull, mechanical, electrical and damage control (HMEDC) control systems have also experienced an advancement in control systems technologies, though about 20 years behind combat control systems technology.

In the 1930s, many ships were coal fired, making the use of remote and automated control of propulsion and auxiliary systems impractical. The introduction of oil-fired power plants, first heavy oil, then light, distilled oils in the 1960s, allowed the first elements of propulsion (power plant) *remote control* to be developed. There were even attempts to use *automated control* for oil-fired steam plants, but these were not very successful. In the 1960s and 1970s, the platform control systems remained based on analog controls technologies rather than the digital technologies then entering use with NTDS combat systems. The introduction of gas turbine power plants in the 1960s, however, introduced digital controls technology for propulsion and ancillary data collection, thus beginning the transition to digital control for surface ship platform systems.

Platform Control Systems – Three Types

- Analog
- Hybrid
- Digital.

These platform control system types support the following HMEDC functions using one or a combination of these three control technologies.

The functions performed by platform monitoring and control systems include:

- Propulsion control
- Ancillary control
- Auxiliary control
- Electrical control
- Steering control
- Damage control

The following discussion describes the capabilities and limitations of the three control systems types.

Analog Controls Architecture

Analog controls architecture provides separate systems for the control and monitoring of the platform systems. There are separate control and monitoring systems for each of the propulsion, electrical, auxiliary, steering, and damage control functions. The consoles in this architecture are comprised of conventional analog instrumentation, and these instruments are point-to-point connected (wire, pneumatics, hydraulics, etc.) directly to the sensors and actuators in the plant in most ships and submarines. There is little or no information exchange between the different operator consoles, thus this design architecture is considered vertically structured.

Analog systems are highly maintenance intensive, requiring onboard more than 300 line replaceable unit (LRU's) types, and generating an average maintenance mean time to repair measured in hours[4]. This architecture is used on virtually all U.S naval ships and submarines except the new DDG-51 and MHC-51 Classes. While the use of direct electro-mechanical remote control is possible with analog systems, automated control has proven to be impractical.

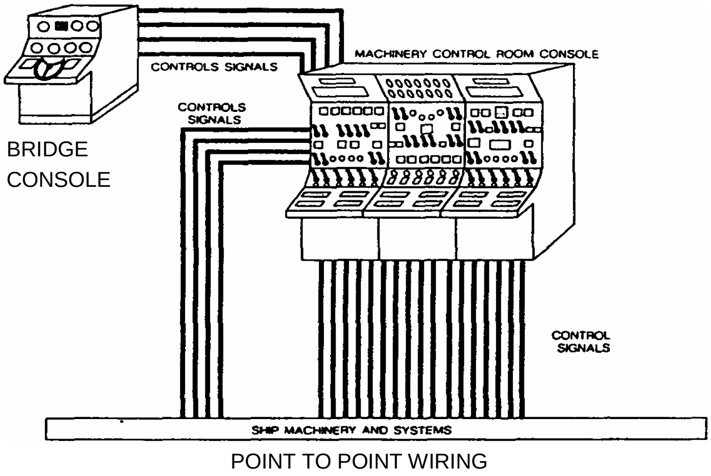

Figure 2. Typical Analog Control System

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[4] Naval Sea Systems Command, Fleet Maintenance Data, FFG-7 Class, 1988-1990.

Hybrid Controls Architecture

In the 1960s, the development of the marinized gas turbine engine for naval ships initiated the first practical steps to provide remote control of the power plant from the ships Main Control and from the Pilot House. Automated engine start and shutdown sequences became possible for gas turbine propulsion and electrical power generation. Other ship auxiliary systems also gained some degree of remote control in the 1970s through predominately hardwired, analog control systems technology.

The first significant use of digital controls technology for platform systems was with the DD-963 and CG-47 Class ships in the 1970's, and the DDG-51 Class ships in the late 1980's. Both of these class ships use what is frequently referred to as hybrid control systems. The term hybrid is used because these types of control systems use a mix of analog operator console interfaces (gauge boards, levers and dials) tied to the respective control system (propulsion, auxiliary, electrical, damage control, etc.) by a digital data highway for system status information to and from a central data processing computer complex. Actual system control remains point-to point via hard wire or pneumatic actuation.

For example, the control consoles used in DDG-51 have a combination of conventional analog instrumentation and plasma displays and contain six AN/UYK-44 standard microcomputers.[5] The consoles are connected to a Data Multiplexing System (DMS) data network between each of the HMEDC consoles and the monitored machinery. DMS uses a five cable, 20 channel network for graceful degradation when damaged. Monitoring and control takes place through the use of a combination of DMS for monitoring and point-to-point wire for control signals. All consoles share common inputs of control and monitoring information twice a second provided by the DMS net, from the status of the weather to intrusion alarms. The consoles, because of their analog design, support only their own functional system, and thus retain the vertical design architecture. Monochrome graphic data displays are provided in Central Control, on the Bridge and in CIC through the use of keypad numerical page call up.

This architecture reduces maintenance requirements, but is still relatively demanding. There are more than 1200 Navy standard electronic modules (SEMs) in each system, plus an extensive number of analog components. The DDG-51 control system contains 211 different LRU components. The built-in test for SEM boards narrows the maintenance actions to testing a three or four SEM board set to isolate the problem.[6]

Because the hybrid system is a digital computer-based control system it is possible to use both remote control and automated control. However, there are two limitations in the hybrid architecture, as implemented, that restrict the degree of remote control and automation. The first is the use of single function, analog consoles. This does not support operator control redundancy. The second is the use of central computer processing in Control Central. The use of only one central computer complex renders the control system vulnerable to a single point of failure, and the data rate on the data bus is too slow to support high-speed closed-loop control of machinery located away from the Central Control.

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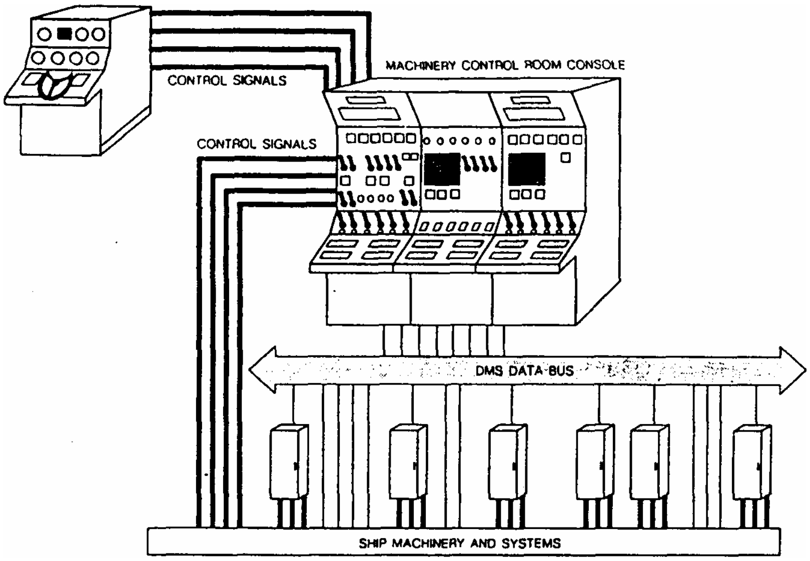
[5] CDR J. H. Preisel Jr., "High-tech Below the Main Deck, "Proceedings. (October 1988).

[6] Ibid.

BRIDGE CONSOLE



POINT TO POINT WIRING

Figure 3. DDG-51 "Hybrid" Machinery Control System Digital

Digital Distributed Controls Architecture

The major development in integrated digital distributed platform systems control for the U. S. Navy was the introduction of the AN/SSQ-109 machinery/ship control system in the MHC-51 Class ships.[7] This digital distributed technology originated in Canada in the early 1980s, and was installed in the Canadian Patrol Frigate Class, Canadian DDH-280 Class ships prior to its introduction into the U. S. Navy. The first MHC-51 with the AN/SSQ-109 control system was commissioned 20 November 1993.[8]

The AN/SSQ-109, digital distributed architecture, supports the use of a single integrated system for the monitoring and control of all HMEDC systems. However, the implementation of AN/SSQ-109 in MHC-51 provides monitoring of all systems, but uses the control functions for only the propulsion and steering systems. This system is the first to use *multi-function consoles* for machinery control, each with a high-resolution color CRT as the operator man-machine interface (MMI). *The use of multi-function consoles, operated similar to the manner in which NTDS consoles operate, is the major enabling technological improvement over the analog control and hybrid control systems*. Every console has the capability, through the use of color mimic pages and system icons, hard and soft keys and a track ball, to control and monitor every ship HMEDC control system. Aboard MHC-51, control consoles are located in Central Control, the Bridge, and CIC. Ship speed and steering, for example, can be done from any of these locations. (AN/SSQ-109 consoles can be located in any ship space such as Repair Stations, Fuel Control and Ballast Stations, etc.)

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[7] Lt Jon Walman, "21st Century Engineers Enter New Frontier," Surface Warfare (January - February 1994).

[8] J01 Roger L. Dutcher, "The Hunt is On," Surface Warfare. (January - February 1994)

The consoles in the MHC-51 system are connected to three data bus cables, and each cable carries 100 percent of the monitoring and control signals all of the time for fully redundant data communications. The one exception is a point-to-point connection for the main engine emergency trips.

Another key difference from analog and hybrid control systems is the ***distribution of the control system microcomputers*** from central control to each of the operating machinery spaces. This greatly improves combat survivability, as there is no single point of failure in the control system.

There is a significant degree of sharing of control and monitoring functions between all of the consoles, thus this design architecture is considered both vertically and horizontally structured. This architecture is inherently survivable in the most severe damage situation, and makes a large step toward reducing maintenance actions.

Using a small set of common components, only 36 LRU types are required in a typical control system, and the electronic boards have built-in test to the single board level.[9] Maintenance demonstrations conducted indicate a mean time to repair (MTTR) of just over 15 minutes.

The digital distributed architecture resolves the restrictions on remote control and automation of the digital hybrid systems, and can support what ever degree of remote control and automation that the designers and the fleet users desire.

The MHC-51 class is the first U. S. Navy ship to use the AN/SSQ-109 machinery/ship control system architecture.

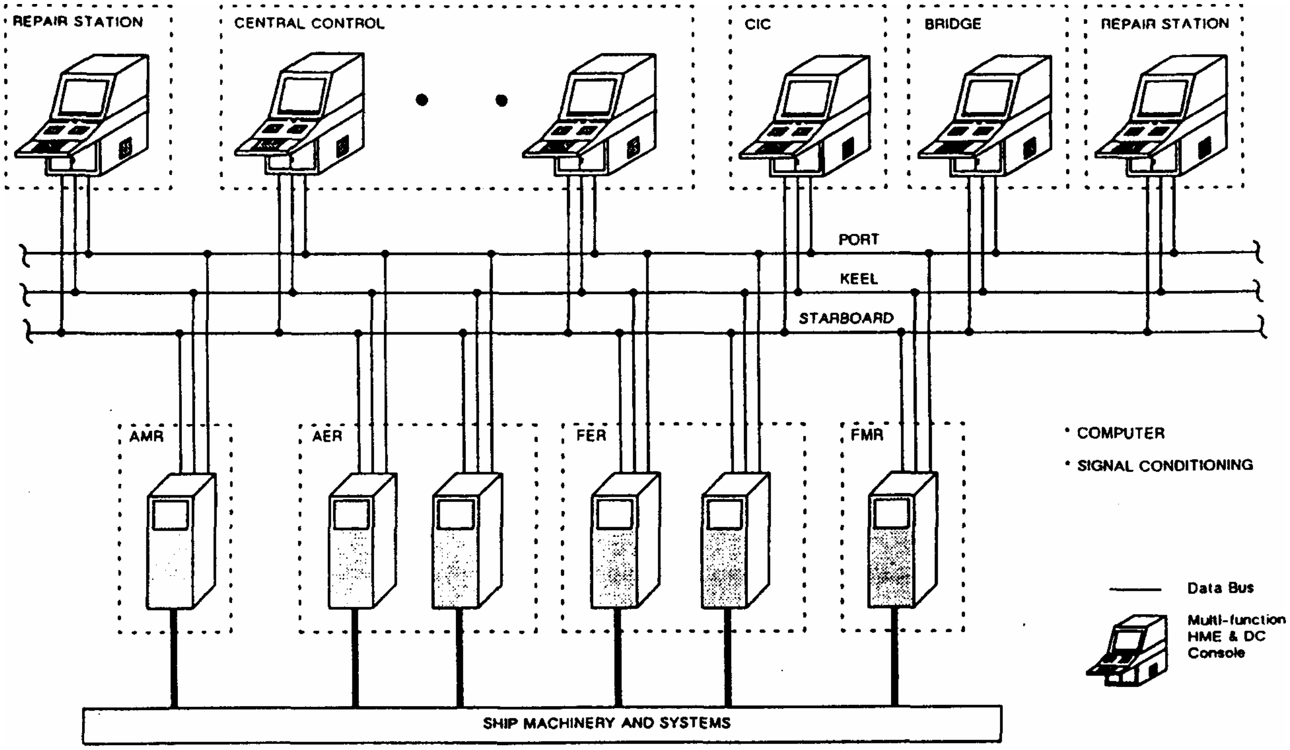

Figure 4. Digital Distributed Architecture (AN/SSQ-109)

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[9] Vicedomine, J., Taylor, B., Galindo, V., "Glass Controls for a Glass Ship," Proceedings,

Standard Monitoring and Control System (Digital Distributed) Architecture

The positive evaluation of the MHC-51 AN/SSQ-109 machinery/ship control system (described previously), as well as evaluation of similar AN/SSQ-109 derivative control systems in the Canadian and Israeli navies, lead NAVSEA to issue a contract in May 1993 to acquire an advanced development model (ADM) of Navy Standard Monitoring and Control System (SMCS).

The purpose of the SMCS ADM contract is to provide the specifications for a U. S. Navy owned hardware and software ship platform control systems that will be standard for all classes of Navy ships, in a way similar to that which NTDS provided a standard control system for combat systems. SMCS is to be platform system for all future ship control systems, both new construction and backfit upgrade. The SMCS ADM system commences Hardware Software Integration in September 1994.

SMCS consists of four standard hardware enclosures and modular software. This hardware and software (Ada) provides flexible building blocks for constructing any future ship platform control system. A typical architecture is shown for DDG-51, 1996, in Figure 5.

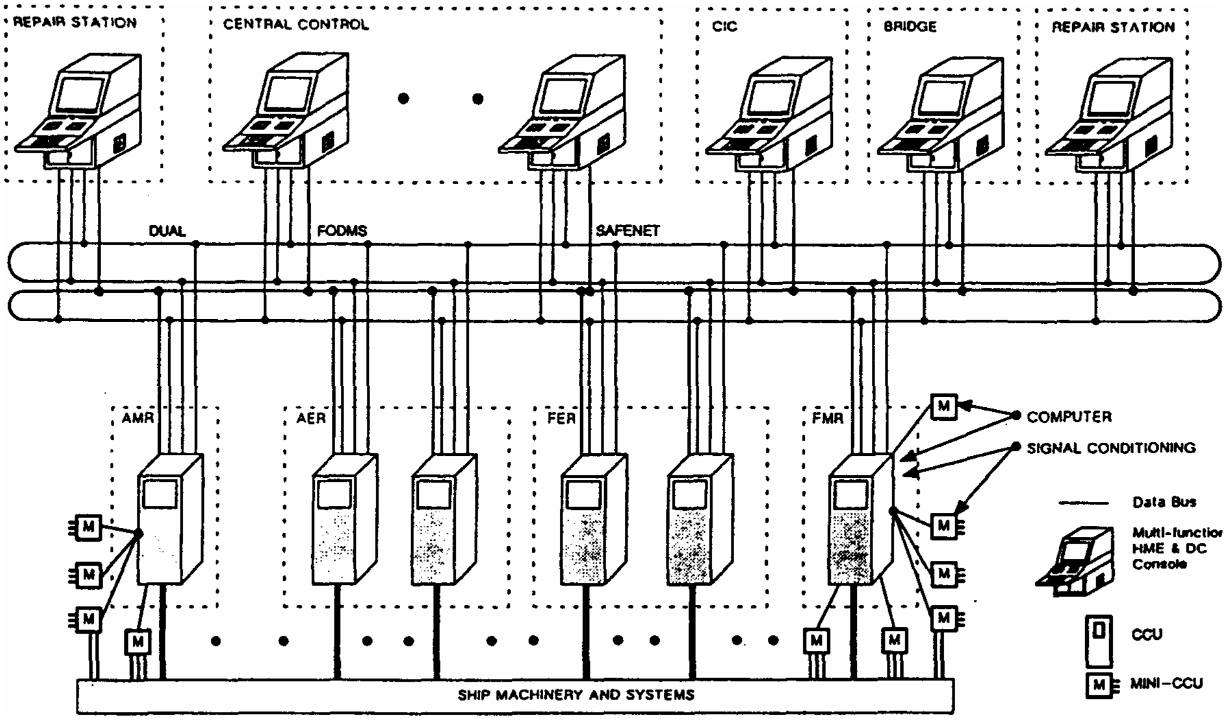
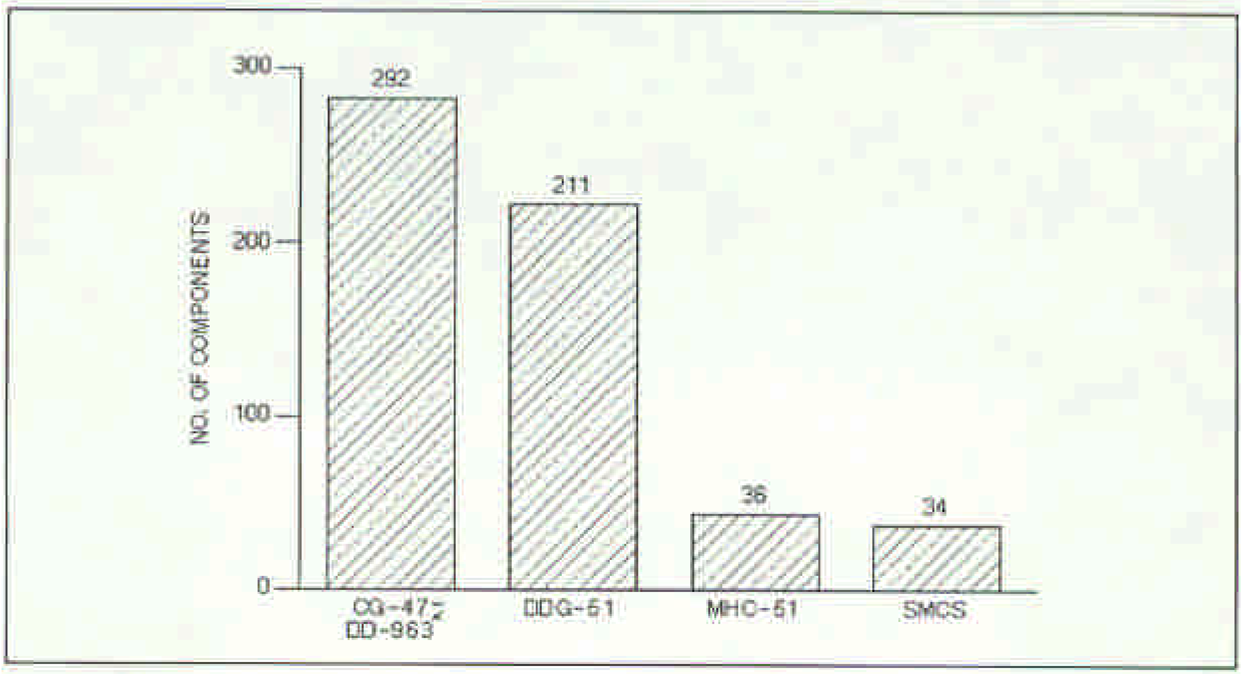


Figure 5. Standard Monitoring and Control System Architecture

Summary of Platform Control Architecture

As can be seen from the descriptions of the three control systems there has been a significant evolution in platform control systems architectures. The digital distributed control system designs in the MHC-51 and the new SMCS provide the technology necessary to support manpower reduction through the use of remote control and automation, as well as reducing the maintenance requirements. Table 1 provides a summary of the number of components necessary to support platform control systems now in the Navy.

Table 1. Control System Components by Ship Class[10]



SMCS is designed to provide a flexible and robust, open architecture to support all ship platform control systems requirements well into the 21st century, including ship control automation technologies. Without this evolution to full digital control systems, such as AN/SSQ-109 and SMCS, the following discussions of platform automation would not be possible.

The application of automation technologies will be addressed after a quick review of the warfare requirements that are driving new ship designs.

2.0 NAVY WARFIGHTING REQUIREMENTS

The Chief of Naval Operations' (CNO) Ship Operational Characteristics Study Report (SOCS Report, 4/26/88) detailed the operational characteristics that must be embodied in the design of the 21st century ship to enable it to perform its mission against the forecast threat. The principal objective of this study was to maximize the 21st century warship's ability to put ordnance on target. With regard to the hull, mechanical, electrical and damage control systems (HME&DC), this means designing a HME&DC system that supports the ship's combat systems, increases the survivability of the ship and provides a capability to fight through damage in all circumstances, with less people.

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[10] Table Data prepared by NAVSEA for the SMCS Program

Among the 12 imperative operational characteristics that were identified in the study were:

- Integrated machinery systems
- Survivability and the ability to fight through damage
- Embedded readiness assessment, mission planning and training
- Condition-based maintenance
- Collocation of ship control and CIC.

In meeting these operational characteristics, the design engineer must consider the goals of drastically reducing manning requirements aboard ship and life-cycle costs. Analysis of the capabilities of the control systems described above show that while both the AN/SSQ-109 and the SMCS architectures provide the necessary and highly survivable architectural building blocks, the SMCS architecture provides the low-cost electronics of the 1990s. The SMCS electronics have been selected based on open architecture and industry standard interfaces that are expected to last well into the 21st century. SMCS must have the following characteristics:

- Integration of systems
- Microprocessor-based monitoring and control
- Distributed system
- Effective man-machine interfaces
- Multi-functional operator stations
- Fault tolerant design
- Built-in-test
- Survivability
- Open architecture
- Embedded training
- Expert systems/AI-based subsystems
- Automated systems
- Modularity
- Data fusion
- Real-time transmission of monitoring and control information

3.0 AUTOMATING SHIP CONTROL SYSTEMS FOR PERFORMANCE, AFFORDABDLITY, AND HUMAN RISK MITIGATION

The purpose of this section is to discuss platform systems automation technologies that will enhance ship performance in combat with reduced manning and lower life-cycle costs. The new, fully digital distributed platform control system architectures can now support a wide range of ship automation strategies that significantly mitigate human risk in combat and reduce life-cycle costs.

Development of automation strategies require analyzing ship's operations relative to the ship's operating environments both external and internal.

The Ship’s External Operating Environment

The ***external operating environment*** of a ship includes such elements as weather, sea state, ocean acoustics, navigational hazards, danger from shipping and threats from enemy sources.

Strategies that should be applied here to reduce manpower and costs include increased remote control and automation of:

- Navigation systems such as the installation of integrated electronic charts with automatic navigational fixes from Global Positioning System (GPS) and radar overlay
- Mission planning
- Threat decision aids, such as water depth versus mine threat
- Autopilots for automated station keeping and shipping avoidance
- Ship's stealth, such as measures to improve ship stealth through acoustic, heat and wake signature reduction, where it is possible to use the environment for masking.

The Ship’s Internal Operating Environment

The ***internal operating environment*** of a ship includes the status of ship's vital and non-vital systems for life support and combat systems (mission) support, and the adaptation of the platform systems in response to the changes in the external and internal environment necessary to accomplish the ship's mission. Strategies that should apply here include increased remote control and automation of:

- HME&DC platform monitoring and control systems
- Combat systems
- Equipment maintenance, such as condition-based maintenance systems
- Readiness assessment, such as the use of on-board training and mission planning systems with built-in assessment subsystems
- Damage control.

This paper will discuss some of the work done to date with platform control systems to support remote control and automation, and suggest areas where additional effort is required.

Specific Remote Control and Automation Strategies

Each strategy for use of remote control and automation technology will be discussed in the following format:

(No.) Strategy Title

- SOCS Performance Requirement:
- Current State of this Automation Technology:
- Affordability:
- Human Risk Mitigation:
- Recommended Future Effort

[*Bullets added for reprint*]

Discussion:

1. Navigation Systems

SOCS Requirements: Collocation of Ship Control and CIC; Mission Planning, Integrated Machinery Systems

Performance Requirement: The current ship pilot house is manpower intensive at Conditions III, IV and General Quarters, and its functions are inefficient, in as much as the primary facilities for communications and combat systems control reside in CIC. The bridge of a ship is exposed to enemy fire and weapon effects with little or no protection for the crew. Sensor systems can replace the need for the mark I eyeball in most circumstances. If eyeballs are needed, then one or two sets should be all that is required. All ships should have the accuracy and real-time support integrated electronic charts with automatic navigational fixes from Global Positioning System (GPS) and radar, controlling ship course and speed, with collision avoidance and contact avoidance radar options, and with the radar overlay available to plot obstructions that were not present when the chart was digitized. This capability will be extremely valuable for mission planning, and especially for mission re-planning, if is the primary military objective is unattainable. Water depth and bottom type correlate to the mine threat. Real-time knowledge of this information can assist in mission planning and execution. IR, ESM and sonar sensors should be able to augment and replace the function of radar, if avoiding radar counter detection is critical. Ship conn should be able to be shifted to several survivable locations distributed within the ship, complete with autopilot control of position, course and speed.

Current State of this Automation Technology: MHC-51 is the first ship in the U. S. Navy (other than a submarine) to provide ship control (course and speed) in CIC, as well as the Pilot House. It also provides the capability in Main Control. Yet as advanced as is the MHC-51, it does not include digital color charts with radar overlay, or autopilot to assist in the complex maneuvering and position holding required of a ship in the midst of a minefield. All of the technologies required are commercially available. The Navy SES-200 surface effect ship operating out of the Patuxent River Special Trial Unit has been conducting trials with a commercial digital chart with GPS and radar integration over the past year.[11]

Affordability: Commercial technologies to meet the performance requirements for electronic charts, GPS, radar positioning and collision avoidance, and autopilots are affordably available. The Navy already has access to IR, ESM and sonar systems that can be added to meet the performance requirements.

Human Risk Mitigation: Watchkeeping reductions of 2 to 3 personnel per watch section should be possible.

Recommended Future Effort: The Navy officially evaluates available commercial technology to meet the performance requirements.

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[11] Lt Jon P. Walman, "Investing in Readiness," Surface Warfare. (March - April 1994)

2. Mission Planning

SOCS Requirement: Embedded Readiness Assessment, mission planning and training

Performance Requirement: The ship's control systems should have built-in test to the single LRU and provide command with readiness assessment on demand or as the ship's mission is changed (i.e., new systems demands are expected, e.g., AAW-to-ASW mission change). Mission operational orders, combined with digital charts, enemy order of battle and current intelligence, etc., should be supported with expert systems mission planning review including lessons learned and approved tactical doctrine.

Current State of this Automation Technology: Under development by ARPA and ONR.

Affordability: The software development and testing will be expensive and require extensive human factors and doctrine validation.

Human Risk Mitigation: May reduce watchkeeping requirements by 3 to 5 people per watch section (9 to 15 crew members per ship).

Recommended Future Effort: Continue ARPA and ONR efforts.

3. Threat Decision Aids

SOCS Requirement: Ship survivability, mission planning and training

Performance Requirement: For every element of the enemy order of battle there exists a body of knowledge, tactics and strategies to counter the threat. The ship systems should always be aware of the external and internal environment status as well as the ships operation requirements. As an example in the area of mine warfare, the use of digital charts makes it possible for the ship's navigation systems and combat systems to interact in background using the enemy order of battle, intelligence, water depth and bottom type to keep command informed on the likely mine threat and recommended countermeasures. With command approval, the system should automatically configure the ship's HM&E systems for mine countermeasures through monitoring and control of the ship's magnetic signature and noise emissions as the ship maneuvers through different threat areas.

Current State of this Automation Technology: Digital distributed control systems technology can support this level of machinery integration with ship navigation and threat detection systems.

Affordability: Only a moderate cost is estimated to integrate these functions using existing digital distributed control systems with integrated digital charts, GPS and existing combat systems information.

Human Risk Mitigation: This technology should be able to reduce watch keeping requirements by 2 to 3 personnel per watch section (6 to 9 personnel per ship).

Recommended Future Effort: Continue ONR and ARPA efforts.

4. HM&E Monitoring and Control

SOCS Requirement: Integrated machinery systems, survivability and ability to fight hurt, readiness assessment, mission planning, training, condition-based maintenance, collocation of ship control and CIC, and alternative use of volume.

Performance Requirement: The HM&E machinery of the platform should be able to carry out the operational demands for course, speed, power generation and load shed, providing, and configuring to provide, power and services to the mission critical systems in a fully automatic mode. Ship control in CIC (the ship command center) is key. For redundancy, ships of the future should have both a primary and secondary command center, separated and located for survivability. The command centers should each be able to access all sensors and weapons, and be able to monitor and control all HM&E platform systems including ship control. Each command center should fully protect the crew with "over pressure" citadels, and all crew members should be protected. The Pilot House (or open conn) should be minimum in size and be used only for special sea detail evolutions. Built-in training in engineering casualty control should be available at each watch station to maintain crew proficiency as individuals and as watch teams. All machinery should be self assessing using built-in test to the single LRU level. Maintenance repair should be reduced or eliminated by the use of new electronics technologies. The primary electronic "repair" should be the use of spare capacity in the existing control system, and should this fail, then a quick remove-and-replace policy should be used using a small set of onboard spares. Combat volume should be increased by decreasing the size and weight of non-combat systems and components, or reducing the space and weight for crew members through automation.

Current State of this Automation Technology: Almost every element of the automated HM&E control strategy technology exists today and is being introduced in some navies of the world. For example, the MHC-51 provides three ship control locations. The Israeli SA'AR-5 corvette, built at Ingalls Shipbuilding, provides most of the features described in the performance requirements for HM&E automation. Consider that the average manning level for 1200-ton corvettes world wide as listed in Jane's is a crew of 120 to 150. The SA'AR-5 has a crew of only 55, yet supports the following sensor and weapon systems, significantly more firepower than exists in any other corvette: three missile systems, two gun systems, hull-mounted and towed sonar array, manned helicopter capability (with hanger), two diesel and one 30,000 HP gas turbine engine automatically connected to twin CRP shafts through a 5-way gear box, capable of speeds to 35+ knots, all controlled by a digital distributed platform control and combat system control systems using color CRT operator consoles. The SA'AR-5 and the MHC-51 share the same hardware and software building blocks and the same basic set of 36 LRU's to support the machinery control system. The SA'AR-5 simply has more software (higher control signal count) to support a much higher degree of remote control and automation. Relative to combat volume, SA'AR, through manpower reduction and automation, has a combat volume of 37%, compared to the combatant like CG-47 or DD-963 which has a combat volume of 23%.

Affordability: The SA'AR-5 digital distributed platform control system is composed of the same components as the U. S. Navy's Osprey Class, MHC-51. The acquisition cost of these digital machinery control systems is about one-half of the cost of a comparable (by signal count) analog or hybrid machinery control system. The life-cycle cost savings for the platform control system will be even greater, as there are only 36 LRU's in the control system, compared to 211 LRU types in the most modem hybrid control systems now at sea in DDG-51.

Human Risk Mitigation: The SA'AR-5 crew is 54% to 63% smaller than the crew of a similar 1200-ton ship, yet the ship carries more firepower than the other corvettes.

Recommended Future Effort: Investigate the design criteria for automation used in SA'AR-5, and determine how this class ship used the digital distributed platform and combat systems controls technologies to achieve a greater than 50% manpower reduction.

5. Damage Control

SOCS Requirement: Integrated machinery systems, survivability and the ability to flight through damage, embedded readiness assessment, and embedded training.

Performance Requirement: Current technology should be able to replace the highly manpower intensive manual damage control plotting and massive requirements for verbal communications during damage control actions. On DDG-51, for example, at Condition I, it takes 49 people to plot and communicate damage control information between the DC stations. This manual method is highly inaccurate and slow, and does not include the readiness plotting of mobility systems and combat systems. The commanding officer should have instantaneous readiness status of his total ship: damage control, mobility and combat systems. Automated response to damage should be possible such as recommended setting of damage boundaries, load shed and reconfiguration of vital systems to support mission requirements and fight hurt, if required. Battle damage estimation, fire spread, flood spread and stability models should continuously run in background using liquid load and other sensor information from the ship's digital distributed platform control system. The calculations made from this information should alert the command structure immediately of forecast instability conditions, or out-of-control conditions likely to impact weapons magazines. All plots and data should be automatically archived for reconstruction and training. The information data rate should be packaged so that, if desired, the battle group commander can "observe" the damage control effort in progress including the consumption of supplies, like Obi’s, so that re-supply and assistance can be rendered without delay.

Current State of this Automation Technology: The Navy has been funding Integrated Survivability Management System (ISMS) for about five years in order to meet the performance requirements described. To date, this effort supports damage control plotting and inter-station communications. The USS Anzio (CG-68) has participated with NAVSEA and private industry in a parallel research and development effort to meet the performance requirements. A prototype battle damage control systems (BDCS) was installed aboard USS Anzio in December 1992 and has now completed 18 months of prototype testing. *The BDCS provides instantaneous readiness assessment for damage control, mobility and combat systems at nine stations throughout the ship.* Phase I of the research is information only. Later phases of the development will provide response to damage using the ship's installed machinery and damage control systems. BDCS incorporates embedded training with the ability to create scenarios aboard ship including support for Total Ship Survivability (TSS) exercises as required by the Afloat Training Groups (ATG's) as part of the normal Aegis ship workup for deployment. This training can be patched via telephone to other ships or shore bases for joint training, including incorporation into the Navy's battle force tactical training (BFTT) exercises when this capability comes on line in 1995. The BDCS architecture, now referred to as DCS, has been selected by NAVSEA as the baseline for incorporation into the Navy's Standard Monitoring and Control System (SMCS) architecture for installation in DDG-51, 1996. Watch station reduction using DCS to date has been 16 personnel at Condition I and 15 at Condition III. These people have been reassigned to direct damage response from their current positions of plotting and taking. Yet to be completed by the U.S. Navy is research to define the characteristics of improved damage control sensors, actuators and algorithms for responding automatically or remotely to a broad range of possible damage control scenarios. Again, however, SA'AR-5 is leading the way. SA'AR-5 uses rapid cross checking of multiple fires, smoke and flooding sensors to determine the extent of damage combined with the automated response of fire fighting and dewatering systems. Manual and remote control systems are also provided. Note that it is the small crew size of SA'AR-5 that permits the more aggressive use of automated damage control response systems. Since most compartments are unmanned, there is reduced risk to the crew by the rapid or instantaneous use of Halon and other fire suppressing measures. For the U.S. Navy there is a sizable effort being coordinated by NAVSEA, ARPA and ONR. Improved sensors and actuators, or better use of existing sensors and actuators, can be readily integrated into modular digital distributed control systems now being introduced into the fleet such as the AN/SSQ-109 or SMCS systems.

Affordability: The damage control system (DCS) architecture uses the same digital distributed architecture as used for AN/SSQ-109 or SMCS, using commercial hardware and software tools thus supporting integration of these capabilities.

Human Risk Mitigation: The goal is to mitigate the loss life in combat operations. A method for accomplishing this goal includes reassigning manpower from damage control "overhead" positions of plotting and talking, to direct damage control response positions. If excess billets remain, then crew reduction is possible, thus mitigating human risk in combat.

Recommended Future Effort: Support ARPA, ONR and NAVSEA in the development and implementation of advanced damage control sensors, actuators and software algorithms. Incorporate these technologies as they are developed.

6. Condition Based Maintenance

SOCS Requirement: Condition based maintenance, embedded readiness assessment, mission planning and embedded training.

Performance Requirement: In constructing a ship's manning document for a combatant ship, watch stander positions are filled and then these billets are assigned maintenance duties at the rate of 11 hours per week. The remaining crew of the ship is made up of non-watch slanders by dividing the remaining maintenance man-hours by 67 man-hours per week per non-watch stander. Maintenance requirements are significant manpower drivers. The most effective manpower reduction action that can be taken is to convert watch standers to non-watch slanders, as this gains a net of 56 maintenance man-hours per week for every billet conversion. Thus every effort must be made to reduce watch standers, as well as the requirement for maintenance in the first place. The current maintenance policy of *time based maintenance* is very expensive as frequently machines are overhauled when they do not require maintenance. The goal is to use machinery vibration and other sensor inputs to determine machinery condition to forecast remaining service life, and to repair only that machinery which is projected to require repair during the pending mission period, i.e., condition based maintenance. The ship's normal platform control system should be able to retrieve the equipment condition signals as a by-product of machinery control so that additional data networks are not required. Additionally, the platform control systems should be able to automatically adjust the use of machinery in response to its condition and the mission requirements of the ship, either by conserving certain machinery for mission critical use, or placing even use on all machinery, depending on the maintenance philosophy selected.

Current State of this Automation Technology: NAVSEA has developed an Integrated Condition Assessment System (ICAS) which provides a shell for NAVSEA and third-party suppliers to provide modular hardware and software for HM&E equipment condition based assessment subsystems. This capability is planned to be integrated into the Navy SMCS for

DDG-51 in 1996, as well as into CVN class ships.

Affordability: ICAS uses commercial hardware and software tools similar to DCS, discussed above. Its modular design makes it compatible with digital distributed platform control systems architectures.

Human Risk Mitigation: When ICAS is fully employed and populated with appropriate condition based maintenance subsystems, significant reduction in maintenance requirements, ergo manpower requirements should be possible, thus reducing crew size.

Recommended Future Effort: Support NAVSEA in the development of advanced condition based maintenance hardware and software systems.

REQUIRED ENABLING TECHNOLOGIES AND CULTURAL CHANGE

Before many of the specific applications of remote control and automation as discussed in this paper can be put into service with the Navy, it will be necessary to resolve enabling technical and cultural changes.

Enabling Technology Requirements

Sensors and Actuators

The introduction of increased remote control and automation requires that the installed sensors and actuators that replace the human operator be fully proven to perform the tasks. There are several areas of concern.

Availability: Are there sensors and actuators available that can reliably replace humans?

The response is yes, in most cases. If we look at the space program, commercial ships and aircraft, we see that with proper engineering for redundancy and feedback to the human controllers that minimal operating crews can operate in the hostile environment in space, at high altitude and on the seas with great reliability.

Cost: Can we afford the acquisition and maintenance of these new sensors and actuators?

The response is yes. Compare the acquisition and maintenance cost of a sophisticated sensor or actuator to the cost of acquiring, training and replacing every year or two, three human operators (one each per Condition III watch) to perform the same tasks.

There are two options as to cost for sensors. One is the use of very expensive, multi-function sensors. The other is the use of many low-cost digital and/or fiber optic sensors that are polled and correlated rapidly by the control system to determine the current state.

Also consider human risk mitigation in combat. The American public has come to expect that future combat operations will reduce the exposure of humans to injury and death. This cannot be done with the current design of our combatant ships. Current ship designs for a cruiser, for example, place at risk more than 330 people in order to store and employ 120 missiles. It would seem prudent to try to reverse that ratio: 120 crew to employ 330 missiles. ARPA has a goal of reducing crew size by 90 percent[12].

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[12] ARPA Broad Agency Announcement 93-05, October 1993

Required Cultural Changes

As stated at the beginning of the paper, perhaps the largest challenge to automating naval ship systems is resolving cultural barriers. U. S. naval warfighting is very complex, and is based on 200 years of developed technology and culture, including naval regulations, customs and traditions. There are many aspects of naval warfighting doctrine, naval regulations, customs and traditions that will require significant modification. For example, assume that ARPA, ONR and NAVSEA demonstrated successfully that a warfighting ship with a missile load of 330 and a crew of 36 that could sustain itself at sea and fight long enough to fire all of its weapons before withdrawing to rearm. Consider the impact relative to the current concept and role naval ships for supporting diplomatic missions, the combat role of the pilot house (bridge), the routine control of the ship from the command center, the methods of maintenance and at sea replenishment, the duties and training level of the crew.

Not every naval ship would be built to be this lean and mean, but some ships could be and should be as part of an overall naval mix. How would this ship fit in? How does the Navy convince the future crew that this ship is viable for the mission? This is where simulation can find the answer, just as it did for the space program and the landing on the moon.

Measures of Effectiveness (MOE)

One of the challenges is constructing valid measures of effectiveness to use in evaluating each automation strategy. The MOE must include attainment of the ship's mission given the reduced number of personnel aboard in the context of the ship's external and internal environmental conditions.

Confidence Building

The demonstration of the automation strategies must include confidence building with the ship's crew and crews of other ships in the battle group to prove that the remote control and automated systems will actually perform as programmed. A major step in this direction can be taken by "simulating" a high firepower, low crew size ship during fleet exercises using the BFTT technologies. How would a battle commander employ a ship with 330 missiles and a crew of 36 assuming it had the same defense against enemy threats as today's best combatants like DDG-51 andCG-47?

Enroute to inserting the automated future ship into the BFTT, it would be essential to build a full or partial mockup of the automated ship of the future and train its crew in the use maintenance and use of the ship's highly automated systems, and train the ship's warfare commander in roles and missions (or at least the postulated roles and missions) of such a ship. If the warfighting and battle survivability of the ship show through extensive simulation using real crew members that this level of automation is achievable, then these ships should be transitioned into the fleet as part of the mix.

CONCLUSION

This paper has reviewed the evolution of ship platform control systems to show why it is only now, with the digital distributed machinery monitoring and control technologies entering the fleet, such as the AN/SSQ-109 and the SMCS, that large-scale use of remote control and automation of the ship platform functions is possible. Digital distributed controls technology is available to highly automate platform functions. However, much remains to be done to validate the performance of sensors and actuators in order to extend the range and depth of the automated functions, such as fire suppression and damage control.

But solving just the technical problems will not produce high firepower ships with radically reduced manning. Extensive warfighting doctrine and cultural changes must also be put in place and be acceptable to the future men and women that will make up our Navy. Fortunately, we can borrow on the experience of other navies which have already experienced severe budget reductions and have had to reduce manpower as much as 60% while maintaining a full combatant capability. The U.S. Navy also has available very strong simulation and training technologies that can be used to "prove" the capabilities of automated ships with reduced manning.

ARPA, ONR and NAVSEA have recognized the need to meet the naval warfighting requirements of the fleet with fewer people at risk. The development and employment of ship systems automation technologies will be mandatory to meet these objectives.

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