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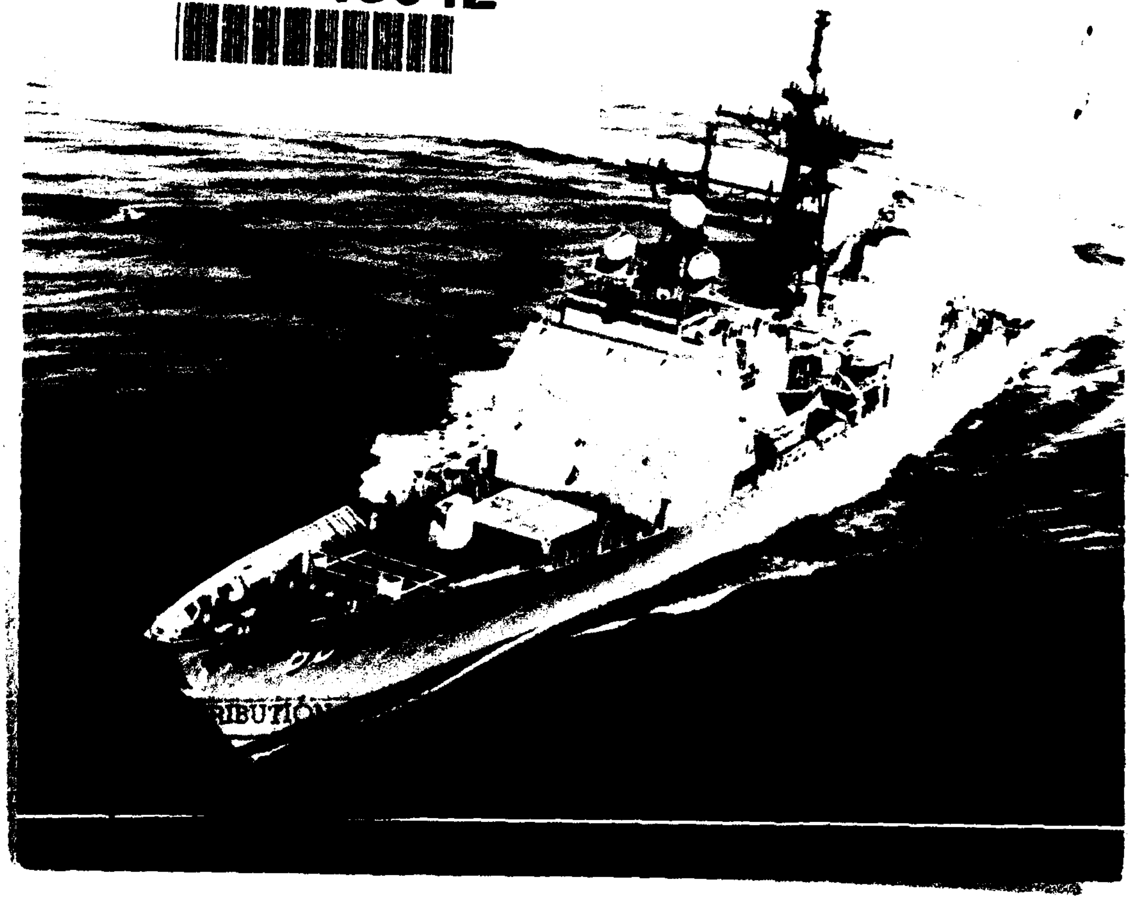

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Expert Systems: Track guidance mathematical models, automatic berthing neural controllers, and damage surveillance and control systems.
Machinery Monitoring and Control Systems: Generic controller card set, engine control, and icebreaker controls.
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SHIPBOARD TOKEN RING LOCAL AREA NETWORKS (LANS): DATA HIGHWAYS TO THE FUTURE

by
Ross L. Bennett
Sperry Marine Inc.
and
Dr. Alfred C. Weaver
University of Virginia
Department of Computer Science

1. ABSTRACT

The design of naval ships is beginning to be impacted by the rapid advances in high-speed information networks being placed on them. An example of such a network is the Navy's emerging SAFENET (Survivable Adaptable Fiber Optic Embedded Network) standard [1]. These networks use fiber optics media, new high-reliability networking techniques, and developing standards in hardware and software.

Sperry Marine has pioneered the effort to place high-speed data networks aboard commercial vessels through its development of SeaNET, a 4 Megabits/sec (Mbps) IEEE 802.5 [2] standard token ring with real-time data transfer capability. As a logical advancement of its shipboard networking expertise, Sperry Marine is now developing a network, with associated real-time interfaces, which will meet the SAFENET standard. As part of this development effort, the University of Virginia Computer Networks Laboratory has been contracted to design and implement a software version of the Xpress Transfer Protocol (XTP) [3], the light-weight protocol specified in the SAFENET standard.

This paper presents a summary of lessons learned through the development of the SeaNET real-time commercial shipboard network and a description of the new work under way to develop a SAFENET-compatible network. Included is a summary analysis of the impact such a network will have on future ship design.

2. INTRODUCTION

Traditionally, shipboard equipment has been distributed throughout a ship in the form of stand-alone systems with very little interconnectivity among units. This approach leads to equipment employing a variety of user interfaces which require more space than desired. It also promotes inefficiency because of the myriad different controls and displays.

Modern techniques allow equipment to be networked together to derive the maximum benefit from the fusion of data from many sources. This fused data can now be accessed through integrated display and control consoles. When fused information is accessible at user-friendly centralized locations, higher efficiency is achieved. Operational decision-making is further enhanced by the ability to monitor data with microprocessor-based units, freeing the operators to concentrate on the decision-making process.

In order to satisfy the requirements for integration of shipboard navigational equipment, Sperry Marine, in conjunction with the University of Virginia Computer Networks Laboratory, has developed an Integrated Bridge System (IBS) that uses a real-time token ring network called SeaNET. The network integrates all of a ship's bridge equipment, including sensors, navigation units, display devices, radars, and steering control units.

The design and development of SeaNET has resulted in four major attributes:

- The hardware and software is based on existing standards.
- It is able to interface all types of equipment, whether made by Sperry Marine or by other manufacturers.
- It has distributed control so that single point failures will not bring down the network.
- It is flexible, expandable, and able to be integrated with other shipboard data systems.

The first requirement insures us that second sourcing of components is available and that the network will be acceptable to a wider field of customers. The second requirement enables customers to configure their own system with navigational units with which they are most comfortable. The third requirement addresses the reliability issue. Real-time systems must continue to operate even if one of the stations on the network fails. Finally, the fourth requirement insures that the Sperry IBS can share information with other, non-SeaNET-based systems such as an engine room monitoring system and SAFENET.

3. LAN SEARCH AND SELECTION

In 1986, Sperry Marine contracted with the Computer Networks Laboratory at the University of Virginia to evaluate the suitability of extant LAN products (Ethernet, token bus, token ring, etc.) and to recommend one for shipboard use. The result of this analysis was the selection of the token ring topology. The primary advantages are:

(1) Token rings easily accommodate copper or fiber media, or both, on the same network; for a ship, this means we can run inexpensive shielded twisted pair media in low-noise areas such as the bridge, and reserve the higher-cost fiber optic media for high-noise areas such as the engine room.

(2) Commercially available token rings provide a range of performance options, from 4 to 100 Mbps.

(3) They can be made fault-tolerant by using a star-ring topology (i.e., wiring centers) and counter-rotating dual ring design.

(4) Choosing the IEEE 802.5 token ring (at 4 or 16 Mbps) assures us of multiple hardware vendors and conformance to international standards.

(5) The token ring topology and the IEEE 802.5 standard are consistent with the Navy's direction for SAFENET.

4. SEANET DESIGN AND DEVELOPMENT

Once the selection of the IEEE 802.5 standard was established, Sperry contracted the University of Virginia Computer Networks Laboratory to develop a real-time network interface which could handle the sensor update rate requirements. At the same time, Sperry performed an investigation to select the network components and a ruggedized PC-based unit to be used for the network interface unit (NIU). Sperry also developed several interfaces for sensors to be attached to the network, including the selection of the analog and digital interface boards required for each sensor. Finally, Sperry developed three sophisticated units for the fusion, control and display of navigation and ship control information.

4.1 Real-time Network Interface

The Computer Networks Laboratory knew from their previous network performance evaluations that the commercially available ISO protocol packages (1) would not meet our real-time performance requirements and (2) were really overkill for a relatively short, single segment LAN with a modest number of stations. To solve this problem, they designed and implemented a real-time network interface, provided as a set of library functions which the user links into his application program. To encourage interoperability, the interface adheres strictly to the IEEE 802.2 logical link control (LLC) standard [4].

SeaNET provides a basic datagram service, with optional acknowledgements and checksums, to multiple application processes running on microcomputers. Communication occurs through sockets which are equivalent to IEEE 802.2 LSAPs (link service access points). The user interface is a set of 'C' procedure calls which create and manage sockets, set options, send and receive messages, and report network status [5].

Messages received from the network are filtered at both the hardware level and software level. At the hardware level, each station assigns itself to a functional group which becomes part of the address for the network interface board. When a message is received whose destination address matches the functional address of a station, the message is copied to the incoming message buffer. The real-time software interface then looks at the header information of the message itself to determine if the message is meant for any of the tasks requesting services. If not, the message is ignored. Otherwise, the task is notified of receipt of a message and, when requested to do so, the network interface copies the message into the task's buffer.

4.2 Hardware Selection and Configuration

There are four basic components of most token ring networks (see **Figure 1**):

- processor units (nodes) containing the applications which use the network as a data transfer vehicle
- network interface boards which plug into the processor units and control the actual transfer of data on and off the network

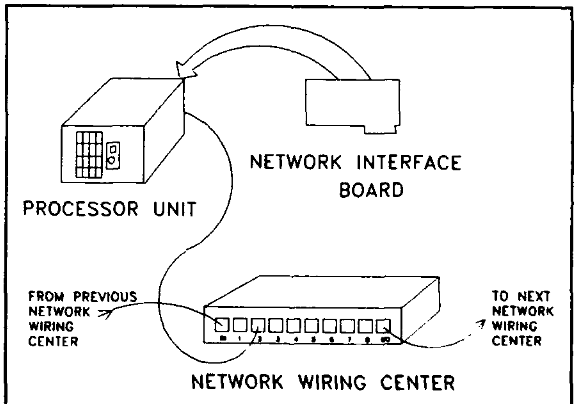

Figure 1 - Network Components

- network wiring centers (NWCs) which contain bypass switches allowing stations to be attached and disconnected from the network without halting the network

- the network cable

a. Initial Prototype. The initial SeaNET prototype development was started more than four years ago. At that time, ProNET-10[1] network components were used. This was necessary because, although the token ring standard was already adopted by the IEEE 802.5 committee, the hardware was not yet commercially available. The ProNET-10 hardware is similar to the IEEE standard and allowed easy transition to the 802.5 standard as our development effort progressed.

PC-based units were selected to serve as network interface units (NIUs) because they offered both lower development cost and lower cost for our customers. Because of the harsh shipboard environment, we investigated several potential units as NIU candidates. Our investigation resulted in selection of a PC chassis with a passive backplane, allowing us to configure our units with various manufacturers' microprocessor boards, sensor interface boards, and network interface boards.

The prototype was configured as shown in **Figure 2**. We selected the Sperry MK-37E gyrocompass as the initial sensor since it has the highest update rate requirement. The gyro NIU was initialized with the current heading. This was done remotely using a PC workstation attached to the network. Once initialized, the NIU began receiving step (1/6°) changes from the gyrocompass and used these changes to calculate a new absolute heading for transmission on the network. When this data was received by the autopilot NIU, it was converted back to step changes. These changes were fed to the Sperry SRP-690 autopilot causing its heading indicator to turn.

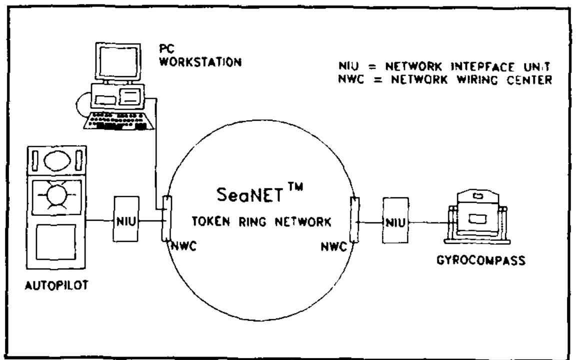

Figure 2 - Prototype Configuration

[1] proNET-10 is a trademark of Proteon, Inc., Westborough, MA.

Once we proved these interfaces worked across our SeaNET prototype, we began developing a suite of additional sensor interfaces for other Sperry equipment. This was done in a phased manner with each interface being tested and checked for performance before implementing the next.

b. Conversion of Prototype to Target System. When the IEEE 802.5 4-Mbps token ring products became available, all interfaces were converted to this standard. The real-time network interface was ported to both the Proteon ProNET-4[2] token ring interface board and the IBM PC[3] Token Ring Adapter. Since the IBM board showed better performance in raw throughput measurements, we selected this board as the primary network interface for our NIUs, with the Proteon board to be used for second sourcing.

Recently we acquired several of the new IBM 16/4 PC Token Ring Interface Boards. These boards are switchable between 4 and 16 Mbps. We were pleased to find that these boards are completely compatible with our applications and require no changes to our real-time interface.

The primary reason for SeaNET's ease of portability is its modular design. Operations which are network dependent (e.g., the device driver for a particular vendor's token ring interface) are isolated from the user interface. From the point of view of the user, the interface to SeaNET is identical regardless of the token ring's speed or its manufacturer.

c. Performance. SeaNET's most important attributes are its high throughput and low latency performance characteristics. **Figures 3-5** show SeaNET's performance when executing on a 25 MHz Intel 80386 CPU. These figures compare SeaNET performance for two token ring interfaces: the 4-Mbps ProNET-4 and the 10-Mbps ProNET-10.

Figure 3 records the load generated by a single station for messages of various lengths. The graph compares the performance of the ProNET-4 using programmed I/O (solid line), ProNET-10 using direct memory access (dashed line), and the ProNET-10 using programmed I/O (dotted line). Using ProNET-4, SeaNET can sustain an offered load of about 2 Mbps. That is one half the network's total capacity generated by a single station! Using ProNET-10, throughput rises to almost 4 Mbps.

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[2] proNET-4 is a trademark of Proteon, Inc., Westborough, MA.

[3] IBM and PC are trademarks of International Business Machines Corporation.

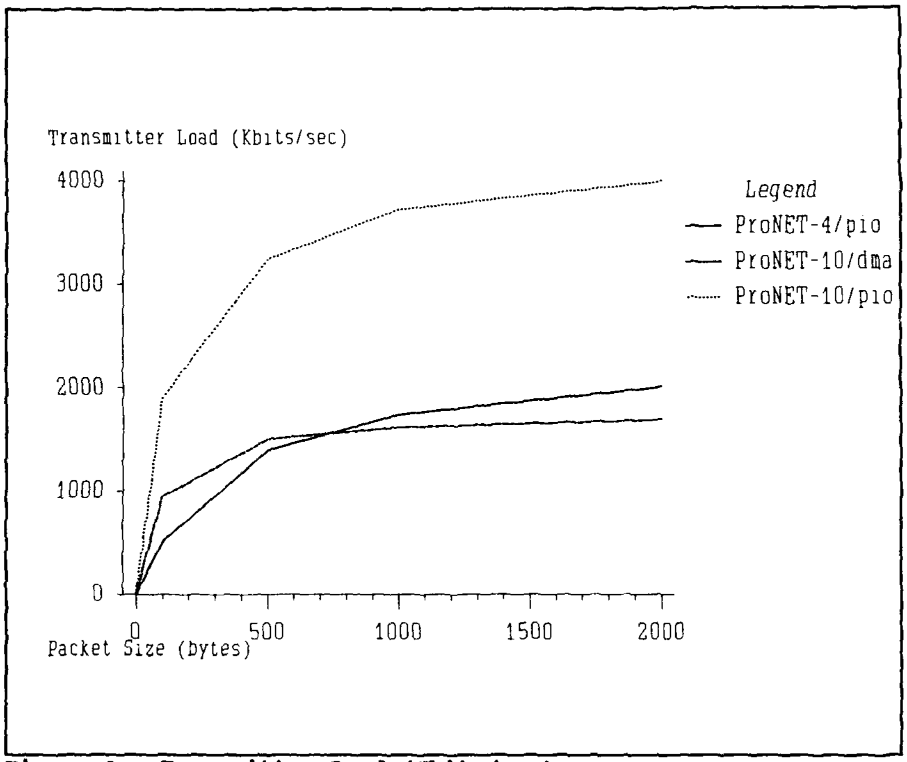

Figure 3 - Transmitter Load (Kbits/sec)

For a control system, total station throughput may be less important than the message rate, i.e., how fast individual control messages can be emitted. **Figure 4** shows the transmitted load in units of packets/sec. For short (100-byte) messages which are typical of control applications, SeaNET can sustain 636 packets/sec on ProNET-4 and 2380 packets/sec on ProNET-10.

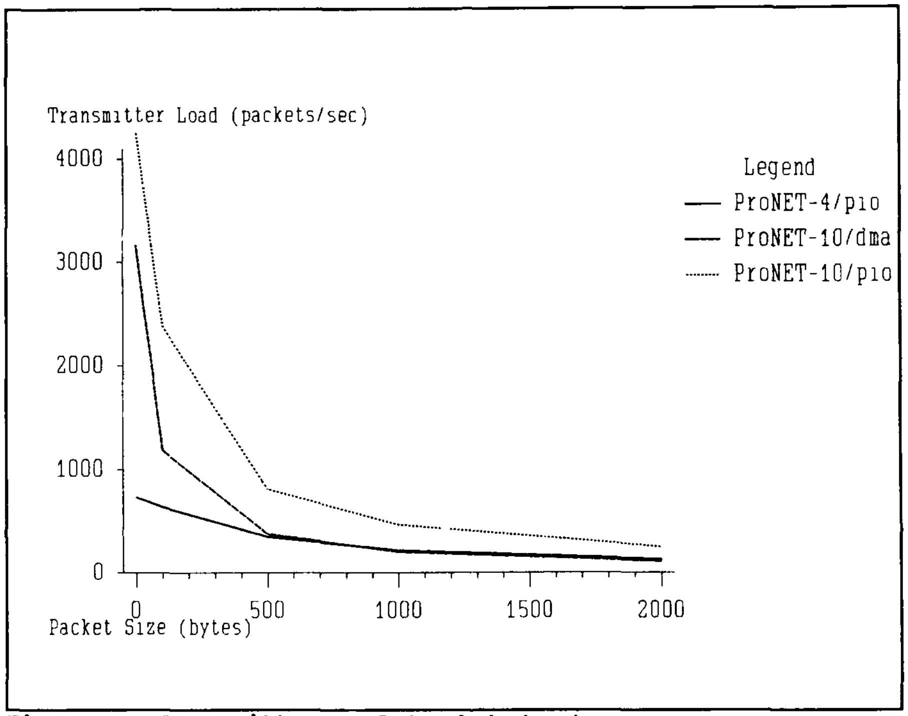

Figure 4 - Transmitter Load (packets/sec)

In any real-time system, end-to-end latency is a very important factor. Our measurements of end-to-end delay include all factors which a user message would see: posting the message buffer, interacting with the operating system, copying the message across the backplane bus, network access time, and network transmission and propagation delays. **Figure 5** shows elapsed time from when a user posts a message for transmission until the message is received by the destination's application program. SeaNET delivers 100-byte messages end-to-end in 2.63 milliseconds for the ProNET-4 and in 680 microseconds for the ProNET-10.

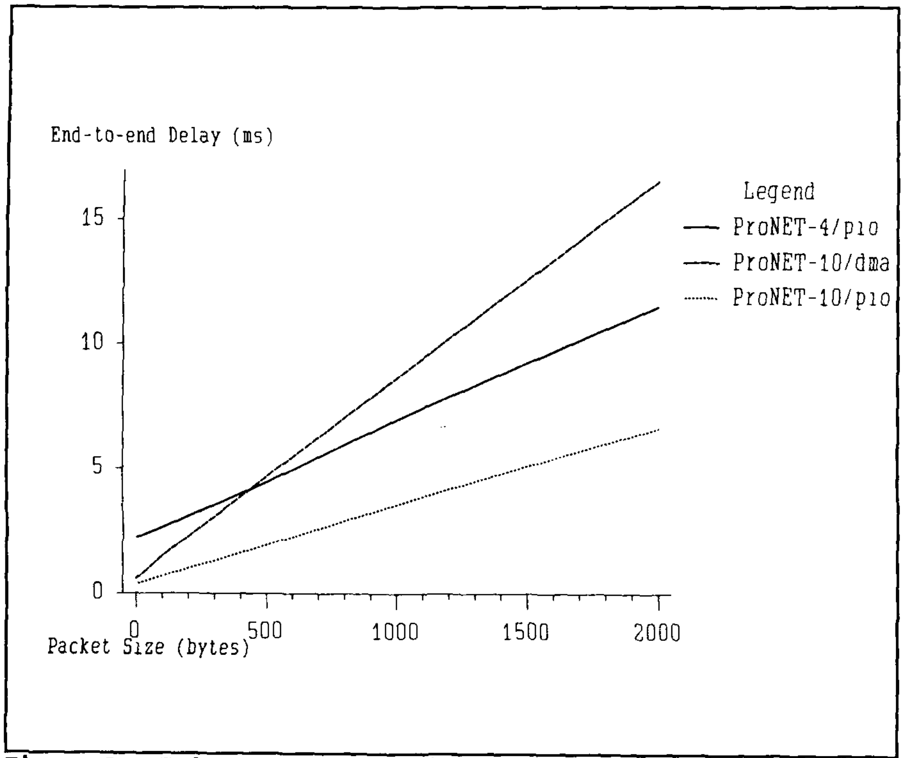

Figure 5 - End-to-end Delay (milliseconds)

d. Network Wiring Centers. All stations on the SeaNET token ring attach to the network through network wiring centers (NWCs)[4]. These units have normally-closed relays in each station attachment port which are caused to open via an electrical signal from the attachment station itself. Removal of this electrical signal causes the relay to return to its closed position, thus bypassing the station.

[4] Some manufacturers refer to these units as multistation access units (MAUs). This paper refers to all such units as network wiring centers (NWCs).

Two basic types of NWCs exist: unpowered and powered. Each of these units usually contains 8 ports for station attachment and two additional ports for connection to other NWCs. The unpowered units contain no indicators to inform users of their health or which stations are currently active on the ring.

Powered NWCs usually have LEDs to indicate that the unit is powered up and to indicate which stations are active. A subclass of the powered NWCs are the "intelligent" NWCs which allow special diagnostic tools and network configuration management programs to have access to the network. Another subclass are the "repeating" NWCs which are used to boost the network signal over long runs. A third class of powered NWCs are the fiber optic units which allow fiber optic cabling to be used between NWCs. Some units have all of these capabilities.

Sperry initially chose the IBM passive, unpowered NWCs for their installations because of their low cost and simplicity. However, it has been discovered that severe vibration or strong magnetic fields can cause the internal relays to switch to an improper state. This, in turn, can cause degradation or, in some cases, complete failure of the network. Of course, a shipboard environment can have both severe vibrations and strong magnetic fields present. Therefore, we have now switched to the Proteon powered NWCs which insure that the relays are held in their proper state.

e. Network Monitor. During the development of the SeaNET real-time interface, the University of Virginia Computer Networks Laboratory also developed a real-time network monitor. This monitor contains both a graphics mode and a trace mode.

In graphics mode, the monitor displays color-coded scroll graphs of recent network traffic. Network data is sampled at a user-defined rate (up to 100 times per second) and a graph shows traffic intensity in packets/sec and bits/sec.

Trace mode allows the user to trap all network traffic, or any subset as specified by a user-defined address filter. Trace data may be displayed on the screen in real-time (i.e., as it is captured) or diverted to a disk file for off-line analysis.

The user can also define event or frequency alarms. Whenever these events occur, the monitor notifies the user and then displays the sequence of messages which preceded and followed the alarm event.

4.3 NMEA 0183 Software Protocol for Real-Time Data

The NMEA 0183 Standard for Interfacing Marine Navigational Devices [6] is gaining worldwide acceptance as a standard in the marine industry. This is an 8-bit ASCII protocol which allows a "talker" to transfer data to one or more "listeners" in a prescribed sentence format. The 0183 Standard contains a list of sentences which has been approved by the NMEA 0183 Committee. Two example sentences, one for heading data and one for position data, are shown below:

$HEHDT,032,T*30<CR><LF>

where:
- **$** = start of sentence indicator (Hex 24)
- **HE** = talker identifier (Gyro, Earth Seeking)
- **HDT** = sentence identifier (heading, degrees, true)
- **032** = heading in degrees
- **T** = true
- ***** = checksum delimiter
- **30** = checksum
- **<CR><LF>** = sentence terminator (Hex 0D0A)

$LCGLL,4728.31,N,12254.25,W*6D<CR><LF>

where:
- **$** = start of sentence indicator (Hex 24)
- **LC** = talker identifier (Loran C)
- **GLL** = sentence identifier (geographic latitude & longitude)
- **4728.31,N** = Lat. 47° 28.31" North
- **12254.25,W** = Lon. 122° 54.25" West
- ***** = checksum delimiter
- **6D** = checksum
- **<CR><LF>** = sentence terminator (Hex 0D0A)

The checksum field is optional. It is calculated by exclusive or'ing all characters between, but not including, the "$" and the "*" and converting the two nibbles (4 bits each) of the resulting hexadecimal value to two ASCII characters (8 bits each). All SeaNET NMEA 0183 messages include the checksum.

Sperry selected the NMEA 0183 protocol to transfer its real-time data over SeaNET because it is the only recognized standard in the marine industry today. Any devices attached to the network which support this protocol can communicate with each other over the network.

The sensor messages are sent onto the network in a "broadcast" mode. No acknowledgements are used. If a message becomes corrupted during transfer, the message is simply discarded and the "listener" waits for the next uncorrupted message to be received. It is expected that a "listener" will implement a timeout mechanism in case a valid message is not received within a required period of time.

4.4 File Transfer

SeaNET also provides the capability to transfer files across the network. So as not to interfere with the real-time sensor data, the file transfer facility breaks files up into small packets of less than 2000 bytes. Virtual circuits are first established between units. The packets are then sent in a sequential manner with validity checks. Error detection and reporting insures that the operator is informed if the file transfer failed for any reason.

4.5 Real-Time Multi-Tasking Executive (MTX)

Since Sperry Marine's SeaNET is primarily concerned with the gathering and transfer of real-time data, Sperry Marine has also developed its own real-time multi-tasking executive. This executive, called MTX, provides the following services:

- convenient access to device interfaces
- configuration of multiple sensor interfaces into one NIU
- scheduling of multiple tasks
- timing services
- efficient intertask communications

MTX simplifies a system's program by moving the timing and scheduling details into the realm of the runtime system and out of the program itself. By simplifying the program it becomes easier to design and understand, thus improving software development efficiency.

One traditional programming method is the top-down, functional decomposition approach. In this method, each level of refinement is designed to satisfy precisely the requirement of the level above. It makes sense. But when the top level requirements change (as they always do) the entire structure is affected.

MTX, on the other hand, adheres to the object-oriented programming concepts. In this method, each object module comprises some data and the functions which access and manipulate it. The only way the data may be accessed is through its defined functions. The functions associated with each object may be invoked by any of the various tasks in the system and possibly concurrently. By structuring the system in this manner, the scope of conflicts between tasks over a particular data item is limited to the module which encapsulates it.

Another advantage of this approach is the generation of reusable modules. This is because the module can be treated as an entity in itself without having to care about its relation to the particular system being built. This has other implications as the system requirements are modified over its lifecycle. The individual modules are less likely to change since their design is not strongly tied to the particular system requirements. This advantage also simplifies software configuration control.

4.6 Equipment Interfaces

Sperry Marine has developed an extensive suite of equipment interfaces to SeaNET. Following is a partial list of these interfaces. The interface type is shown in parentheses. Those that are shown as "direct connect" connect directly to the network. All others interface through an NIU.

- Gyrocompass (1X, 90X, 180X, 360X, combined 1X/36X, step)
- Rudder Angle Indicator (synchro)
- Sperry SRD-421 Dual Axis Doppler Speed Log (RS-422)
- 40 Knots/Revolution Speed Log (synchro)
- Sperry 501 TR/GPS Satellite Navigator (RS-232)
- Sperry ADG-6000 Gyropilot (RS-422)
- Sperry RASCAR Raster Scan Collision Avoidance Radar (RS-232)
- Northstar 800 Loran-C (RS-422)
- Robertson-Shipmate RS4000 Decca Navigator (RS-422)
- Honeywell ELAC Echo Sounder (parallel BCD)
- Coastal Climate Weatherpak Weather Station (RS-422)
- Sperry MCS2B Satellite Communicator (modem/PABX)
- Sperry Navigation Workstation (direct connect)
- Sperry Voyage Management Station (direct connect)
- Sperry Position Filter Module (direct connect)
- Sperry Socket Scanner (direct connect)
- UVA Network Performance Monitor (direct connect)
- ESA Engine Room Monitoring System (RS-422)

New interfaces are being added continuously as each new system is designed to meet the customer's exact requirements.

a. Navigation Workstation and Voyage Management Station. The Sperry Navigation Workstation (NWS) and Voyage Management Station (VMS) are closely related products which provide centralized ship control and real-time systems monitoring. The NWS allows development of voyage plans and digitized charts which can be transferred to the VMS via the network, and can serve as a backup unit for the VMS. The VMS provides display and tracking against the voyage plans and digitized charts. It also allows display of sensor data, data logging, and track plotting. The VMS has a state-of-the-art touch screen display which provides the operator with the most natural and direct user interface. New displays can readily be added as more sensor interfaces become available and new applications are implemented.

b. Raster Scan Collision Avoidance Radar (RASCAR). The Sperry Raster Scan Collision Avoidance Radar (RASCAR) also has close interaction with the VMS. Navlines and target files can be transferred between these units via SeaNET. Position and sensor information is also exchanged between these units at regular intervals. Like the VMS, the RASCAR has a state-of-the-art touch screen user interface.

c. Position Filter Module (PFM). The Sperry Position Filter Module (PFM) receives position, speed, heading, set, drift, and other related data from the network. The operator can input the required offsets for each position sensor remotely via the VMS or NWS. The PFM employs a Kalman filter which uses this information to calculate the best estimate of true position, speed, and heading. The result is then sent onto the network for use by other navigational units.

d. Satellite Communicator (SATCOM). The Sperry Satellite Communicator (SATCOM) is interfaced to the network via the SATCOM NIU. This allows the transfer of information and reports between ship and shore. Using Sperry Marine's STARBAUD software, the SATCOM sends data 48 times faster (2400 baud versus 50 baud) than a conventional SATCOM with telex. The normal effective data transmission rate is about 1700 baud, allowing for protocol and error correction. However, text compression raises the effective rates to 3600 baud or higher.

4.7 Configuration Management

Configuration management is an important element of Sperry Marine's success in the IBS marketplace. A database of hardware components with their corresponding part numbers and prices is available for generating proposals and satisfying purchase orders. A database of software interfaces for SeaNET-supported equipment makes configuration of the NIUs flexible and efficient.

System block diagrams can be generated and revised very quickly using our in-house graphics workstations and database libraries. This capability allows us to show a customer a conceptional drawing of his system before it is actually implemented. During negotiations, requested modifications and suggested alternatives which address specific customer's needs can be easily included. These drawings can then be given directly to the configuration team for system build and checkout.

All software is stored and issued under control of Sperry's Engineering Computer Operations (ECO). The ECO operates under strict control procedures for software updates and maintenance. The ECO maintains all information and software support tools necessary to re-create current and past versions of each software element.

4.8 System Testing

Sperry Marine has implemented an IBS System Validation program specifically aimed at addressing the special issues involved with testing such highly interactive systems. This program begins with the IBS Validation Policy and IBS Validation Methodology documents which address these issues in general terms. There is also a set of Test Procedures which addresses the common components of all Sperry IBS systems. Finally, a separate set of Test Procedures is produced for each individual system which addresses the specific differences in software and hardware components peculiar to the actual system under test. The Test Procedures are generated using the Functional Specification, the Operator's Manual, and other pertinent system documentation.

Several simulators have been developed which allow data from actual voyages to be replayed for test purposes. Adverse conditions, such as loss of sensor data and erratic sensor readings, can also be simulated to test their effects on the system.

4.9 Installations

The SeaNET-based Sperry Marine IBS is installed or is being installed on more than two dozen vessels throughout the world. A partial list of these installations is shown below:

- North Sea Project - MS LANCE
- Finmare (Italy) - 4 Ferries, 6 Container Ships
- P & O Cruises (Italy) - 2 Cruise Ships
- RCCL (France) - 3 Cruise Ships
- Lauritzen (Denmark) - 3 Reefers
- Bell Lines (Japan) - 1 Container Ship
- Exxon (USA) - 1 Tanker
- MODO (Korea) - 1 Roll-on/Roll-off Vessel
- B.A.S. (U.K.) - 1 Research Vessel
- U.S. Navy - CVN-72 (U.S.S. Abraham Lincoln)

Installation of a system aboard the U.S.S. Abraham Lincoln (CVN-72) demonstrates the use of commercial grade equipment on military combatants. **Figure 6** shows the configuration of this

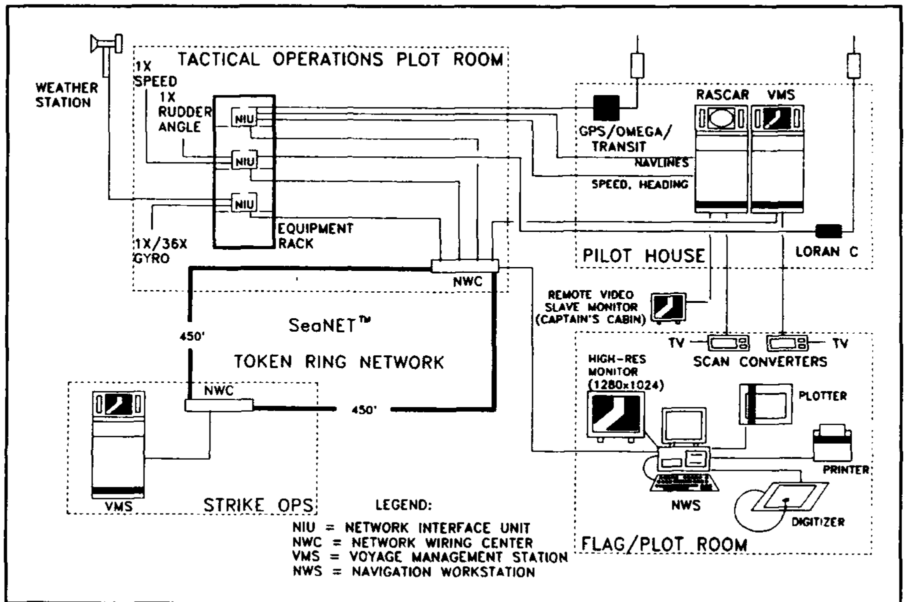

Figure 6 - CVN-72 (U.S.S. Abraham Lincoln) Configuration

system. The sensors are interfaced through three NIUs, one 80286-based unit and two 8088-based units. In addition there is a remote video RASCAR slave monitor installed in the Captain's Cabin. Two scan converters are installed which allow the RASCAR and VMS displays to be sent onto two of the ship's TV channels for distribution to other areas of the ship.

There are two network wiring centers located approximately 450 feet apart. These units are connected using type SU-7 (7 shielded, twisted pair) cabling. When no stations are active on one end, such as when the VMS in the Strike OPS area is turned off, the total cable length between these two units becomes quite long (i.e., about 900 feet). Although no problems have been encountered due to this distance, the installation of fiber optic components would insure that noise problems would not be a factor over such a distance. The replacement of the network wiring centers with fiber optic wiring centers and replacement of the SU-

7 cable with multi-mode fiber optic cable is all that is required to accomplish this.

4.10 Lessons Learned

Through the design, implementation and refinement of SeaNET, several lessons have been learned. First, we have found that there are not only advantages but also disadvantages in the use of standards. For example, the NMEA 0183 protocol standard makes it difficult to place sensor information on the network for which no "approved" sentences exist. By the time the NMEA 0183 Committee reviews requested additions or changes, many are already implemented and in the field. One can only hope at that point that they will be approved. If not, a decision must be made to either change the design or leave it as it is, knowing that deviations from the standard are now present and will remain as such.

Another lesson was learned from the message addressing schemes used. Initially, only the software level "sockets" were used for filtering messages. Since sensor data was broadcast to all nodes, this resulted in sensor interface NIUs receiving their own messages, effectively doubling the processing of these messages for each unit. When heading updates are occurring at eight times a second, this additional processing affects performance dramatically. Therefore, we implemented hardware level functional addressing which is supported by the IEEE 802.5 interface. This places more burden on the hardware interface itself and allows the main processor to concentrate on other work, thus improving performance.

We also proved the value of thorough system testing. It is not sufficient to simply perform exhaustive unit testing of each device to be integrated. Testing of interactions with other devices often reveals problems which are not caught during unit testing. Furthermore, total confidence can never be placed in the use of simulators alone for system testing. When dealing with products from other customers, we have often found simulators to be inadequate. Discrepancies between documentation and reality occur frequently. There is no substitute for bringing the actual equipment in-house for final checkout.

5. SAFENET DEVELOPMENT EFFORT

The SAFENET committee was organized by the Naval Ocean Systems Center (NOSC) in early 1986. It consists of industry and government volunteers tasked with developing a set of tactical communications standards for the Navy. The committee meets bi-monthly to discuss progress of its sub-committees and to give opportunity for industry and government participants to present information about their products and applications. As a result of this effort, several standards are evolving. The first are the SAFENET I and SAFENET II standards themselves. These two standards define the hardware, software, and network management requirements for use by local area networks in Naval applications.

The SAFENET I standard applies to those applications which utilize the IEEE 802.5 Token Ring standard. It includes both the original 4-Mbps data rate and the new 16-Mbps data rate. The SAFENET II standard applies to those applications which utilize the 100-Mbps ANSI X3T9.5 Fiber Distributed Data Interface (FDDI) standard [7]. Aside from the difference in data rates and associated hardware, the two standards are virtually identical in their basic specifications, each specifying dual, counter-rotating rings and fiber optic media throughout.

Sperry Marine has followed the development of the Navy's SAFENET standard with much interest. Our SeaNET development history closely parallels that of SAFENET. Our selection of the IEEE 802.5 token ring standard was occurring at the same time that the SAFENET committee was making the same decision.

Since SeaNET was initially targeted for the cost-competitive commercial shipping industry, the added cost of redundant rings was not practical. Where necessary, critical operational functions are backed up with direct links between units. An example of this is the direct connection of the gyrocompass to the autopilot. The primary link, SeaNET, provides the autopilot with heading from various sources, including the PFM. If the network fails, the backup link allows the autopilot to continue to operate properly.

Sperry also realized that most customers would not want to pay the additional cost of installing a fiber optic network. For this reason, all SeaNET installations to date have used shielded twisted pair cabling. However, as noted earlier, fiber optic cabling is available between wiring centers if requested.

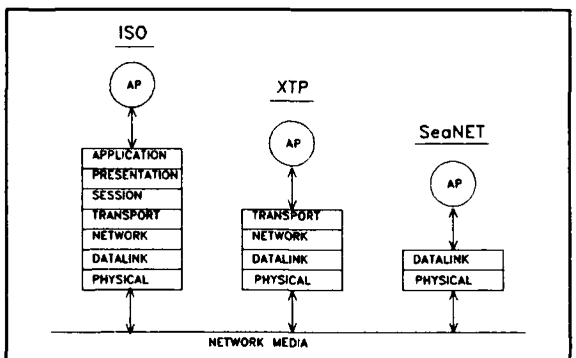

Figure 7 - Protocol Stack Comparison

SAFENET specifies its own real-time lightweight message passing protocol called Xpress Transfer Protocol (XTP). The SeaNET real-time protocol satisfies only the bottom two layers of the ISO protocol stack [8]. When XTP is placed above a real-time protocol such as SeaNET, the bottom four layers of the ISO protocol stack are satisfied while maintaining the high efficiency needed for real-time applications (see **Figure** 7).

5.1 Comparison: SeaNET vs. SAFENET I

The following table summarizes the differences between SeaNET and SAFENET I:

Table 1. SeaNET vs.SAFENET I

Parameter	SeaNET	SAFENET I
Network Type	IEEE 802.5	IEEE 802.5
Network Speed	4/16 Mbps	4/16 Mbps
Real-time Protocol	ISO 8802/2 Class I	XTP
Message Standard	NMEA 0183	(TBD)
Cable	STP / Fiber Optic	Fiber Optic
Processor Units	PC, PC/AT	VME/Futurebus+
Architecture	Single Ring	Dual Ring
Station Types	Single Attachment	Single Attachment, Dual Attachment
Station Attachment	NWC	TCU
Time Service	Station Local, Non-synchronized	Network Global, Synchronized

Except for the lack of fiber optic cabling from the attachment stations to the NWCs and the use of the PCbus rather than the VMEbus or Futurebus+, the SeaNET stations can meet all the requirements for SAFENET I single attachment stations as defined in the SAFENET I document. A PC-based version of XTP has already been developed, as will be discussed in the next section, and has been added to the Sperry real-time network interface. The SAFENET global time service has not yet been implemented. Once it is, the Sperry units can also be updated to use this service.

5.2 Xpress Transfer Protocol (XTP) Development

Like the ISO standard transport protocol (TP4) or DOD's Transmission Control Protocol (TCP), XTP provides the user with the ability to establish, manage, and control connections between end-users. Transport protocols provide end-to-end reliability across any number of intermediate network segments and routers.

Unlike TP4 or TCP, XTP provides a number of new features which are of interest to the real-time and system control communities:

(1) The transport and network layers are combined for efficiency; both ISO and IP (DOD Internet Protocol) addressing are supported.

(2) XTP uses a header/trailer format, rather than just a header, so that hardware can be used to calculate the network and transport layer checksums.

(3) Data can be transferred reliably with a three-packet handshake rather than six as in TP4.

(4) In addition to conventional error control and flow control, XTP permits rate control; using rate control, a receiver can restrict a transmitter to data bursts of a fixed size and frequency.

(5) Selective transmission allows a receiver to request transmission of only lost packets, rather than the lost packet and all subsequent packets.

(6) XTP supports transport-level multicast whereby one multicast transmission potentially replaces many unicast transmissions; this is especially useful for sensor data distribution, time distribution, and event synchronization.

(7) XTP supports both static and dynamic, deadline-driven message priorities.

(8) XTP is designed for eventual implementation in VLSI; the first chips will interface directly with FDDI.

The Computer Networks Laboratory has implemented XTP on top of SeaNET using a 25 MHz Intel 80386, a PCbus backplane, and both Proteon and IBM 4/16 Mbps token ring interfaces. The next project will be to develop XTP on top of FDDI using Motorola 68020 processors, a VMEbus backplane, and Martin-Marietta FDDI token ring interfaces.

5.3 Fiber Optics Investigation

Sperry Marine has investigated fiber optics use aboard vessels for several years. Our optics laboratory has participated in the development of many sophisticated devices, including fiber optic gyros and other fiber optic sensors.

Sperry Marine's parent company, Newport News Shipbuilding (NNS), is heavily involved in the building of Naval vessels. Because of the emphasis on fiber optics in the U.S. Navy, NNS must determine ways of designing and implementing the new ship-of-the-future which will have fiber optic cabling throughout. The advantages of such a ship would be realized in the form of weight and volume savings, noise immunity, security, and survivability .

A recent Sperry Marine/Newport News Shipbuilding report on fiber optic networks indicates that the design and installation of fiber optic network components is rapidly reaching the point of feasibility for shipboard environments. Two examples of such components are the mil-spec fiber optic cable being designed by AT&T and the rugged fiber optic switches being designed by Dicon.

A more specific project has been undertaken in the Sperry optics laboratory. A prototype system has been set up to show the feasibility of using standard IEEE 802.5 fiber optic NWCs and fiber optic switches to produce a reconfigurable, redundant fiber optic network. Currently, the switches are operated manually from an electrical switch box. The next step will be to automate detection of network failures and reconfiguration of the network via the attachment stations. Additionally, an attempt will be made to provide fiber optic cabling directly from the attachment station to the NWC by replacing the electrical drivers and receivers with their fiber optic counterparts.

5.4 Continued SAFENET Development

Sperry Marine is continuing to follow the development of the SAFENET standards by participating in the bi-monthly meetings. In addition, design has begun on a SeaNET-to-SAFENET bridge which will allow SeaNET to hook up to and share data with any SAFENET network. This will be a VME-based unit which can later be upgraded to Futurebus+. It will employ both the SeaNET real-time network interface software and XTP. A program will be developed which will handle the protocol conversions between the two networks. This will allow the Sperry SeaNET-based IBS to be installed aboard military vessels today with easy expansion to the SAFENET-based systems as they become available. Depending on the mission requirements, some vessels may never need anything beyond SeaNET's capabilities.

6. IMPACT ON FUTURE SHIP DESIGN

There are several aspects of ship design that will be affected by integration of shipboard systems using local area networks such as SeaNET or SAFENET. First, vendors will be able to offer turn-key systems which can literally be transported and placed on a vessel as self-contained modules. These modules will be fully tested in vendor staging areas in the factory and will offer plug-an-go installation.

The integration of displays and reduction in controls which are possible through use of these systems also manifest themselves in the form of weight and volume savings. Furthermore, the layout of consoles can be better designed. Console configurations are more flexible and can be designed to fit the mission requirements. They can also be designed to make better use of the physical area in which they will be placed.

One of the major impacts will be on installation of wiring. Fiber optic cabling requires special handling. The number of splices and connectors must be minimized in order to minimize signal losses. The splices and connectors must be installed properly to insure correct alignment of the fiber. Cable bends must not exceed the minimum bend radius. Special tools are needed to install the splices and connectors, and to test for proper operation following installation. The shipboard environment is certainly not the best for accomplishing this task, especially with its maze of bulkheads and tight spaces. However, with the proper planning and design, and with proper choice of equipment, these obstacles can be overcome.

The advantages of fiber optic cabling greatly outweigh the disadvantages. Where weight and volume is saved through the use of this cable, men and supplies can be increased. The noise immunity will virtually eliminate data errors caused by such disturbances. The lack of radiated noise will make communications more secure. As higher speed communications capabilities are implemented, the fiber optic cabling system will be ready to support the additional bandwidth.

7. CONCLUSION

Sperry Marine has successfully implemented real-time shipboard communications in its SeaNET token ring network. SeaNET provides a high speed data highway which enables the integration of shipboard navigation, ship control, and shipboard communications equipment. The system is based on established hardware and software standards. Sperry Marine's Integrated Bridge technology has received rapid acceptance by both the commercial customers and international marine regulator bodies, such as Det Norske Veritas (Norway). Recent evaluations indicate that Sperry Marine's SeaNET-based Integrated Bridge technology offers Navy and Coast Guard vessels improved performance, greater design flexibility and the ability to keep pace with the advancements in shipboard systems.

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INTEGRATED PLATFORM MANAGEMENT
THE SOFTWARE CHALLENGE

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1. ABSTRACT

This paper described the challenges facing the software engineer implementing an Integrated Platform Management System. Vosper Thornycroft have designed and implemented for the Single Role Minehunter the only front line Integrated System, where the vessel's command, control and machinery platform make available various types of common information, eg ship speed and ship position, useful for the efficiency of both systems.

The Single Role Minehunter's Integrated System improves efficiency by allowing more flexible manning levels, through the introduction of automatic control techniques, such as the Ships Positional Control System (SPCS).

In the continuing search for greater efficiency, warship developers will increase the level of automation even further.

While Integrated Systems offer improvements in the operational flexibility of a warship, it increases the demands placed upon the developers of such systems, most notably software engineering. These engineers are faced with the task of designing the more automated systems which are becoming increasingly large and highly complex.

2. INTRODUCTION

The increases in automation of the machinery platform have arisen as a response to the need to:

- reduce manpower costs
- reduce operational overheads
- improve operational effectiveness
- counter skill shortages

In addition where any automation is introduced into the naval environment there are the general naval criteria to consider, that is to provide systems which have:

- low through life cost
- high reliability
- high availability
- high survivability
- high maintainability

3. BACKGROUND

3.1 General

Warships which are just entering service with the Royal Navy are fitted with machinery platforms that have a greater part of their function provided by software. Examples include the Type 23 frigate and the Sandown class of Single Role Mine Hunters (SRMH). The facilities provided by the platforms are made up of several systems such as propulsion, electrical power, auxiliary and ancillaries. Individual functions within each of the systems are often based upon microprocessor technology. One such common example is the engine controllers of the propulsion system.

It is the software in conjunction with the electrical interfaces which change to define the functions needed for the application of, for instance, engine control.

Even on these recent machinery platforms the systems are not entirely integrated. For the Type 23 frigate the current arrangement is one in which the main power system Man Machine Interface (MMI) is located adjacent to the other platform MMIs, with integration of the systems being confined to the secondary surveillance function.

Other recent arrangements, for example the SRMH, use a common data highway to link the propulsion (manoeuvring) system with the command system, but even here centralised control from one point is not a feature.

3.2 Integration Options

For future platforms, as with the current ones, the options available to the procurement agencies are a balance between technical risk and operational costs. The choices can be summarised as:

(1) **Discrete System**: this is generally considered to be current practice whereby the systems operate independently, although the MMIs may be located adjacent to each other in the machinery control room. Figure 2.1 shows the arrangement of a typical discrete platform.

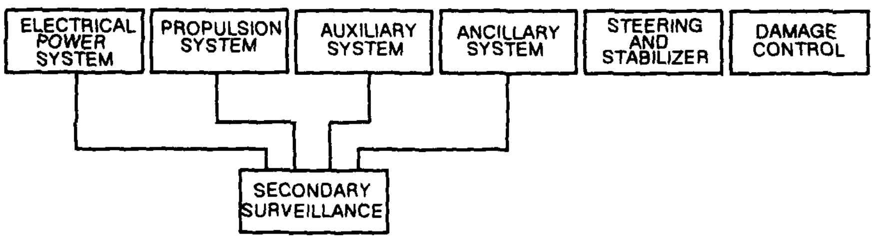

Figure 2.1 - Discrete Platform Management System

(2) **Integrated Platform Management System:** here the machinery systems are linked to each other via a machinery management highway (Figure 2.2). Control and measurement of, for example, the propulsion and electrical systems can be accomplished through a common MMI workstation. Where necessary, the machinery platform may exchange information with other ship facilities via a communication gateway.

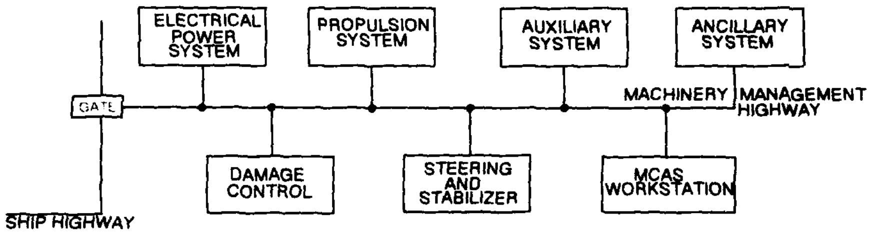

Figure 2.2 - Integrated Platform Management System

(3) **Integrated Ship Management System:** the machinery systems are linked to each other and all other systems via a ship's management highway (Figure 2.3). The entire ship's automatic facilities can be accessed through a common MMI, and the functions accessible are not confined to the machinery systems.

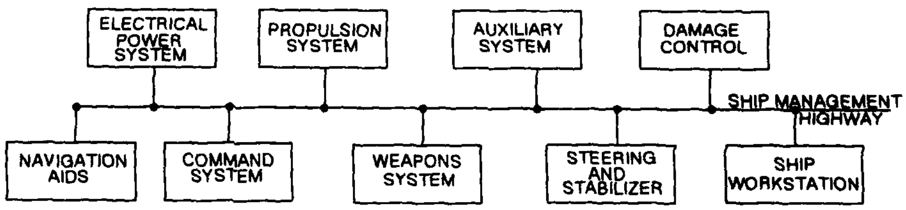

Figure 2.3 - Integrated Ship Management System

The discrete system reflects current naval practice and is clearly viable but achieves the least reduction in manpower or improvement in operational effectiveness. At the other extreme the integrated ship management system can yield the greatest benefits, but it also carries the greatest technical risk. For the software engineering task this can be summarised as:

(1) Procurement difficulties in partitioning the boundaries of responsibility to suppliers.

(2) Project management difficulties in measuring and controlling a large software project.

(3) Test and acceptance complications caused by the very nature of the product, ie real time embedded systems.

(4) Commissioning complications caused by the need to undertake setting to work activities in parallel.

(5) Maintenance complications caused by the need to validate changes within the framework of a large system.

(6) Extended risk as the suppliers depend on each other, and failure of one to meet their requirement could impact on the other suppliers' performance.

The Integrated Platform Management System (IPMS) and Integration Ship Management System (ISMS) although suffering similar complications, differ in the scale of the software challenge. IPMS recognises that the information exchanged between the platform and the ship's highway can be limited, and as a consequence achieves a substantial reduction in risk. Table 3.1 which follows illustrates the possible systems that an Integrated Platform Management System might contain.

TABLE 3.1

POSSIBLE SYSTEMS WITHIN AN INTEGRATED PLATFORM MANAGEMENT SYSTEM

MACHINERY CONTROL AND SURVEILLANCE		
PROPULSION	**ANCILLARY**	**AUXILIARY**
Main Engines Shafts Clutches Couplings Gearboxes	Sea Water System Fuel Oil System Lubrication System	Chilled Water System Fresh Water System Air System

ELECTRICAL POWER MANAGEMENT
Generation Distribution Propulsion Motors Conversion

STEERING AND STABILIZATION
Rudder Control Stabilizers Ballast

DAMAGE CONTROL AND SURVEILLANCE
NBC Detection Fire Detection Flood Detection Fire Control Ventilation Control

While IPMS does reduce the size of the task it still contains a large amount of software. Already the expectations of software as a method for changing systems easily and cheaply have not always been fulfilled. The questions facing both platform suppliers and procurement agencies is, how can the software be controlled in terms of both risk and cost?

4. REDUCING COST AND RISK

4.1 General

The production of an IPMS will be a highly complex task involving tens of thousands of man hours of effort. The management of this task in terms of delivering on time, within budget and meeting the expectations of the customer is difficult.

Some of these aspects are described as follows:

4.2 Risks in Procurement

The functions needed for effective operation need to be adequately specified when procuring the systems from separate suppliers. One frequently used method is to identify the behaviour in terms of a textual requirement. This is used to partition up the system into separate procurement packages. These requirements can be difficult to check and may be contradictory especially around the interfaces between systems, for example the propulsion and electrical systems.

To overcome some of these potential engineering difficulties the customer is adopting more rigorous technical methods in their specifications.

4.3 Project Management Difficulties

Project Management of a software task as large as an IPMS is inherently difficult. Within such a system there may be thousands of interfaces and functions to be specified and produced. In addition, the task carries a major overhead as a large number of software engineers will be involved.

Production of code has often been perceived as the main focus of project managements' attention, particularly when timescales for delivery are tight. This has encouraged the emphasis away from performing a thorough analysis and design.

Recent figures indicate that 64% of software errors are introduced in the analysis and design phases, and of these some 45% remain undetected until customer acceptance. This of course is a major source of customer dissatisfaction. In addition the cost of error correction increases the later in the software life cycle the errors are discovered. For the platforms currently entering service, such as for example SRMH, the trends have been towards placing more emphasis on the analysis and design phases, where error correction is relatively cheap. For project management the difficulty with this approach has been the visibility of progress. To overcome this, most current methods use, as a means of assessing progress, the validation and verification milestones at the end of each development phase, for example analysis, design and coding.

4.4 Testing Complications

The large software systems that make up the platform will contain software which is time critical in responding to events from the environment, for example a surveillance system will need to stop an engine should the oil pressure fail. These event stimulus may result in complex scenarios for the system to manage. Testing for all eventualities is therefore seen as essential, but this is seldom achieved due to the complexity of the task. Figure 3.1 shows the traditional testing based on a 'bottom up' technique, starting with low level unit testing through software integration testing, system integration and finally acceptance testing.

Incremental integration is a common strategy used where each function and code path is tested as the software is constructed.

The 'bottom up' technique attempts to demonstrate that the software products from each development phase satisfy the requirements. It can be characterised by:

(1) Consuming 50% of the time and resources of a project.

(2) It is difficult for management control.

(3) It involves large quantities of low quality testing.

(4) It terminates when the project runs out of patience.

A further feature of this system development is the lack of traceability of the initial customer requirements which results in the lower level tests being performed against an interpretation of the requirement that is the result of two to three layers of abstraction. This results in deviations from the requirement only being discovered in the later stages of the testing cycle when they are more expensive to rectify.

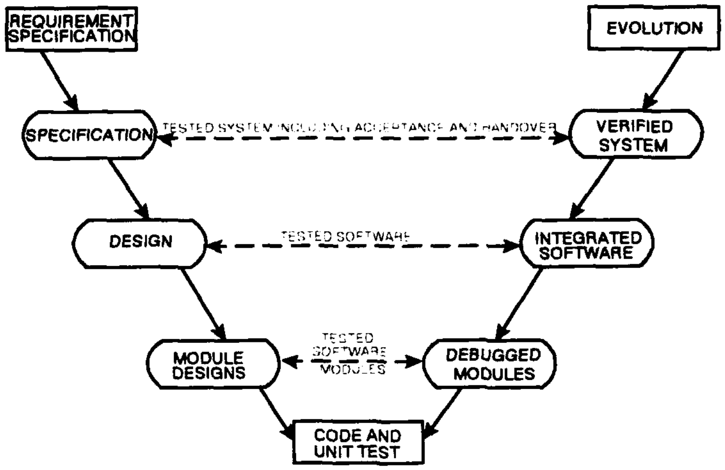

Figure 3.1 - Software Testing Cycle

One way to counter these deficiencies is to have full traceability of requirements. This would enable the lower level of testing to be performed with the confidence that specified customer requirements have been met.

4.5 Commissioning Complications

The IPMS may contain systems produced by separate suppliers which are to be integrated to provide the facilities of the platform as a whole. During this risky integration phase, extensive delays to the ship's programme may occur, should any one of the separate suppliers encouter unforseen difficulties. The dependency of the suppliers on each other is therefore a major consideration where for example, one system requires data from another to successfully operate. One very common problem area could be the control of message compatibility along the machinery management highway.

One of the most successful ways of addressing this problem has been for the shipbuilder to adopt the role of machinery management highway custodian. This role involves integration planning, and risk assessment as well as defining interface protocols.

4.6 Maintenance Complications

A potential drawback with an IPMS is when changes occur to a particular system. Consideration needs to be made as to how such changes affect other systems and hence the platform as a whole.

Good design practices such as loose coupling and data hiding principles can go a long way to solving this potential problem, in conjunction with the continuation of the role of machinery management highway custodian.

4.7 Extended Risk

Outside the scope of this paper as the main controlling method is probably cost penalty.

4.8 System Methodology

The requirements for software that has real time responses, highly concurrent processing and unique hardware interfaces, which are all aimed at a target system that does not support the development environment, add up to a remarkably complex software task. If you then add in formal documentation and methodology requirements, plus maintenance for a one to thirty year product life cycle, you are looking at an order of complexity not found in most previous software developments.

Even with the discrete platform systems currently entering service the key to managing this complexity has been to develop software within the framework of a system methodology. Figure 3.2 shows how such a framework is constructed, which includes both methods and management control.

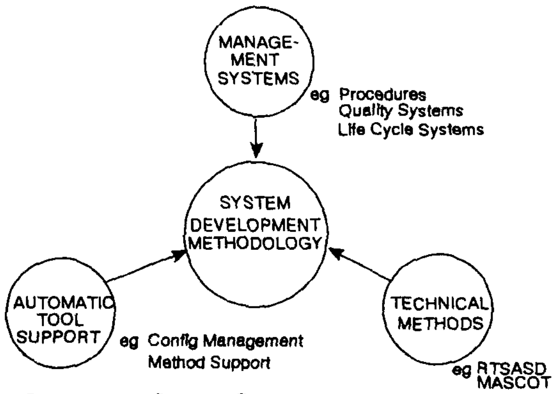

Figure 3.2 - System Development Methodology

The general capabilities that the system methodology must have are:

(1) Technical Methods

(a) The capture of the requirements precisely, without ambiguity or duplication.

(b) Traceability of the requirement throughout the development phases of, for example analysis, design, implementation and test.

(c) The flexibility to accept changes in the requirement easily throughout development.

(d) Methods for partitioning the problem into smaller easier understood packages.

(e) Tools for modelling all the aspects of the systems behaviour, for example dynamics, data and objects.

(2) Management Systems

(a) Methods for validating and verification.

(b) Methods for measuring and controlling progress.

(c) Guidelines for producing design and maintenance documentation to the required standards.

(d) A metrics collection system to improve estimating on future projects.

(e) Methods for controlling changes and baselines issued to the customer.

(3) Automatic Tool Support

(a) Technical methods support.

(b) Configuration management support.

a. **Technical Methods** - Traditional requirement expression contains redundancy, is contradictory, monolithic and implementational. The question often asked by industry is "Is this what the customer wants?" What is required in the initial stages of the system development process is the ability to engineer the unstructured customer requirements to enable the support of traceability and compliancy throughout the project life cycle. To add to this problem it is now becoming mandatory on more recent projects, to demonstrate how customer requirements have been met.

The traditional method of maintaining traceability of the customer requirements is by the implementation of manual procedures. By automating the initial requirements phase, it allows the customer requirements to be linked to subsequent stages of the system development process. This linking allows the dynamic update of compliancy relationships between the requirements and the other stages of development. This in turn enables the project managers to produce compliancy reports, perform impact analysis of requirement changes and provides visibility of progress.

Complex embedded software engineering projects require a more comprehensive approach than in the early days of embedded system development.

Development teams now replace the single programmer, while structured methods for requirement analysis, design, coding, integration and test augment the old seat-of-the pants instincts and know-how.

For machinery platforms, structured methods were first used on the Type 23 frigate and Single Role Mine Hunter projects of the early 1980's. These methods were used with corresponding tool support, in order to maximise the productivity of the teams and to allow them to remain relatively small and efficiently managed.

These structured methods were concerned with building a series of models of the system. The use of models is a long standing engineering practice (blue prints, circuit drawings, prototypes) and there was no obvious reason to treat software engineering any differently.

The models were a representation in miniature of the system which highlighted the most important issues at a particular stage of development. Different system development methods propose different models but they all have the same common characteristics. The strategy used on SRMH was the Real Time Structured Analysis and Structured Design (RTSASD) method which has the important advantage of permitting expression of the required behaviour of the system without implementation detail.

Structured methods have advantages over traditional methods in that the models provide:

- Better communication through the use of graphics with textual support and an hierarchic organisation.

- Management of complexity through problem partitioning and abstraction.

- Quality assurance through evaluation criteria and iterative refinement.

The model of the system provides everyone involved with a single visible focus for understanding and discussion. In addition, building the right sequence of models provides the fundamental basis for an organised development cycle. From experience using models as a basis means that specifications are more likely to be partitioned, non-redundant, succinct, maintainable, unambiguous, testable, comprehendable, complete and consistent.

b. Management Systems - Management systems are probably the most important aspect of the system development process. They provide mechanisms for quality management, progress measurement and configuration control.

For quality management the key to success is the ability to continuously monitor the software development process. This is achieved by verification and validation throughout the software development, or to put it another way, to continually ask "Are we building the product right?" and "Are we building the right product?"

Most of the validation and verification is achieved using a technique known as the walkthrough, where a produce of the development process is reviewed by a group of interested parties. The phases of the software development that are subject to verification or validation follow closely the life cycle of:

(1) **Requirements Specification** - The Requirements Specification is validated against all contractual and management material to ensure that it is an accurate, unambiguous specification of what is required.

(2) **Structural Software Design** - The Structural Software Design is verified against the Requirement Specification and Quality material to ensure that it specifies the architecture, control and data structure of the software.

(3) **Detailed Software Design** - The Detailed Software Design is verified against the Structural Software Design to ensure that it specifies the organisation of the code.

(4) **Coded Unit Tests** - The Coded Unit and test plan is verified against the Detailed Software Design to ensure that the implementation is correct and the testing is thorough in all aspects.

(5) **Software Integration** - The Software Integration Plan is verified against the test philosophy and strategy specified in the Structural Software Design.

(6) **System Integration:**

(a) The integrated software is tested as a whole in its deliverable form, ie firmware.

(b) It is validated against a system test specification which has been derived directly from the requirements specification.

(c) The system will be tested as a whole, including any items other than software, ie electronics, mechanical items etc.

(d) Functional and performance criteria form a major part of these tests.

(7) **Factory Acceptance** - Factory Acceptance Tests are derived directly from the system test specification. These tests demonstrate to the customer that the system will fulfill its required function and performance.

Various metrics have been suggested for measuring software development quality and progress, these range from the rate of error removal through to the lines of code produced. All these methods have their own strengths and weaknesses but most of them rely on tangible output, ie lines of code. This measurement is seldom adequate for systems as large as the IPMS where development time is lengthy before any code is generated. One practical way to gain visibility of actual progress is to measure the validation and verification milestones which occur throughout the development cycle.

It is essential to have metric collection programmes which measure factors such as complexity, code size and software engineering experience, so that these can be used in conjunction with software estimation methods, for example Constructive Cost Models (COCOMO), to predict more accurately, delivery dates and budgets for both existing and future systems.

One area of increasing emphasis is the need to produce software to a specific reliability figure. This cannot be achieved without a comprehensive metrics programme which measures, for example, the error removal rate. This particular metric can be used to predict reliability growth patterns for the software.

Finally, the whole of the system development process needs to be controlled and managed to allow changes to be implemented with minimal risk. This is achieved by configuration management which is 'the discipline of identifying the software components of a continuously evolving system for the purpose of controlling changes to the software and maintaining integrity and traceability throughout the software life cycle'. Configuration management enables configuration control to be implemented which is 'the discipline which ensures that proposed changes shall be prepared, accepted and controlled in accordance with set procedures'.

Thus configuration management ensures that precisely the specified software is produced and issued and it also makes the production process visible.

As a minimum the configuration management process should provide the facilities detailed below:

(1) Controlled access to a securely held set of software.

(2) Automatic enforcement of administrative, modification and quality control approval procedures.

(3) Administrative support for QA activities.

(4) Help for project managers in establishing and maintaining software production procedures and standards.

(5) Help to project leaders in organising and controlling software production.

The only constraint is that the configuration management production overhead should be small to make it cost effective.

c. Automatic Tool Support - Underpinning the technical methods and management systems is the need for a complementary set of integrated tools.

Having determined the methods and techniques to be used, the choice of the tools to support them will be influenced not only by their ability to support the chosen method, but also by their ability to interface with one another, allowing automatic, safe transitions from one phase to the next.

A point worth emphasising is that the tools are only there to support the methods. The success of producing a real time embedded system still depends on having an abundance of skill, knowledge and creativity in the team working on the project. The tools will then alleviate the tedious, time consuming aspects of the work allowing the system to be produced on time, within budget, meet the specified quality standards, and at the same time reduce through life costs.

Finally in order to achieve maximum combined effectiveness of the methods, tools and hardware platforms, a rigorous definition of how they are to be used together to achieve the project goals has to be produced.

5. POST DESIGN SUPPORT (PDS)

5.1 General

The technical risk is significantly lowered once the new system has been commissioned, and therefore known to fulfill its requirements. As the system enters the post design phase, procurement agencies are now faced with the problem of balancing between costs and the time taken to make a change. Whereas previously, during the design phase the problem was one of balancing between costs and technical risks.

5.2 Sources of Change

The sources from which change can originate are summarised as follows:

- Rapidly changing technology may force changes to interface software as obsolete hardware components are designed out.

- Rapidly changing technology may force changes to the software as the tools for supporting the system become obsolete. Examples might include the host development computer and software language compilers.

- Requirement changes as the systems are used in new ways not foreseen by the designers but which improve operational efficiency even further.

- Equipment faults discovered as the systems are used. This may be a common source of change within the first few years of the system's life.

5.3 Types of Support

As discussed previously, the question facing the procurement agencies is, how do we get changes done in a sensible time frame and at a reasonable cost? The options available can be summarised as:

(a) **Event Post Design Support**: no specific suppliers are nominated for the post design tasks. As changes are needed they are considered in isolation and placed as separate contracts.

(b) **Continuous Post Design Support**: dedicated resources are set aside by the suppliers nominated for the post design tasks. Changes are made on a continuous basis by a support team and software updates can be released periodically.

Event Post Design support can be clearly the most cost effective. It does however have serious drawbacks which are:

- original design team is disbanded and the applications knowledge is lost.

- minor changes may become prohibitively expensive as the system is re-learned by a new team perhaps for each change.

- minor changes will take considerably longer.

- hardware vehicles for validating changes to the software need to be rebuilt for each change.

- delivery dates will be poor as a team is recruited for the change.

Continuous Post Design Support overcomes these issues with a subsequent higher cost penalty while the team is maintained during slacker periods.

Probably the best solution for the procurement agencies is a combination of the two Post Design Support Methods. In the early lifetime of the system adopt continuous post design, here the changes needed will occur frequently and be needed quickly. Experience invested in the design is then held intact and should there be any slack periods these can be utilised to increase productivity, by for example, improving documentation. Once the systems have matured, and changes become less frequent then the event driven post design method may be adopted. However, no matter which method or combination of methods are preferred there will be difficulty in maintaining the host development computer for periods of thirty years and in keeping engineers who are willing to maintain the older systems.

6. CONCLUSIONS

Recent machinery platform systems have allowed suppliers to prepare for the software challenge facing them when new more integrated systems are procured. The key to this preparation has been the development of rigorous system methodologies which are comprised of three basic elements; management practices, technical methods and automatic tools. It is these systems which allow the risk of large software development to be controlled. Most of the methods now used allow the supplier to focus software solutions around the system requirements, rather than the technology needed to implement such systems. Cost control, again a notoriously difficult area in software development, has also improved by the introduction of metrics and estimation systems. In short, the technical and cost risks for producing the highly complex software needed in an IPMS can be successfully managed by developing the system under a rigorous environment which allows adequate specification of the boundaries for each system.

7. REFERENCES

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8. TERMS

COCOMO : Constructive Cost Model
IPMS : Integrated Platform Management System
MASCOT : Modular Approach to System Construction, Operation and Test
MCAS : Machinery Control and Surveillance
MMI : Man Machine Interface
PDS : Post Design Support
QA : Quality Assurance
RTSASD : Real Time Structured Analysis and Structured Design
SRMH : Single Role Mine Hunter

INTEGRATED PLATFORM MANAGEMENT SYSTEMS - GOALS AND OPPORTUNITIES

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1. ABSTRACT

The procurement of a new vessel offers a great deal of freedom in the specification of the ship control machinery and associated electronic control and surveillance systems. The ship platform system comprises many subsystems each of which is further decomposed into individual units. The extent of this equipment is such that its operation places a significant load on operators and maintainers which is unlikely to be acceptable in future platforms. Advances in information technology make it possible to integrate the various control subsystems so as to provide a centralised highly automated user interface. This will allow a well defined interface to the command system to be introduced, manning levels to be reduced, and improvements in maintenance and reductions in long term costs to be achieved. The paper considers the requirements of such an integrated system, and highlights the design and development issues that must be addressed to meet these requirements.

The paper surveys the opportunities that arise in terms of for example new system architectures, technologies, human factors and standardisation and argues that in order to be successful such a development must be controlled by an overall System Design Authority.

2. INTRODUCTION

Sema Scientific (formerly CAP Scientific) has been involved in integrating platform systems for the past decade, and has been involved in platform systems since CAP Scientific's formation.

An Integrated Platform Management System will encompass the following systems:

- Propulsion including propeller, prime mover and gear box.
- Propulsion Auxiliaries
- Auxiliaries
- Electrical Generation and Distribution
- NBCD control

The system would be expected to be extendable to include other ship systems and in particular allow for interfacing to the Command System.

In Section 3 we define the scope of the Integrated Platform Management System and discuss the requirement in Section 4.

Section 5 discusses the current state of the platform systems, and suggests some future goals, which should be used to measure the effectiveness of any new architectures.

We discuss the proposed technological features of the system in Section 6 and conclude by stating the need for a System Design Authority to co-ordinate and manage its development.

3. OVERVIEW OF THE PLATFORM SYSTEMS

The term 'Platform Systems' is generally used to encompass the following:

- Propulsion including propeller (controllable or fixed pitch), prime movers, shaft line, brakes and gearbox.

- Propulsion Auxiliaries including Steering and Stabilisation System, Main Forced Lubrication System, Main Lubricating Oil Transfer and Renovation System, Low Pressure Sea Water System and Fuel Supply Renovation and Transfer System.

- Auxiliaries including Refrigeration System, Special Services Air System, Avfuel System, Desalination System, Sewage System, Fresh Water System and Bilge and Sullage System.

- The Electrical systems including Electrical Generation and Electrical Distribution.

- NBCD systems including Chilled Water System, Ventilation System, Low Pressure Air System, High Pressure Air System and High Pressure Sea Water System.

- Damage Control including the state of the ship with respect to fire, flood, smoke, stability and the operational state. The operational state includes the state and requirements for hatches and other compartment penetrations.

An Integrated Platform System should therefore cover all the above systems but in addition take into account the future need to supply and receive information from Weapons and Navigation Systems.

4. MOTIVATION FOR INTEGRATED PLATFORM MANAGEMENT

The requirement for an Integrated Platform Management System is driven by the need to achieve overall ship-wide improvements in the following areas:

- Cost.
- Vulnerability.
- Safety.
- Availability.
- Flexibility

We will examine each of these in turn, starting with cost.

4.1 Cost

Cost is almost always a prime motivation for change. Clearly the development and production costs of an Integrated Platform Management System will introduce an increase in the initial ship purchase price although there may be some scope to re-use components from existing equipments. The scope for cost benefits therefore derives entirely from any potential reduction in through life costs.

The reduction in through life costs would result from better utilisation of the manpower, utilisation of the longer mean time between failure inherent in the newer technologies (and allowing a possible reduction in spares), and the ability of the system to accommodate change and expansion. If change and expansion can be achieved with minimal disturbance to the ship then this would have a significant effect on refit costs.

An Integrated Platform Management System should also be able to improve the performance and the economies of operating the ship systems, and not only in terms of optimising performance of a single ship's systems. It would also allow interactions between various systems to be used effectively instead of independently operating each system as at present. Control interactions from one system would produce feedback parameters on a second system. If these feedback interactions were anticipated then the second system may assist and certainly would not resist the stimulus from the first system.

The benefits arising in terms of manning depend on the mode of operation:

- Normal Operation Use.
- Harbour Watchkeeping.
- Planned Maintenance.
- Breakdown Maintenance and Breakdown Manning.
- Training.
- Special Sea Duties.

Table 1 gives a breakdown of typical current manning levels.

Normal usage relies on the watchkeepers in the ships control centre (whether located in a specialist room or within another compartment), and roundsmen. Currently the watchkeeper is an experienced highly trained individual who has to scan information and decide when the information deviates from its normal position. He is assisted in this by a surveillance system which annunciates warnings. Corrective action is not initiated unless either the operator notices that the information is abnormal or that a warning level has been exceeded. Slow changes in information do not readily trigger the operator to take corrective action.

The Roundsman is similar to the operator except that the collection of data has to occur from a non centralised position. He spends much of his time moving from one source of information to another source of information and recording the readings. Much of the expertise of the Roundsman has been dissipated.

Sound often triggered the Roundsman to instigate an investigation. Similarly the Roundsman would notice increases in temperature in locations where there were no sensors and again instigate an investigation.

Normal operational use unfortunately covers several operating modes from action, through defence states to cruising. In each of the modes there are various operational states. The manning levels through the state will vary enormously, however the peak occurs during action states when man power is called into use to ensure that only current information is used in directing the ship and if any systems is damaged (or fails) the operators will already be in place to take over the running of the damaged equipment. In performing the control role for the damaged systems the operators will have indelibly noted the information related to those systems and will continue to manually update the information. This will enable operation of the function in spite of the damage to the system.

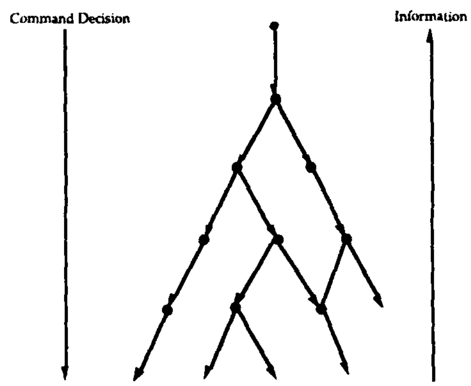
When a ship is in harbour some machinery still continues to run. This requires the use of roundsmen and watchkeepers to ensure that platform systems will not be endangered. When entering and leaving harbour and during re-fuelling at sea it is necessary to call up "special sea duty men". These personnel are required to maintain a close monitor upon certain instrumentation or equipment. The equipment is selected such that if it failed it could endanger the ship if remedial action were not immediately effected.

From the above discussion it is clear that the roles of the watch keeper and roundsmen is extremely diverse. However in essence their tasks are related to two basic functions:

- The implementation of command decisions.
- The distribution of data.

The command decision role consists of either receiving or making a command decision and then amplifying this decision so that an operator or the operators can implement it.

The distribution of the data enables that operator to either make his own command decisions, implement command decisions or filter the information sufficiently so that it can be passed back to a superior in order that the superior can evaluate the data and make the correct command decision. The following figure shows "Command Decision" implementation and information filtering diagrammatically and expresses the amplification of command decisions and the filtering of information.



Key: ● Amplification of command decision or command decision, also assessment of data and filtering of information.

Implementation of command decision, assessment of data and filtering of information, to pass through the command structure.

↓ Command decision implementation and Information Filtering.

The goal of the Integrated Platform Management System therefore must be to assist them in these tasks, reducing the manpower requirement at the same time. It is clear that the reliable availability of information from all relevant sources at a central position is the key to achieving this goal. However, a degree of intelligence must then be available within the computer systems at the central positions to ensure that the operator workload doe not become excessive. Intelligence is also called for to replace the experience of the roundsman in fault diagnosis and failure prediction. Having placed such a heavy reliance on the information system, survivability of the system is paramount.

Unplanned maintenance causes malfunctioning equipment to be either shut down or run at a steady state while maintenance is achieved. Steady state running during a breakdown requires additional personnel to be called up to monitor the systems to ensure that no further damage can occur. Additionally personnel required to repair a breakdown are usually highly skilled and work at the location of the breakdown either using built-in test equipment or by using special test equipment. Current special and built-in test equipment usually analyses down to the zone of the fault and speedy fault finding still requires an experienced operator to operate the test equipment. The need for unplanned maintenance must clearly be eliminated as far as possible.

Planned maintenance has been an area where improvements have occurred during the last decade. Much of this improvement has resulted from merely timing the period of use for the equipment.

However, it is recognised that greater improvements could be achieved by condition monitoring and by the use of more extensive computer based diagnostics aids. These must be incorporated in any future Integrated Platform Management System.

Training currently requires the use of handbooks supported by out-of-use equipment. Except in the case of procedural trainers, training is not interactive and normal operators can not anticipate unusual situations and their re-actions cannot be developed. In the future Integrated Platform Management System we can reduce the time devoted to off-line training by incorporating training aids in the system and making them realistic enough to train personnel in coping with all scenarios. On-board training makes use of otherwise wasted time and reduces the overall manpower requirement by saving the resources that would be devoted to on-shore training.

4.2 Availability, Vulnerability and Safety

Availability, Vulnerability and Safety are closely coupled system parameters. Vulnerability would be reduced by increasing the likelihood that any failure in one system would be covered by the availability of an alternative system. Safety would be improved in a similar manner to vulnerability, except that the alternative system would be active and checking the states of the first system.

Key factors which impact upon vulnerability and safety are:

- Interactions with other systems.
- Dependencies on other systems.
- Redundancy within the system.
- Interlocks and information from other systems.

Extensive improvements have been achieved in the last two decades by the use of interlocks and redundancy. Unfortunately the use of single interlocks has resulted in an increase in the system unavailability.

Reliability has been increased by duplication of key equipments, however there has been an unfortunate side effect of drastically increasing costs, not merely doubling in costs but often trebling or quadrupling costs as the equipment has to diagnose when to use its redundant sections.

Safety has been increased by monitoring dependencies and increasing the number of interlocks internally and from other equipments. Accidents still occur and there is further scope for improvement in both vulnerability and safety.

The significant developments in electronic systems over the past decade should enable a fresh approach to be taken in developing systems that meet the combined targets of reliability, availability/vulnerability and safety in a more cost-effective manner than in the past. This clearly is a requirement for future Platform Systems and can only be gained by deploying world-products which through their wide market exposure have been given the opportunity to mature more satisfactorily than the custom-fashioned systems which have been deployed to date.

4.3 Flexibility

The previous decade has also seen an acceleration in the rate of change of electronic computer facilities. Decisions on whether to incorporate a change or to wait for further developments has been a major headache. Usually the incorporation of advances will necessitate the scrapping or major modifications of an existing system. Architectures for future Integrated Platform Management System must be be expandable and amenable to change without major impact on the existing structure. This points decisively in favour of using internationally accepted system communication and interconnection standards.

5. MEASURING THE ACHIEVEMENT

To evaluate any solutions we must have a set of goals which outlines the requirements. Probably no single solution will satisfy all the requirements, however a clear definition of the goals will allow the most appropriate solutions to be evaluated. This section is intended to define the goals.

The present systems and any future systems will have the following critical requirements:

- No single failure will fail the entire system.

- Multiple failures will leave the remaining systems operative.

These requirements must be satisfied.

In the earlier section we found the major cost driver to be Through Life Costs. Through Life Costs were mainly associated with manning and with system enhancements. Table 1 defines our current manning requirements and Table 2 defines a goal for the future.

Analysis of the manning levels, currently in place, and towards a future goal shows that we will have to address two areas in particular:

- The reduction of operator manning levels required for special sea duties, defence watches and action stations.

- The reduction of manning levels required for both planned and unplanned maintenance.

The high manning levels inherent in special sea duties, defence watches and action stations are not actually required for the operation of the system. They are required to observe the system, familiarise with the system states and then to take over control of the system in the event of a failure or damage.

High manning levels are required for planned and unplanned maintenance. The unplanned maintenance would be reduced by more effective planned maintenance and/or by increasing the meantime between failures for the various systems.

Maintenance manning would also be reduced if faults could be diagnosed more rapidly or by having systems which were quicker than the current systems to repair.

Table 1. Current Manning Levels

Manning	State	Operator O	Operator N	Roundsmen O	Roundsmen N	On Board Training O	On Board Training N	Planned Maintenance O	Planned Maintenance N	Unplanned Maintenance O	Unplanned Maintenance N
Special Sea Duty	Normal	11	15	2	4	-	-	2	0	0	0
	Failure	11	16	2	5	-	-	0	0	2	4
Action State	Normal	12(+4)	16(+6)	4	6	-	-	0	0	0	0
	Failure	12(+4)	18(+6)	4	6	-	-	0	0	2	4
Defence Watch	Normal	6(+4)	9(+6)	2	4	-	-	3	5	0	0
	Failure	6(+4)	10(+6)	2	5	-	-	1	1	2	2
Cruising State	Normal	2(+4)	4(+6)	1	3	-	-	8	11	0	0
	Failure	2(+4)	5(+6)	1	3	-	-	2	4	2	2
Harbour State	Normal	1(+3)	2(+4)	-	1	-	-	10	10	0	0
	Failure	1(+3)	2(+4)	1	2	-	-	7	14	2	3
Training on board currently if possible and no failures		-	-	-	-	5	4	-	-	-	-
Training ashore Pre-joining Training		10 (weeks)	20	10 (weeks)	20	-	-	26 (weeks)	35	included in planned training	

Key: N = Normal
O = Optimistic
(+) = indicates extra manning per day required during a single watch.

Note: With the exception of training ashore the number in the column indicates the average number of men per watch.

Table 2. Goal Manning Levels

Manning	State	Operator O	Operator N	Roundsmen O	Roundsmen N	On Board Training O	On Board Training N	Planned Maintenance O	Planned Maintenance N	Unplanned Maintenance O	Unplanned Maintenance N	Standby Party O
Special Sea Duty	Normal	6	10	(+1)	1	-	-	0	0	0	0	0
	Failure	6	9	0	1	-	-	0	0	2	2	0
Action State	Normal	6	10	0	1	-	-	0	0	0	0	2
	Failure	6	9	0	1	-	-	0	0	2	2	0
Defence Watch	Normal	4(+1)	6(+1)	0	1	-	-	2	2	0	0	2
	Failure	4(+1)	7(+1)	1	1	-	-	0	0	2	2	0
Cruising State	Normal	1	2	0	(+1)	2	2	2	4	0	0	0
	Failure	1	2	0	(+1)	3	2	0	2	2	2	0
Harbour State	Normal	0	0	0	(+1)	3	2	2	4	0	0	1
	Failure	0	1	0	(+1)	3	2	0	2	2	2	0
Training ashore (Pre-joining Training)		4 (weeks)	8	1 (weeks)	2	-	-	10 (weeks)	18	included in planned training		4

Key: N = Normal
O = Optimistic
(+) = indicates extra manning per day required during a single watch.

Note: With the exception of training the number in the column indicates the average number of men per watch. The standby party is a rapid response group for taking over local control in the event of a critical failure.

If system meantime between failures could be increased, maintenance manning could be reduced and one of the reasons for the standby manning during special sea duties etc could be reduced. It must be recognised however that the critical systems could fail because of information supply failure and this is the state which occurs once action damage has been sustained by a vessel.

The second through life cost driver was flexibility of the system for enhancements. When a system is totally autonomous space and power are the only new requirements imposed on the ship. However most new systems require information or will modify the information supplied from other existing systems. Table 3 shows the current situation for interactive systems and a goal for future systems.

One of the required criteria for any design is minimising vulnerability. To discuss vulnerability it is necessary to have a definition of its meaning. We would propose the following sub-set in any definition:

"Minimising the number of systems effected if one system is damaged".

Some systems currently only have local controls, hence there are only vulnerable to local damage. Many systems have local and remote controls, in these cases damage in two locations could effect that single Plant.

Future vessels are anticipated to reduce manning, and with this reduction in manning it will not be possible to have as many roundsmen and hence remote control will become more prevalent.

Most remote controls have currently been concentrated in a single control compartment. The loss of this compartment would result in widescale loss of remote control. All plant could be controlled from its local positions however coordination and manning levels would have to increase drastically from a single action. With respect to our definition, the number of systems affected if the remote control location were damaged and there is only a single remote control position, this configuration maximises vulnerability and is therefore highly undesirable.

Table 4 shows the current vulnerability and a desired goal.

Manning levels both in terms of operability and maintainability are a function of many variables Table 5 shows the variables for both operator and maintainer. The table shows the functions that could be modified to affect the manning.

Safety has already been given a high priority on present day vessels. The safety of future systems and vessels should not be any less than current safety standards.

6. TECHNOLOGIES FOR INTEGRATED PLATFORM MANAGEMENT SYSTEMS

Our study has shown that there are a number of key target improvements that are essential to properly benefit from the development of Integrated Platform Management Systems. We summarise these first before discussing their implementation.

6.1 Key Targets

Manning

a. Operators

Table 3. System Interactions

		Present Situation	Goal
Type of Change	**Required Change**	**Percentage number of system requiring change if a dependent system is introduced ± Tolerance**	**Percentage number of system requiring change if a dependent system is introduced ± Tolerance**
Mechanical/Electrical	Extra output wiring/plugs required.	75 ± 20%	10 ± 10%
	Extra input wiring/plugs required.	80 ± 20%	10 ± 10%
Electronic	Extra output hardware drivers required.	75 ± 20%	10 ± 10%
	Extra input hardware driver required.	80 ± 20%	10 ± 10%
System	Extra definition of information required.	40 ± 20%	20 ± 10%
Computation	Extra manipulation or extrapolation required.	20 ± 20%	20 ± 10%

Table 4. Vulnerability

Plant Type	Present Situation	Goal
	The column represents the number of plant effected if a compartment damaged.	The column represents the number of plant effected if a compartment is damaged.
Local Control Only	≤ Number of plant in the compartment. + Number of plant systems dependent upon the services of the compartments plant.	≤ Number of plant in the compartment. + Number of plant systems dependent upon the services of the compartment plant.
Local Control and Remote Control	As local control **OR** ≤ Total Number of systems with remote control. + Number of plant systems dependent upon the services of plant with remote control if remote control lost.	As local control **OR** ≤ 15% (+15%) of total number of systems with remote control. + ≤ 5% (+5%) Number of systems dependent upon the services of plant with remote control if remote control lost.

Table 5. Maintainability and Operational Manning Variables

Maintenance Manning	= f	(Availability)
Availability	= f	(MTBF, MTTR) or (Maximum Reliable period of operation without repair, Time to Maintain)).
MTBF	= f	(Components used, quality of components, (complexity of system, engineering of system), Duty cycle, stress on the components).
MTTR	= f	(Meantime to diagnose fault, Meantime to replace components).
Maximum Reliable period of operation	= f	(Components used, quality of components, (complexity of system, engineering of system) Duty cycle, stress on the components, calculated error in estimation of period of operation).
Time to Maintain	= f	(Meantime to replace component).
Mean Time to diagnose fault	= f	(Operator Training, usability of Bite).
Calculated error in estimation of period of operation	= f	(error in Duty cycle, ability to predict stress in components.)

Operator Manning	= f	(Number of Assignments, Number of standby operators).
Number of Standby operators	= f	(Vulnerability, Number of Key Items of plant).
Number of Assignments	= f	(Number of Tasks, complexity of tasks).
Complexity of Tasks	= f	(Skill level, level of prompting, amount of data, presentation of data related to task).

Key: f = function of

- Increase the amount of automated surveillance and ensure the surveillance is cognisant of the ships operating state and the trip values that should be representative of that state.

- Reduce the number of operator tasks.

- Reduce the complexity of the tasks and allow a lower skilled operator.

- Reduce the number of standby operators necessary and still ensure that failure or damage does not endanger operations.

- Decrease the training time.

b. Maintainers

- Ensure that the systems are engineered such that the components can be replaced more quickly than is the current practice.

- Enable faster diagnosis of the failed components even with a lower skilled operator.

- Improve the evaluation of the effective duty time that any equipment has sustained in order to enable increased times between maintenance.

Vulnerability

- Decrease the vulnerability caused by the loss of the remote control station.

Expandability and Flexibility

- Reduce the changes to hardware and wiring on existing systems when new systems have to be introduced.

- Reduce the modifications necessary to existing systems to enable data to be extracted from those systems for any new systems.

The following section describes how these targets may be met.

6.2 Meeting the targets

Vulnerability

Our vulnerability target requires that we reduce the susceptibility of the system once the remote control position is lost. Our options are as follows:

- Remove the remote control position (this is not a viable option as it conflicts with the need to reduce manning).

- Distribute the remote control position (again this is probably not a viable option as distributing the remote control position would increase the number of operators).

• Create an alternative remote control position to take over in the case of loss or damage to the first control position.

Most of the control and surveillance data supplied by auxiliary systems is digital and has low data rate. Currently it is often supplied by direct wiring from the local control panel to the remote control panel. Each of the pieces of information is contained as a single signal, and each system is managed as an entity. Figure 1 shows the current configurations. Figure 2 shows the same architecture but with a second remote control position.

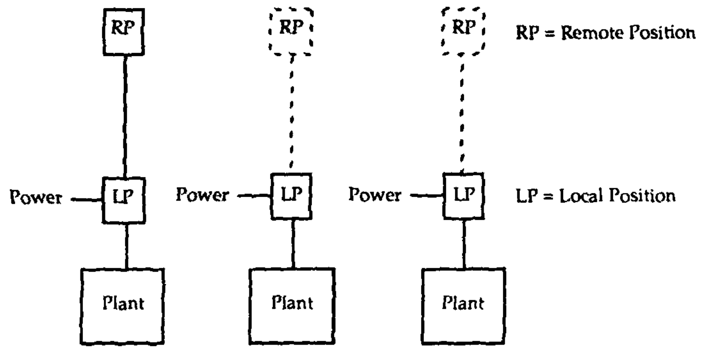


Figure 1. Current Local and Remote Control and Surveillance

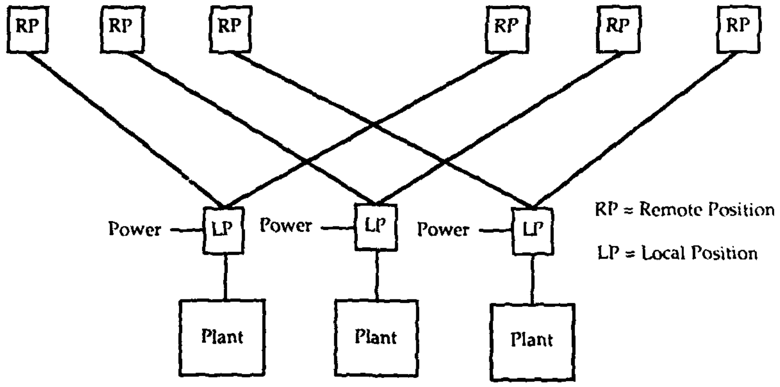


Figure 2. Future Local and Remote Control following the existing architecture.

The cost of increasing any system by this Figure 2 will be prohibitive as it would require between 1,000 and 10,000 cable cores.

Any system to provide a second remote system must therefore be linked via a multiplex data link, which may be implemented for example as a Local Area Network. Figure 3 shows a suitable configuration. The complexity of the electronics in the local position and at the remote position has increased. Each position now includes a multiplexer and de-multiplexer for the data and then conversion from the multiplexed data to the communications driver.

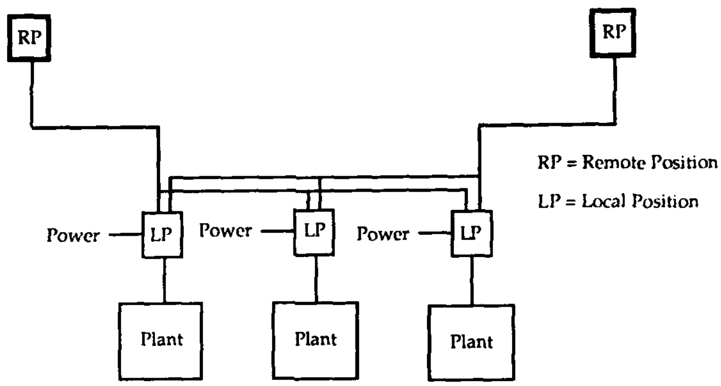


Figure 3. Future Local and Remote Control using a Multiplexer Architecture

This architecture efficiently provides data paths for local position plant data along 2 independent routes to 2 (or more) remote stations. If a ring network is used, there is further scope for path redundancy in that a ring breakage in each ring could be tolerated.

Flexibility and Enhanceability

Our goals for flexibility and enhanceability are to reduce the amount of hardware change necessary when a new system is introduced and to reduce the amount of modification necessary within the existing systems.

If hardware changes are to be minimised then existing interfaces must be flexible enough to accommodate change. This constrains us to using a multiplex data link, such as the Local Area Network proposed above to link the Local and Remote Positions. It may be acceptable for plant transducers to be connected to the Local Panel via discrete links, but if transducers themselves were intelligent and connected to the Local Panel via a multiplex digital link then this would allow for even greater flexibility. It should be noted that additional Local Positions can be added to the main network with minimal hardware impact, as can new external system interfaces, for example to a Command System.

A common requirement for change is for an additional item of data to be monitored by the system. Future platform management systems need to be far more tolerant to such changes which should be possible without major software upgrade and achievable during in-service operation. There are of course complex configuration management problems which need to be taken into account if this degree of adaptability is to be provided..

Although standards already exist for various types of multiplex data link the format of the data within the data links, in the majority of cases, have not been agreed. To achieve the desired flexibility and expandability would require not only that the data link be defined but also the format of the messages to be transmitted. It is essential that the data link standard employed is one that has been adopted widely within the international community so that its maturity and the level of support given to it is adequate.

Reducing the manning of any future vessels will depend on reducing the number of both operators and maintainers.

a. Operators. Our primary objective is to reduce the number and complexity of tasks performed by operators. The history of Platform System automation shows that most effort has been concentrated on producing a centralised surveillance system leaving many control tasks as manual activities. This has allowed some reduction in the number of operators, but very little has been done to assist in interpreting the information that is presented to the operator by the support systems.

To further reduce the centralised operators tasks it will be necessary to provide a level of data interpretation so that information that it outside the norm is presented to him as a priority, and the norm is context sensitive. Such systems are already well advanced in the avionics field.

Highlighting the problem areas to the operator will reduce the operator's workload. The operator will still have to decide upon the correct procedures to correct the problem. To lower the skill levels of the operator it is necessary to advise a lesser skilled operator on the probable correct remedial strategy. These advice systems are an extension of the knowledge based systems which are already becoming widely used on many industrial surveillance systems.

During the previous decade many of the more complex or fast control functions have been automated. The simpler start/stop routines have been left unaltered. Most of these require very little logic to decide when to start and when to stop or when to switch to a second system. If these unsophisticated systems are automated then again the operator's workload could be reduced. Even if the task could not be removed from the operator, action from the operator could be prompted by the system to reduce the complexity of the operator's tasks.

When faults develop on our current complex platform systems it is often difficult for the operator to appreciate the consequences of the fault. Evaluating the options open to him and making the correct decision to effect corrective action requires skill and training. Usually not all the options are appreciated by the operator and often not all the consequences are foreseen. A simple solution is to provide a list of the options available, and the consequences for each of those options. If any of the options required further actions then these actions should also be listed within the option.

One of the problems that arises from the reduction in the role of the Roundsman will be that problems cannot be recognised until specific sensors are triggered. These can be thermal sensors, thermocouples or smoke detectors. The problem with this type of sensing is that it is triggered only once a problem has become critical. The Roundsman often detected problems before they became critical. He would notice anomalous hotspots or sounds. A means will have to be devised for duplicating this role of the Roundsman.

A generalised surveillance system would have to be created covering the whole of a ship's compartment. One generalised system could be an infrared picture of the whole compartment. The thermal signature of each piece of equipment in the various running modes would be identified. If the thermal signature deviated from an expected signature then the operator could be triggered into calling extra manpower to investigate the problem.

A simple two dimensional picture of the compartment could provide sufficient data to prove that a Roundsmen was required for an investigation. A more productive approach could be to build a three dimensional image and collate the three dimensional image with various operational information within the plant management system. The temperature at a particular power setting or operational mode would be registered as a norm. Deviation from the norm would be used to trigger the operator into instigating some action. Conventional closed circuit television monitoring is also a viable operator aid.

An area which requires considerable improvement is that of the human-computer interface. Various types of flexible display system have been tried during the past decade. Touch screens, flexible keyboards, reconfigurable function keys, tracker balls and light pens are all tools in the armery. Windowing and pull-down menus are likely to be a feature of any future systems. It is also essential that the operator be given the freedom to configure the formats of displays to his requirements so that the on-line modification of mimic diagrams, for example, is a facility which will become the norm.

In summary the operators tasks would be reduced by following the following the strategies:

- Increasing the sophistication of the surveillance system including data filtering and interpretation.

- Increasing the coverage of the control systems such that the simple systems are also within the scope of the system.

- Prompting the operator with suggested actions during normal activities to ensure effective utilisation of equipments.

- Prompting the operator with suggested remedial actions once a fault has been recognised or has been recognised as developing.

- Replacing some of the Roundsman's monitoring role with a general surveillance facility.

- Providing an effective and efficient human-computer interface.

b. Maintainers. The following aspects require improvement:

- Ease of repair.

- Improved diagnostics.

- Improved life prediction.

Improvements in ease of replacement of components have already occurred during the past decade. Modularisation and better selection of line replaceable items have enabled mean time to repair to be reduced. Unfortunately connectors, backplanes and assemblies have as yet not succumbed to the same improvement. These areas will require effort to reduce the mean time to replace these items.

Built in test equipment has improved the location of faults. During the past decade, built in test equipment has often used spare processing power to find or indicate the failed component. This philosophy ignores external indications that can help diagnose the fault and the system also fails once the processor or its power supply has failed.

Highly reliable (and independent) built in test equipment would increase the cost of the unit; however the independent BITE could receive external interfaces information which when collated would give a much more accurate fault finding picture. This in turn would give a higher probability of diagnosis and remove some of the need for the highly skilled maintainer.

Prediction of the safe life expectancy of a component has until now been totally statistical. A life expectancy has assumed the stress levels and has always had to err on the side of caution; that is the highest stress levels normally attainable are assumed to be ones to which the component has been continually subjected.

The duty cycle and power setting levels in related systems and dependent systems are now available within the surveillance system. This data is available for life expectancy calculation. Using these monitored parameters and the same equations as the previous statistical predictions a much better life prediction can be calculated.

Some systems have a signature parameter. This signature parameter can be used to indicate if a system has approached the end of its safe operating life. Some signature work has already occurred but results to date have not been very promising.

The present most likely route appears to be extended life prediction via the use of measured duty cycles. The work has already started on the more costly systems where extending the time of use will save on early unnecessary replacement. This same trend will have to be extended to the less expensive items if maintenance times and utilisation are to be increased.

A Maintainer facility in a Platform Management System would enable the collation of related duty cycles and allow the maintainer to be directed to the most appropriate items for periodic maintenance duties.

7. MANAGING THE DEVELOPMENT OF FUTURE SYSTEMS

A future Integrated Platform Management System poses new management challenges. The range of engineering disciplines involved is wide embracing amongst others mechanical, electrical, electronic, control and software fields. To be successful system-wide considerations, for example relating to reliability, maintainability, and availability must take precedence over individual plant or sub-system factors. By its very nature an Integrated Platform Management System relies upon the flow and collation of information from many sources, generally under the control of different manufacturers. Parameters which are critical to the operation of a sub-system are often totally unimportant within the context of operating a total platform and vice versa. The trade-offs to be made are numerous and complex.

This paper calls for standardised interfaces for the various systems. These interfaces would have to be implemented on one or more types of multiplexed data links for which the protocols will have to be established. A traditional problem areas for systems has been associated with interfaces and the definition of the signals on the interfaces. Multiplexed digital data systems have increased the problem except where a single authority has control of the specification.

The only way to manage and resolve such system-wide issues in the design of an Integrated Platform Management System will be to designate a System Design Authority. This is a significant and in the UK a new and challenging role in Platform System procurement.

VOICE COMMAND INVESTIGATION FOR CONTROL OF MODERN CANADIAN WARSHIPS

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1. ABSTRACT

The potential use of speech recognition technology in the control and monitoring of computer controlled systems is receiving increased attention. The Department of National Defence of Canada contracted CAE Electronics to develop and test a speech recognition system to control the SHINMACS* Advanced Development Model (ADM). The SHINMACS ADM is a distributed microcomputer based ship control system connected to a real-time computer simulation of a DDH-280 class destroyer. Because it combines the flexibility and reliability of digital computers with the simplicity and ergonomics of graphic displays, it provides a unique test environment for the investigation of an advanced concept in the control of a modern warship.

After a brief introduction on the theory behind speech recognition technology, this paper describes the methodology followed to develop a Voice Command system for SHINMACS ADM, and it presents the results of the investigation. The overall requirements for the Voice Command system for SHINMACS ADM are described together with the criteria used in the selection of the Speech Recognizer units. The system architecture is presented together with hardware and software block diagrams to assist in the description of the overall principle of operation.

The paper concludes with an identification of the issues which must be addressed and the investigation to be performed before actual implementation of Voice Command onboard operational ships.

2. INTRODUCTION

In November 1987 the Department of National Defence (DND) of Canada commissioned a study by CAE Electronics Ltd of Montreal to

* SHINMACS: Shipboard Integrated Machinery Control System (Registered Trademark of the Department of National Defence)

investigate voice recognition technology for machinery control. This study was to investigate the feasibility of voice command in conjunction with the Integrated Machinery Control System (IMCS) as fitted in the Canadian Patrol Frigates (CPF) and the Tribal Update and Modernization Program (TRUMP) ships. This project was consistent with DND's desire to continuously improve the Man Machinery Interface (MMI) of the IMCS.

The perceived benefit of voice control is improved operator performance in a busy environment. An example illustrating the potential benefits of Voice Command is the requirement to open the starboard boost pump suction valve. Using the MMI's on the IMCS the operator would:

- bring up fuel service screen (one button push)
- move cursor to "control point" (trackball manipulation)
- enable cursor selection (one button push)
- select desired option - open valve (one button push)

Visual feedback is an on-screen graphic representation of the valve being opened.

Using a voice command the operator would:

- issue a voice command "open the starboard boost pump suction valve"

The visual feedback would be the same as above.

It is expected that operator performance under duress could be improved by replacing multiple manual actions at the MMI with voice commands.

3. SPEECH RECOGNITION CONCEPTS

There are four basic categories of speech recognition system from the "user" perspective. A speech recognition system can be either speaker dependent or speaker independent. If a system is speaker dependent, then it requires a sample of the user's voice to be stored. Speaker independent systems contain algorithms designed to handle differences in the human voice, such as accents and voice pitches.

Another way of grouping speech recognition systems is by determining whether they recognize either discrete isolated words or continuous connected speech. In discrete systems a number of sound patterns, such a distinct words or short phrases are stored in the recognition system. The user must pause at the end of each word so that the recognizer knows to search its database. The connected speech system requires no pause after each word or phrase. A recognition algorithm is used to decipher where each word or phrase ends. Discrete and connected systems can be either speaker dependent or independent.

Figure 1 illustrates a typical process used by voice recognition units to "recognize" a spoken command. It would be naive to suggest that these four categories are the only aspects of speech recognition. Other techniques such as the distinction between phoneme based and whole word template matching, statistical modelling of sets of templates, signal transformation operations, dynamic time warping and so on are beyond the scope of this paper and the authors' expertise.

Successful implementation of a speech recognition system must take a number of factors and constraints into account. Speaker related factors are very important. Dialects and speech variability may significantly affect the performance of speaker independent systems. Speech variability, or the consistency that individuals replicate words, adversely affects the recognizer. Background noise often affects the speakers consistency. Background noise can also affect speech transmission characteristics, by degrading the signal and thus may cause substitution errors.

The design of the vocabulary is an important consideration in the successful implementation of a speech recognition system. To minimize errors the vocabulary should be limited in size and distinct. Enrolment, or the process of creating and storing speech templates for matching is very important. The speaker must act natural and enrol in the representative environment. A good enrolment process will pay dividends later in system use by increasing the recognition percentage.

4. SYSTEM DESIGN REQUIREMENTS AND CONSTRAINTS

4.1 System Constraints

The major constraints placed by DND on the contractor in the design of the system were:

a. the system had to interface with the existing SHINMACS ADM without any hardware or software modifications. This meant that the voice system had to simulate the input functions of the existing keypad and trackball, and

b. the speech recognition units had to be commercially available.

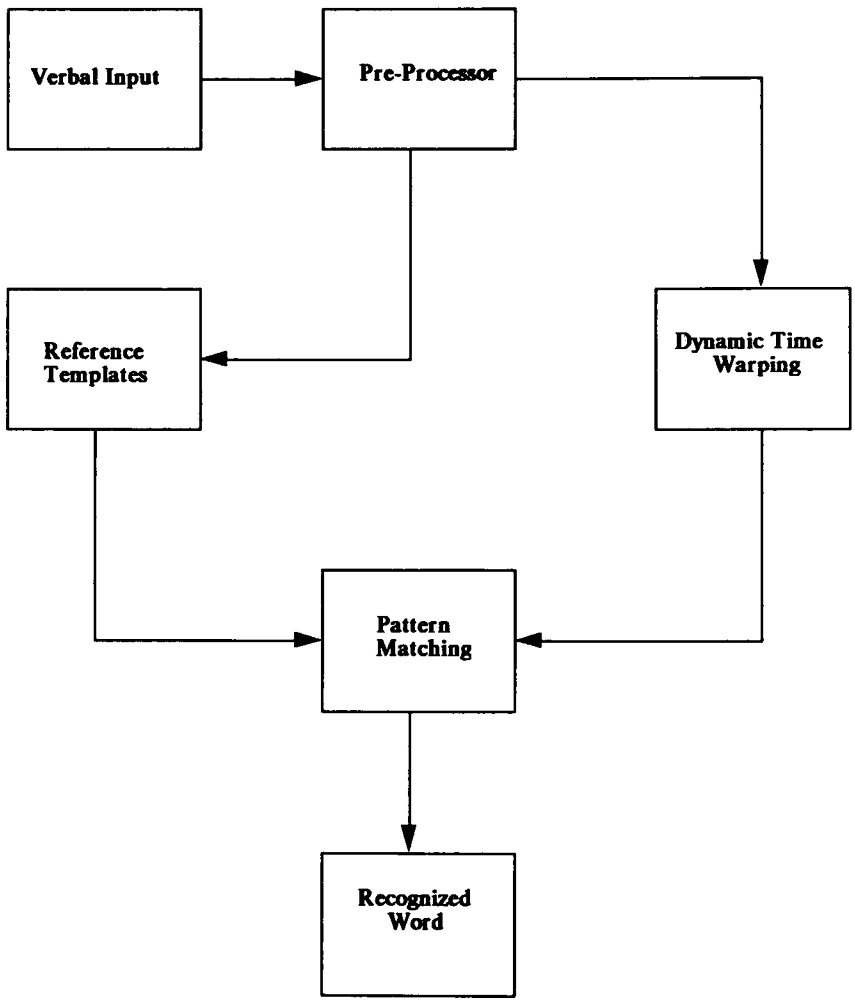

Figure 1 : Acoustic Pattern Matching Algorithm

4.2 Speech Recognition Requirements

The preliminary requirements established in order to conduct an evaluation of the various available speech recognition units were that the system had to be able to:

a. operate with a vocabulary size of approximately 160-200 words. This was based on the current page and line menus of the MMI,

b. perform in a high noise environment. This variable is difficult to measure since there are no applicable standards. Therefore, this requirement was judged on previous applications of the various speech recognition units in comparable environments,

c. operate via a standard RS-232C serial interface,

d. allow expansion in both hardware and software, and

e. permit MMI operations to occur without undue delay. In practice, recognition times are about the same for most commercial systems, ranging from 200 to 300 milliseconds.

5. HARDWARE SELECTION

5.1 Speech Recognizer Selection

The above requirements and others were used to establish the selection criteria for an evaluation of the available recognition units. Two recognition units were selected to be used in the evaluation were the Marconi Macrospeak and the Scott Instruments' Coretechs VET 3. The Marconi Macrospeak was selected as the preferred system due to its fast response time, expansion capabilities, vocabulary size, success in similar applications, and complete development tools package. The Macrospeak was the most expensive product. All of the basic system requirements were satisfied. The Scott Instruments' Coretechs VET 3 was selected as the other recognition unit to provide comparison. The Scott system was the least expensive unit that met the basic system requirements.

5.2 Computer Selection

Several manufacturers produce microprocessors that appeared capable of performing the VCC (Voice Command Controller) functions. The estimate of necessary coı.puter power was envisioned to be somewhere between an IBM PC/AT and a DEC Microvax II. Since the voice recognition systems were anticipated to have a throughput delay of approximately 300 milliseconds, computer speed was an important function, although not the only priority. The requirement was to maintain a total throughput delay from the speech recognizer to the MMI of 1 second.

The identified computers were the IBM PS/80, the Microvax 2000 and the Macintosh II. All three processors had similar execution speeds, but the IBM PS/80 was eliminated because it ran under a new operating system which was not available at that time. The system selected was the Macintosh II. The major advantages of the Macintosh II over the Microvax 2000 were the user interface, the expansion capability, and the cost. System software was to be developed under A/UX (Apple Unix). The Unix development system provided the most flexibility. By using Unix access was gained to powerful tools and compilers.

6. SYSTEM OVERVIEW

6.1 Hardware Configuration

The overall hardware configuration is presented in figure 2. The system consists of a speech recognition unit interfaced to a VCC software package running on a Macintosh II computer. The Macintosh II is connected to the SHINMACS ADM via the record/playback RS-232 port of the Datapath M General Purpose Interface (MGPI) in the MMI console.

6.2 Software Configuration

The operation of the MMI console using verbal commands is illustrated in figure 3. This voice command set up typically operates in the following manner [1]:

a. Incoming Data Handler. This module is custom tailored to the voice recognizer being used. Its task is to accept output from the voice recognizer, covert this data into a Standard Data Packet (SDP), and transmit this data to the Voice Interpreter task. This data packet contains information such as flags for connected-isolated words and speaker dependent-independent modes.

b. Voice Interpreter Task. This module receives the SDP of information from the incoming data handler and provides a corresponding command. This task outputs commands, which are simple integers that can be used to look-up in a master table. This module has different run states set by arguments passed to the executable program so that the voice system can run in an isolated or connected mode.

In isolated word mode the voice recognizer (Scott VET 3) chooses the target word (command) and passes along a corresponding reference number for future use.

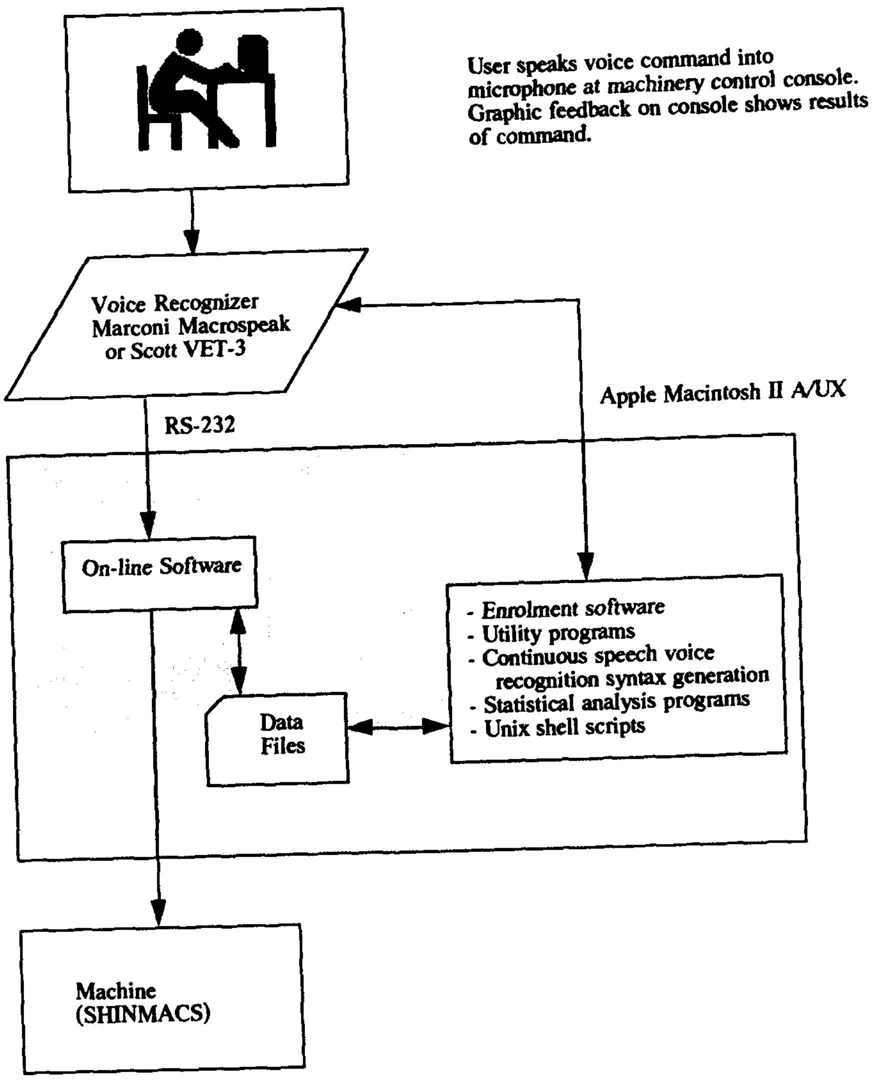

Figure 2 : Hardware Configuration [1]

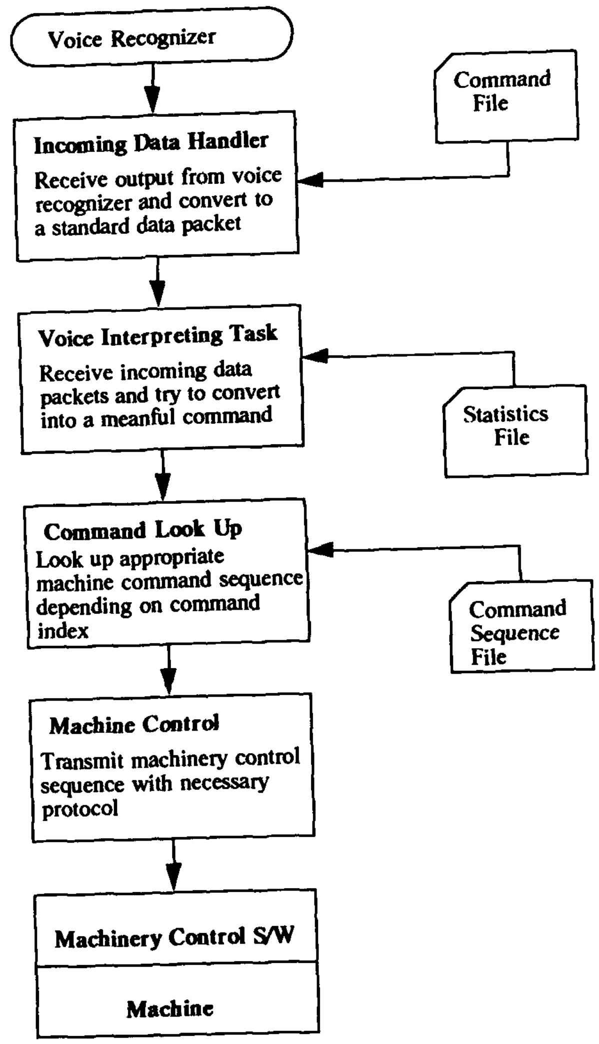

Figure 3 : Software Configuration [1]

In the connected speech recognition mode (Marconi Macrospeak), incoming data packets are received on a per word basis not on a per command basis as with isolated recognition. This module must buffer incoming candidate words until enough words are queued to complete a command. When this occurs the appropriate command reference number is sent out, buffers are reset and the command building task continues.

c. Command Look Up. This module is based on a data driven look up procedure. Using the command received from the Voice Interpreter module, this module finds the appropriate commands to be sent to the device being controlled. In the present application this module maps input commands to escape sequences that are sent to the MMI console.

d. Machine Control. The final module transmits the escape sequence from the Command Look Up module to the machine being controlled. The design of this task will depend upon what the target machine expects for a communication protocol.

7. **EVALUATION**

The evaluation of the voice recognition units was conducted at CAE Electronics in Montreal, March 13-15 1989. The evaluation team consisted of eight persons, four from CAE and four DND personnel (two Marine Systems Officers, one Marine Engineering Technician and one Marine Electrician).

The evaluation scenario contained standard operations and typical alarms and warning conditions that an operator must handle in the routine operation of the IMCS. This included the operation of auxiliary and ancillary systems, and the starting, operation and shutdown of main engines. The scenario was designed to test normal start-up and shutdown procedures, system operations during engine trips, and alarm conditions with machinery component failures. The commands to the recognizer were also mixed with communications to and from the Engineering Officer of the Watch (EOOW).

For this evaluation, both speech recognition systems, the Marconi Macrospeak and Scott Instruments Coretechs VET3 were interfaced with one of the SHINMACS ADM MMIs. Since both systems are speaker dependant, each member of the evaluation team had to "train" the recognizer to recognize his/her voice by storing a representation of his/her voice called a template. Since the Macrospeak is a continuous recognizer, only the individual words involved in a command need be stored as templates. The VET3 was used in an isolated mode. This meant that every possible command phrase had to be enroled and stored as a template. This was time consuming.

A three day evaluation was planned. The first day was to begin with a familiarization of the console operation and the test scenario. Then template training for both recognizers was to take place. The second day was allocated to practising the test scenario with both speech recognizers and retraining the templates as required. The final day was to be dedicated to the actual evaluation. The CAE personnel followed the three day evaluation program. Unfortunately during the DND evaluation there was a province wide power blackout forcing the three day evaluation to be compressed into two days. To accommodate this the number of template training passes for the VET3 was reduced from ten to five. This affected the accuracy of the VET3 recognizer.

8. EVALUATION RESULTS

The results from the evaluation are presented as a number of correct and incorrect responses by the recognizer to an operator command. A correct response by the recognizer constitutes properly identifying the spoken verbal command or rejecting an invalid verbal command. Likewise incorrect responses include improperly identified verbal commands, not rejected invalid commands, operator error and poor templates. The measure of performance for the Macrospeak and VET3 speech recognizers was the number of correct responses over the total number of correct and incorrect responses and then averaged over the whole evaluation team. Overall performances of 92.4% correct for the Macrospeak and 80.2% correct for the VET3 were found. These figures corrected for operator error and poor templates, were 94.9% and 86.5%. A comparison of the results for the CAE and the DND personnel revealed that the results were almost identical. Recognition accuracy for the Macrospeak was 96.7% for the CAE personnel and 93.3% for the DND personnel. Likewise the accuracy for the VET3 was 86.4% for the CAE personnel and 86.5% for the DND personnel.

Compounding the difference between the Macrospeak and the VET3 was the fact that the Macrospeak was working in a connected mode and approximately four templates must be recognized for each command, while the VET3 was working in the isolated mode and each template was a complete command.

The Macrospeak and VET3 voice recognizers both met all the requirements and constraints established for this project. Noting these constraints, limitations and subjective nature of this project, the connected speech recognition mode implemented in the Marconi Macrospeak appears to be more suitable. User acceptance of voice command by the evaluation team was generally good for the Macrospeak and fair for the VET3. The evaluation team also indicated that the preferred mode of operation of the MMI would be a combination of voice and manual inputs to the MMI.

9. CONCLUSIONS

Based on the evaluation results, the feasibility of using voice as an alternative input medium in the control and monitoring of computer controlled systems was successfully demonstrated. As an input medium for the control of machinery systems the system was well received by the evaluation personnel with few problems encountered.

The evaluation determined that speech recognition as an input medium, rather then manual input, has the following advantages :

a. direct access to any page without the need for the menu hierarchy;

b. less time required by the operator to perform each task;

c. potential for the use of macro commands; and

d. the system is language independent (i.e. English, French, etc).

However, several problems were encountered with the system. Substitution errors, where an erroneous command was substituted for the intended action, were noted as the most critical. Background conversations, being picked up and acted upon as commands, was another area that created problems. However, the majority of the difficulties dealt with concepts involved in the definition of a man-machine interface (MMI).

10. FUTURE DEVELOPMENTS

Future developments in voice command of MMI's for Navy ships would incorporate additional system logic into the voice recognition units to reduce the possibility of error. An example of this would be the voice command "stop the number one diesel". If the number one diesel was the only diesel running and provided the recognizer detected the words "stop" and "diesel" then the system would stop the only running diesel on the screen. Other logical areas of investigation would be the incorporation of the "abort" and "undo" commands. Macros that define a series of commands can also be investigated. Examples of this are "shut down the plant".

Perhaps the most important area of investigation would be incorporating the design of voice command right into a machinery control system. The investigation detailed in this paper used a voice recognizer that simply replaces a trackball or keypad. This is probably not the most efficient method of incorporating voice recognition technology and other methods must be investigated.

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12. DISCLAIMER

The opinions expressed in this paper are those of the authors and, as such, are not necessarily endorsed by the Department of National Defence (Canada).

SHIP CONTROL - THE HUMAN FACTORS

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Sema Scientific

1. ABSTRACT

Ships have evolved from relatively simple systems where most functions were performed by hand to extremely complex ones where a very small number of people are responsible for, and remote from, many complex subsystems. The resulting human task in the machinery area has many similarities to those found in command systems on the same ships.

The evolution of MMI in RN command systems over the last twenty years is reviewed to draw lessons which should carry over into modern ship control systems.

2. INTRODUCTION

The earliest ships were fairly simple. Their capabilities were limited, but within those limits they could be operated effectively with a combination of practical experience and brawn. As ships grew, the need for brawn expanded in proportion, leading to a complex organisational structure whose purpose was to operate an equally complex mechanical system, the ship.

In the pre industrial days, although the technology may have been primitive, the amount of distributed intelligence in the control system was very high. Even the most humble seaman could see that a rope had broken and realise that someone ought to do something about it. More significantly, he could do this even if his job was carrying cannon balls and not monitoring rope condition.

It may be argued that the seaman was a 'labourer' and so his knowldge outside his immediate task was shallow. However, the technology used was 'visible' in the sense that the function of most components could be inferred from looking at them. The crew's work brought them into close contact with the equipment. They would be familiar with the sounds made by the ship and its equipment and they would be aware that a component about to fail 'sounded wrong' to an extent which would make an expert system based condition monitoring equipment turn green with envy.

The advent of powered technology did several things. It allowed ships to become bigger and more complex in themselves, and in the case of warships, it allowed them to carry a proliferation of ever more complicated payloads.

But perhaps the most significant change was in breaking the link between brawn and brain. The need for men was not abolished, since the machines needed minding. They had brawn, but they neither knew what to do nor when to do it. They could not even take orders. Men were used increasingly as control elements. They combined the ability to turn an order into an action with a degree of local common sense. Compared with the machines, they were 'managers', even if their jobs involved a lot of humdrum and arduous work.

As long as the equipment needed minding, the density of brain power around the ship still stayed pretty high. The men could become proficient in understanding their part of ship and how it worked. Continuous familiarity ensured this. What was much less sure is that they would know what it ought to do. The operator's view of an equipment is very different from its designer's. They can have very different ideas about what it can and ought to be able to do. This has both strengths and weaknesses. It means the operators will find ways of overcoming design deficiencies to coax more out of equipment when needed, but it may also mean they never try to make it do things they find unfamiliar or difficult.

The other problem of specialisation and localised control is that good old human problem of communication. More specialisation means more people have to trust others to do what they do not understand themselves in detail. There is more interpretation, more transformation of information en route. In short, more chance that the impossible will be asked and that the inappropriate will be done.

Following hard on the heels of power technology, came control engineering. This really does have the power to empty the compartments. The development of reliable servo mechanisms allows direct control and monitoring to be replaced with output demand and alarm thresholding. The bandwidth of the human input required drastically falls, and can be centralised. This really does allow the brainpower density around the ship to be reduced.

3. AUTOMATION

So all the problems are over? That was the popular vision in the few decades after the war when the potential of automatic control was becoming more apparent. Utopia seemed to be round the corner. Manual work would be poerformed by machine, tedious chores would be automated and the 'electronic brain' would schedule and organise the whole process. Has it happened yet?

The technology is certainly there. There is an actuator for every need, there is communications and processor bandwidth in abudance. We can construct control systems of undescribable complexity. But it is here that we meet the limitation. A control system will only do what we want, if its designers can wrestle with the complexity of specifying and testing it. A monitoring system is only as good as the sense that its operators can make of what it tells them.

These dual problems of specifying what the system ought to do and understanding what it has done provide one of the biggest challenges of system design. The problem is by no means limited to ship control or even to process control. They have parallels in military and civil command systems and in many other information systems. In fact, information is the key issue. Having solved the brawn problem, we are now faced with the brain problem. How can we heap the control of far more complex systems onto a far smaller number of brains, especially since we usually expect them to do everything in much quicker timescales.

4. INFORMATION

Information is slippery stuff. Shannon's theory allows us to quantify the information content of a signal quite precisely in terms of the number of possible signals which could be sent along a communication channel. This is very useful for ensuring that the interfaces between different parts of a system do not become bottle necks for data transmission, but is less helpful for 'real information'.

For example, faithful transmission of speech requires 64kbits/second, viewed as an accoustic signal. Statistical analysis and predictive algorithms can reduce this to a few thousand bits/sec. In fact the message can be transmitted with a few tens of bits per second, if we first translate it into English and then send coded text. The information changes when we 'know what it means'. To the transmission channel there is less information while to the listener, there is more information, since it does not mean anything until he has understood it. This subtle difference is crucial to understanding the way people work with machines and designing machines they can use effectively.

The men in a ship rely on the increasingly complex collection of machines which it contains to help them achieve a mission, but their ability to do so depends critically on whether they can understand and take decisions based on the wealth of data which the machines can handle. This means the interface between the men and the machines must be designed for human capabilities and human needs. As in most areas of human endeavour, progress comes in fits and starts with occasional reversals. Paradoxically it is not easy to design effective user interfaces, especially when technological motivators take over. We shall look at the progress made during the era of rapid system evolution enabled by the advent of onboard computers.

5. KNOBS AND DIALS

Ships and submarines have been around for far longer than terms like MMI and its many synonyms have. They were full of machines and they were operated by men, but no one thought to identify the interface between the two as such. At the basic level equipment was designed to be used. Most equipment needed controls of various forms but these related quite closely to what was being controlled, often in a one to one relationship with each variable.

At this level there can be good intuitive grasp of the underlying process. A flow is controlled by a valve, a valve is screwed down by a wheel, and the pressure in the pipe is read out by a gauge. Gauge designers take pride in producing clear readable instruments and valve wheels are designed to be gripped so that force can be applied. (There are, of course exceptions).

This cosy picture breaks down because it takes rather a lot of valves to operate a submarine, and success depends on opening and closing the right ones by the right amounts at the right times. So we impose higher level models to help us understand the relationships between them. Flooding aft or forward tanks makes the boat bow or stern heavy and causes a corresponding pitching moment. We can build controls and indicators into 'pictures' such as deck plans, piping or wiring diagrams to help understand them. Such mimic diagram style control panels can be very successful, but as they get bigger we can't show both the overall scope and the full detail, especially if the system model does not neatly map onto a 2-D representation. This is a much more general problem, as we shall see.

6. VALUES, SYMBOLS, AND IMAGES

A submarine may swim and breathe supported by machines which are essentially analogue. They deal with real physical values like speed, pressure voltage and so on. But the submarine's mission is made of more rarefied stuff. It is a tactical machine, and tactics hinge on information, lots of it. Intelligence about intentions and possibilities, copious output of sensors and masses of reference information about everything from the environment to tactics. Whilst many of the data in this mass of information do in fact relate to physical variables, many do not. Tactical information is primarily symbolic. It is information with a capital 'I'.

Another useful broad category of information, very pertinent to a submarine, we may loosely call 'images'. Images can be thought of as masses of value, whose overall pattern is important but where individual values are relatively unimportant, and indeed may be quite 'noisy'. This is in stark contrast to symbolic information where individual errors can significantly alter meaning.

7. COMPLEXITY

Complexity is the enemy and the challenge of human information systems. People over load under pressure of excessive information. This simple fact, well known to psychologists, is masked by two remarkable human mechanisms. The human mind has an appetite for pattern and order. (Pure scientific endeavour, for instance, is driven by the urge to find order and predictability in the physical world). By extracting pattern and order from information, by 'seeing what it means', we are able to handle far larger amounts than we could otherwise.

The other mechanism is more severe. Overloaded brains simply shed load. In the case of perceptual overload, we just fail to see or hear things. Unfortunately we often do not know what we failed to see, - until it becomes too late.

The battle against complexity can only be won by abstracting from the detail to the underlying essence or structure of the concepts which allow people to organise the information and make it manageable.

8. EVOLUTION OF COMMAND SYSTEMS

8.1 Technology Drivers

Each age of history has been driven by different concerns. Similarly, with the application of a new technology, there is a natural progression from 'can it be done', through 'can it be done better, more efficiently, more cheaply', 'how should it be done', to 'what should we actually be doing'. This is as true of technology in submarines as it is of technology in the office.

Introducing computers into fighting vessels was a challenge. Making them small enough and feeding them with high grade power was an achievement. The tasks they were asked to perform were more demanding than those being performed by many civilian computers at the time. By supporting real time information display and management, they were at the forefront of MMI technology.

Early shipboard computer systems pressed into service and adapted the MMI technology that was available. Radar systems had already perfected large CRT displays capable of high speed precision X-Y scanning. The computer manufacturers rose to the challenge and developed sophisticated display drivers to allow large quantities of symbolic information to be written on the displays.

The parentage of these systems is apparent at a glance; they are circular. With an electrical generator capable of producing a square picture and a square area of the valuable console space in front of the user available, we would not otherwise have specified circular screens, and then often only written information in a square area inscribed within the circie.

Television already used rectangular CRTs, but it took a while for the glassware to find its way into high performance military displays. TV display technology itself was in a much lower league. We could not seriously contemplate TV style raster technology for high density information displays until digital storage had become much faster and cheaper. In the early '70s, core storage would have been too slow, and at around 4p per bit would have cost several hundred thousand pounds, (more than the cost of the computer systems of the day), to support one screen of what is now a standard technical workstation, commercially available, for under ten thousand pounds, with its own built in computer.

Two decades ago, military display systems led the field. Only very high value civilian tasks were supported by such technology. Now the high grade raster display has came into its own thanks to the phenomenal advances in cheap semiconductor store. Raster displays are more energy efficient than cursive ones, and more amenably offer multi-colour pictures. They allow the generation of the picture to be divorced from its refresh, (the main headache of cursive displays). This means a screen-full can be displayed as easily as a few symbols, but at the cost of storing the screen image in a bit-thirsty way.

As memory prices tumbled, more and more commercial jobs could afford not only to use computers, but also to use high performance displays. The initiative passed from the military to the civilian developers. The IT market poured in the dollars and the yen while military buyers concentrated more on trying to get systems into service rather than expecting to fund the advance of technology. Increasingly, military hardware became a hardened derivative of technology originally forced into being by commercial pressures.

8.2 Early Days in Command Information System MMI

In a sense, the User Interface is the raison d'etre of a command information system, so it was no surprise that the 'automation' of many jobs previously relying on charts and chinagraph in the '60s raised many MMI problems.

Early computers were too large to be carried on submarines and so it fell to the surface fleet to suffer the early part of the learning curve. Display capability was severely limited, despite exploiting the persistence of fluoride phosphors to run the tubes at very low refresh rates. But some of the worst surprises came on the input side. Using keyboards seemed appropriate, but no one can have foreseen the problems of managing a real time system using memorised sequences of cryptic codes. It may all seem very logical when you are inventing them, but use in anger, under pressure, is a different matter.

Using codes could have been less painful as part of a more forgiving dialogue, but such was the respect for computers in those days that users were assumed not to make mistakes, or if they did, then it was not the system designers problem.

8.3 Pioneering

As in so many areas, it is best to be second. When DCA was introduced into submarines, technology had moved on somewhat, as had ideas about user interfaces. Using a light pen enabled the selection of individual items displayed on the screen with a reasonably natural action. This made possible a 'conversational mode' of interaction with the system. At any one time, the system shows what it can respond to and control consists of selecting one or more of these options. The changing presented options reflect the dynamics of the interaction.

This style of interaction was a major advance over the use of key codes. It was more learnable, and less error prone. It was in advance of most commercial systems of the day. The surface fleet had this style of MMI on the WSA4 weapon control system, but had to wait another decade until CACS brought the ideas to the main stream Action Information systems.

While the command systems were going to sea, the research establishments were pushing back the barriers for the sonar operator. As the sonar systems were developing to generate ever more complex sets of 'image data' a better means was needed to display it for interpretation. Although raster technology in its present form was not yet mature, pioneering work with displays refreshed direct from magnetic disc allowed considerable progress from a choice between paper readouts and fading images on fluoride phophors.

DCA opened Pandora's box by showing what could be done. Unfortunately, neither it nor its successors could keep up with the demands placed on them. This led, among other things, to the need for add-ons like DCG, and a consequent complication of the user interface to the total enhanced system suite.

DCG, born out of Corporate, is a good example of accepting the constraints of using commercial technology. The MMI also reflects what was commercially acceptable at the time, and although the system as a whole gave a much needed functional upgrade to DCB, the MMI itself was less advanced than DCB in using indirect selection by keyboard with a constrained menu format.

8.4 The Present

The move from DCB/DCG to SMCS will represent a major step on many fronts. The display capacity per seat exceeds DCB and DCG, and for the first time offers colour. The greatly increased underlying processing power, although it is not superficially an MMI feature, will change the way the system is used by providing results after delays small enough to be tolerated, whereas long delays encourage distortion of the task to work round them.

SMCS retains the concept of control by selection from a dynamic set of displayed features, though the structure and organisation differs quite markedly from earlier systems. At the physical level, the need for hands up operation has been replaced at the cost of splitting the interaction into two. The main display, primarily responsible for the tactical picture, uses a mouse-like puck with pull down menus, leaving the more detailed procedural and data oriented actions to a desk level display with a touch overlay doubling as a 'glass key panel'.

The success of this combination in service will depend as much on the logical structure of the detailed interactions, and how well they can be made to match the inherent needs of the tasks, as it does on the more visible physical aspects. SMCS represents such a major departure from previous systems that it would be premature to speculate on the cognitive ergonomic aspects, since the tasks themselves will be changed by the system provided to support them. This joint evolution of the job and the tool could provide some valuable lessons for the bigger steps to be taken in the next generation.

SSCS, the new command system for the Type 23 Frigate, will build on the basic technology established in SMCS, but it has made the transition to an object oriented style of user interface. Extensive use of direct interaction and an adaptive windowing system provide the user with a much clearer set of views of the resources under his control. The interface style is specifically designed to support an appropriate conceptual model for the users.

Another major advance introduced for SSCS is a comprehensive Human Engineering Plan. Although human factors have played an accepted role in the development of aircraft cockpits and primary instruments for many years, large command systems have traditionally been procured predominantly as bundles of functionality. The SSCS development will deliver functionality, but the behaviour of that functionality as it will be experienced by its intended users will be systematically validated throughout the development cycle.

8.5 The Next Step in Command Systems

It is significant that before SMCS is even at sea, the foundations are being laid for an Integrated Weapon System for the new generation SSN20. This is a far sighted approach, since new concepts can not be rushed through without time to mature. The MoD needs time to draw together the ideas which it is stimulating from its contractors into a coherent whole in line with its high level goals.

The integrated approach from the outset should help to ensure that all sub-systems properly communicate with each other. Using people to pass information from one piece of kit to another merely raises the noise level, both literally and metaphorically, by distracting the users from its meaning and use.

The inherent recognition in SSN20 of the human team as a 'people subsystem' inseparable from the whole system design process is undoubtedly an important step ahead. If Weapon System Integration on the scale envisaged is to succeed, in an era of reducing complements, the human issues of what the system is about must be given equal prominence to the more obvious technological ones.

9. FUTURE ISSUES FOR COMMAND SYSTEMS

The future will be different, but we should try not to repeat past mistakes. Some things will remain invariant, such as men's size, vision, response speed and cognitive abilities. Reduced complements may allow for less cramped working spaces, but equipment will still have to pass through hatches.

We noted that as a technology matures, the focus shifts. We can build fairly good devices to display information, and there are well established paradigms to support its manipulation and use. Though both will continue to advance somewhat, the real issues are about how the systems need to match the way they are used. More and better integration of sub-systems should push rote tasks like data entry and coordination to the periphery. Having men there just to drive the systems while others think about the problem will no longer be necessary and indeed will be a hindrance, a barrier between the decisions maker and his problem. The inevitable consequence will be a move to men as information managers rather than many being information servants. The resultant up-skilling can provide more stimulating jobs, but only if the career progression structures can evolve to match.

As the complexity of the resources available to each user continue to grow, it will no longer be sufficient to provide a 'sanitary' interface, free of weak points. Increasingly, the whole edifice of the information and its representation will have to be designed to support the way the problems need to be solved. In particular, as the machines provide increasing support to the decision making processes, rather than just the data gathering and processing aspects, they will become more and more embroiled in supporting the combat team as a team rather than as a collection of individuals.

The navy has a long tradition of developing procedures to allow teams of men to work effectively together under stress. This has relied on a good understanding of human behaviour and communication. In the future, this perspective must broaden to embrace communication between men mediated by machine, as well as face to face. They will increasingly share the resources provided by the system rather than be constrained by a narrow set of facilities.

Knowledge based technology will mature. It can provide a richer set of resources to the men. But the way of using such resources will be different. Creating machine 'agents' to which tasks can be delegated or from which suggestions be elicited will provide good models for the new dimensions of communication needed. The issues of trust, authority and responsibility for information are challenging ones which must be solved if men are to use the next generation of machines as effective tools to help them achieve ever more demanding missions.

10. LESSONS FOR SHIP CONTROL

10.1 Similarities

Command systems installed or in the pipeline for RN ships and submarines have come a long way since digital computers first went on board in the '60s. Many lessons have been learnt and are still being learnt about how the people who use them relate to the information they use and the tasks they do. How many of these can be carried over into ship and machinery control? What are the similarities between command systems and modern ship control systems?. Both of them are:

used by people with a fairly broad training

used to monitor uneventful situations for most of their service lives

intended to be used for unpredictable, intensive bursts, of non scheduled activity

capable of processing and storing far more data than their users can hope to absorb quickly, (if at all) give the feeling, when things are at their worst, that there is someone out there trying to make everything go wrong!

There are, of course, many differences, but the similarities drawn out here stem directly from the most important common element, the men. By taking a user centred view, complementary to the equipment centred view, there are many lessons which can be fed across form other areas.

11. LESSONS FROM COMMAND SYSTEMS

There are several conspicuous lessons from the command and control experience which appear to carry across.

Building a system with the sole goal of throwing data at the men will swamp them.

The only way to make the information manageable is to structure it in ways which relate to the men's knowledge of the real world objects it represents and to provide different views on the information to match the user's task(s).

Trying to establish and define the user's conceptual model of the information base and the problem space at the start is a far sounder basis for design than allowing an ad hoc model to emerge from the implementation of the software and then enforce it on the users.

Capturing the 'real requirement' is extremely hard. There is no guaranteed way to succeed in every detail, but there are many widely used ways nearly guaranteed to fail in several important details.

'Users' have to be involved as they have a unique input to make, but merely building straight implementation of a past system user's wish list can be as risky as relying on knowledge of the functions of the equipment being used.

No reports of defects does not mean the system is OK, that the users like it or that they can use it to any useful purpose; it means it is behaving in the same way that it always does. If that way is no good, its users will either suffer in silence, or simply find a way to avoid using it.

The distinction between novices and experts, (with the inference that technical systems are designed for experts who do not need 'fancy' user interfaces), is a red herring. Most users become expert in some aspects of the system but less so in others. In the less familiar areas, they need to be able to be reminded as they go along, rather than come to a brick wall. This is helped by consistency of the user interface, (and hence the available system functions), across different parts of a system.

The only way for contractor and customer to know whether a delivered system is 'fit for use' is to submit it to representative trials with real users performing realistic tests of comprehension, interpretation and action to defined performance criteria. Supplying systems on these terms sharpens the minds of all involved. It can only sensibly be undertaken when human engineering is applied throughout the development cycle and where the customer values the extra quality and lower risk which come from doing so, but it will lead to systems which perform their intended function better in service.

12. CONCLUSION

Many machinery control systems currently being built have user interfaces which would be recognisable by the command system users of the late '60s. Making such systems work, relies very heavily on the skills and mental agility of the people who use them. It is likely that many systems 'will not work' in the sense of allowing their users to do the tasks they were intended to do in the circumstances where it really matters.

Such a situation is not new. Experience with early command systems in use was a poor shadow of the visions which conceived them. The man is the common element, and it is reasonable to ask, as the US and UK Manprint Programmes do, whether this man, with this training, in these conditions, can use this system to do this job. The answer should guide the development of the system. It may be hard to fit the system to the man, but it is more likely to succeed than ignoring the question.

HUMAN FACTORS TODAY AND TOMORROW IN SHIP CONTROL CENTRES

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1. ABSTRACT

The Type 23 Frigate is a trend-setter in the integration of ship control functions. It provided an excellent platform for a static and dynamic analysis of human factors in the ship control centre. The methods and results are described and discussed in this paper. The static analysis revealed many good design features and plenty of opportunities for improvements to the present and future designs. The dynamic analysis pioneered an approach which sought to measure workload. Mission critical tasks were defined and then filmed whilst being performed by a crew in a simulator. Dynamic analysis of the resultant video proved the effectiveness and efficiency of this approach. Task snapshots showed where the perceptual, cognitive and psychomotor loading built up to critical levels. This enabled the assessors to make a more calculated judgement than has hitherto been possible on the degree of performance enhancement achievable from good human factors design. The recommendations from this work provide opportunities for improving ship control centre designs both in the Type 23 Frigate and future ships. They are especially relevant in the context of the current pressures on manpower and the need to enable the few watchkeepers still required to be as effective and efficient as possible.

2. INTRODUCTION AND BACKGROUND

The Type 23 Frigate is a trend-setter in the integration of control and surveillance functions. Designers decided at an early stage to integrate ergonomically all the facilities necessary in a Ship Control Centre(SCC). This required a difficult compromise in the need to optimize between the very different demands of peace and wartime operation. It is during the peacetime cruising conditions that constraints on manpower make the need to minimise the number of watchkeepers, paramount. For action conditions the design must provide for co-ordination of the Marine Engineer Officer's fighting responsibilities and must enable everybody closed up to be as effective as possible. There is no universal remedy.

About 30 square meters were allocated for the SCC. The design was required to provide a man-machine interface(MMI) for peace time cruising conditions manageable by a watch of 3 persons with specified skills. The same design had to provide the action team with the facilities required for the control and surveillance of damage, stability, propulsion, auxiliaries, electrical generation, distribution and weapon support services.(Figure 1)

Figure 1. Type 23 ship control centre.

Designers started with the requirements for propulsion and auxiliaries control and surveillance. Tasks were defined and analysed and an initial layout was proposed. Liaison with similar work being undertaken for the design of a submarine control room led particularly to the double layer console which provides supervisors with a central and slightly raised desk behind the operators. This was assembled as a mock-up in cardboard and then reviewed by people with operational experience in order to provide sufficient confidence to proceed. Definition of other areas, especially those concerned with Nuclear, Biological, Chemical Defence and Damage Control(NBCD) followed later.

As well as taking a modern approach to the design of the layout of the SCC, the designers adopted the new technology of a distributed digital control and surveillance system using D86 hardware based on the INTEL 8086 processor. D86 is a VTC proprietary family of microprocessor boards. As there was an element of risk in this approach it was decided that the complete system would be assessed independently. It was intended that this should enable any problems to be resolved before they hindered the shipbuilding programme and that the facility should give the procurement authorities confidence in the system.

A ship set of Machinery Control and Surveillance(MCAS) equipment was supplied to the Admiralty Research Establishment (ARE), West Drayton where it was interfaced to a simulator of the Type 23's machinery and electrical systems. The simulated system generated signals equivalent to the transducer outputs of the real equipment so that the MCAS system was performing its design role. Additionally the consoles for the SCC were positioned as in the ship, thereby providing an excellent opportunity to review the human factors(ergonomics) achievements of the design by the static and dynamic analyses described in this article.

3. HUMAN FACTORS STUDIES

A programme to examine human factors aspects of the design was initiated with LIVEWARE Human Factors Consultants in January 1989. Key issues included the need to quantify human performance and the practical application of human factors techniques. The approach was deliberately kept simple so that all findings would be easily understood. The human factors study programme consisted of two phases.

The first phase involved a static analysis. Carried out at ARE West Drayton the system ergonomic layout was reviewed without operators present but with explanation from a subject matter expert. The expert was videoed during the explanation, in front of each panel so that the analyst could later refer to specific panels in laboratory conditions. This technique proved most effective and simple to implement.

The second phase involved a dynamic analysis using video recordings of operators performing actual mission tasks on the simulator at HMS SULTAN, Gosport. Inevitably, the work produced criticism of the Type 23 Frigate SCC. Although important, this criticism must be viewed in the context of the notable achievements of the designers. The application of digital technology and ergonomics has achieved a design which needs only 3 watchkeepers for a peace time watch compared to the 6 required in a Type 22 Frigate. Such a 50% reduction in watchkeeping numbers between successive classes of ships is dramatic and extremely welcome in this current era of manpower shortages.

3.1 Static analysis

For the static analysis the SCC was reviewed from console layout, through panel design down to the design of displays and controls, including local controls. Judgements about human factors aspects of the design were with-held until the operation of each panel was fully understood.

Although there is much data in the literature on how to design ergonomic control rooms, there is very little practical advice aimed at time-efficient analysis within commercial constraints. For this programme the SCC layout was reviewed from 5 fundamental design criteria:

(1) Positioning of devices for frequency of use.

(2) Positioning for sequence of operation.

(3) Positioning for safety of operation.

(4) Grouping of devices by function and task.

(5) Choice of display medium according to the task.

The static analysis drew attention to many good applications of human factors. For example, the concept of a concentric console arrangement splitting the supervisory function from the watchkeeping functions achieves a natural task hierarchy.

The static analysis also revealed opportunities for improvements to the design. The main areas involved aspects which might lead to an incorrect response in an emergency. For example, all control buttons should be provided with both tactile and visual feedback of their operation. Controls dis-associated from their relevant displays can result in a tortuous feedback loop for the operator. Controls which are crucial to mission success or which function differently should look and feel different so that they are not confused. The amount of information on a display should be limited to that which is absolutely essential. Technology has facilitated almost limitless opportunities for presenting data and the engineer must not fall into the tempting trap of displaying permanently "nice to have" data.

Perhaps one of the most interesting features is shown by the shaft speed indicators. The propeller shafts on the Type 23 Frigate rotate in opposite directions. This characteristic has been represented on analogue dials by showing the port shaft increasing revolutions anticlockwise and the starboard shaft vice versa. This is interesting because it represents the engineer's viewpoint of how the actual mechanical components work. The fact that the shafts are counter-rotating is interesting from an engineering viewpoint but less important to the operator's task of increasing or decreasing the speed on each shaft by pushing the power demand levers forwards or backwards. It is, however, a reminder of the "corkscrew effect".

The dark bezels around the displays could be improved by toning each bezel to a shade lighter and closer in contrast to the console panel. This would have the effect of attracting the user to the important information, namely the needle and the scale. (Figure 2)

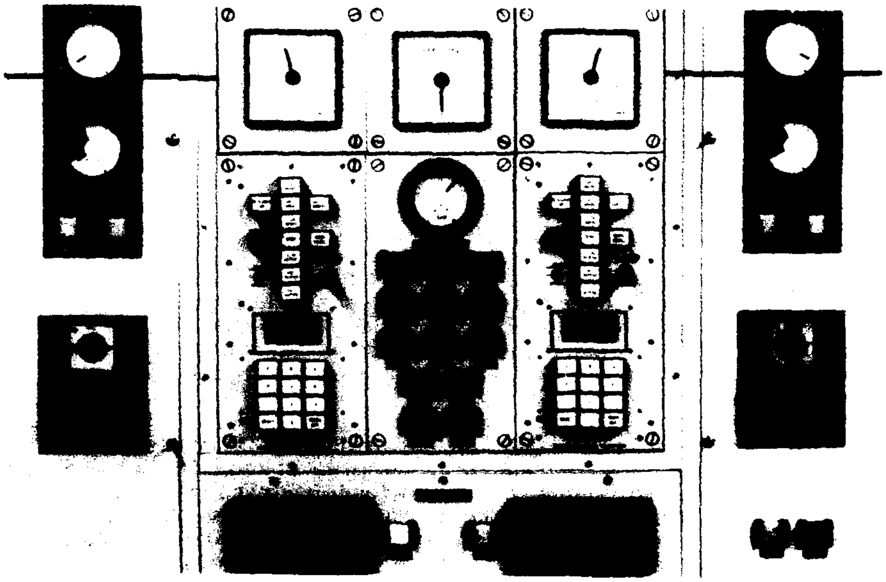

Figure 2: Propulsion panel

Display policies vary around the panels depending upon when the design was finally settled. Similarly, software access codes for parameters vary between parts of the system. Several such inconsistencies illustrate that the procurers of future systems, especially where large numbers of parameters are involved, will need to encourage more systems co-ordination from an early stage and more regular reviews of their achievements during the design programme.

3.2 Dynamic analysis

The static analysis looked at the basic disposition of devices from fundamental human factors principles. The dynamic analysis measured how well the system performed in realistic use. To the hardware and software engineer the silicon chip and the byte are key attributes determining system performance. To the human factors specialist it is the human operator and the design of the interface, tasks and environment that determine optimum human and therefore overall system performance. This is reflected in the method used for the dynamic workload analysis summarised as follows:

(1) DEFINE MISSION CRITICAL TASKS(MCTs).

(2) DEVELOP WORKLOAD MODEL.

(3) PERFORM VIDEO ANALYSIS.

(4) TEST WORKLOAD MODEL.

(5) PRODUCE WORKLOAD CHARTS.

(6) ANALYSE AND QUANTIFY DESIGN IMPROVEMENTS

The Type 23 SCC simulator at HMS SULTAN provided an excellent platform on which to carry out the dynamic analysis. As in phase 1, video analysis was selected as the best means of capturing the necessary data for subsequent analysis. A subject matter expert accompanied the analyst to explain what was going on during the mission.

a. Define MCTs. First the tasks needed to be defined. Since there are many tasks in running a complex system it was considered more efficient to focus on the Mission Critical Tasks (MCTs). Improving performance of these tasks would be the most cost-effective way to maximise potential enhancements to the system. The following are examples of MCTs which were identified in consultation with the designers and operators:

MCT1: FIRE IN MACHINERY SPACES

MCT2: TELEGRAPH ORDERS

MCT3: START PORT GAS TURBINE

MCT4: CRASH STOP ASTERN MANOEUVRE

b. Define workload model. Measurement of workload is based on workload being a function of 4 fundamental concepts:

(1) THE TASK - How difficult

(2) THE OPERATOR - How skilled

(3) THE SYSTEM - How well configured

(4) THE ENVIRONMENT - How comfortable

Thus: LOAD = f(TOSE)

The Task is concerned with what the operator does with the equipment at his disposal. For example, the sequence of operating controls and looking at displays is part of the task, as is making decisions on courses of action. For any piece of equipment, the arrangement of tasks can have a significant effect on the performance of the crew with that equipment. This study involved observation of tasks which were already rigidly defined.

The Operator, his skill and his training are also significant performance determinants. The investment in the Type 23 Simulator at HMS SULTAN is testimony to the Royal Navy's commitment to training.

The System and how it is configured were major reasons for undertaking this study of the way in which the controls and displays are laid out on the panels, in the space available. This branch of ergonomics is sometimes called the Man-Machine Interface(MMI) and is part of the whole study of human factors.

The Environment refers to the surroundings within which the operator is working. For example, other crew members, noise, heat and lighting can significantly affect operator performance.

In summary, of the four determinants of human performance, this study concentrated more on the System and how the control room could be enhanced by better layout of controls and displays.

In performing effectively, operators depend upon their own human skills. There are 3 fundamental human skills:

1 PERCEPTUAL - Receive information

2 COGNITIVE - Process that information

3 PSYCHOMOTOR - Operate a control device

Perceptual skills are those concerned with our ability to receive information, that is, observation. The human perceptual system has five senses to achieve this, the predominant sense being the eyes. An example of a perceptual skill is the ability of a pilot to observe another aircraft or the ability of an operator to notice a warning on the operator's console.

Cognitive skills are those concerned with our ability to process information and make decisions. An example of a cognitive skill is the ability of a judge to pass sentence on a defendant or the ability of an operator to decide what course of action to take following a warning.

Psychomotor skills are those concerned with our ability to act upon the information we receive. An example of a psychomotor skill is the ability of a tennis player to hit an effective shot or the ability of an operator to take corrective action or simply make a control adjustment.

In developing the workload model it can be seen that, in summary, the four determinants of workload must be understood together with the three basic human skills. A typical workload model such as that illustrated in Figure 3, shows a task snapshot consisting of 2 observations R1 and R2, 1 decision, P1 and 4 actions, A1-4 over a period of time from 0-T seconds, the length of which depends on the task sampling period. Two of the actions are seen to be simultaneous. This is a simplified graph of a task. In practice, the operator "footprints" of workload are more complex although, as more charts are created, designers will quickly recognize high workload patterns as opposed to low workload patterns. They will then be able to make early design alterations to smooth the workload over the task period. Such remedial action may involve re-designing the task, providing more system automation and removing an operator, re-training the operator or improving the environment. (Figure 3)

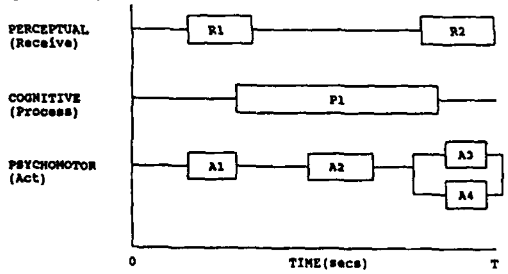

Figure 3. Workload model.

c. Video analysis. Video analysis was found to be very effective for task analysis. Benefits include: a total record of the events in sound and vision; capture of a lot of data where note taking is prohibitive; the facility to replay the precise events, and a convenient medium for presentation and demonstration purposes. The first MCT was analysed to test the workload model.

d. Test workload model. The video for the first MCT was analysed with a stop-watch under laboratory conditions to separate each event over the time period and categorise each action into the 3 basic human skills. This was a pains taking process which would have been much easier had a clock been available within the video. The result was a table summarising the events, the time and the skills used. The workload model was refined and the analysis technique improved before the remaining MCTs were filmed. An example of an actual mission critical task snapshot is shown at figure 4.

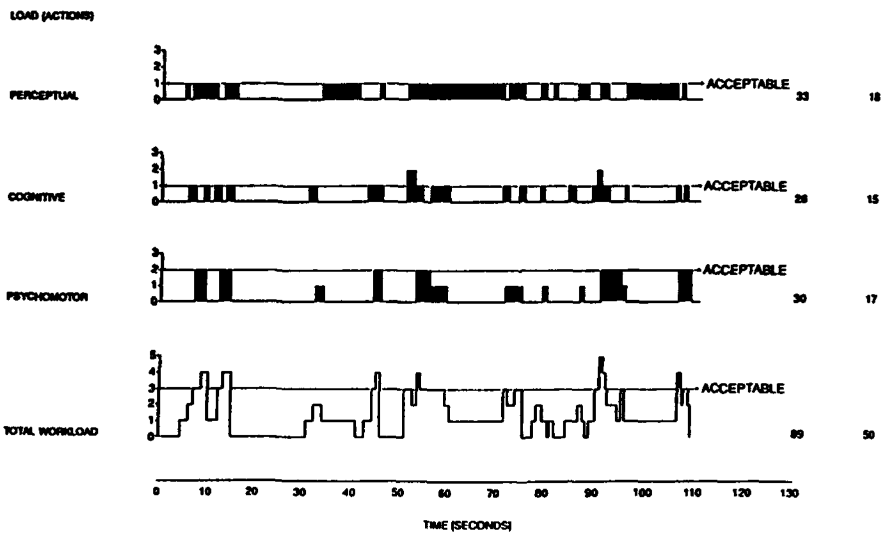

Figure 4. Mission critical task snapshot.

e. Produce workload charts. When the workload model was perfected, the remaining MCTs were filmed. Workload charts were produced, resulting in nine graphs in total, one for each MCT. Figure 4 above is one example of these nine graphs and shows the workload in the number of "actions" for each of the three human skills. The lower performance curve shows the total load over that snapshot. This is a summation of the three individual loads incurred on the operator.

f. Analyse and quantify design improvements. Analysis of the videos of the MCTs highlighted some interesting features. Alarm systems must be designed to attract operator attention to the source of the alarm, both visually and audibly. This will save time, reduce errors and enable the operator to use the system more effectively. All system users can be disturbed by alarms which are too loud. Whilst alarms, by definition, must be instantly detected, they must not startle the operator into confusion and inaction. Ideally the alarm annunciator should gradually increase in volume and be designed to encourage the operators to look in the correct direction. The annunciator should be positioned centrally thereby removing the temptation for the operator to turn around each time an alarm sounds.

The videos show examples of where operators misinterpret their primary instrumentation, port for starboard, for example. CCTV systems are now available and could be beneficially fitted for machinery surveillance. Operators able to confirm their conclusions by reference to such a secondary surveillance system are more likely to avoid erroneous actions. Reports from the Boeing disaster at Kegworth illustrate this because they suggest that the pilot may have saved the aircraft had he been able to see the engines. Cameras are now being fitted to certain British Airways airliners.

The videos also illustrate that operators have difficulty interpreting a large number of indications quickly. Previous generation instrumentation consisted of separate display devices for each transducer. Then instruments combined data within one display until limited by the space available. Now, a virtually unrestricted amount of information can be displayed using computer-driven paging facilities.

A composite of hardwired devices and multi-function displays, as in the Type 23 Frigate, seems appropriate for future MMIs. However, a balance must be achieved and, in particular, indications on a console must be kept to a minimum. A computer-based secondary surveillance system provides an ideal way to amplify information but must provide a user-friendly dialogue and quick access to the required data page.

Consideration of the "task snapshots" suggests that workload has a maximum and minimum level for optimum performance. If loading is too high the operator will miss information. If it is too low the operator will become bored. Good task design should provide an optimum level of activity. The analysis in this case highlighted areas in which further automation could beneficially remove workload peaks.

4. BENEFITS FOR THE FUTURE

The analyses have shown that there are many good human factors aspects to the Type 23 Frigate MCAS system. The hierarchy of alarms and warnings, the sighting of displays above controls, and the concentric console arrangement splitting yet combining the operator, supervisor and MEO tasks, are all examples. The effort to achieve an ergonomic design has been worthwhile and provides firm principles from which to propose improvements for future ships. The videos have also enabled assessors to draw the early attention of designers and operators to areas of risk in the layout.

The assessment quantified the potential reduction of workload thereby giving procurement authorities a positive basis on which to assess improvement proposals. The techniques used are simple, practical and cost-effective to apply. Potential benefits demonstrate the value of such human factors reviews and if improvements to the design are implemented then there should be consequential savings on operator training and improved ship performance and safety.

Analysis of perceptual load illustrates that an operator should not be required to receive 2 sources of information simultaneously. Highly skilled operators appear to be multi-processing but are in fact either "chunking"(grouping) discrete tasks together and treating them as one action or are switching rapidly from action to action. A virtuoso pianist exhibits both of these human traits, however, for multi-populations, the human factors analyst must design for the least skilled rather than the most skilled person.

Similarly, an operator should not be required to make more than one decision simultaneously. The action of making a decision is a single channel cognitive operation. There is another kind of mental loading related to decision making but concerned only with the amount of data which can be held in short term memory. This is sometimes also called "chunking", and is part of short term recall and the way this relates to activation of long term memory. Operators should not be required to hold more than 5 chunks of data in short term memory at any one time. These chunks are not mental actions as such, but are a function of the span of attention.

Under stress psychomotor and perceptual performance are enhanced until breaking point renders them ineffective. Cognitive performance, on the other hand, rapidly degenerates. The more decisions facing the operator, the longer it takes with mental load increasing exponentially with the number of decisions required.

The psychomotor load should be limited to operating two controls simultaneously, especially for unfamiliar tasks. In a car, the driver steers and changes gear together easily. This may seem small, but if this rule is followed, it errs on the safe side and makes allowance for less skilled operators performing new tasks in hostile situations.

If these 3 rules for perceptual, cognitive and psychomotor load are not violated then an operator should not be required to perform collectively, more than 3 actions simultaneously. A driver might steer(a psychomotor skill), observe the road ahead(a perceptual skill) and think about the worsening weather(a cognitive skill) simultaneously. Such a composite of 3 actions should be regarded as a limit if the philosophy for the least able operator is to be followed. The acceptable limit for these workload levels can be more easily understood by looking back at Figure 4.

The static and dynamic analyses were conducted on a completed design. Looking head, the principles of human factors analysis and design must be applied early to new designs. Human factors aspects should then be addressed continually as an integral part of the design, development and delivery. The process of human factors analysis is summarised in Table 1 which illustrates that the essential output of analysis is the Top Level Specification for the user.(Table 1)

Table 1. Human factors analysis method.

• APPROVE HUMAN FACTORS PLAN WITH CLIENT • BRIEF STAKEHOLDERS • DESCRIBE TOTAL SYSTEM LIFE-CYCLE PLAN	PLANNING
• TASK ANALYSIS AND ELICITATION • TRAINING ANALYSIS • TASK REPRESENTATION • USER CHARACTERISTICS	ANALYSIS
• AGREED USER MODELS • TASK DESIGN • TEAM AND WORK ORGANISATION	MODELLING PROTOTYPING SYNTHESISING
• GOAL SPECIFICATIONS • TOP LEVEL SPECIFICATION	SPECIFYING

The Top Level Specification can then be used by all members of the design team during the design phase. The human being is a dynamic and variable organism. Tolerances in design for humans tend to reflect this variability. Any human factors technique must respect this and avoid wasting time and money by placing a tighter tolerance on methods which try to inflict too much precision. Urgent issues should be addressed first in a clear and simple way. This practical approach will result in an increased probability of human factors issues being resolved. A complicated method risks being abandoned all together. As illustrated by this programme the potential reduction in workload can be simply quantified thereby providing a positive basis for the assessment of improvement proposals. The design method is illustrated in Table 2.

Table 2. Human factors design method.

* PLAN DESIGN PHASE	>	PLANNING
* TASK ALLOCATION * USER CHARACTERISTICS * TASK DESIGN	>	SYNTHESIS
* HUMAN-MACHINE INTERFACES * USER-USER INTERFACES	>	INTERFACE CONCEPTS
* IN-BUILT TESTS AND FEEDBACK * IN-BUILT PERFORMANCE AIDS	>	HUMAN PERFORMANCE SPECIFICATION
* IN-BUILT TRAINING	>	TRAINING DESIGN
* USER DOCUMENTATION	>	DOCUMENTATION
* WORKSTATION AND WORKPLACE DESIGN	>	HMI DESIGN
* HEALTH SAFETY AND COMFORT * JOB DESIGN * TEAM AND WORK ORGANIZATION	>	WORKING ENVIRONMENT
* EVOLUTIONARY DELIVERY * TEST PLANS AND PROTOTYPES	>	FULL PROTOTYPE

All such work relies upon accurate assessments of the tasks, in this case the mission critical ones. These must be thoroughly understood and need considerable input from the end user, instructors being especially useful. Once the tasks are agreed the human factors specialist still needs advice from a subject matter expert with extensive professional knowledge and operating experience. This person is needed to advise during the observation process and subsequently to guide opinion on the practicality of improvement suggestions. The design phase starts with a plan which aims to allocate tasks appropriately to humans. The output of the design phase is a specification for the first prototype system. (Table 2 above)

5. CONCLUSIONS

Consideration of human factors should be an integral and early part of the design and development process. It will enhance operating commonality between systems by imposing interfaces designed to match normal human stereotypes. The evidence has illustrated that human factors assessments can give early warning to areas of risk, and the potential for improvements can be cost-effectively quantified using techniques such as the "task snapshots" described in this article.

This human factors assessment has identified possible design changes which could contribute to further reductions in workload and, equally importantly, to the improvement in effectiveness and efficiency of those operating future warships. The application of CCTV within machinery spaces and the need to design carefully, the alarm annunciator, are good examples.

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APPLICATION OF A GENERAL PURPOSE DATA BUS IN A MAJOR SURFACE COMBATANT CLASS

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1. ABSTRACT

General purpose data buses offer advantages to combatant warships which have not always been well understood. In this paper, the role of general purpose data busing in modern surface combatants is explained, and the application of the Data Multiplex System (DMS) AN/USQ-82(V) in the U.S. Navy's new Arleigh Burke class of guided missile destroyers is examined. It is important to note that this paper is not about a data bus; it is about the application of data busing. It is about real world issues of design compatability, equipment interfacing, and systems engineering which arise when systems which were conceived and designed in isolation must be combined to form an integrated ship system. Some of these issues are clear cut and become obvious during design; others are not so simple to diagnose and do not become apparent until integration testing has commenced. This paper will describe the issues, their resolution, and the characteristics a general purpose data bus must have to allow resolution of these issues without causing major impacts on user systems.

2. INTRODUCTION

Naval surface combatants are unique among military platforms in that they include a very large assortment of diverse systems and subsystems. The combat system of a surface combatant is a good example of this, since it typically consists of separate subsystems designed for air, surface, and subsurface target engagements. The engineering plant, the navigation system, the damage control system, and the steering control system are other examples of systems which, in major surface combatants, are quite different one from another, and are composed of a variety of technologies in their lower-tier subsystems. These different systems and subsystems are normally designed and built by different Navy/industry teams, each one targeting a specific set of problems and using a particular design approach which may have little in common with the designs of other subsystems. Frequently the subsystem design is optimized to perform the subsystem's mission with little regard to optimizing the design of the ship as a whole. Add to this the variability in age of these multiple subsystems (all-new designs for any individual ship class would result in a prohibitively expensive ship, not to mention an unreasonably high schedule risk), and it becomes clear that Naval ships are unlikely ever to consist of a homogeneous set of parts.

To further exacerbate the non-homogeneous nature of major surface combatants, it is not realistic to expect any universal standard to be developed for any single aspect of a ship's systems which will be viable during the ship's 30+ year lifespan. In fact, for major shipbuilding programs such as the U.S. Navy's DDG 51 program, it is unlikely that the standards will remain constant throughout the building phase of the ship class. Advances in technology are frequently incorporated during the building phase, resulting in "subclasses" or "flights" of a shipbuilding program. Between ship classes, of course, there is even less homogeneity.

The advantages of distributed processing have been enumerated in many sources, and such an architecture is clearly the trend in control system architectures today. Highly survivable control system networks can be designed in which multiple processors and displays located strategically throughout the ship can share or swap roles as the situation demands. In present systems, these shared functions are primarily built into individual systems, not between systems. However, there is no reason to believe that future ship designs would not incorporate redundant architectures across system boundaries.

To implement practical distributed control systems which capitalize on the flexible, adaptable nature of digital processors is virtually impossible without data busing. Not only would it quickly create an unmanageable mass of signal interface cabling, but it would soon overwhelm the most potent computer input/output controllers available. Combat systems, which were the first to implement distributed control architectures in large scale, have seen this problem creeping up over the past 20 years or so. Newer control system designs, such as the US Navy's Machinery Control System (MCS) and Steering Control System (SCS), are attempting to avoid this problem by relying, at least in part, on the services of a general purpose data bus.

3. REQUIREMENTS FOR A GENERAL PURPOSE DATA BUS

A general purpose data bus is one which has been designed to accommodate data transfer among diverse systems and equipment. It must be capable of handling the data transfer needs of multiple control systems communicating simultaneously without these systems interacting in any way and without requiring the designers of these systems to know or care about what other systems are sharing the data bus. A general purpose data bus does not attempt to impose a single standard on equipment interfaces. It must accommodate non-digital users (analog, synchro, discrete, etc.) as well as a variety of digital interfaces each with its own appropriate protocols.

With the above in mind, it is not difficult to define some of the high level requirements placed on this general purpose bus:

- The general purpose bus must be capable of supporting a large number and variety of user interface connection points. Use of digital technology at the source user end as well as the sink user end of the communications link could reduce the total number of interfaces needed, but for the foreseeable future there will continue to be a plethora of non-digital equipment such as pump controllers, valve controllers, environmental sensors, and display panels. As an example, in the DDG 51 application there are 1617 interfaces to the Data Multiplex System, only 27 of which are digital.

- A bus which provides service to critical ship systems must be both reliable and survivable. In fact, general acceptance of such a bus depends on overall survivability surpassing that of older hardwired designs.

- Finally, the long expected life of surface combatants today demands that the bus system support considerable growth in terms of quantity and type of users serviced, and in terms of its own upgradability. As the user device technology is upgraded in a ship's modernization periods, the bus must be capable of keeping up with user service demands.

This paper traces the practical aspects of the application of the first general purpose data bus system in the U.S. Navy: the Data Multiplex System (DMS) AN/USQ-82(V) in the DDG 51 class of destroyers. The topic is covered from the point of view of user systems and system integration issues rather than from a DMS-related perspective. Many of the concepts illustrated would apply to any general purpose bus implementation, and are presented in a "lessons learned" format. Thus, rather than describe the structure of DMS in isolation, this paper investigates the evolution of the user device networks, the problems encountered, and solutions implemented. Some of the solutions consisted of making use of DMS's inherent flexibility. This serves to illustrate some of the features needed in data bus systems generically. A more detailed discussion of DMS structure and operation was given in (1) and (2).

Perhaps the most telling message, however, is that with all of the interface signal and protocol questions which have surfaced between the early Contract Design and the late Detail Design phases of the DDG 51 program, never were the internal DMS data bus protocols the issue. All of the problems and solutions related to the bus-to-user interfaces. This is where there seems to be constant demand for flexibility and adaptability.

The Appendix presents an Open System Interconnection (OSI) model view of DMS. The OSI representation illustrates graphically some of the concepts which will be discussed, such as how a general purpose bus can be used to support communications between otherwise incompatible systems.

4. APPLICATION DESIGN OF THE DDG 51 DATA BUS

Very early in the DDG 51 design cycle, it had been decided that a general purpose data bus would be installed to save weight through reduction in the ship's signal cabling, reduce the cost of future upgrades, and provide more survivable data transfer paths. The networking aspects of a data bus were also required by some of the new subsystems being developed for this ship class.

To assist in the application engineering required to configure DMS for a specific ship class, two automated tools were applied. The first, the Application Design Automation Program (ADAP), assigns users to input-output channels while minimizing user-to-DMS interface lengths, and defines an optimal message management structure within DMS. The second, the Timing, Event, and Load Simulation (TELS), performs a simulation of the data bus and its constituent parts. The output from ADAP is used as the TELS input. TELS then provides the application designer with the bus and terminal loading data. These tools had served the DMS design team well during the development program, but proved to have deficiencies when applied to the first "real world" application of DMS.

Early in the contract design phase it became necessary to modify ADAP. At first blush, the goal of minimizing interface cable length between users and DMS appears reasonable. However, in the face of real world design issues, strict adherence to this goal had to be abandoned. During the contract design phase of a shipbuilding program, the design is still somewhat fluid, but design products (drawings, specifications, etc.) are being produced. The addition or deletion of a single user could result in the reassignment of literally dozens of user channels to reoptimize the ADAP parameters. Clearly the impact of such reassignment was unacceptable in terms of both time and costs. A decision was made to "freeze" the existing channel assignments. Users could still be added or deleted, but this addition/deletion would have no bearing on the channel assignment of existing users. Thus, only the design products applicable to the users being changed required updating.

ADAP was therefore extensively changed to better accommodate the needs of real ship design programs. The current structure of ADAP can best be described as a rule-based database. Rule-based because ADAP must check that all interface and message assignments, and all signal and message control firmware are made consistent with prescribed DMS requirements and constraints.

The new ADAP is also a database which contains all pertinent information the user device interfaces with DMS, such as the location of the user, the source(s) or sink(s) of data for that user, signal update rates, type of protocol used, type of interface signal, jack number, and so on. This database is the fundamental tool used in configuration management of the bus system, and programs have been developed to allow contract drawings, interface design specification documents, technical manuals, test documents, and shipyard databases to be updated automatically from ADAP files.

When communications issues surfaced in the DDG 51 Machinery Control System (MCS), TELS did not have the capability necessary to assist application designers in resolving these issues. TELS has proven to be remarkably accurate at predicting measures of bus performance. In popular data busing parlance, TELS is concerned with the inter-terminal communications. However, in real world applications, bus performance can be very misleading measure of what is actually occurring. Bus system performance can be adequate, yet problems at the user interface level may still exist. Additional effort was therefore needed to study the effectiveness of MCS processor communications via DMS. This effort involved careful modeling of the communications evolutions beyond the boundaries of the DMS terminals - to include mechanisms which are critical to the overall communications process but which are beyond the scope of TELS.

For analysis of the DDG 51 Machinery Control System (MCS), the U.S. Navy developed an MCS communications simulation that treats the entire DMS as a "black box", in order to evaluate proposed modifications to user protocols. The lesson learned here is that the data bus simulation should extend to users' application program interface, and the user simulation ought to be easily mated to the bus simulation to allow for analysis of complete user to user communications.

5. AEGIS COMBAT SYSTEM

All systems, including the combat system, were initially considered as potential DMS subscribers in DDG 51. The AEGIS combat system, which had already been installed in CG 47 Class cruisers, was a well developed network of computers and peripherals. This network uses point-to-point cabling for intercomputer and computer to peripheral communications.

When DMS was proposed for use in the AEGIS combat system, the concept was merely to use DMS as a direct replacement for the existing intercomputer and computer to peripheral cables. A redesign of the existing AEGIS architecture to one which capitalizes on a data bus was not contemplated, as it would have involved significant efforts by communities outside of DMS. Because DMS was proposed this way, the benefits to a mature computer network such as AEGIS were small from a capabilities standpoint, and the risks inherent in adding communications electronics to the existing AEGIS network were perceived as real.

There were, however, two areas related to the AEGIS combat system where analysis showed the application of DMS to be clearly beneficial. First, DMS could provide a needed service to AEGIS in distributing Inertial Navigation Set AN/WSN-5 data, both digital and synchro, to the various users. This was considered a valuable service because DMS could:

- Convert the MIL-STD-1397A Type A (NTDS Parallel Slow) used by the AN/WSN-5s into a Type E (Low Level Serial) used by the AEGIS computers,

- Provide a port expansion function to enable a single AN/WSN-5 digital output channel to provide data to all digital users of navigation messages, and

- Distribute the synchro data to all synchro navigation users, eliminating the need for large switchboards and synchro amplifiers.

Secondly, DMS could provide a backup source of data for the Digital Dead Reckoning Tracer (DDRT). This device, a plotting table which automatically tracks own ship's movements, is normally provided with inputs from the Command and Decision (C&D) System computer. To increase the reliability of data to the DDRT, DMS processes messages from the two Inertial Navigation Sets (the same messages it distributes to the combat system) to offer two alternate sources of inputs for the DDRT, identical in frequency and format to the existing C&D message, should the C&D computer be off-line.

The lessons learned from attempting to apply data busing to an existing network were revealing:

- Although weight reduction is a laudable goal, it is probably not sufficient reason to warrant the restructuring of an existing, carefully optimized, digital control network.

- Where data busing provides a clear advantage to the overall system architecture, its introduction occurs smoothly, even when the introduction is a retrofit into an existing system.

6. MACHINERY CONTROL SYSTEM

Perhaps the first surface ship control system whose architecture evolved into a network optimized around a general purpose data bus is the DDG 51 Machinery Control System (MCS). During Preliminary Design, high level drawings were already showing digital processors controlling or monitoring non-digital devices, or these same processors communicating with each other, over only two redundant interfaces and a data bus. The details of the implementation and documentation of such a system were not worked out yet, but the computer network conceived for the MCS did not consider the data bus as an add-on. The data bus was, from the start, an integral part of the architecture.

By the end of Contract Design, much of the MCS network structure and some of the communications parameters between the MCS processors had been established. For example, the quantity and location of each of the MCS processors had been defined, as had been a good portion of the non-digital sensors and controlled devices. To support MCS communications, a fairly detailed protocol to be implemented in the MCS processors had been worked out.

Soon after the Detail Design phase got underway, several aspects of the MCS network which had previously appeared to be well established were suddenly open to redesign. The flexibility of the bus system was heavily taxed during this period. The following are some of the changes which had significant impact on use of the data bus, and which illustrate the need for flexibility in the bus system:

- Change to Bridge Control Unit - Each of the six MCS consoles had been assumed to include a data processor - an AN/UYK-44 - for data processing and communications. The Bridge Control Unit, which is the console on the bridge used to remotely control engines and propellers, was redesigned at the start of Detail Design to become a non-digital peripheral. What had been two redundant NATO STANAG 4156 serial digital interfaces became almost 200 separate discrete switch closure, discrete logic level, and synchro interfaces with DMS. This was a lesson in ensuring that generous spare capacity be designed into a data bus in the initial design phases. What had approached 50 percent spare capacity in this area of the ship suddenly was almost totally absorbed by this one change.

- Change to MCS Message Structure - The original intent had been that the MCS processors would only communicate with each other "by exception." In other words, if all parameters stayed unchanged over a particular period of time, no communications would be required. The protocol which had been designed during Contract Design assumed this approach, and was therefore quite robust but also cumbersome. It was decided early in Detail Design that too many parameters would change too often to allow such a structure to be implemented.

If the "by exception" design were to be used, an unacceptably high number of different message types would have to be generated each second by many of the processors. This would have dedicated too much processor time to the communications task. Instead, an asynchronous and periodic communications architecture was adopted whereby each console would send status updates to each other console two times per second. These status messages were to be very long, up to 1Kbyte each.

• Change to MCS Protocols - When the MCS interprocessor messages and the messages between processors and non-digital devices are combined, the resulting communications load was such that the protocol defined during Contract Design for MCS computers was deemed unacceptably slow and prone to disruption. As a result, a more streamlined protocol was developed, one which capitalizes more effectively on the connection-oriented nature of DMS. In addition to this, the message error checking accomplished within the AN/UYK-44 processors was also abbreviated to reduce the overall time spent in communications.

• Future MCS Protocol Modifications - A network of computers which only communicates "by exception" would logically adopt a source initiated message structure. Since the MCS computers now communicate periodically rather than by exception, one can decide on source or sink initiation of messages depending on which is most efficient. (Note that this topic is independent of DMS. Even if the MCS computers were hard-wired together, these protocol issues would arise. If the bus system can efficiently implement source or sink initiated protocols, which DMS can do, it is only the user application which determines which approach is best.) Generically, with or without a bus, to reliably transfer source initiated messages between two computers involves four steps:

1. Message transfer request from source to sink device.
2. Sink indicates ready/not ready for data.
3. Source sends data when sink is ready.
4. Sink acknowledges receipt of correct message.

Equally reliable sink initiated messages only involve two steps:

1. Message request from sink to source.
2. When ready, source sends data.

In sink initiated transfers, the fact that the requesting computer receives the data message implicitly means that the other computer was available and that the message transfer occurred correctly.

The inherently more efficient sink initiated protocols are currently being tested for MCS communications. The DMS suite used to perform these tests can accommodate either source or sink initiated protocols concurrently.

Another important lesson learned in the application of DMS for the Machinery Control System related to documentation. The MCS processors interface with many hundreds of non-digital devices via DMS. The quantity and location of these devices is often not under the purview of the Machinery Control System NAVSEA code. Not only did the MCS community not know what all of these peripherals were, but they also did not know exactly how a processor connected to DMS would read or control these devices. Interface Design Specifications (IDS) are a common document used in ship design to define precisely how two digital processors communicate, but IDSs had not been needed in the past between processors and non-digital peripherals. To meet this need, a system was designed which automatically provides DMS addresses and message formats for all non-digital peripherals connected to the bus, using the DDG 51 Contract Drawings and the DDG 51 DMS database as sources. The document and floppy disks generated are used by the MCS community to augment their MCS IDS and allow software development to proceed. In addition, this automatic message format tool allows the MCS software to keep abreast of changes that occur to the configuration of these non-digital peripherals.

7. MCS LAND BASED TEST/DEVELOPMENT SITES

Two land based sites have been established to develop MCS and to test the MCS operating with DMS: the MCS Vendor Test Site at the General Electric Simulation and Control Systems Division in Daytona Beach, and the Land Based Engineering Site (LBES) at the Naval Ship Systems Engineering Station in Philadelphia. Both of these sites are provided with a DMS suite which is considerably smaller than the DDG 51 DMS, but which emulates its functionality. Thus, each MCS processor is connected redundantly to DMS over STANAG 4156 serial digital interfaces, DMS provides redundant data paths between terminals, and user devices related to MCS which are not present at the test sites are emulated by simulation computers.

During testing at these sites, a number of problems surfaced. Below is a summary of problems and resolutions related to the non-trivial system level issues encountered.

7.1 DMS Problems Found at MCS Test Sites

Early communications testing was hampered by a number of small but disruptive problems in the DMS terminal-to-user device interface. These were found to be errors in execution rather than intrinsic design faults.

a. Unintentional DMS mode enabled. The DMS Specification for the STANAG 4156 interface includes a mode called the "Type B DMS-Initiated Source Device Transfer." This mode, which is not included in the NATO STANAG 4156 Specification, is not understood by the AN/UYK-44's STANAG 4156 interface adapter. DMS was occasionally enabling this mode unintentionally, and the result was that communications with the particular computer port would be disrupted for periods of up to 6 msec. The mode was disabled. The lesson is that when Specifications for a particular system impose requirements beyond those stipulated in the Standard, extreme care must be taken to ensure that complete compatibility is maintained with the Standard, in all operational modes.

b. LBES DMS saturation. Although not strictly a "DMS problem" in the sense the others are, this is listed under DMS because it is clearly not an MCS problem. The original LBES MCS system was to consist only of three processors communicating over DMS. To meet this need, a small DMS was designed which would support two simultaneous intra-terminal conversations or one bus-mode conversation. Later, two Integrated Test Sets (ITS) were added to the MCS processors to emulate the traffic caused by the three missing consoles and by some of the non-digital peripherals. If the three actual MCS consoles are communicating, DMS supports the message traffic properly. If the two ITSs are also enabled to respond to messages but not to initiate their own traffic, DMS still supports the data load. However, if the ITS which emulates the three missing MCS computers is set to emulate more than one of the missing consoles, DMS becomes saturated. The symptom is that scheduled messages are missed at a rate of 100 or more per minute. To resolve this problem, the LBES DMS was upgraded to a two bus, two (internally redundant) terminal system identical to the MCS Vendor Test Site configuration.

c. LBES production hardware Turn-Around Mode problem. When the newest production STANAG 4156 interface modules were installed in the two-bus LBES DMS, the turn-around mode (i.e. when data are transferred internally rather than over the main bus cables, used for "local calls") was found to be unreliable. The bus mode, however, operated correctly. Older STANAG 4156 modules operated correctly in all modes with the new DMS equipment. The problem turned out to be caused by an unfortunate accumulation of tolerances between the new DMS terminals and the new STANAG 4156 modules. A modification to the terminals' operating program and to the STANAG 4156 modules corrected the problem. This demonstrates that, especially in situations involving production runs which are extended over long periods of time, it is important to strive for the lowest possible sensitivity to timing tolerances. If "equivalent" components from different manufacturers will be used, or even components taken from different lots produced by one manufacturer, worst case combinations of timing variability must be expected.

It should be noted that all of the above problems related only to the user-to-DMS STANAG 4156 protocols (including protocols between DMS-user interface and the DMS terminal). None involved basic DMS protocols or timing. As might be expected, the Navy officer and GE engineers assigned to MCS development work at Daytona Beach became very adept at detecting and correctly identifying these faults, and in numerous cases these same individuals replaced DMS circuit cards or PROMs mounted on the circuit cards without DMS engineers being present. NAVSSES personnel have become equally familiar with DMS.

7.2 MCS Problems Found at MCS Test Sites

In spite of the fact that the above DMS problems were being resolved, MCS communications were still not meeting expectations at the test sites. It appeared that an inordinate number of messages were being transmitted by one computer but not acknowledged by the intended sink computer. The details of what was modified to correct each of the problems are not known to the DMS community, but the MCS-related problems can be roughly organized in the following categories.

a. "Periods of darkness". After an MCS processor had received a message via DMS, periods of time in excess of 5 msec were sometimes measured during which other message traffic appearing at the interface (from other computers in the MCS network) would be "dropped on the floor." During these periods, aptly dubbed "periods of darkness" by the NAVSEA MCS Project Engineer, the interface appears free to DMS, so the protocol adopted for MCS communications allows DMS to send the message to the sink interface. The sink device, however, could not process the incoming message. Several changes to the MCS software were implemented which reduced considerably these periods of darkness. Among the changes was a more efficient message checking procedure, such that conducting quality checks on received messages would not preclude processing other message traffic to as large an extent.

b. Inefficient interface status criterion. The original MCS protocol required that, should an interface with DMS appear to be faulty, the MCS console associated with that interface would send out test messages, and would only resume communications on the interface after receiving a correct test message response. Very often, however, what appears to be a faulty interface is simply a busy interface, which clears itself in due course. But the MCS user protocol caused all subsequent messages attempting to go through the interface to be ignored unless they happened to be test messages responses. So the initiating processor was bombarding that interface with test messages to other devices, attempting to reestablish the DMS port, causing a bad situation to become worse. To correct this problem, the MCS software was changed such that any correct message appearing over what was assumed a faulty interface is enough to consider the interface fully operational. Thus, interfaces are typically assumed faulty for a much shorter period of time, good messages are not being ignored, and a smaller quantity of test message traffic is generated.

c. ITS not ready for data in time. The original protocol established for source-initiated transfers from an MCS processor to an ITS dictated that DMS forward the request header to the ITS to allow it to prepare itself for the incoming data message. Having forwarded the request header to the ITS, DMS would then immediately indicate to the source MCS computer to start sending the data message. Using this protocol, DMS would send the first data word to the ITS about 50 to 70 μsec after forwarding the request header. This was not allowing the ITS enough time to configure itself for the incoming message. The protocol was changed such that the DMS, having forwarded the request header into the ITS, must now wait for the ITS to acknowledge when it is ready for data. This acknowledgement is then used by DMS to indicate to the source processor that it can start sending the data message.

d. Excessive computer response time to Receive Requests. As mentioned previously, a sink initiated intercomputer protocol is being tested at the MCS Vendor Test Site. To alert the data source computer that someone has requested its data message, DMS forwards the request header into the source computer. This processor then converts its input buffer into an output buffer, filling the output buffer with its (long) message, then sends the message to DMS. Very often, the 2 msec DMS waiting time was being exceeded, and the message transfer would be aborted. To solve this problem, the MCS processors are now using the STANAG 4156 Burst Mode, whereby the processor starts sending message words to DMS before the entire message is loaded in the computer's output buffer.

e. Busy signal not available for Receive Requests. (This is not strictly an MCS-related problem, it is actually a STANAG 4156 shortcoming. However, the solution involves the MCS processors, so the problem is described here.) STANAG 4156 does not specify a "busy signal" during interprocessor sink initiated transfers, although such a signal is available with peripheral device protocols. As is the case for source initiated transfers, DMS could, by means of a busy signal, indicate to a requesting computer within 3.4 msec whether or not the requested channel can be established. If the AN/UYK-44 is not provided with this signal, the only alternative is for a timeout timer to be set within the AN/UYK-44. For several reasons, in this application this timeout timer cannot be less than 20 msec, which means that 16.6 msec are wasted whenever DMS cannot establish a communications channel. It also means that the potential for message disruptions exists during this 16.6 msec, because DMS is free to send requests to the processor, and the processor is still waiting for DMS to honor its previous request for service. One solution to this problem is that the AN/UYK-44 must, having sent its request header to DMS, temporarily change to a peripheral sink initiated protocol. When

DMS senses that the processor is using the peripheral protocol (STANAG 4156 Type A), it will provide, as necessary, the busy signal. As soon as the data message or the busy signal have been received by the processor, it must restore the intercomputer protocol.

This experience with the two MCS test sites shows clearly that, especially when intercomputer communications are involved, testing of the equipment is extremely valuable. When large systems are involved, hard to detect human error and hard to predict timing incompatibilities are bound to exist and must be systematically whittled away. In spite of the visibility these user interface problems received at different periods, in retrospect there was nothing intrinsically wrong with the MCS-DMS system design, nor was there anything particularly surprising about the nature of the problems encountered.

8. STEERING CONTROL SYSTEM

A modern, digital computer-assisted, Steering Control System is designed into the Arleigh Burke class. This highly survivable control system includes an autopilot, a fuel conservation mode, a ship roll reduction mode, and several backup modes of operation should the steering system computer fail and should all bus communications fail.

The Steering Control System (SCS), like the MCS, was designed with the assumption that a general purpose data bus would be available, although a less capable non-bus variant also exists. The SCS consists of only one AN/UYK-44 processor, located in the Steering Gear Room, one digital peripheral located on the bridge, and numerous non-digital devices on the bridge and in the Steering Gear Room. The AN/UYK-44 and the digital peripheral are equipped with serial digital STANAG 4156 interfaces. Because SCS incorporates only one digital processor in its design, the message flow turns out to be considerably more predictable and orderly than the asynchronous, six-processor MCS network.

The SCS evolved much like the MCS during the DDG 51 Contract Design phase, although on a smaller scale. The original design included primarily digital equipment on the bridge, a processor and non-digital devices in the Steering Gear Room, and backup steering cables from the bridge to the steering room. To maintain more similarity between the DDG 51 SCS and the non-bus variant, several functions of the SCS were changed from digital processor functions to contact closure discretes. For the DDG application, these discrete signals are sent over DMS using a scheme whereby each of the two rudders is serviced by redundant paths over DMS.

The current design allows steering system commands to be passed to the AN/UYK-44 over DMS, steering system commands to be transferred between non-digital equipment over other DMS paths, or rudder commands only to be sent over the backup cables between the bridge and the Steering Gear Room.

The steering system's AN/UYK-44 processor was always intended to provide autopilot operation, but the details of the implementation had not been worked out at the beginning of Contract Design. The fuel conservation and roll reduction modes had not been included originally. Here was a good example of the the value added to a system design by the existence of a general purpose data bus.

The SCS, from the start, included a processor redundantly connected to DMS. The SCS designers, when faced with having to implement an autopilot capability, needed to acquire Own Ship Head from the Inertial Navigation Sets. How best to accomplish this? Because the SCS computer was already connected to DMS via STANAG 4156 interfaces, and because the two AN/WSN-5 navigators were also connected to DMS, it became a simple matter to provide the appropriate addressing information to the SCS processor, and have the processor request Own Ship Head from either AN/WSN-5 through the redundant STANAG 4156 interfaces. Note that this change was limited to SCS software upgrade; no changes to DMS, to ship drawings, or to cabling were required.

When the SCS was upgraded to include roll reduction algorithms, the same strategy was used. The AN/WSN-5s provide DMS with Own Ship Roll (OSR), Own Ship Pitch (OSP), and the North and East components of true speed (respectively Vn and Ve) in addition to Own Ship Head from their synchro outputs. (The AN/WSN-5s also provide many other parameters, including ship position, from digital outputs.) The ship's Electromagnetic (EM) Log provides DMS with Own Ship Speed (OSS) through the water. These data were provided to the SCS processor by incorporating the appropriate DMS addresses in the SCS program. Once again, with no changes to ship drawings and cabling, roll reduction and fuel conservation algorithms were added to the SCS software.

Since the steering control system only needs OSH, OSR, Vn, Ve, and OSS for the autopilot, fuel conservation, and roll reduction functions, DMS converts these synchro data into digital messages and sends the messages, upon request, to the steering processor over the STANAG 4156 interfaces. The advantage of using the converted synchro rather than the digital AN/WSN-5 messages is that the steering processor does not need to conform to the AN/WSN-5s' message timing; the processor can instead request these DMS-formatted navigation messages at any time. Message formats are documented as are the non-digital peripheral message formats for the MCS. Because DMS constructs the messages "on the fly," data senescence is less than it would be from the AN/WSN-5 digital messages - on the order of 15 μsec worst case.

In the future, more functions can be designed into the SCS, still with no change to cabling or drawings. Ultimately, for example, the steering system could compute the best routes to any point on the globe from AN/WSN-5 ship position data and geographical data stored in memory.

The operation of the SCS with DMS was tested in a full-up DDG 51 DMS demonstration at the Rockwell International Marine Systems Division plant in Anaheim, California. Only one problem was discovered of a non-trivial nature: a condition in which one of the redundant halves of a DMS terminal would occasionally not service initiate requests.

This problem, referred to as "RM lockup," was also noticed at the Combat Systems test site in Moorestown, N.J., and was cured by means of a modification to the operating program of the Remote Multiplexer (the Remote Multiplexer, RM, is the DMS terminal). The problem was found to occur in a narrow window of time, if a particular terminal were to receive simultaneous initiate and response mode requests. This condition had not been noticed previously because situations involving very high retry rates are needed to cause the problem to occur. Data traffic at the MCS test sites does not create the conditions favorable for this anomoly.

9. NAVIGATION DATA DISTRIBUTION SYSTEM

Much about the distribution and conversion of navigation data from the two Inertial Navigation Sets AN/WSN-5 has already been mentioned in previous sections. This function, which includes distribution/conversion of both synchro and digital navigation data, was assigned to DMS before the Contract Design phase started. From the start, an unmutable design requirement for this DMS application was that introduction of DMS cause no changes to AN/WSN-5 or combat system computer software or interface hardware.

Originally, the AN/WSN-5 digital messages were only available in an Input/Output configuration, which means that the user computer connected to each digital port was to provide control messages to the navigation set on a constant basis. In the original implementation, one of the combat system computers connected to DMS was assigned the task of providing the AN/WSN-5 control messages. The others would receive the messages periodically with no need to respond. When Output Only AN/WSN-5s became available, no control messages from the combat system computer, via DMS, to the navigation sets were required, and the appropriate interfaces were deleted from the design.

DMS distributes navigation data to combat system computers, to certain weapon systems, to numerous indicators throughout the ship, to certain search radar systems, to the Digital Dead Reckoning

Tracer, and to the Steering Control System. In addition to this, DMS includes an embedded microprocessor which also receives the periodic navigation messages, strips out the Greenwich Mean Time words, and maintains GMT with a resolution of about 5 msec for any computer user of DMS. The embedded microprocessor includes logic to select the preferred navigation set as its source of data. This GMT from the "ship's master clock" is currently being accessed by the Machinery Control System computers, and is a requirement of the MCS Specification.

As mentioned previously, DMS provides digital navigation data messages to the combat system computers via MIL-STD-1397A Type E (or Low Level Serial) interfaces, while the AN/WSN-5 sends the data to DMS via a Type A parallel interface. This involves not only a conversion in interface electrical properties and bit rate, but also changes to handshake protocols and word length. The DMS implementation of this conversion function is such that the message formats for the converted LLS messages are identical to those prescribed for the future LLS AN/WSN-5s. However, certain details of the DMS-to-computer LLS interface timing are not identical to the expected LLS AN/WSN-5 to user timing. For example, the AN/WSN-5 is expected to offer the message to the user, then retry one time, 10.24 msec later, should the user be unable to receive the message on the first attempt. Since the AN/WSN-5 and the users are essentially isolated by DMS, this retry at 10.24 msec becomes meaningless. Instead, DMS will allow the user devices up to 4 msec to accept data or command interrupt messages. Should a user not accept the message, DMS will discard those data and provide the next message update on schedule.

These differences between the DMS LLS navigation messages and the future AN/WSN-5 LLS navigation messages meant that an Interface Design Specification tailored to the DMS interface was needed. This DDG 51 digital navigation data distribution IDS also identifies which of the numerous AN/WSN-5 options were selected for use in the DDG 51 application.

The MIL-STD-1397A Type E interface was designed with numerous System Integrity Features (SIF) to permit constant monitoring of interface status by the connected devices. Among these are continuous "keep alive" signals and optional parity checks. The DMS Type E interface card includes error messages or Command Interrupt Words to inform user devices of any errors detected by DMS in a message transfer. In the initial enthusiasm for this new interface standard, the design was to include use of most of the SIFs between DMS and combat system computers. However, it soon became evident to the combat system software designers that using all of the SIFs would involve a considerable software effort. Most of these features were eventually dropped from the requirements. The changes to DMS, as specific SIFs were selected and deselected, were limited to coding of a PROM at each of the interface cards.

10. NAVIGATION DATA DISTRIBUTION TESTING

The Combat System Engineering Development Site (CSEDS) in Moorestown, N.J. is provided with a three-bus DMS for the purposes of testing many of the combat system interfaces with DMS. Among these are the two AN/WSN-5 sources (one of them a simulator), numerous synchro navigation data sources and sinks, antenna bearing signals, and wind speed and direction. To emulate other signal traffic in the DDG 51 DMS, the CSEDS DMS is also provided with selectable background data load in four stages: no extra load, a DDG 51 equivalent load, and two overload levels to stress DMS beyond the DDG 51 traffic load. These extra DMS messages are created by remotely enabling PROMs which send data through the bus between actual source devices and unused sink interface channels. The maximum load is designed to be approximately the highest message update rate which the DMS at the site can service. Some of the problems and resolutions encountered at this site have been:

a. Occasional loss of End Of Message External Function. Each digital message from the AN/WSN-5s actually consists of three messages: two External Functions (EF) and the data message. The AN/WSN-5 first transmits a one-word Start of Message (SOM) EF, then a variable length data message, and finally a one-word End of Message (EOM) EF. The End of Message EF appears while DMS is still busy distributing the data message to the combat system computers. At times, the EOM attempting to reach the message distribution processor within DMS during this busy period just does not succeed. This problem was addressed by means of adjusting the internal DMS retry parameters. EOMs are currently lost at the rate of about one per hour. Another approach for resolving this issue would be to program DMS to ignore the EFs from the AN/WSN-5s, and instead to generate its own EFs based upon the arrival of data messages. This approach, under consideration at this time, should noticeably increase the digital navigation message success rate.

b. RM lockup. As described in the steering control section, the DMS terminals associated with the AN/WSN-5s, the ones with the numerous retries, occasionally were locked out of initiate mode. An update of the operating program resolved this problem.

c. Synchro instability. When DMS is connected to synchro repeaters, the internal DMS digital angle value is converted to a synchro value by means of digital-to-synchro (D/S) converters. In some cases, the synchro signal provided by DMS becomes unstable in certain quadrants. It turns out that some D/S converters, particularly those of commercial grade, become unstable if the load includes a significant amount of capacitance, such as would be encountered with long interface cable runs. Since the problem only occurs with certain brands of D/S converters, those brands could be avoided. Another solution, not sensitive to converter brand, is to include a series resistor at each synchro interface.

11. IC ALARMS AND INDICATORS

In addition to combat, machinery, steering, and navigation systems, DMS services a host of other DDG 51 Interior Communications (IC) signals. These include the wind data distribution system, rudder angle indicators, various door alarms, dew point alarms, fuel system alarms, the Collective Protective System alarms, and many other such signals. Many of these DMS communication links are between sensors and non-digital indicators or indicator panels. DMS in these applications was introduced primarily because it is well suited to select alternate redundant data sources, and multicast the data to numerous sink devices. Another reason for connecting some of these signals to DMS is to make them available to the Machinery Control System computers, over their STANAG 4156 digital interfaces. Again, the architecture of the IC system communicating over a general purpose data bus offered an overall performance benefit.

Issues involved in the application of DMS to the IC alarms are typically less complex than the ones described previously because most of these are signals between non-digital devices. DMS provides message timing and signal conversion. Verification of correct message flow for the "dumb to dumb" device signals was accomplished on the DDG 51 DMS shipset during the DDG 51 DMS demonstration.

12. SUMMARY

Application of the DMS general purpose bus to the DDG 51 Class has illustrated the following general concepts:

- Cable and cost savings are only preliminary goals of data busing, and are not enough by themselves to justify use of a data bus system in a shipbuilding program. A fundamental understanding of system performance enhancements or, better, systems designed to operate with a data bus are needed to ensure that the bus be used to its potential.

- To extract the full potential from a data bus application in modern surface combatants, the application cannot be viewed merely as replacement for point-to-point cable. It is doubtful whether a data bus applied in this manner could ever result in an overall improvement over hardwired methods of communication. A data bus application must be considered at a whole system architecture level.

- The isolation provided by a general purpose data bus between user devices, and between the core bus structure and user devices, is a desirable attribute to ensure long term system compatibility.

• The DDG 51 experience has shown that virtually all of the technical problems encountered involved the user-to-bus terminal interface rather than internal bus system problems. Whether the goal is to achieve a prescribed level of performance, to correct an unforeseen problem, or to add communications modes in support of new user system features, flexibility in the user-to-bus interface is an important asset of the general purpose bus system.

• System level testing is extremely valuable. As the adage says, "You don't know what you don't know." The potential for problems is significant when so many different systems, developed by diverse activities, are connected together. It is much easier to find and correct problems in a laboratory environment than on board ship during construction.

• Maintaining configuration control, in a large general purpose bus application such as the DDG 51 DMS, is a demanding and critically important endeavor. To track the constant changes occurring in a ship design, and their impact on the data bus, requires the use of sophisticated database techniques.

13. THE FUTURE

In the introduction it was mentioned that the bus system must be capable of supporting user interface upgrades as well as upgrades to its own capabilities. It is clear that, as message volume and data rate requirements increase, eventually changes to the bus are needed as existing spare capacity becomes exhausted.

One advantage of a general purpose data bus is that the isolation between the bus-user protocols and the internal bus protocols allows upgrades to either to be accomplished "transparently." For example, should a new user interface be introduced, neither the bus system nor other existing user devices need be affected. Similarly, should a new, faster main bus architecture be introduced, perhaps to allow more effective servicing of new user types, the other devices connected to the bus need not be affected.

There are plans underway at this time to upgrade the main DMS bus architecture to increase the maximum system data rate from the current gross of 24 Mbps to 100 Mbps or more. The plan is to convert the existing DMS coaxial, linear main bus cable structure into a dual token-passing ring Fiber Distributed Data Interface (FDDI) architecture. The FDDI approach involves the following modifications to the existing DMS:

a. Each IOU is changed to interface with two FDDI ring pairs instead of the current Remote and Area Multiplexers,

b. For existing user devices which depend on a connection-oriented protocol, the FDDI IOUs convert the user protocol to the connectionless, source-initiated scheme needed for communicating over the FDDI medium,

c. The existing DDG 51 DMS user devices must notice no change in service. This includes maintaining all critical timing parameters as they are now, maintaining message structures as specified in the current DMS, and, to the extent possible, maintaining the same physical connection between existing users and the Input Output Units.

d. Future, faster users must be capable of taking advantage of the faster channel data rate offered by the FDDI medium.

Thus, the FDDI upgrade plan consists of developing an emerging commercial ring bus standard, FDDI, into a general purpose, militarized data bus system which would transparently upgrade the current DMS.

A future refinement of this upgrade could be to pursue the same general course as described above, but to replace the FDDI medium with emerging, faster media. This would allow the upgraded DMS to maintain service unaltered for existing user devices, but would also support faster devices, such as equipment with video and voice interfaces.

Irrespective of the specific bus medium used, the objective will always be, when upgrading individual systems for surface combatants, to remain compatible with current equipment. The next decade will doubtless bring significant advances to busing technology, greatly surpassing FDDI, so it is imperative for any standard Navy general purpose bus to remain flexible and compatible with numerous different technologies.

14. APPENDIX: OSI PROTOCOL LAYERS AND GENERAL PURPOSE BUSES

This brief introductory discussion of the relationship between general purpose data bus systems and communication protocol layers is intended to facilitate the understanding of how the Data Multiplex System AN/USQ-82(V) was applied to DDG 51, and to more clearly categorize the nature of problems encountered in this application.

The International Standards Organization (ISO) has developed a model to describe generically the different layers of protocols which digital devices must implement to communicate. The model, referred to as the Open System Interconnection (OSI) Reference Model, is intended primarily to provide a framework for understanding the communications process; OSI does not specify how each layer of protocol must be conducted.

The OSI model organizes the steps taken by users to communicate into seven categories or layers, the lowest level being the physical connection medium, and the highest being the interface with a processor's application programs. A very brief description of each of the layers follows:

Open System Interconnection (OSI) Model
Protocol Layers

Layer Name	Protocol Function
1. Physical	- Mechanical, electrical interface medium.
2. Data Link	- Data formatting, data routing scheme.
3. Network	- Message formatting, segmenting, addressing.
4. Transport	- End-to-end error correct, routing to Appl.Progrms.
5. Session	- Structuring, organizing of communications.
6. Presentation	- Translation of data presentation schemes.
7. Application	- Interface to Application Programs.

If two computers are hardwired together, then all of the protocol layers would be conducted by the computers themselves, since no other entity would exist to carry out these functions. On the other hand, addressing of messages between physical connection points would be fairly trivial, since a hardwired connection only ties two points together. A message being transmitted by a particular channel of computer A would always appear at the same channel of computer B.

A bus system between the two computers would dictate that certain specific standards be adhered to in order that computers and bus operate together. A general purpose bus is a system which allows computers with various interface types, or even non-digital devices, to use the bus for communications.

The Data Multiplex System AN/USQ-82(V) is a general purpose bus system which operates from the OSI Physical through much of the Network Layer. Higher levels of protocol are left to the user processors. There are several areas in which general purpose buses such as DMS differ from the more common applications of the OSI concept to data busing:

- Interfaces between users and bus system can be any of a list of Navy standard digital or non-digital types. DMS is designed to provide physical and protocol conversion functions such that subscribers communicating over DMS need not conform to one particular standard. (Internally, DMS uses a connection-oriented protocol which supports periodic, aperiodic, source initiated, or sink initiated message transfers. Access to the multiple main buses is achieved via a polling scheme from bus controllers to terminals, and via a prioritized queue contention scheme between user devices and terminals.)

- DMS can be set up to allow a user device to format, schedule, and address its own messages or DMS can provide some or all of these services. How much of the inherent bus system's flexibility a subscriber takes advantage of depends on how much bus control-related software the subscriber develops. A computer application which was formerly hardwired may opt not to change any aspect of its software if the bus control features are not required.

- Since the bus system must convert user signals to its own standard at the source end, there is no reason why it cannot provide the signal to the sink device using a different interface format. In fact, just as the physical interface at each end of the link can differ, so too can the user-to-bus system protocols.

Figure 1 shows the physical connection between two processors using DMS and, by means of the familiar OSI protocol stacks, Figure 2 is the representation of an example of the protocol interactions. The example shows a serial digital STANAG 4156 processor communicating with a parallel MIL-STD-1397A Type A computer. In the example, the STANAG 4156 computer is dynamically changing message routing through DMS by acting directly at the DMS Network Layer. The MIL-STD-1397A computer is connected as if hardwired.

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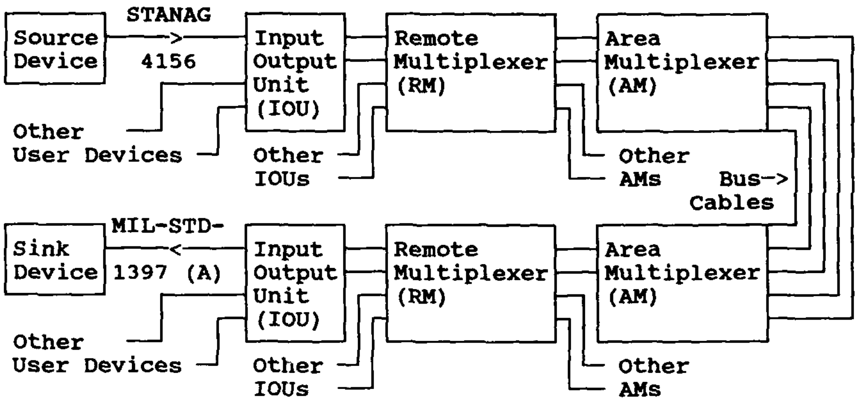
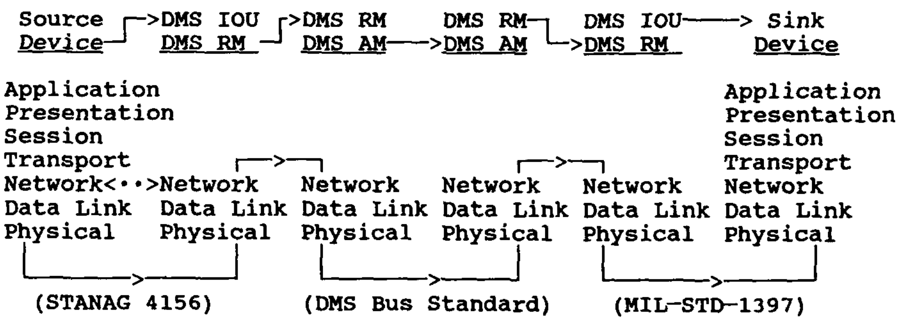


Figure 1. Schematic Representation of Two Computers Non-redundantly Interconnected via DMS



Notes:

1. The dotted arrow between the source user and the DMS Network Layers ' 'icates that the source user device is acting directly on DMS me ¬ add) ing. The sink device in the example is not aware oı ns . n message routing.

2. RMs conduct DMS and user addressing functions, message formatting, message timing. AMs route messages through first available of 20 data channels on the 5 main bus cables.

Figure 2. OSI Protocol Layer Representation of Two Computers Communicating via DMS

INDEPENDENT ASSESSMENT OF MACHINERY CONTROL SYSTEMS, A CASE STUDY

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1. ABSTRACT

The planned introduction of digital control systems for RN warship machinery control and surveillance led to the requirement for independent assessment of their performance, prior to ship trials.

This paper describes the computer-based Assessment Facility, established at the Admiralty Research Establishment West Drayton, which performed this task for the Type 23 Frigate. It discusses the reasons for the significant cost of such a facility but demonstrates, through consideration of indirect as well as direct benefits, the value of such an approach and concludes that a policy of independent assessment should be retained.

2. INTRODUCTION

The first Type 23 Frigate, H.M.S. Norfolk, was accepted by the Royal Navy from the shipbuilder in November 1989. She has the first digital computer-based Machinery Control And Surveillance (MCAS) system for a RN warship. At the time this type of control system was selected an immediate concern was the question of proving its operation and reliability before sea trials.

It was agreed that the Admiralty Research Establishment , West Drayton (ARE (WD)) would produce a computer-based machinery simulator to which a production set of MCAS equipment would be connected and undergo thorough assessment in support of the acceptance programme for the MCAS design. The simulator and associated environment is known as the Assessment Facility. It was produced during the period 1985-1989.

This paper firstly describes the Type 23 MCAS system and its boundaries. It then describes the structure of the Assessment Facility and some of the lessons learnt during its development. This is followed by an outline of some of the MCAS trials that were performed using this facility, and a description of how the existence of this test environment led to ideas for future MCAS

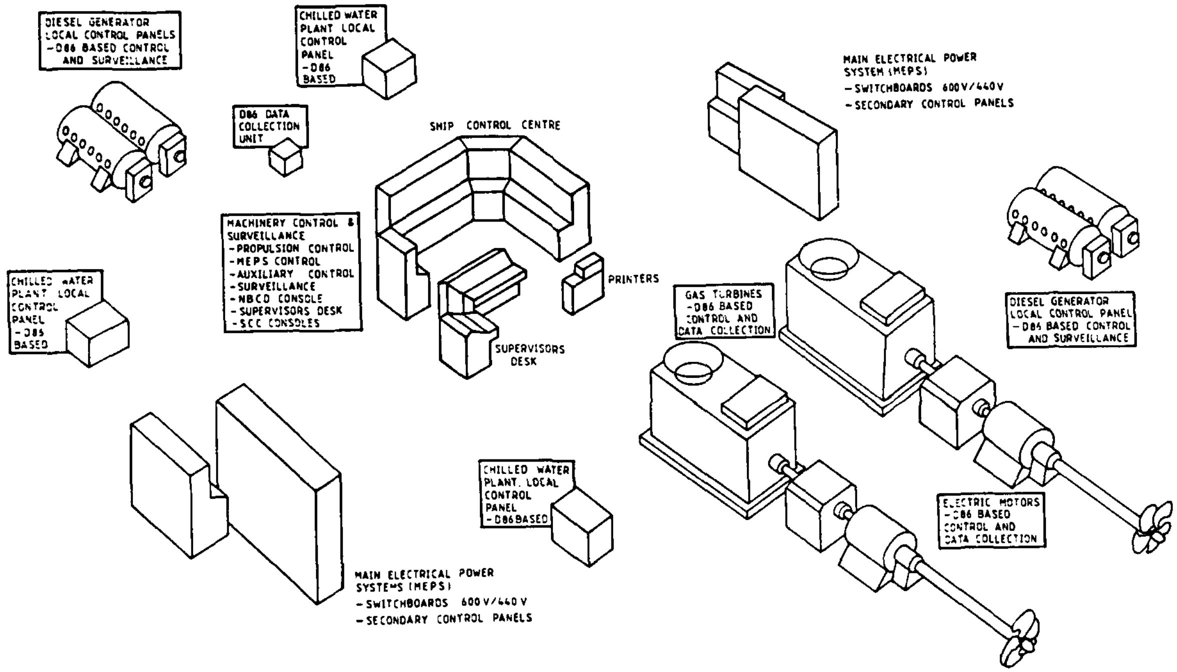

Figure 1 Distribution of MCAS D86 units with machinery items

developments which could be investigated with minimal recourse to the manufacturer and without affecting any ship timetable.

The paper finally demonstrates how an agreed plan for a through-life assessment facility could have large benefits, which would be maximised if some degree of independence is retained.

3. THE TYPE 23 FRIGATE MACHINERY FIT

The Ship Control Centre (SCC) for the Type 23 provides control and monitoring of the propulsion, electrical generation and distribution, and auxiliary systems.

The propulsion system consists of two shafts each driving a fixed pitch propeller. The drive configuration for each shaft is CODLAG with a gas turbine driving through a gearbox, via a Self Shifting and Synchronising clutch, and a direct drive electric motor providing cruise and astern drive. The electrical systems comprise 4 600V diesel generators which provide the electrical power for the propulsion electric motors and drive the 440V motor/generator sets for ship service loads. The auxiliary systems are listed in Table 1.

TABLE 1. Auxiliary Machinery Systems.

Fuel supply, transfer and renovation system.	
Lubricating oil supply, transfer and renovation system.	
Chilled water system (3 off)	Refrigeration system.
Ventilation system.	Low pressure air system.
High pressure air system.	Special services air system.
Low pressure salt water system.	High Pressure salt water system.
Aviation fuel system.	Desalination system.
Steering system.	Stabilizer system.
Fresh water system.	Sewage system.
Bilge and sullage system.	

4. THE TYPE 23 FRIGATE MACHINERY CONTROL AND SURVEILLANCE SYSTEM

Vosper Thornycroft Controls (VTC) was contracted to produce the SCC consoles (encompassing remote control and primary surveillance of the machinery systems), local plant controllers for the diesel generators and chilled water plants, and a secondary surveillance facility. For the purposes of this paper these items will be regarded as forming the Type 23 MCAS.

The Type 23 MCAS is a distributed digital system based around 'D86' hardware. Each D86 unit contains a standard backplane into which a range of double euro-card height pcb assemblies are inserted. This range comprises processor (Intel 8086), memory, interface, and communications cards. There are a total of 17 D86 units utilised in the Type 23 MCAS, 5 being installed in the SCC, and 12 distributed throughout the ship as shown in Figure 1.

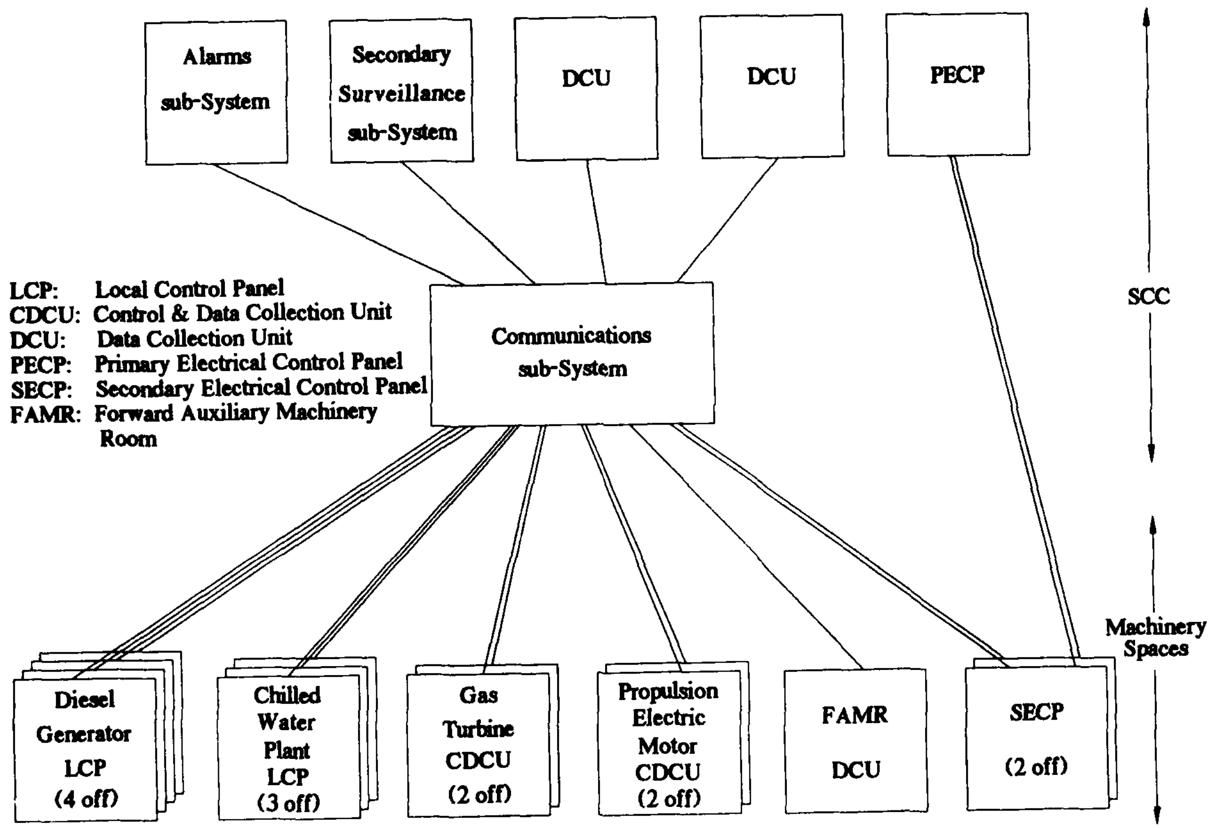

Figure 2. D86 based units connected by serial data links.

Each Local Control Panel (LCP) consists of an operator panel and D86 unit which provides sequential control of starting and stopping, primary surveillance and data collection functions for that machinery item (diesel generator or chilled water plant).

The Control and Data Collection Units (CDCUs) for the Gas Turbines and Electric Motors consist of D86 units which accept power demands from the operator at the SCC and schedule power between the prime movers, transferring the resultant signals to the local Plant Control Unit (PCU). These PCUs provide reversionary control positions and contain analogue electronics performing governor-type functions. They do not contain D86 units, the CDCUs collect data from the prime movers.

Data collection from auxiliary machinery is performed by data collection units (DCUs), one of which is housed in a machinery space while the others are housed within the SCC. The LCPs, CDCUs and DCUs are all connected, by individual serial data links, to a D86-based communications sub-system housed in the SCC. These links form a 'star' network with the communication sub-system at the hub. Figure 2 shows the interconnection of the D86-based units.

Although the Type 23 MCAS is correctly described as a distributed digital system the control system is essentially hardwired. State-demand signals are wired directly from the SCC switches to the local D86 unit or on-plant actuators. Value-demand signals (lever position) are wired directly to the CDCUs. Parameters displayed on the SCC consoles are hard-wired directly from the outputs of the local D86 units or from on-plant sensors. Alarm conditions recognised by on-plant sensors are wired directly to a D86-based alarms sub-system, housed in the SCC, which drives the relevant SCC displays. Warning conditions recognised by local D86 units are wired directly to the SCC displays.

Hence control and primary surveillance does not use computer communications. The serial data links are used to carry secondary surveillance information. This consists of transduced plant values collected on a cyclic basis and warning conditions deduced from these values. Thus the warning conditions are hardwired to the SCC for primary surveillance purposes and communicated to the secondary surveillance system.

The secondary surveillance hardware brings about 2200 parameters to the communications sub-system in the SCC. There are 2 plasma panel visual display units (VDUs) in the SCC, one in the Supervisor's console and one in the power distribution console. These can be used independently. There are 2 printers, the Event Printer and the Log Printer, both use dot-matrix technology. The printers and VDUs are connected to a D86-based secondary surveillance sub-system which is connected to the communications sub-system by a serial data link.

Secondary surveillance facilities include:

* Automatic printing of telegraph movements, warning and alarm conditions.

* Parameter monitoring and trend display.

* Request printing of watch changeover logs and log sheets.

5. ROLE OF ASSESSMENT

It was agreed that an early production set of MCAS equipment, together with associated documentation, would be supplied to ARE (WD).

Hence the assessment role required funding to divert this equipment to ARE (WD), to provide engineering staff from VTC to help set the equipment to work, and to cover the cost of refurbishment when that set was returned for subsequent ship fitting. The outright purchase of a set of MCAS equipment for the Assessment Facility was not considered to be cost-effective.

The high-level objectives of the assessment process were:

* Assess all aspects of the system as fit for purpose.

* Identify any shortcomings in the system including those affecting the system's ability to meet the Statement of Technical Requirements (STR).

* Assess diagnostic and maintenance facilities.

* Assess the system documentation.

* Investigate the operability of the system under normal and abnormal conditions.

These objectives were to be achieved by a combination of documentation review, equipment trials, and ergonomic studies.

Two bodies, the Executive Trials Authority (ETA) and the Joint Trials Team (JTT) were established to oversee the assessment process.

The ETA was solely comprised of Ministry of Defence (MOD) representatives. It co-ordinated all aspects of the policy of assessment from the scope, delivery and procurement of equipment to be assessed, through the definition of the trials' objectives and approval of the trials' programme, to consideration of actions to be taken based upon trials' results.

The JTT comprised representatives from MOD and from the control system and machinery sub-contractors. Its role was to provide technical information to define the simulator performance requirements, and to plan, produce, execute and review the trials' procedures and results. The JTT considered any risks contained in proposed trials, JTT agreement of such trials denoting the acceptance of any risk.

The stages through which equipment trials passed were:

a) Proposal for trial, and JTT agreement.

b) Production of trial schedule, and JTT agrement.

c) ETA approval, and incorporation into the trials programme.

d) Execution of trial, with simultaneous report preparation.

e) Comment by JTT.

f) Issue of report.

The Conducting Authority for the trials was ARE (WD).

6. THE ASSESSMENT FACILITY

The Assessment Facility was required to simulate the characteristics of the Type 23 machinery systems and to connect to a production set of MCAS equipment. The first problem lay in defining the simulator boundaries.

6.1 Simulator boundaries.

The Main Electrical Power System (MEPS) controls the generation and distribution of electrical power for both the 600 and 440 volt systems, and provides automatic parallelling of the diesel generators onto the 600 volt buses. It consists of a Primary Electrical Control Panel (PECP) in the SCC which contains a D86 unit that is connected, by serial data links, to 2 further D86 units housed in Secondary Electrical Control Panels (SECPs) which are co-located with the main switchboards . The D86 units in the SECPs are also connected, by serial data links, to the communications sub-system. There are thus a total of 18 D86 units connected to the communications sub-system, as shown in Figure 2.

MEPS is not part of MCAS, but its interactions are so strong, both in control functions and in provision of secondary surveillance data, that MCAS assessment clearly required provision of MEPS hardware. This was achieved by including a production PECP in the SCC console and procuring a D86 unit, known as Alternate MEPS, configured to contain the functionality of the 2 SECP units. The performance of this unit did not form a direct part of the assessment.

The gas turbine PCU contains relay logic for control of starting, stopping and running the gas turbine, and contains the fuel system controller, but is not part of MCAS. The electric motor PCU provides closed loop control of electric motor power and performs motor protection and start interlocks, but is not part of MCAS.

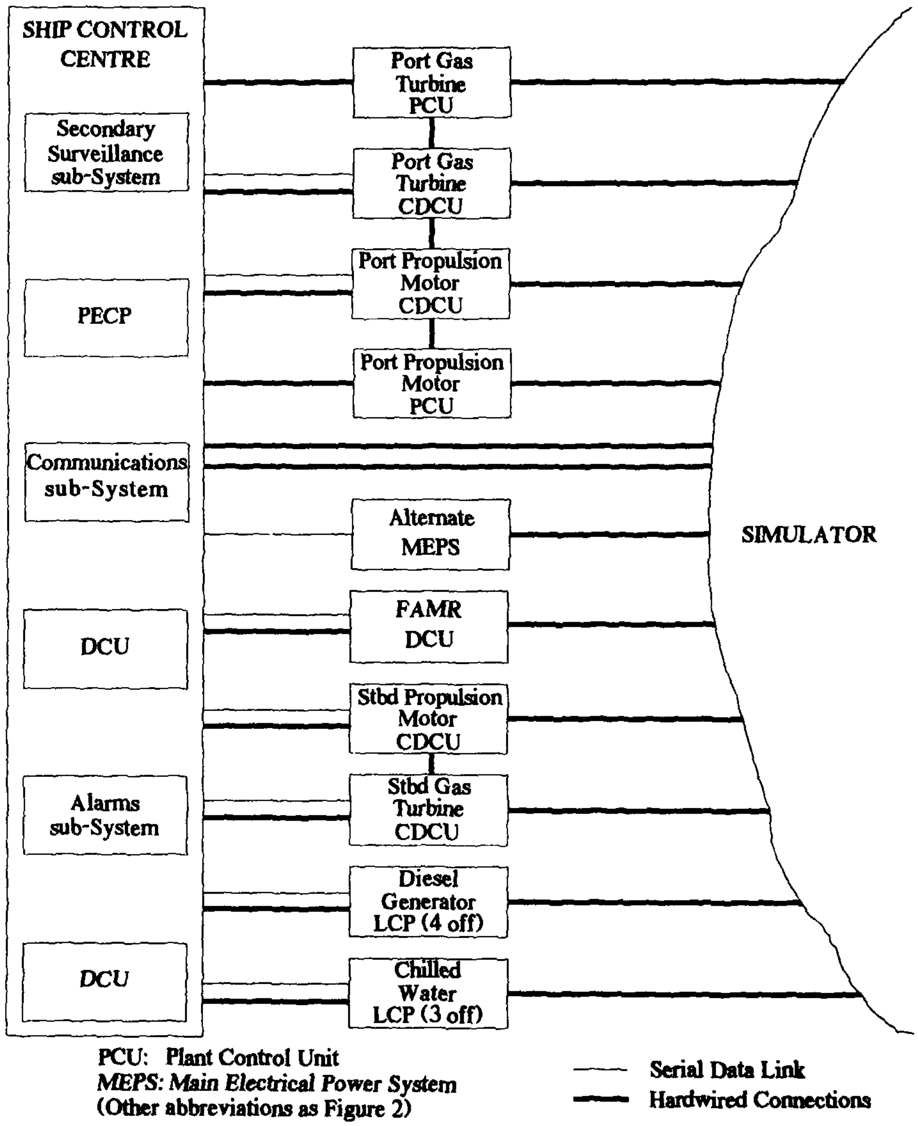

Figure 3. Type 23 equipment at the Assessment Facility

It was accepted that MCAS system assessment required the provision of both PCUs for one shaft whilst their functionality would be simulated for the other shaft.

The total package of equipment connected to the simulator is illustrated by Figure 3. At the interface the outputs from the simulator represent transducer signals that would be expected by control and surveillance equipment onboard a ship.

<u>6.2 Equipment cabling.</u>

The SCC and console-installed D86 units were arranged in the Assessment Facility as per the ship SCC installation (in terms of relative positioning). The outstation equipments were grouped to represent their compartmental allocation within the machinery spaces.

Equipment cabling was prepared, at ARE (WD), in advance of equipment delivery. The serial data link cables were terminated by standard connectors. The cables to carry hard-wired signals between the units were terminated at one end with lugs for use in the screw type terminals in the SCC consoles, and at the other end with multi-pin plugs for connection to the local D86 units. The cable reels were drawn from Naval stores with pattern numbers corresponding to ship details, but were not made to ship's lengths. A measure of the cabling effort can be seen from Figure 4.

Figure 4. Controls equipment cabling.

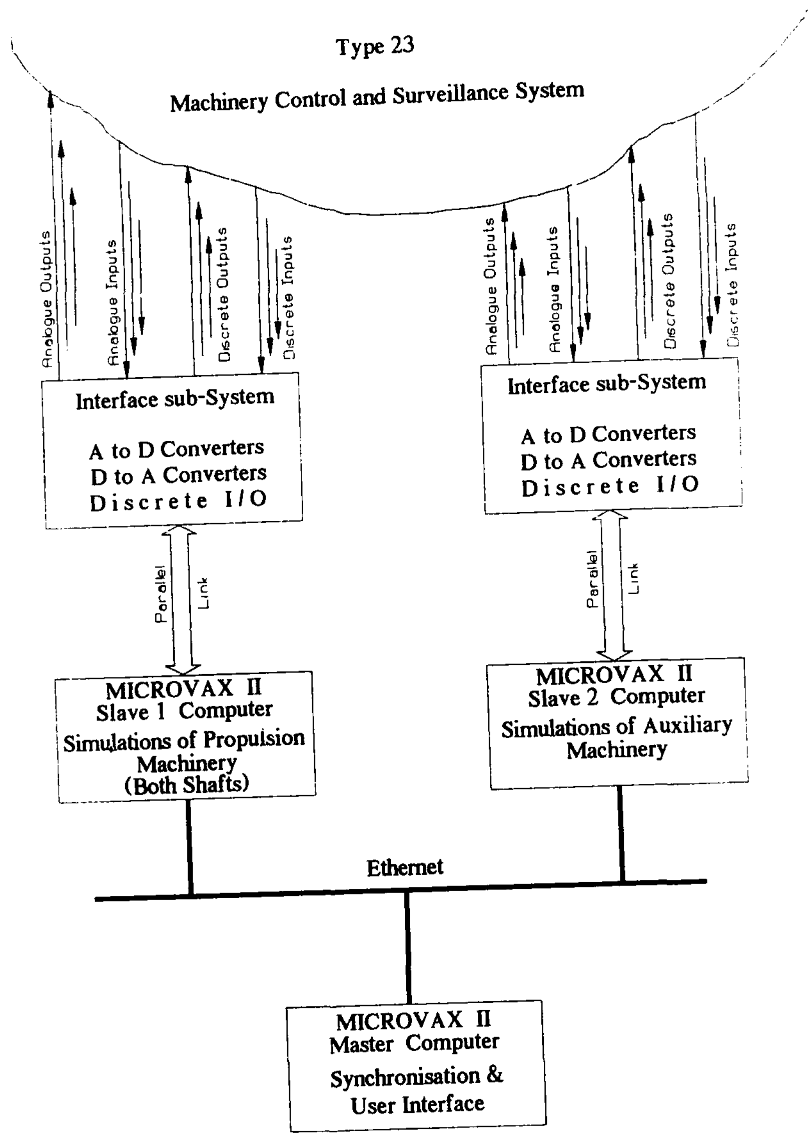

Figure 5. Simulator Computer Configuration

6.3 Simulation detail.

The machinery systems to be simulated comprised the propulsion, electrical power, and auxiliary systems previously listed, together with the gas turbine controller and electric motor regulator for the starboard shaft.

ARE (WD) was not the sole body producing computer simulations of Type 23 machinery systems. A Performance Modelling Working Group (PMWG), comprising MOD, the shipbuilder, equipment manufacturers and consultants, was set up to co-ordinate aspects of simulation development. The PMWG maintained a data base of machinery performance characteristics, based upon machinery specifications, experimental and simulation data.

The level of detail required within individual simulations in the assessment facility was determined by the importance of the machinery systems to ship operation and by the degree of interaction between the machinery and the control system. The main propulsion elements are represented by detailed dynamic models. These characterise the response of the machinery to control system demands over the full operating profile. In other systems the models are much simpler.

All of the models were developed specifically for the assessment facility The approach was to define the characteristics of the systems and their interactions in a set of Machinery Performance Definitions (MPDs) and to use these to write a set of Simulation Performance Definitions (SPDs) which could be developed in-house or by software sub-contractors.

These MPDs were sought after by others involved with the Type 23, especially by those preparing operating instructions.

6.4 Simulator structure.

Figure 5 shows the computer configuration used for the simulator. Ideally hardware decisions should be left as late as possible although this must be balanced by the need for appropriate training before software development can progress with confidence. Furthermore capital expenditure will be governed by the availability of funds, which may only exist for a narrow period of time. In this case the hardware was purchased at the start of the programme (late 1985) to meet capital expenditure requirements.

The requirement was to procure a computer system that would be powerful enough to handle the simulation and associated requirements. Unfortunately the simulator boundaries were not agreed at that stage and hence the required computational power could only be estimated. This was not as unusual as it sounds because such simulation projects are often hard to quantify (some of the machinery systems may be novel) and boundaries are often changed during development ("if only you could also simulate ... "). Thus the required computer system needed an estimated performance, together with a safety margin (200%), with a painless upgrade path as a further safeguard.

A single large computer within the budget would not have been powerful enough. Many small computers were an attractive option but would have incurred high development costs. The MicroVAXes benefited from the extensive support expected to be available. The use of Ethernet to interconnect the computers was attractive because of its high transfer rates and relatively small hardware cost to connect additional processors.

Loading considerations required the simulation models to be split between two computers: 'Slave 1' and 'Slave 2'. The 'Master' provides synchronisation, monitoring and data logging facilities. Table 2 shows the simulations split between the slave computers.

TABLE 2. Split of Simulations between the Slave Computers.

Slave 1 Computer.		Slave2 Computer.
Gas turbine.	)	Diesel generator (4 off).
Propulsion electric motor.	)	Electrical distribution.
Gearbox.	) P	Chilled water (3 off).
Transient brake.	) O	Refrigeration.
Clutch.	) R	Ventilation.
Shaft.	) T	Low pressure air.
Shaft brake.	)	High Pressure air.
Propeller characteristics.	)	Special services air.
		Low pressure salt water.
Starboard systems as for Port		High pressure salt water.
+ Regulator logic.		Aviation fuel.
		Desalination.
Hull characteristics.		Fresh water.
Fuel supply.		Sewage
Lubricating oil.		Bilge and sullage.
		Steering.
		Stabilizer.

Each simulation model consists of several subroutines. There are a total of about 500 such routines, manipulating a total of 3500 variables. Machinery co-efficients and some characteristics are stored in 1500 constants and many look-up tables of various sizes.

The individual simulation models clearly do not act independently. The values of torques for example are transferred between simulated machinery in the same way as shafting connects the real machinery. By siting the main propulsion simulations in the same computer the need for information transfer between the computers has been kept down but still totals 60 variables. For instance fuel tank values are transferred from the fuel system simulation in 'Slave 1' to the diesel generator simulations in 'Slave 2'.

The simulator, which must operate in real time, uses an overall time step of 200 milliseconds. This is too long for some of the dynamics within the gas turbine and electric motor simulations, and would not satisfy stability needs in their local control units. Thus software in 'Slave 1' only is executed with a time step of 100 milliseconds. Clock signals are generated and transmitted from the 'Master' computer every 100 milliseconds, with every alternate signal being ignored by 'Slave 2'.

The facilities available to the simulator operator are:

* Simulator control (Start,Pause,Resume,Stop)

* Dynamic, or file-based, selection of simulated variables to be monitored.

* Dynamic, or file-based, selection of simulated variables to be logged to disc, with selectable logging rate and control (start,pause,resume,stop) of logging.

* Dynamic modification of simulated variables.

* Dynamic modification of simulator outputs, to provide a transducer 'freeze' facility.

* Dynamic selection of pre-selected groups of simulator outputs to be cyclically modified.

Ethernet carries the synchronisation information, inter-computer simulation values, data recording requirements and the values of variables to be monitored or logged. The total load on the Ethernet is merely 1% of its capacity. Data transfers have been sequenced to minimise the risk of collisions. Thus data communications were a low risk item in this multi-computer system.

6.5 Simulator interface.

The simulator does not solely consist of the computers. It includes an interface in which the floating point and integer values within the digital computers are translated into the transducer and actuator values expected by the MCAS system. The extensive digital to analogue conversion needed at the interface was difficult to achieve and required much electronic hardware. It was beyond anything that could be achieved by cards connected within the slave computers.

Manufacturers of data acquisition equipment tend to service the control equipment market where there are many analogue inputs but only a few analogue outputs. Few supply digital to analogue cards which handle more than four signals on single euro-card height pcb assemblies. This system uses 450 digital to analogue converters and caters for 1250 discrete signals. The cards require a large space

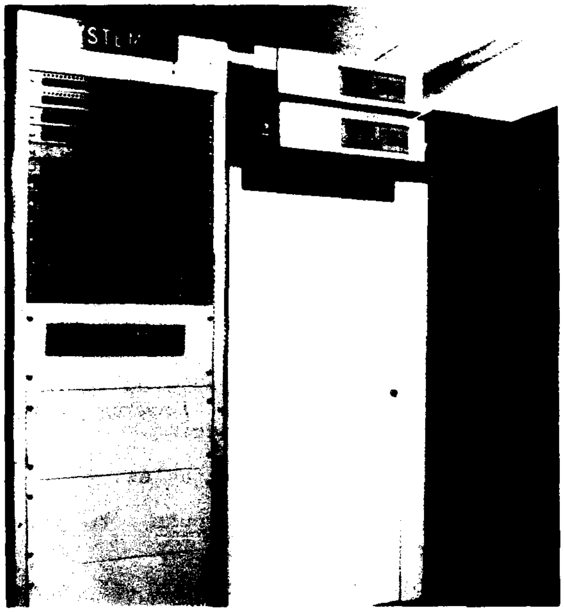

Figure 6 - Simulator hardware.

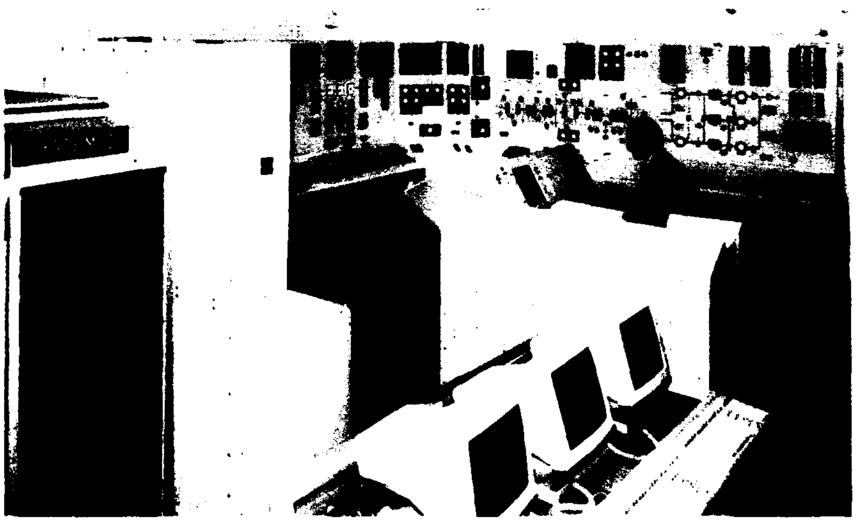

Figure 7. Ship Control Centre, at the Assessment Facility.

and fill many racks. They need power and absorb much calibration effort.

As shown in Figure 5 these cards are contained in separate cabinets, one connected to each slave computer. To minimise the technical risk in this project these interface sub-systems were purchased as essentially off-the-shelf systems, but the high data-transfer requirements combined with the large number of I/O channels limited the choice to those that connected to the computers by parallel links. Such systems were not processor based, and required signal conversion to be performed in the slave computers.

Analogue output signals are not simply obtained by transferring the floating point simulation value to the appropriate digital to analogue channel. The value must first be normalised and adjusted to the range of the converter. Such floating point arithmetic is processor intensive and presents a large computational overhead in the simulation computers. In fact approximately 30% processor power in each slave computer is consumed in signal conversion. This clearly impacts upon simulation software expansion capability. In any future project (with possibly greater I/O requirements) intelligent interface sub-systems would be necessary.

One possible improvement is to connect the computers, by high-speed links or network, to a chassis containing a processor and high-speed links to non-intelligent racks of signal conversion hardware. Such a solution could safeguard the considerable investment in signal conversion hardware at ARE (WD). (Despite quantity discounts the interface sub-system hardware cost 3 times that of the simulator computer hardware.)

The conversion hardware simulates the characteristics of transducers and sensors, and consists of a mixture of voltage, current, and frequency cards. Each card contains a number of channels, some channels are connected directly to the SCC, most are connected to local D86 units. It was decided that all these interface signals would be connected to junction boxes fitted between the interface sub-systems and MCAS. This allowed manual injection of test signals and ease of signal monitoring, but added to the cabling work required.

Figure 6 shows the interface sub-systems, in 6 foot high cabinets, separated by one (of 3) signal junction boxes. The 2 slave computers are sited above the junction box.

6.6 Setting to work.

Cabling preparation began in mid 1987 and MCAS system equipment on loan from the shipbuilder was delivered between January and December 1988. The extensive installation and setting to work procedures completed in May 1989 having followed the instructions of drawings and documentation prepared for ship fitting. Figure 7 shows the MCAS equipment in use at the Assessment Facility.

There were many benefits from the setting to work process. Inaccuracies in the drawings and problems with change control procedures were spotted before they hindered the ship building process. As units were set to work their reliability could be assessed and by the end of 1989 the equipment had been in use for over 8000 hours.

The multi-pin connectors used between the local D86 units and the SCC experienced pin displacement problems after repeated connections. The number of repeated connections at ARE (WD) was higher than during setting-to-work on the ship, but indicated a likely through-life problem.

During development of the electric motor regulator a prototype unit was tested at the shore test facility in Scotland. Due to the short timescale, modifications could not be fully proven before the facility was dismantled. Early tests of the first production regulator against the simulation showed that further modifications would be needed before the unit could be sent to HMS NORFOLK. Some of these tests involved unsafe operating conditions which would not have been possible on the real plant.

7. THE ASSESSMENT PROCESS

The initial trials, referred to as Functional Trials, compared the performance of MCAS with that specified in the STR, to confirm safe operation of ship equipment under all normal operating conditions. These were performed between August 1988 and July 1989.

Functional Trials started with tests of units within the MCAS system against appropriate simulations. They completed with tests of the whole system fully integrated with the simulator. Reports concluded that the equipment is generally satisfactory and identified shortcomings. This encouraged changes to the design where modifications could be cost-effectively implemented.

The later trials, referred to as Evaluation Trials, assessed the peformance of MCAS under various operating conditions in order to determine the nature and extent of its operating limitations. These trials included the following tests:

* Vulnerability of MCAS to power failures.
* Evaluation of the 'failset' policy implemented.
* Performance of the Secondary Surveillance Facility under various workloads.
* Effects of processor and communication loading.

An example of such work was the communications loading trial. This trial consisted of generating known amounts of traffic on the serial data links within MCAS to plot the change in response times of the secondary surveillance facility and to verify that high communications loading did not affect the processors' performance of machinery control functions. The traffic was generated by using the simulator to change the values of selected outputs on a periodic basis. Loading factors were selected independently for each serial data link, the cycling period was also varied. The assessment facility allowed these complex tests to be performed easily and repeatably.

A further requirement of the assessment process was to examine human factors aspects of the MCAS design. Several points were raised during the performance of the Functional Trials. A full human factors analysis of MCAS was subsequently performed, the static analysis phase being performed at the Assessment Facility. This work is documented in Reference 1.

8. ADDITIONAL BENEFITS FROM THE ASSESSMENT FACILITY

The assessment environment within ARE (WD) produced ideas for several potential improvements to the Type 23 MCAS system.

Undoubtably the most significant has been tackling the problem of what to do with the vast amount of information collected by a secondary surveillance system monitoring over 2000 parameters. The Type 23 MCAS system automates the data collection previously done by hand and by Decca Isis systems. Like the earlier systems it produces paper records which must then be monitored, checked and stored. As designed it is relatively inflexible especially since it is without an interface facility for passing information electronically to any other on-board system.

ARE (WD) have developed and demonstrated a Personal Computer based system capturing data from the MCAS system. It is a non-interfering, listening system which can be used to store and subsequently to process all data which is sent to the log and event printers. The system has very significant potential, as was demonstrated in HMS NORFOLK during final machinery trials, and could be implemented without hardware changes to existing equipment in the Type 23.

Users could then search records quickly for particular events or trends and make use of the wide range of standard software packages. Health monitoring at a system level could be automated. Information could be passed ashore electronically for further study and not least the space and weight of stored paper onboard could be radically reduced.

The Assessment Facility was used to help define the Upkeep Plan for the Type 23 MCAS. It provided an ideal opportunity for general maintenance requirements to be thoroughly assessed and proven, without the limitations that would be applied in alternative environments (on-board ship, at manufacturer's premises). The facility was further used to assess the MCAS diagnostic facilities.

This was achieved by the deliberate introduction of signal faults, and by the inclusion of faulted boards, with ship's staff attempting to diagnose and rectify the faults.

The existence of the Assessment Facility also provided the opportunity to evaluate the installation instructions for a damage control data retrieval system. This had been designed and developed independently of the MCAS system although it will be fitted within the supervisor's console. A prototype unit was provided to ARE (WD), the resultant report recommends several fundamental changes to the document and illustrates the value of this small exercise.

9. LESSONS LEARNT FROM THE ASSESSMENT PROCESS.

The main lessons learnt from the assessment process were:

* Need to integrate assessment requirements within the overall ship building programme.

* Need for early and good quality documentation which should include design intentions and system operating principles.

* Need to design on a system basis.

* Need for a continuous assessment programme.

* Need to allow time for findings from assessment to be actioned.

* Need to control software issue meticulously.

* Difficulty of amending software.

The last 2 points are related. Distributed, digital MCAS systems at their conception were claimed to be much easier than their predecessors to change. Experience has shown that because very comprehensive configuration control is required software changes are expensive. Furthermore the mechanism of incorporating software updates into the control system computers may generate further work. For example powering-down the computers to allow new Read Only Memory modules to be inserted may incur the loss of user-provided information, and the consequent need for re-keying.

The Type 23 MCAS system includes over 2000 parameters. Studies of the Integrated Platform Management System (IPMS) concept suggest that there could be a several-fold increase in the number of parameters within such future systems, and more extensive use of VDU-based displays. System integration will become more complex and the need for independent assessment even stronger.

Steps to control the number of parameters will also be needed. Distributed principles should be applied even to health monitoring. There is a great danger of too much information being supplied to central watchkeepers who only really need a 'healthy' or 'not healthy' indication.

10. SUMMARY

The technological change from centralised analogue control systems of previous warships to the distributed digital control system for the Type 23 required a means of assurance that the system would cope with normal and abnormal conditions. Such assurance could not have been obtained from a machinery test facility. Hence the need for a simulation-based facility.

The production of the Assessment Facility has been a major project requiring the development of a real-time simulator of the Type 23 propulsion, electrical and auxiliary systems, together with extensive interface hardware. Over 30,000 wire terminations had to be made while integrating the simulator to a production Type 23 MCAS system.

It has been suggested (2) that the justification of the facility would lie in the answers to:

* Whether the assessment reduced the risks during first of class trials.

* Whether the assessment reduced the ship acceptance timescale.

* Whether the facility would cope with more advanced technology.

The assessment facility has helped notably to give confidence in the Type 23 MCAS from an early stage. It identified problems which needed to be rectified before they delayed the ship and reinforced conclusions from early trials in the ship.

The simulator has worked well and could cope with more advanced technology both in terms of the equipment under assessment and that to be used to perform assessment:

* Potential improvements to the interface arrangements are being researched to cater for the increased numbers of signals that future plant management systems may require.

* The facility could be expanded to cater for more complex simulation requirements of future systems.

* A computer-based mimic display facility has been added at the interface demonstrating possible future approaches.

The experience of producing and operating the facility had several 'knowledge' benefits:

* MOD has an in-depth knowledge of the MCAS system.

* Ship's staff have enhanced their experience whilst helping with trials on the equipment.

* Maintenance requirements have been assessed on actual equipment, without interference to the ship building programme.

The wide variety of personnel who worked at the Assessment Facility made many suggestions for improvements to MCAS. Some suggestions, such as computer storage and analysis of secondary surveillance information, were then demonstrated on the facility.

Tight timescales inevitably mean that many suggestions will only prove to be cost effective for future warships. Maximum benefit could be obtained from such input if equipment were available for assessment earlier in the production cycle, preferable at prototype stage.

It could be argued that this could only happen if the assessment facility existed at the manufacturer's premises, as an extension of their in-house test facility. This approach may be be feasible if, as in this case, the system components to be assessed were all manufactured by the same contractor. The crucial question would be the independent usage of that facility for the role described in this paper. The 'independence' of the assessment process is of paramount importance. Furthermore the use of a test facility remote from the manufacturer's premises has the benefit of reinforcing the case for early supply of documentation.

The Type 23 equipment at ARE (WD) is being removed, refurbished and returned to a shipbuilder for installation into a future Type 23, now that the objectives of assessment have been met. The question of a through-life simulation-based reference facility, to allow testing of control system software and hardware updates, is currently being addressed. An Assessment Facility could clearly perform that role, also enabling problems at sea to be investigated and corrected ashore.

Additionally such a facility could be used in a training role, as a supplement, but not replacement for, dedicated training facilities. For example the complete Type 23 equipment set assessed at ARE (WD) provided the opportunity for more detailed maintainer training scenarios than at the official training facility.

Whilst a facility established to cover any of these additional roles would require the outright purchase of a set of controls equipment the overall benefits would be considerable, as well as providing the safeguard of an extra set of equipment available as immediate emergency cover.

Taking a wider viewpoint the question of on-board training arises. When machinery is idle, ship's staff have limited opportunity to increase their understanding of the operation of the controls and machinery operation. The use of an on-board machinery simulator connected to the controls equipment would be governed by safety, cost and size. The repeat costs, and the size, of a simulator such as that at ARE (WD) are dictated by the interface sub-systems. However it would be possible, in this role, for a computer-based simulator to communicate directly with the computer-based MCAS units, avoiding the need for much of the signal conversion hardware. The safety aspects of switching between simulated and physical machinery systems would have to be addressed, but should not present an insurmountable problem.

11. CONCLUSIONS

The significant investment in independent assessment has provided a very firm basis for confidence in the Type 23 MCAS system. Although the assessment has identified several aspects which could be improved it has confirmed that the Statement of Technical Requirements (STR) is generally satisfied. Through the ideas and suggestions which have resulted from the project, there is now an excellent springboard from which to develop much improved systems and better STR both for later Type 23 frigates and for future classes of warships.

Such independent assessment should be policy for future ships. It should be done early and be well resourced. Consideration should be given to integrating the requirements for assessment and support, and to providing a supplementary training facility. Each should be addressed from a whole system point of view.

12. DISCLAIMER

Any views expressed are those of the authors and do not necessarily represent those of the Department.

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DISTRIBUTED PROCESSOR CONTROL AND MONITORING SYSTEMS
-ENSURING "FITNESS FOR PURPOSE" FOR THE END USER

by A. T. Mitchell and E. N. Knaggs
Shell Seatex, London

1. ABSTRACT

Distributed processor control and monitoring systems are becoming common fixtures in all types of vessel. They offer advantages to the shipbuilder, ship owner and ship operator. The process of stating requirements, manufacturer selection and the subsequent development of the system with the manufacturer are critical in ensuring 'fitness for purpose' and it's importance is often underestimated - particularly in the marine and offshore world - but also in the naval world when contracts are treated on a commercial basis.

Experience gained in the technical auditing of offshore vessels fitted with such systems and in the design of these systems for LNG tankers and naval fleet *replenishment* vessels will be discussed. Experience suggests that such systems usually fall short of expectations in many respects and particular examples will be given.

Common to all vessel types are the requirements for non-degraded performance under extreme operating conditions and a reasonable level of fault and damage tolerance. The main factors to be considered in the selection and development of systems to meet these requirements will be outlined.

Finally, the paper will draw on the experience gained to highlight areas ripe for development in the design of these systems and propose some particularly attractive features for the future.

2. INTRODUCTION

Distributed processor control and monitoring systems, those "new" systems which deploy electronic computing power around the vessel and which utilise data highways for communication purposes, are perceived as offering significant advantages over traditional systems one of which is the ability for the efficient handling of large numbers of plant signals in real time. The phrase "control and monitoring" is based on traditional systems and probably does not do justice to the power of the processor based systems or the way in which they are employed. A more appropriate phrase is "control and surveillance".

What is often overlooked is that the traditional system with it's multitude of instruments and controls cabled directly to the plant is a perfect example of how the new systems should perform. The traditional systems also handle large numbers of plant signals in real time; a primitive example of parallel processing. Of course there is a limit to the number of signals which can be handled. After all, there are physical limits in the shipborne environment for the size and weight of the equipment needed to handle them and of course limits on the upkeep and maintenance support available.

Present day control and surveillance systems are normally a combination of "new" and traditional system technologies. See figure 1.
"Fitness for purpose" is a term which in itself is self explanatory but applied in practise, in this case to control and surveillance systems, can mean different things to different people. At the plant level, in and amongst the machinery, fitness for purpose is dictated by the requirements of the plant itself and it's operating philosophy. There is little room for error because plant manufacturers hold a wealth of experience and even a standard control package is likely to hold no more than just a few, inconvenient, operating idiosyncrasies. More intangible is fitness for purpose of the shipwide control and surveillance system; that hierarchical system which brings shipwide control to the fingertips of the operator. In the context of this paper fitness for purpose not only concerns this system but also the operators and their actions and reactions. An important consideration here is the interface between the system and the operator; the man machine interface (MMI).

It must be remembered that the development of the MMI is largely a matter of historical convention and preferred operational philosophy. Witness the differences in the form and manning of control rooms in the defence, offshore and marine sectors. What is fitted is not cast in concrete and it is a healthy attitude which questions established methods and procedures. What is unhealthy is if one particular attitude dominates out of all proportion to it's value on the project throughout the project lifetime. A control room designed by traditional accountants would be devoid of instumentation. At sea, an operator would ask the control room accountant, "what is the situation?". "Is it really essential to know that?", would be the recorded reply.

There are various international, national and end user "in-house" standards to be followed and these all help in ensuring a minimum acceptable quality is obtained but do not, in themselves, guarantee fitness for purpose. The assessment of fitness for purpose must address far more than the esoteric aspects of system design.

There are also many project management tools which can be employed but these only ease the process of procurement. They do not ensure fitness for purpose although they may in some cases create an environment conducive to this aim. This paper will address those aspects in the procurement process which do have a direct bearing on ensuring fitness for purpose and will describe the tools considered essential for the technical development of the system.

There is no hard and fast formula for success but experience gained on defence, offshore and marine projects points to there being a preferred path to follow. This paper will first consider the management of the project from the technical viewpoint and will discuss the key milestones in the procurement process.

There are various reasons why changes in direction take place and milestones move and some of these will be discussed in terms of management of the design of the system.

Of all importance is the equipment itself and some particular points will be mentioned. 3. MANAGING THE PROJECT

Experience has enabled Shell Seatex to formulate a practical philosophy for the procurement of complex systems and ensuring fitness for purpose, one which has been practised with distributed processor control and surveillance systems in both merchant marine and defence sectors. See figure 2. The philosophy relies very much on maintaining personnel continuity throughout the project and the path is marked out by the following milestones.

A statement of requirement for the vessel

The formulation of the operational philosophy

The writing of a performance specification

The selection of a shipyard

The agreement of a contract specification

The selection of equipment manufacturers

The detail design stage

Plan approval stage

Factory acceptance testing

Commissioning

Sea trials

The guarantee period

3.1 A statement of requirement for the vessel

Although the requirement is usually for a new vessel, the philosophy for procurement can be applied equally well to retro-fit of new equipment or updating of equipment on existing vessels.

Timing is crucial. The stated requirement for the vessel may arise out of years of study, in which time suitable hardware solutions can be researched if adequate budgets are allocated. More often time for research is short; in this case it may help if those involved with the project are currently involved with similar work elsewhere and this is one of the benefits of employing someone who is used to working as a "3rd party" and who has experience of other end user's requirements. This is a very effective way of introducing new ideas and questioning established standards, introducing a process of challenge into the formulation of requirements.

Some particular end user requirements may not stem from purely technical considerations. Sometimes there is a necessity to demonstrate enhanced safety features or to maintain an outward appearance of being at the forefront of technology. Sometimes budget limitations demand that an "adequate - no more, no less" approach is adopted.

In all cases the operational philosophy has to be determined and clearly stated.

3.2 Operational philosophy

Possibly a more correct title for this section would be, "operational philosophy, within the allocated budget at any particular time". Unfortunately, the control and monitoring system budget tends to be looked on as something which can be trimmed in favour of more substantial parts of the vessel, those parts which are more generally understood and appreciated. This attitude should be countered. There are opportunities to make long term operational savings, for example by reduced manning arrangements, in return for increased initial outlay and these should be thoroughly investigated.

One consideration is the calibre of the personnel to be employed to operate and maintain the equipment when the vessel is at sea. What is the extent of their expertise? To what extent can their expertise be enhanced by training? What expert assistance can be made available from shore based facilities either by attendance or communication? How readily will shore side expertise be made available?

If there is limited expert knowledge held by the personnel on the vessel it does not necessarily follow that technical complexity of equipment should be limited. In combination with system redundancy, automated fault analysis, module replacement techniques and shore based assistance by communication and attendance, operating and maintenance personnel need only be conversant with the basic building blocks of the system and be familiar with the basic terminology.

There may be an application here for expert systems; bridging the gap between the system and the operatator.

If a centralised form of control is to be adopted a decision needs to be made as to the locations at which these control "rooms" will be located and the physical communication to be afforded with other key areas of the vessel. The optimum locations vary with each class of vessel. In the case of the majority of merchant vessels the machinery spaces and the control rooms are designed to operate unattended. In the event of a machinery alarm the first point of call for the duty engineer is usually the control room to acknowledge the alarm and to initiate corrective action. It is convenient to have the control room close to the engineers accommodation on route to the machinery space; very often the control room is sited within the accommodation block. Where the machinery control room and the cargo and ballast control rooms are combined there can be an improvement in overall ship operational efficiency.

Also of importance is the design of the control infrastructure in terms of intercommunication facilities and the opportunity for delegation of work by the control room operators to those in other areas. The distibuted processor type system demands a review of traditional operating methods. When it fails there can be an immediate demand on manpower resources for it's repair and for the resumption and/or maintenance of operation at local manual level. Such is the nature of these systems operators should practise operation under simulated failure conditions as part of regular drills otherwise unfamiliarity will lead to operational problems at critical times.

An operating philosophy is an essential foundation stone in the design process.

3.3 Performance specification

The performance specification for the control and surveillance system should be just what it says it is. It should concentrate on the requirements as far as the end user is affected and should not preclude alternatives in terms of equipment or system configuration unless this is considered essential. Often, on a project which involves a long period of research, a number of possible system manufacturers are included in the early feasibility work. While this is useful in keeping options open and in keeping final system costs at reasonable levels, care should be exercised to ensure a manufacturer who is obviously not capable of meeting the requirements for performance is relieved of further involvement.

A very useful inclusion in the performance specification is the reasoning behind the requirements. This helps manufacturers to assess their own proposals and acts as an effective first line filter in the approval and selection process.

3.4 Selection of the shipyard

In present day circumstances the selection of the right shipyard is even more important than ever before. Care has to be taken to ensure that the necessary expertise is available either at the yard itself or by proper subcontract to a reputable organisation.

The selection process depends on many factors and may include political or other intangibles. This, coupled with todays popular option of delegating total design responsibility to the shipyard can introduce further problems. A carefully considered concept can be diluted out of all recognition by a shortage of expertise at the shipyard coupled with lack of technical support from the end user.

3.5 Contract specification

There are many ways the contract specification can be written to ensure adequate resources are made available and suitable manufacturers are selected. It is often the case that this specification is, as far as the detail design is concerned, the last chance for the end user to impart any real influence on the final system form. The end user will view this document as a means of directing and guiding the shipyard toward a preferred solution and the end user will attempt to use it to steer a course for design development by the shipyard. For the shipyard, the contract specification represents an agreed level of performance for the system and the yard will invariably resist any attempt to be tied down to particular methods and solutions.

3.6 Selection of the equipment manufacturer

There are as many manufacturer selection processes as there are manufacturers. One aspect which is always addressed but which is very difficult to control is that of resources in respect of people and equipment. Most manufacturers have extremely experienced and qualified people and can demonstrate excellent pieces of equipment but these may not be the ones to be employed on your project, at least not for long after the contract is awarded. Even if they are, if they are particularly skilled they will almost certainly be shared between two or more similar projects. These people are a valuable manufacturers asset.

In many cases manufacturers lack a depth of experience from the end users point of view. It is only very rarely that a manufacturer will be able to perform a "turn-key" contract in which he accurately identifies the end users needs and meets his requirements in all repects. Where this is successfully carried out the manufacturer has usually hired expertise to enable him to do it. He will only do this of course if he is contractually obliged to do so, in one form or another, and he has a budget available.

One of the more important activities of the end user is ensuring that the contract between the shipyard and the manufacturer does not compromise technical content.

3.7 Detail design

It is in the stage of detail design discussions that those aspects which are peculiar to a manufacturers own equipment are addressed. Technical solutions must be selected which allow the overall requirements to be met and for this reason the process must be led by someone with an overall picture of the project. This can not be achieved efficiently by committee. There is a sensible balance to be maintained between, on the one hand, "all party discussions" in achieving end user's approval of a particular solution and, on the other hand, a single person authorised to approve on the spot. The former ensures all interested parties have an input and therefore the final design will be acceptable to all - in theory. The latter ensures rapid progress. Experience has shown that approval on the spot, whenever this is at all possible, is the more practical arrangement. The authorised person(s) must also have the necessary authority within the end users camp to ensure unpopular solutions and even compromises are accepted and that other areas of the project are controlled, for example, to preserve interface compatability between systems. It is imperative that the end users representative maintains a level of credibility with the shipyard and manufacturer and this can not be achieved by hesitation or reneging on previous decisions.

3.8 Plan approval

Plan approval is the process of confirmation that the end users requirements are being met and that the solutions agreed during design discussions are being adhered to. Again it is important to maintain credibility and therefore as short a period as possible for approval purposes is called for. In some cases it may be worthwhile approving drawings on the shipyard and manufacturers "drawing boards", particularly where early influence is essential, before the design goes too far down one particular road.

3.9 Factory acceptance testing

The manufacturer will design the factory acceptance tests to prove the system works. It is the responsibility of the end user to confirm at these tests that his requirements have been met in all respects and to prove that the system has acceptable failure modes and effects. This means that those attending the tests should be those who have been involved throughout the project, those who will be able to look beyond the black and white text of the test procedures and the staged demonstrations.

The tests should include an assessment of the system in relation to the shipyards commissioning programme. If it is proposed that the system should be commissioned piece by piece then the tests should include piece by piece power up and operation.

The tests should also include simulated failure conditions and repair procedures.

The only way a complex system can be tested effectively is as a complete system and the first time the system comes together in this way should be at the manufacturers works. Tertiary devices and systems should also be included as far as possible, particulary other manufacturers equipment which communicate over data links.

3.10 Commissioning

Successful commisssioning relies on the knowledge of those involved gained through documentation and training. Only a knowledge of "what the system is about" will enable accurate observations and feed back to take place. Operating manuals and drawings are essential tools. Training courses given by the manufacturer and the shipyard design teams are invaluable.

3.11 Sea trials

The final proof lies in the sea trial when all systems are running together. This is the final proof of fitness for purpose and therefore, once the system has been proven to work as intended it should then, once again, be subjected to simulated failures to check response. These checks are worthless without some baseline against which the results can be measured. The baseline is the original design intent therefore these checks should be attended by the system designers. An important aspect of the simulated failure tests is the performance of the operators.

3.12 Guarantee

If the system is fit for purpose any claims under guarantee should be limited to normal failures associated with "running-in". In the guarantee period there is the opportunity to observe how the settling down process progresses and to gain valuable feedback from the operators. The designers must be prepared to listen and if equipment or operational philosophy changes are necessary they should be implemented at the first opportunity. This exercise should not be looked on as
the result of deficiencies in the design but an essential end stage of the design process.

In spite of all efforts, very often the distributed processor control and surveillance system is not completely ready at sea trials time. In some cases it turns out to be never quite what was intended. A hind sight view is a very useful facility and those involved with any project which converts concepts into reality will be able to identify with the notion of "doing it better the second time around". Some of these second time around observations will now be discussed.

4. MANAGING THE DESIGN

There is no doubt that the end user knows exactly what he wants when it comes to a control and surveillance system for shipwide applications. So too does everyone else involved with the specification, the purchase, the design development and the ultimate setting to work. Unfortunately, everyone involved tends to have their own view of what the requirements really are and these views are, invariably, different. The end result is often a compromise.

At one time the task was relatively simple. Each part of the plant could be looked upon as an independant entity and those people involved with the control and surveillance aspects, the chain of people from end user to designer, would talk the same language and there was little opportunity for misinterpretation. Each had sufficient knowledge to express their requirements in terms understood by all and then to check that these had been correctly implemented. Now there seems to be a necessity for the transmission of large amounts of data around a vessel and no longer can the parts of the plant be treated as independant entities. Now the chain of people includes operators, electrical engineers, control engineers, electronic engineers and software engineers. Such is the rate of development in these disciplines, and particularly in electronics, that the chain of people is now only tenuously linked and there are far more opportunities for misinterpretation. Each member of the chain is well versed in his own discipline but can only ever have a cursory appreciation of the phraseology and methodology of the others. The end user and the software designer are often worlds apart; they may use the same words but they talk a different language.

The control and surveillance system usually does appear at the end of the day and it usually performs in a satisfactory manner. The project is successful and is within budget (though not necessarily the same budget the project started with). This does not mean to say that the frustration felt by some people, because they are the ones who compromised the most to make it successful, is made any more tolerable.

The reasons for compromise are numerous and they arise in every project at every stage. Some are glaringly obvious to outsiders and some are subtle to the extent that it may not be deemed necessary to inform all those involved that a compromise has indeed been made. Compromises are necessary when any one or a combination of the following occur;

The end user or his agent has unrealistic expectations of the system.

The end user or his agent puts an unrealistically *low* monetary value on the system.

There is insufficient helicopter for the interpretation of requirements and design constraints in order to reach a sensible balance.

4.1 Expectations

The users expectations tend to follow a set pattern as he sets out on the learning curve for the application of distributed processor systems, those "new" systems employing data highways and which are software driven. Initially a safe course is steered by insisting that all essential controls and surveillance signals be cabled independantly in the traditional way and only the non-essential signals be included in the new system. After a short while, either through a process of learning or confidence building or both, it is realised that as long as the system is engineered properly, fault tolerance, particularly in fire or damage situations, can be much improved by the use of the new system with all it's redundancy features in preference to traditional cabled systems. There are also reductions possible in the amount of cable insulation materials installed. All "essential" signals are thereafter allocated to the new system.

The next stage involves an analysis of the new system with respect to installation and overall project time. It is soon realised that the new system allows all the initial design effort to concentrate on hardware. The hardware is usually needed very early on in the build programme. The process of developing software can be undertaken later when the rest of the vessel's equipment has been better defined. In this way the design development peak workload experienced at the start of a project can be reduced.

There are also savings to be made in terms of reducing the numbers of cables running through the vessel. With the new system, cabling and terminations are concentrated into specific areas of the vessel and there is a minimum of through ship cabling so reducing space and installation time requirements. The benefits can be numerous. Suddenly the new system has become very useful; every possible use is made of it.

As far as performance is concerned the new system has a lot of attractions. Every control station has the potential for controlling and monitoring all the plant on the vessel. If one control station is lost through fire or damage control can revert to any other convenient station. Data can be transmitted around the vessel, processed, displayed, duplicated, analysed, time delayed, checked, conditioned, converted, archived.. the options appear to be unlimited. Colour displays mimicking the layout of plant and equipment are used as backdrops for displayed data showing measured values, alarm messages and trend analysis' and watchkeeper logs are available at the touch of a button. Within seconds new displays can be brought to the screen and displayed data is continually updated. The specific characteristics of data bus systems whether they be fibre optic links or copper conductors can include features to assure immunity to the effects of electrical interference.

How these expectations are realised in practise depends on how the manufacturer interprets them and relies very much on a qualatitive assessment of each feature in relation to the others and in relation to the operation of the system as a whole. This is a key element in the development of the system and requires careful consideration and discussion between all parties concerned.

4.2 Monetary value

The purchaser of the system, the shipyard or the end user, considers that the new system, on the basis of experience with traditional systems, is bound to be a little more expensive. After all, there will be a lot of time and effort to be spent in discussing the particular requirements of such a complex system. However, this has to be measured against the savings to be had in terms of installation costs and the potential for shortening the construction programme. Overall, can one probably expect to break even on a cost per signal basis?

A distributed processor system is a complex collection of requirements and there is always great difficulty in putting a monetary value on it until it has been defined in detail. This leaves a lot of room to manoeuvre at the early stages of negotiation. It is quite an easy task for a strong commercial team to force the cost of such a system down. It is even easier for a strong technical team to ensure that you only get what you pay for. Commercial and technical representatives should both be in attendance at the final pre-purchase negotiations between the manufacturer and the purchaser.

Once the cost and scope of supply has been agreed there is a tendency to put the emphasis on the manufacturer to develop the design and very little money is allocated to provide the manufacturer with technical support. This is surprising. An analysis of the cost benefits of the new system include a substantial saving for the project in terms of electric cable and a reduction in installation peak workload. (As the new system involves specific areas of high density cable installation and connections with little through ship cabling, fewer teams of electricians are needed. One team can be set to work in different areas of the vessel at different times as the steelwork and outfit progresses rather than having to wait until these are substantially complete as with traditional systems).

All too often the purchaser places the order and then opts for a short term gain by failing to remember that development work is still required. A proportion of his purchasing budget should have been set aside for technical support to the manufacturer. What suffers first is support to the manufacturer in terms of an overview; an element of technical management which balances the requirements of the end user against the constraints of the manufacturers design. An element called helicopter.

4.3 Helicopter

The chain linking end user to manufacturer relies on clear communication of requirements and constraints (they flow in opposite directions) and as long as this is done effectively at all stages of the project then there is no reason why there should be any surprises or disappointments later on. The length of this chain and the disciplines of the people who make up the links varies according to the project management techniques favoured for any particular project. Communication tends to break down when people decide to stay where they are most comfortable, in their own field of activity, stating their own case and leaving others to come up with appropriate solutions no matter how difficult this may be. In a chain this can be time wasting and ineffective. Contractual and financial limitations promote isolationism and members of the chain attempt to make others take the lead in providing a technical co-ordination service, a role in which someone takes it on themselves to talk to all members and sensibly balance requirements against constraints all down the line. It is expensive to take on this role. A strong end user or purchaser can distance himself from the designer or manufacturer and may employ contractual tactics rather than commit a proper budget for the provision of technical guidance and co-ordination or "helicopter".

Although the helicopter element can be provided by others outwith the chain it has most effect if this element is provided by someone directly involved, preferably someone with the authority to modify requirements as the design develops and constraints are realised. This infers that helicopter is best provided by someone in the chain close to the end user.

5. BUILDING THE FOUNDATIONS

In developing the concepts the end user or his agent must ask the question, "what is the purpose of the system,...what is it supposed to do?"

One of the more obvious considerations is the way in which the system will be used on board the vessel. This depends on the calibre of people employed, their training and their culture. The system is an aid to the operators in performing their duties and should enhance the safety and efficiency of their actions.

There are numerous system configurations possible but it is unlikely that any particular arrangement could or should be chosen at the concept stage. What is more important is that the main operational features and characteristics are addressed. The end user should try to establish a sensible balance between what would be nice to have from the operators point of view and what is, in reality, a practical proposition all things considered.

Despite the wide experience of the "new" distributed processor systems there is still an overriding influence from experience with traditional systems where switches, indicators, dials and a plethora of cables and wires is the norm. The traditional systems are well tried and tested and their shortcomings are well documented. The conceptual design of the new systems is still measured against the advantages and disadvantages of the traditional systems.

Experience has shown that it is not just a case of changing from old technology control and surveillance systems to new technology systems. There are implications for the design of plant and equipment to accommodate new ideas such as reduced manning and automation on a shipwide scale. The control and surveillance system designer has to involve himself more than ever before in the design of the vessels engineering systems and in the re-examination of established operational methods. There is also the problem of upkeep. Maintenance and the consequential effects of system failure are essential considerations in the conceptual design of a system which extends throughout the vessel and which is relied upon to fulfil so many requirements.

Features which support reduced manning and reduced operator workload can be included at the conceptual design stage with minimal effect on overall costs and project completion time. These features are generally very simple and can include facilities which allow, through normal operational practise, the routine testing of equipment; not just the major units and assemblies but the underlying control and protective features also. In all cases the approach to be adopted is to design the system and the operational procedures so that, as a matter of routine, the day to day operation of the vessel results in a thorough checkout of all features. If this is done properly all periodic performance checks can be achieved as a background activity.

As an example, consider a two pump scheme for cooling water supplies. Normally one pump is running as the duty pump and one pump is on standby ready to start if the water pressure falls (if the duty pump stops). By allowing the operator to change the configuration simply by stopping the duty pump he can observe that the standby pump automatically starts. Not only has an operational requirement been fulfilled (say, to balance running hours on the machines), but also a periodic function check of the control devices initiating the start of the standby pump. This proves the arrangement without recourse to dedicated planned maintenance checks. Another opportunity with this example is to provide a check on the availability of the standby pump both at the time it is initially selected and the whole of the time it is on standby by ensuring that the design of the control equipment for the motor allows simple monitoring of power supplies and interlocks. See figure 3. In this way it's correct operation when called upon is assured as far as possible. The operator is alerted to a fault at the time it occurs and not at a critical time when the standby pump is called upon and fails to perform.

Identifying faults as they occur (avoiding hidden failures) can avoid major failure incidents.

6. THE MAN MACHINE INTERFACE

Distributed processing can be considered as a means of processing earlier in the data collection cycle and so reducing the processing required at the system "centre". The effect is to improve the overall performance and comes from increasing the number of simultaneous processing operations being carried out.

There is always a temptation to make sure that operators are in a position to monitor all these processing operations by bringing back to a central control room as much data as possible. This can overload the operator rather than assist him. The right balance can be achieved by considering the operator as part of the system hierarchy and aiming to reduce his processing task by delegation and distribution as for the system itself. Of course there are essential data that he must either be aware of or have access to and these should be presented to him in the clearest and most informative way.

6.1 Visual display unit (VDU) versus mimic diagram

The VDU is a window onto the plant with some interpretation of the plant parameters either by data processing or in the design of the VDU page presentation. One screen can provide a reasonable sized window... but still only a window. Moving around using this window tends to be slow and restricting and therefore movements of this type need to be minimised. As control actions tend to be restricted when using VDU's automatic sequencing should be employed as much as possible.

The man machine interface can simplify or exasperate the operators task. It must be designed correctly in relation to the plant and the actions expected from the operator. It is very difficult for VDU's to outperform the traditional console mounted mimic diagram; a simple arrangement which can provide a comprehensive overview of the plant by careful attention to it's design.

The fundamental requirement is to present the operator with the information and the control facilities he needs to perform his duties under all foreseeable circumstances. One can imagine his task in terms of three specific steps - check a plant feature, assess the situation and take appropriate action. The operator performs these steps continuously under normal and abnormal conditions the only difference being the degree of urgency in each case. The man machine interface must maintain the efficient transfer of information and control commands under all operating conditions. If this transfer faulters the operator will not be able to conctruct his mental picture of the situation and the man machine interface will collapse into a meaningless mass of indications inviting operator error.

These ideas are best presented in relation to a real situation. Consider for example an oil cargo system. There may be three different classes of cargo, fuel oil, avcat and lubricating oil each with it's own set of tanks, valves, pipelines and pumps. The electrical supplies to the system and particularly the cargo pump motors is another unique "set" of plant. Yet another is the "set" of tank level indications which, among other uses, are employed for strength and stability checks.

Each of these sets of plant can be thought of as being represented by a set of plant information which should be readily available to the operator in an unclutterd form. The traditional mimic diagram can combine large numbers of such sets of information and clarity in presentation is achieved through colour coding of pipelines, common designs of indicators and controls for similar pieces of plant equipment such as valves and motors and tank level gauges, and the sensible grouping of plant with common functionality, for example, manifold valves and pump room equipment. The design of the mimic in terms of what the operator sees, the shapes and colours and the groups and subgroups, is a form of data processing which existed long before the advent of the computer.

For reduced manning operation, where a control room may go unattended for long periods, the operator needs a system of display with which he can gain an immediate overview of the plant on his return. This can be achieved with the adoption of the "all dark" principle whereby changes in plant set up can be highlighted immediately by a single indicating lamp. The operator extinguishes the lamp thereby acknowledging the change in plant status. Once again, this is applying a form of data processing to produce a more efficient and hence more effective man machine interface.

How are these features reproduced on the VDU screen?

In the case of the VDU screen the sets of plant information should still be displayed in a clear and concise way. Although the option of colours and shapes is still available there is a limit to how much can be achieved by design of the display pages themselves and most of the processing has to be implemented in software. In comparison to the console mimic where the various sets of plant information are laid out on a common plane the VDU based mimic can be thought of as a set of pages, each page representing a different set of plant information. The VDU screen is a multidimensional device and involves an operating overhead in terms of the processing power required to permit the operator to move between these pages of information in a logical way. In some VDU based systems this overhead is or has been omitted and operators can find themselves confronted by a system of many (in excess of 75) pages with no sensible means of navigating through the mass of data involved.

The most common "navigation" systems for VDU page "libraries" employ overview pages directly leading the operator to more detailed pages on specific areas of plant. Every page displayed includes pointers to related pages which may hold relevant information. The best systems are constructed in the form of fully indexed and cross referenced manuals and allow the operator movement from page to related page with single keystroke actions.

It is fairly obvious that the VDU is not a device with a traditional equivalent except maybe the operators manual. It requires a different philosophy for it's use. To be employed effectively by the system designer it demands a clear understanding of just what is required by the operator in terms of automation and remote control.

6.2 Automation versus remote control

It is important to recognise the relative advantages and disadvantages of automation and remote control. Remote control allows an operator to perform his tasks from a more convenient position, usually a central control room. Although signal processing may be employed in the transmission of signals and data in a remote control scheme, for example, by the use of signal multiplexing techniques, this is not considered to be distributed processing in the context of this paper. Operator action is an integral and essential part of remote control.

Automation is a feature which effectively reduces the central processing requirements and is therefore well suited for implementation in distributed processor systems. There is no requirement for operator action, under normal circumstances, in the true application of automation.

Some applications are best performed by remote control and these tend to be those which rely on "operator re-inforcement" of control decisions; those applications which require confirmation by the operator that the control solution is acceptable. A good example is the control of oil cargo transfer operations where communication is required, maybe with another vessel, to co-ordinate the operation, a number of pipeline valves need to be opened and pumps have to be controlled.

Automatic control, by definition, needs very little operator intervention and should proceed as a background activity leaving the operator to tend to more important things. For these applications all the operator needs is information alerting him if the automation is not working as intended. Very often the mistake is made that the operator is shown the automated process without being shown the elements of automation. For example, in a scheme to automatically control the production of steam from a combined oil and gas burning boiler it is usual to find the operator is quite rightly presented with the key process parameters such as oil/gas mass flow, forced draught air mass flow, boiler drum level, steam pressure and so on and is given access to the controllers involved by which he can alter control set points, gains and other features. Only rarely is he also given the information which relates the controllers to each other so that he is aware of the interactions at each stage of the process. By observing the action and reaction of the automation equipment he would gain a better understanding of the implications of the adjustments and fine tuning he invariably attempts in the course of his duties.

It is remarkable that on a system basis there is always a tendency to overestimate the capability of a distributed processor system and very often performance suffers because the system is asked to cope with all sorts of complicated tasks involving data from all around the vessel. When it comes to the man machine interface the opposite is generally true; tying up valuable processing power to carry out simple operations like illuminating a group of light emitting diodes or simulating "on screen" images of dialled instruments when a more cost effective, dedicated digital circuit or instrument would do the job more efficiently.

Another example is the use of application software to replace the perfectly adequate built-in logic involved with different designs of electromagnetic relays for timing, interlock and latching aplications.
Of course, when it comes to safety related functions it is essential and generally more cost effective to employ dedicated systems.

6.3 The right MMI for the control scheme

Remote manual control of cargo and ballast operations, for example, require the operator to have an overview of the cargo and ballast systems. He should not concentrate on one part in isolation because, while filling one tank another may be filling via an inadvertently opened valve somewhere else in the system. In this case it could be considered foolhardy to operate via VDU screens and keyboards if the system being controlled is at all extensive. This arrangement may indeed turn into an expensive arcade type game with the operator furiously rattling the keyboard in an attempt to initiate the right commands at the right time. It would be more appropriate to provide a console arrangement with individual control and monitoring devices incorporated into mimic diagrams.

An application for integrated automatic control may be found in a machinery control scheme. There may be dedicated software driven control units local to the machinery which communicate to a central management system in the control room for remote control and surveillance purposes. The control room operator will usually have the facility to initiate set control sequences and modify control settings to gain optimum plant conditions. In this case there are few problems involved when implementing this scheme with VDU screens and keyboards as long as the independance of the local control unit is assured and safety functions are provided in addition. In this way failures in the central management system would be contained and the operator could concentrate on repairing the fault and not have to worry about the safe continued operation of the machinery. The operator displays would be more for the analysis of data than the operation of the plant. A development here could be the inclusion of decision making features in the management system to assist the operator in identifying optimising strategies. Some proprietry control equipment include this feature already.

There are of course applications which do not fall conveniently into one or the other categories, some which would benefit by a mix of VDU screen and console mimic facilities. Each must be considered on it's own merit.

6.4 The function of the control room(s)

In modern merchant vessels the control room is only a data handling area linked to the equipment actually controlling the plant by data highways which may also serve to carry signals around the vessel. It is considered good practise to ensure that no automatic control algorithm depends on these "common usage" data highways for continued operation. The data highway (and the data highway associated devices) should be considered an integral part of the control room MMI which should itself be a non-essential part of the plant. All plant should be capable of local operation with plant mounted instrumentation and controls in conjunction with plant mounted independant safety devices active under all modes of control. Those control features which are essential in providing the control room operator with the back-up means of maintaining, for instance, manoeuvring capability in the event of processor failure, should also be independant of the data highways.

While this approach reduces the critical nature of the shipwide control and surveillance system it does not permit a relaxation in the requirement for the system to perform adequately under all foreseeable circumstances. Experience gained in the technical auditing of offshore vessels fitted with these systems and in the design of these systems for liquid natural gas carriers and naval fleet auxiliary vessels suggests that performance can fall short of expectations.

The notion, for instance, that the responsibility for control co-ordination can be transferred from one control room to another as long as there is a workstation (VDU or software driven console facility) available is practical, but only under normal operating conditions. The transfer is usually implemented by duplicating or transferring the MMI; the system data base and the operating system processing facility usually remains in the same location. A true transfer facility, effective under damage conditions, would need to be implemented in the form of duplicated systems including independant plant signal interface devices, data highways and control room MMI.

Although many systems boast a range of features and facilities such as multiple access for control and surveillance purposes in practise the number of simultaneous operations is limited.

Many of the shortcomings in these systems arise out of timing problems. There are inherent delays involved with data sampling, transmission, processing and display and while these delays may be tolerable for the range of normal operations they may become inhibiting when the system is called on to perform under abnormal conditions. Timing of signals is crucial and although different applications have different requirements generally speaking time delays should be kept to a minimum.

When systems are gradually loaded in terms of data changes and processing demands they generally slow down and response times can become excessive. VDU displays have been seen to take in excess of 20 seconds to respond to operator requests under these conditions and some systems have even given the impression of coming to a halt; the processor equivalent to stalling the engine. Analogue tank level indications on one particular vessel were taking in excess of two minutes for sample and display cycles. One vessel was fitted with a system which performed adequately under normal conditions but in the period immediately following a plant shutdown (a total failure of the electrical system) the system could not cope with the mass of alarms and control signals suddenly arising.

The same is true for operating personnel. While they may be perfectly capable of performing their tasks under normal conditions there are experiences of confusion and chaos when things start to go wrong. Many serious incidents have been caused by operator error because of poor MMI design. In the majority of cases of incidents with which we have had experience errors have arisen due to the operator being unable or unwilling to construct an accurate mental picture of the situation. Crisis training for operators is important and Shell Seatex test this aspect of performance in simulated failure conditions as part of technical auditing procedures.

7. GETTING THE IDEAS ACROSS

Once the concept has been defined it is then necessary to explain the concept to those responsible for getting the system built. How well this is achieved will dictate the ease or otherwise with which the design progresses.

It is often said that the biggest problem facing the shipbuilder is in engineering the interfaces between systems from different manufacturers. This is often an understatement.

There are interfaces to be addressed in all areas of the vessel design, not only in the sense of systems from different manufactures but also in the process of design of the control and surveillance system itself. The importance of "helicopter" in the chain of people involved with the development of the system has already been mentioned. It is the interface mismatch between each link in the human chain that helicopter compensates for. At some stage each member of the chain must be presented with a clear picture of what is going on, what is actually required to be designed and built and when it is going to happen. The end user, the operator, must be confident that he is going to get exactly what the manufacturer has agreed he will get. There is no room for ambiguities and misinterpretation. How is this assured?

There are four essential tools required for the development of a distributed processor control and surveillance system. These can take many forms but their purpose remains the same. They are;

system specification

A document which defines the operational philosophy, the extent of the system, it's physical appearance and it's performance in terms of an operating system acting as a framework for some particular application. The document which describes the system.

data base

A document which details the system's application in terms of signals and data, their collection, connection, transmission, processing and display. The definition of what they are rather than how they are to be processed. The definition of what is normal and what is not; the definition of the relationships between voltages, currents and pressures, temperatures. The document which describes the boundary between the system and the outside (ship) world.

operational specification

A document which defines what the application processing does, the definition of automatic sequences and control algorithms, the definition of the performance of the system as far as the operator is concerned.

interface definition document

A document which relates the system to the "real world", it's connection to the other systems of the ship, the definition of where the signals are derived and where they are delivered to. The regrouping of signals under identifiable ship system names (such as main engine, steering gear, generators..) and the quality control scheme which prohibits unco-ordinated changes, and hence unauthorised changes, to the design of plant and system interfaces.

These four tools must be developed in parallel as the design progresses. Each relies on the others for it's own accurate interpretation and each has a unique value to those who use them. Like all tools they must be used properly and those responsible for them should exercise proper care and upkeep; terms which are synonymous with good quality control.

8. DAMAGE TOLERANCE

Damage tolerance is an essential consideration in a system as complex as that being described. The time at which the system will be called on to perform in anger is in the preparation stage prior to an incident (if adequate warning is given) and the period immediately after an incident in which minor system damage has occurred or in which major damage has been sustained by the vessel.

It is not easy or advantageous to seperate those signals and data associated with damage control functions from the shipwide control and surveillance system. The sheer numbers of signals involved and the efficiency and integrity with which they may be handled by a distributed processor type of system usually means there is no real practical alternative. Exceptions to this are made in practise such as signals associated with fire detection and gas detection systems but just how many of these systems have redundancy and fault tolerant features which would ensure their continued operation after a major incident?

There are simple rules which can be applied to maximise damage tolerance and these relate mainly to redundancy and separation. This not only applies to hardware in the general sense but also to the design of control schemes, for example, those which use multiple signal inputs. In this case the rule is to ensure that all signals in the same control scheme are collected by the same means. The situation to avoid is one in which some signals are cabled direct to the processor performing the control action while others are carried over a data bus. The result of not heeding this rule is usually the need for operator intervention at local level in the event of system type failures such as a data bus fault.

There is also the possibility of timing problems. Under normal operating conditions with the system operating correctly all data will be "current". The definition of current varies from system to system but as a guide this will mean sampled data will vary in age from about 0 to 3 seconds and maybe up to 5 or 6 seconds for processed data. Timing difficulties can arise when control algorithms do not, or can not, take account of varying time delays in received data. In a damage situation data update may not occur on a significant number of channels for a relatively long period. On some systems "old" data can exist without update indefinitely - when this occurs command signals are usually affected too and may reside in a system waiting for transmission at some later date. If all the data required by a control algorithm are relayed in the same way there is at least a chance of this part of the scheme failing in an orderly fashion.

The system failure mode in a damage situation can not be predicted therefore due regard needs to be paid to the role which the system will be expected to play in ensuring safe management of the vessel if the worst happens. The control and surveillance system must support personnel in the following way.

While everything is relatively normal the system should support rapid assessment of the ships present condition, rapid attainment of the desired ships condition and should continue monitoring to ensure the assessment is kept up to date.

When damage is sustained the system should support accurate assessment of damage, the formulation and implementation of effective measures to minimise the effects of this damage and subsequent restoration to near normal conditions if at all possible. The system should thereafter continue to monitor events as a means of confirming these measures are effective.

When attempting to carry out emergency repairs in the aftermath of a serious incident the system should support the co-ordination of repair efforts as far as possible.

The principle aim should be to gather and record as much status information as possible within the damage headquarters and main control areas while the system is working normally. Damage may result in the severing of vital data links and disparity in status displays in different areas. There is no practical system configuration which can guarantee this will not occur. The system can only provide greatest support under normal operating conditions.

It is possible to arrange that isolated sections of the system continue to operate for sufficient time to allow the most productive employment of manpower in the period immediately following an incident, but this time is limited. This is achieved by ensuring independence for operations by design of control arrangements and support services such as power supplies.

As the operating situation deteriorates the system can be expected to degrade and other means of recording and displaying status information must be employed, for example, a combination of verbal reporting and manually updated information boards. Care must be taken to ensure degradation is as graceful as possible and the method of transfer of data from the system display devices to the information boards should be designed for ease and accuracy.

As the system degrades through damage it becomes increasingly important to ensure that the displayed information is accurate. To meet this requirement data validation techniques must be employed. There may also be a need for the use of data base models of the plant with some level of inference so that the best picture is constructed from available data. This may mean that data be tagged according to it's confidence level both in terms of true status and age.

Some of these techniques can be found already in service in proven applications. One example is dynamically positioned vessels. The automation is usually carried out by a system of dual computers using position reference and environmental data to control propulsion plant and so enable the vessel to maintain station. Data validation is carried out and both computers maintain a complete model of the data and vessel characteristics so that in the event of a computer failure control reverts to the second computer without interruption and the system can still perform for a time on complete loss of reference data by reverting to the model.

9. FOR THE FUTURE

The rapidly changing technological environment in which we work will not permit a relaxation in the efforts to ensure complex control and surveillance systems are fit for purpose. The learning curve in the application of such systems seems to extend ever higher ahead of us no matter how much experience we seem to gather.

There is no doubt that an increase in power and capacity for such systems will occur in the future. The limitations of existing systems are generally associated with performance; how many work stations can be serviced simutaneously, how much data can be carried and processed. Performance is simply a measure of the speed at which data processing is carried out. The more data and the more processing, the slower the system operates. The most critical time for the vessel, when the system is required to work without failure or delay, may also be the time that the system works at the limit of it's capacity.

As processing speed increases and peripheral device speeds are increased to match, new opportunities will open up for these systems. The area in which the most striking changes will take place is, we feel, in the design of the MMI.

Systems of the future will bring the plant data into focus, permitting many more background processing activities to be performed in real time, thereby presenting the operators with many more opportunities for developing and testing control strategies. The operator will no longer have to restrict his activities to the mundane task of plant operation per se but will adopt a new role almost akin to that of the designer of present times who strives to optimise the performance of the ship as a whole.

It is difficult to predict what form the new MMI's will take but they will certainly incorporate much more processing of plant information and will not only provide checks on the accuracy of data received but will support the operator by prioritising displayed information. Operator actions would be based on recommendations generated by "intelligent" supervisory systems integrated in the MMI which would also check the operator response.

10. CONCLUSIONS

Ensuring fitness for purpose of distributed processor based control and surveillance systems requires good foundation work at the initial concept stage, effective communication of requirements and an overview of the role of the system in terms of the complete project. It also calls for a sensible balance between end user expectations and the constraints imposed by a particular system design.

These requirements are no different to those for any complex system. If they are ignored it may well result a perfect working system but one which is unsuitable for the application. This can compromise both safety and performance.

Fitness requires all concerned to be aware of the purpose; a clear statement of requirements including a consideration of the operational aspects, is essential. Personnel continuity throughout the project maintains a sense of direction.

One of the key considerations is that this type of system is not a replacement for traditional systems of indicators, controls and displays cabled directly to the plant. It is an alternative and it's use should be restricted to those applications and in those areas to which it is best suited.

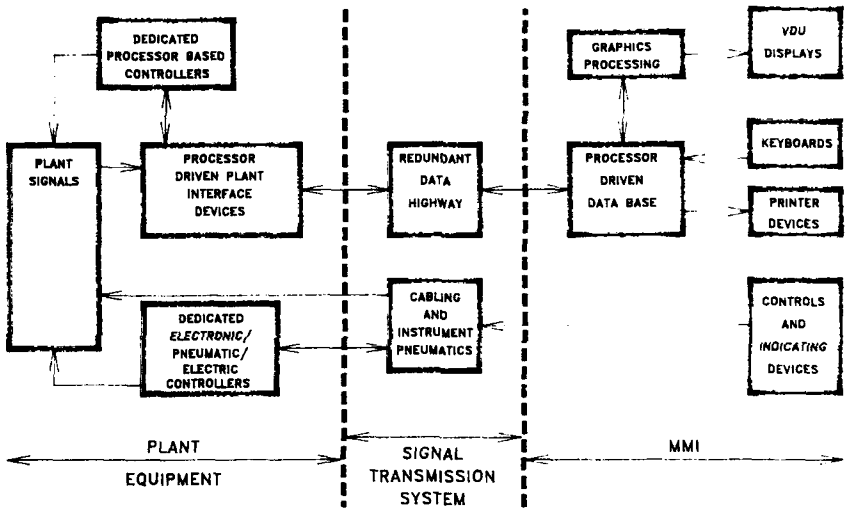

FIGURE 1.

THE SHIPWIDE CONTROL AND SURVEILLANCE SYSTEM UTILISING DISTRIBUTED PROCESSING – KEY ELEMENTS.

NOTE:

THE TRADITIONAL CONTROL AND SURVEILLANCE SYSTEM COMPRISING THE KEY ELEMENTS OF PLANT SIGNALS, CABLE AND INSTRUMENT PNEUMATIC TRANSMISSION SYSTEMS AND CONTROLS AND INDICATING DEVICES IS STILL AN ESSENTIAL PART OF MODERN SHIPWIDE SYSTEMS.

VESSEL TYPE	TOTAL NUMBER OF SIGNALS* HANDLED BY MCAS SYSTEM	MAIN MACHINERY CONFIGURATION	MCAS SYSTEM TYPE	MAIN CONTROL ROOM MANNING
NAVAL FLEET AUXILIARY	≈ 3000	TWIN MEDIUM SPEED DIESEL ENGINES, GEARBOX AND PROPELLERS. TWIN ELECTRIC POWER GENERATION AND DISTRIBUTION. CARGO HANDLING (LIQUID & SOLID)	PREDOMINANTLY SEQUENCING OF DIGITAL INPUT/OUTPUTS. VERY FEW PID CONTROL LOOPS. DEDICATED PROPULSION CONTROL PROCESSORS.	MINIMUM: 0 MAXIMUM: 7
LIQUID NATURAL GAS (LNG) CARRIER	≈ 1200	TWO LNG/OIL FUEL FIRED BOILERS, TWIN STEAM TURBINE SINGLE GEARBOX AND PROPELLER. TWIN ELECTRIC POWER GENERATION AND DISTRIBUTION. CARGO HANDLING (LNG).	HALF SEQUENCING OF DIGITAL INPUTS/OUTPUTS. HALF PID CONTROL LOOPS. DEDICATION PROPULSION CONTROL PROCESSORS.	MINIMUM: 0 MAXIMUM: 3
SEMI-SUBMERSIBLE DIVING SUPPORT AND OFFSHORE INTERVENTION	≈ 1200	MULTIPLE ELECTRIC THRUSTERS. TWIN ELECTRIC POWER** GENERATION AND DISTRIBUTION. DIVING/HEAVY LIFT.	PREDOMINANTLY SEQUENCING OF DIGITAL INPUT/OUTPUTS. VERY FEW PID CONTROL LOOPS. DEDICATED PROPULSION CONTROL PROCESSORS.	MINIMUM: 1 MAXIMUM: 3

* SIGNAL NUMBERS INCLUDE MMI (IF PROCESSOR DRIVEN) AND COMPUTED VARIABLES AS WELL AS ACTUAL INPUT/OUTPUT SIGNALS.
** TRIPLE ELECTRIC POWER SYSTEMS ARE ALSO COMMON.

FIGURE 2. COMPARISON OF APPLICATIONS FOR DISTRIBUTED PROCESSOR MACHINERY CONTROL AND SURVEILLANCE SYSTEMS.

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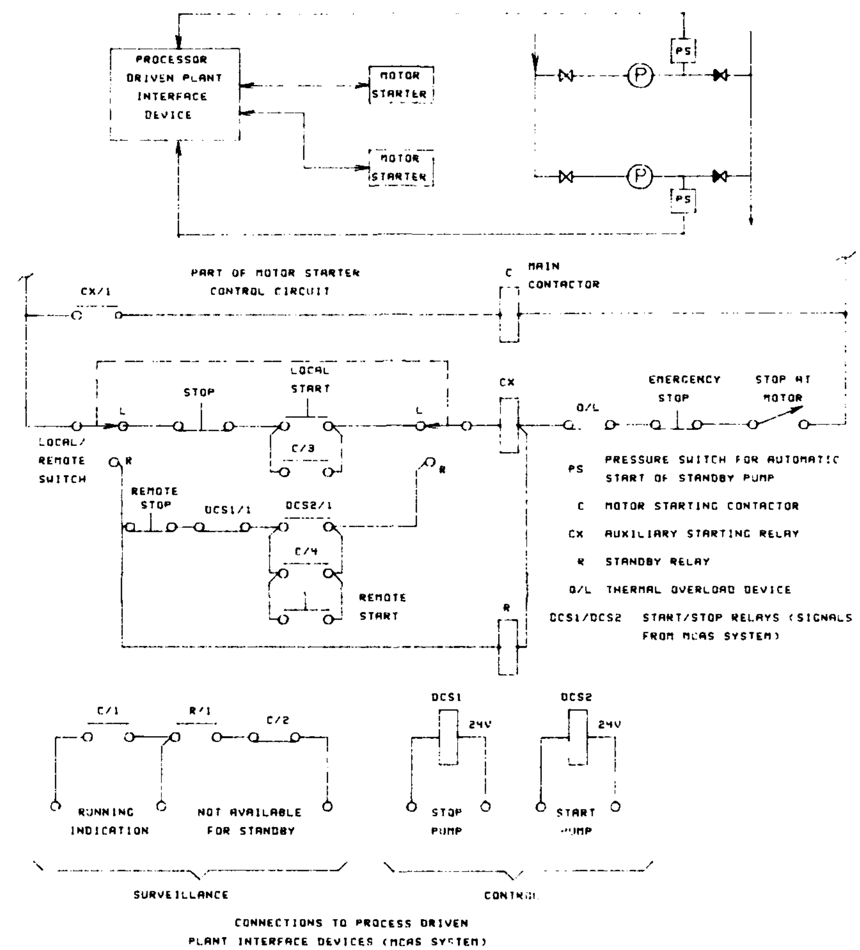

NOTE: STANDBY MODE CAN ONLY BE SELECTED AND MAINTAINED IF THE PUMP IS AVAILABLE (POWER AVAILABLE, SELECTED TO REMOTE CONTROL, OVERLOAD AND EMERGENCY STOP NOT OPERATED) THE NECESSARY CHECKS ARE IMPLEMENTED IN SOFTWARE USING THE "NOT AVAILABLE FOR STANDBY" SIGNAL.

FIG.3 TYPICAL STARTER INTERFACE DIAGRAM FOR PUMPS WITH STANDBY (AUTO 'CUT-IN') MODE, CONTROL AND STANDBY SELECTION FROM A VDU/KEYBOARD

THE USE OF A MATHEMATICAL MODEL IN A TRACK GUIDANCE SYSTEM.

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1. ABSTRACT

This paper describes part of an ongoing research program in automatic navigation and track guidance. In particular it looks at efforts to improve the accuracy of the mathematical model used in an integrated stystem which is to be used for navigation, guidance and collision avoidance. The paper commences with a brief description of the mathematical model and the state space equations developed from it. There then follows a description of the Kalman-Bucy filter being developed for use in a marine navigation system, together with the problems of accurately modelling a vessel in changing circumstances, when these circumstances affect the hydrodynamic coefficients upon which the model is based. It is then suggested that the accuracy of the model and indeed the inputs to it, which must be the same as the inputs to the actual system, are paramount to the use of filtering techniques in marine navigation. To overcome the problems of updating the model under operational conditions system identification techniques are introduced. This is achieved by augmenting the state vector by including sway and yaw coefficients derived from the hydrodynamic coefficients. This, in turn, involves extending the matix which represents the ship, but simplification methods are then introduced to reduce the computation times in the micro-processor based system used in the trials vessel. The paper goes on to explain the complete navigation and track guidance system, and concludes by discussing some of the results obtained, particularly where the technique has resulted in improvements in navigational accuracy.

2. INTRODUCTION

Chudley et al [1] formulate a mathmatical model and outline an application in marine simulation. Similiar models can be used to improve navigation of a vessel at sea, or perhaps more importantly, while operating in confined waters; if this leads to improved accuracy of navigation it increases the safety margins of shipping using narrow channels and port approaches. Research at Polytechnic South West has been concerned with integration of navigation data with mathematical models using Kalman filtering techniques, a technique which is already established in the aerospace industries, and in some specialised maritime applications such as dynamic positioning systems where navigational accuracy requirements dictate the need for precise measurements. For the average merchant vessel however, carrying typically less accurate systems giving a position fix with a random error of between 100 metres and 1 kilometre, forward speed through the water with a random error of 0.1 knots, and a heading to the nearest degree, improvements to navigation accuracy through integration are not so readily available, and may not be necessary. Work by Kalman and Bucy [2] targeted at the aerospace industry, showed how independant estimates of the state of a system can be combined to give the most probable, or minimum variance, estimate. This terminolgy implies a statistical inference, indeed the process assumes that random errors within the measurement systems are Gaussian and the standard deviations known. Dove [3] demonstrates the application of Kalman filtering to marine navigation, combining state estimates from measurements with those from a mathematical model. Trials conducted in simulation show promising results. In this work, however the model used to represent the vessel is also used within the filter. Any deviation between the two, or inclusion of an external forcing function, may lead the optimal estimate to stray from the true value. This suspicion was confirmed by tests conducted using data collected on board a vessel in the Solent (UK) [4]. Later studies directed towards overcoming these difficulties have included afloat trials in the Polytechnic's catamaran and current work involves the use of a 2000 tonne vessel engaged in the European coastal trade. The ship model which forms an integral part of the Kalman filter, and hence a part of the overall track guidance system, is formulated in three degrees of freedom. Central to the goodness of the model is the derivation of a set of coefficients which describe the motion of the vessel under consideration.

3. THE MATHEMATICAL MODEL

The model used in this investigation is based upon a Eulerian set of equations of motion. The forces and moments are derived in the usual way, as originally given by Abkowitz [5], with a modular approach as presented by Tapp [6] for use in marine simulation. Forces and moments are decomposed into contributions associated with the system elements, for example hull, propeller, rudder and disturbance terms. X and Y are the forces of surge and sway and N is the yaw moment, x, y and ψ are the corresponding displacements of the vessel and u, v and r are their derivatives. The rudder angle is denoted by δ, the propeller revolutions by n and the vessel moves on a grid (x_0, y_0) defined on the earth's surface, where x_0 is the direction of true North, giving a reference from which heading (ψ) is measured.

In order to model the behavior of the hull it was first necessary to evaluate the derivatives used in the equations of motion. These hull constants are termed hydrodynamic coefficients and are usually obtained by conducting controlled tests on a scale model in a towing tank. Full-scale trials can be performed, but satisfactory control of the trials is difficult due to unknown forces such as wind, tide and current acting on the vessel and these results are more frequently used to validate the coefficients obtained from model tests. There are also some theoretical methods available for coefficient evaluation. Korvin-Kroukovsky [7] developed a method whereby the vessel's length is divided into strips; each strip is then treated as a buoyant cylinder of equal area, a form which has been well researched and coefficients established. Integration along the length of the vessel then gives some of the coefficients, originally those in heave, pitch and roll. The technique has been extended by Clarke [8] to include sway and yaw. This method is widely used by those concerned with ship handling, an application in which operators are not concerned with cycle time of the program, whereas one of the constraints of filtering is that the model must run in real time with a rapid update rate. This is particularly critical as the filtering theory used to date assumes that the system is linear between sampling intervals. Clarke [8] has evaluated sway and yaw coefficients for a number of vessels using towing tank and rotating arm test data and then, by regression analysis, produced formulae for evaluation of the linear coefficients directly from vessel dimensions of length, beam, displacement and block coefficient.

4. THE STATE EQUATIONS

Addition of first order differential equations to represent the steering gear and main propulsion, followed by rearrangement of equations of motion such that u, v and r are expressed in their canonical form, yields equation set (1). $X_1 \ldots X_8$, $Y_1 \ldots Y_8$, and $N_1 \ldots N_8$ are derived from the vessel's hydrodynamic coefficients.

$$\begin{bmatrix} \dot{\delta}_A \\ \dot{n}_A \\ \dot{x} \\ \dot{u} \\ \dot{y} \\ \dot{v} \\ \dot{\psi} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \frac{-1}{T_R} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{-1}{T_N} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ X_1 & X_2 & 0 & X_4 & 0 & X_6 & 0 & X_8 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ Y_1 & 0 & 0 & Y_4 & 0 & Y_6 & 0 & Y_8 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ N_1 & 0 & 0 & N_4 & 0 & N_6 & 0 & N_8 \end{bmatrix} \begin{bmatrix} \delta_A \\ n_A \\ x \\ u \\ y \\ v \\ \psi \\ r \end{bmatrix} + \begin{bmatrix} \frac{-1}{T_R} & 0 \\ 0 & \frac{-1}{T_N} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_D \\ n_D \end{bmatrix} \qquad (1)$$

The eight first order differential equations are used to define the ship and can be can be written in matrx form as

$$\dot{\mathbf{x}}(t) = \mathbf{F}(t)\mathbf{x}(t) + \mathbf{G}(t)\mathbf{u}(t) \tag{2}$$

where **F** is the continuous time system matrix representing the ship. When tide, wind and current have to be considered it is convenient to partition the forcing matrix **G** into the control and disturbance forcing functions $\mathbf{G}_c$ and $\mathbf{G}_D$, giving

$$\dot{\mathbf{x}}(t) = \mathbf{F}(t)\mathbf{x}(t) + \mathbf{G}_c(t)\mathbf{u}(t) + \mathbf{G}_D(t)\mathbf{w}(t) \tag{3}$$

where **x(t)** is the state vector, **u(t)** is the control vector, and **w(t)** is the vector of disturbances. Integration of equation (3) yields the corresponding discrete solution

$$\mathbf{x}(k+1) = \mathbf{A}(k,k+1)\mathbf{x}(k) + \mathbf{B}(k,k+1)\mathbf{u}(k) + \mathbf{C}(k,k+1)\mathbf{w}(k) \tag{4}$$

where the matrices **A**, **B** and **C** can be obtained from:

$$\begin{aligned} \mathbf{A}(k,k+1) &= e^{\mathbf{F}(t)T} \\ \mathbf{B}(k,k+1) &= (e^{\mathbf{F}(t)T} - I)\mathbf{F}(t)^{-1}\,\mathbf{G}_c(t) \\ \mathbf{C}(k,k+1) &= (e^{\mathbf{F}(t)T} - I)\mathbf{F}(t)^{-1}\,\mathbf{G}_D(t) \end{aligned} \tag{5}$$

5. A FILTER FOR MARINE NAVIGATION AND GUIDANCE

While the vessel's position is of primary importance for marine navigation, the state of the vessel is likely to be passed to a control algorithm for track keeping. Further requirements thus comprise accurate heading to maintain course, and velocity information for feedback, or damping, of the control loop. The system process for the vessel described in equation (1) is tailored to suit these additional requirements. The system is not driven by white noise but by a deterministic control vector and noisy disturbances. Control is assumed to be stable and disturbances are taken as Gaussian processes with a non zero mean.

The theory of the Kalman-Bucy filter is well established and the equations used in the research described in this paper are given by Miller [10]. The filter used in the marine navigation problem is an extended Kalman filter. That is the non-linear system process is linearized about the most recent optimal estimate, while the measurement process is linear and the errors are Gaussian. As a ship constitutes a non-linear system, when parameters such as large alterations of course and/or speed, shallow water effects, and trim are considered there must be some limitation to the technique. The linearization process assumes constant course and speed during each sample period. This is reasonable provided sample times are small when compared with such factors as ship time constants and time between waypoints. A block diagram of the filter is shown in figure 1. The filter quations are used recursively to obtain the state estimate at a future sampling.

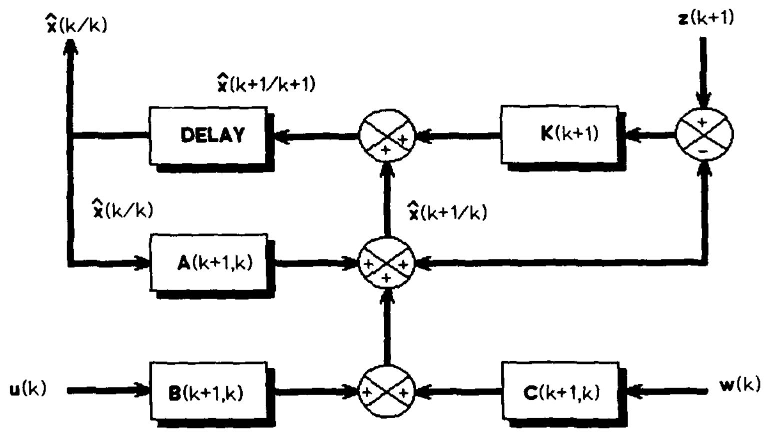

Figure 1. Block Diagram of the Optimal Filter.

Improvements can be made to the speed of the filter algorithm by considering the manner in which the equations are used. Figure 2 shows an iterative loop which commences each cycle by taking a measurement, initiates the covariance to the identity, then computes the Kalman gain and its error covariance. The iterations are used to obtain convergence of the filter. An improvement on this technique can be made by changing the order of these operations. In practice the system error covariance and Kalman gain can be computed prior to performing the measurement process. During this time the computer may well be idling, while awaiting the signal to initiate the measurement cycle, so a saving may be made in computer time. Furthermore, by computing the initial error covariance less iterations may be required.

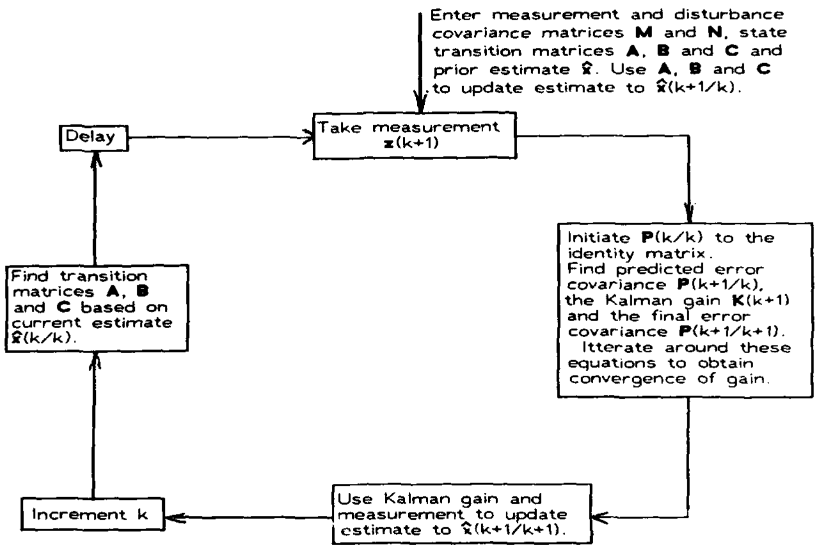

Figure 2. The Kalman Filter Loop.

6. SYSTEM IDENTIFICATION

Much has been written of the difficulties of obtaining an accurate mathematical model of a ship. Experience has shown however that a good mathematical model is required in a maritime optimal track guidance system, and the accuracy of the filter is still further improved if it acquires both control and disturbance inputs, even though the disturbance inputs may only be estimate of the true values. There is the additional problem of changing hydrodynamic coefficients as circumstances change. For example, as the underwater surface of the hull is fouled with growth, when the vesel enters shallow water after an oceanic passage, or when the velocity is changed. This means that the X, Y, and N values in the system matrix will require updating. This may be difficult during routine commercial operations. It certainly would do little to enhance the sale of a filter based integrated navigation system if the potential owner were informed that the vessel would have to be periodically taken out of service to update the model. Established techniques for parameter identification, based upon various optimization criteria, would require new algorithms to be included into the Kalman filter recursive loop. These methods are usually time consuming and consequently are unsuitable for real-time applications. However Gelb (11) proposes a method which can be easily implemented into the existing Kalman filter loop. This method has been applied to the track guidance system under development, optimizing parameters on the minimum variance estimation algorithms already in use.

6.1 Augmenting the State Vector

Let the unknown parameters be denoted by a vector **a**, having dynamics defined by the differential equation:

$$\dot{\mathbf{a}} = \mathbf{0} \qquad (6)$$

with non-linear equations of motion, the system process can now be written:

$$\dot{\mathbf{x}} = \mathbf{f}(\hat{\mathbf{x}},\mathbf{a}) + \mathbf{G}\mathbf{u} \qquad (7)$$

where both **a** and $\hat{\mathbf{x}}$ are to be estimated from the noisy measurement data. Combining **x** and **a** into a composite state vector denoted $\mathbf{x}^*$ such that:

$$\dot{\mathbf{x}}^* = \left[\frac{\dot{\mathbf{x}}}{\mathbf{a}}\right] = \left[\frac{\mathbf{f}(\mathbf{a},\hat{\mathbf{x}}) + \mathbf{G}\mathbf{u}}{\mathbf{0}}\right] \qquad (8)$$

and applying this system process to the extended Kalman filter routine yields estimates for both states and unknown parameters.

6.2 The Modelling Process

Selecting the vector **a** to contain hydrodynamic coefficients for the vessel gives a large dimension augmented state vector and a large transition matrix. This formulation would then lead to cumbersome computations, defeating one of the prime objectives of this research. Furthermore, due to cross coupling, some coefficients cannot be isolated and are therefore unidentifiable. An alternative method was suggested by Robbins [12] who applied this method of parameter identification to aircraft, but used simplified mathematical models. To perform the identification process the system process was reduced to smaller components and controlled manoeuvres were performed. Then, assuming certain cross-coupling terms to be negligible under the control applied, for example when applying rudder to the aircraft surge and sway terms only are considered and the induced roll is neglected, a small number of parameters can be identified from each manoeuvre.

It is not economically viable to attempt to identify slowly varying parameters while on a voyage as the vessel may be delayed at great expense during identification manoeuvres. Furthermore, in order to keep the dimensions of the augmented state vector to minimum, maintain identifiability of parameters and to retain sparse population of the transition matrix it is necessary to identify the components of the latter directly. Initially only sway and yaw terms are considered, as these use the least accurate coefficients and were seen to give poorer results than the surge term. The augmented state vector can be written as:

$$\mathbf{x}^{*} = (\ \delta,\ n,\ x,\ u,\ y,\ v,\ \psi,\ r,\ Y_1,\ Y_4,\ Y_6,\ Y_8,\ N_1,\ N_4,\ N_6,\ N_8\ )^{T} \tag{9}$$

where the augmented parameters are shown in equation (1). These constants are dependent on the vessel states, and hence, assuming a slow transition time of the vessel in comparison to cycle time of the Kalman recursive loop, the parameters to be identified may be taken as having dynamics given by equation (6). The state transition matrix $\mathbf{F}^{*}$ is now of dimension 16 x 16, as shown in equation (10).

$$\mathbf{F}^{*} = \left[\begin{array}{cccccccccccccccc}
1/T_R & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1/T_N & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
X_1 & X_2 & 0 & X_4 & 0 & X_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\hat{Y}_1 & 0 & 0 & \hat{Y}_4 & 0 & \hat{Y}_6 & 0 & \hat{Y}_8 & \hat{\delta} & \hat{u} & \hat{v} & \hat{r} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\hat{N}_1 & 0 & 0 & \hat{N}_4 & 0 & \hat{N}_6 & 0 & \hat{N}_8 & 0 & 0 & 0 & 0 & \hat{\delta} & \hat{u} & \hat{v} & \hat{r} \\
\hline
\multicolumn{8}{c|}{\mathbf{0}_8} & \multicolumn{8}{c}{\mathbf{0}_8}
\end{array}\right] \tag{10}$$

where $\mathbf{0}_8$ is the zero matrix of dimensions 8 x 8.

Writing this as a partitioned matrix of 4 sub-matrices, each of 8x8 dimension:

$$\mathbf{F}^{*} = \left[\begin{array}{c|c} \mathbf{F} & \mathbf{E} \\ \hline \mathbf{0} & \mathbf{0} \end{array}\right] \tag{11}$$

The original 8 states of the system process are still described by equation (1). The discrete transition matrix is then given in partitioned form by:

$$\mathbf{A}^* = \left[\begin{array}{c|c} \mathbf{A} & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{I}_8 \end{array}\right] \tag{12}$$

where $\mathbf{I}_8$ is the identity matrix of order 8, and $\mathbf{A}$ is the discrete solution to $\mathbf{F}$.

6.3 The Measurement Process

The original eight states of the measurement vector can be obtained as before but the augmented states are not measured. Y_1, Y_4, Y_6, Y_8, N_1, N_4, N_6 and N_8 can be obtained from the previous optimal estimates. The revious set of values for the sway and yaw coefficients are used in an iterative manner to obtain new values as given in equation set (13a). Solutions for the equations should be iterated to obtain convergence.

$$\begin{aligned}
Y_1 &= \frac{-Y_4 u - Y_6 v - Y_8 r}{\delta} \\
Y_4 &= \frac{-Y_1 \delta - Y_6 v - Y_8 r}{u} \\
Y_6 &= \frac{-Y_1 \delta - Y_4 u - Y_8 r}{v} \\
Y_8 &= \frac{-Y_1 \delta - Y_4 u - Y_6 v}{r} \\
N_1 &= \frac{-N_4 u - N_6 v - N_8 r}{\delta} \\
N_4 &= \frac{-N_1 \delta - N_6 v - N_8 r}{u} \\
N_6 &= \frac{-N_1 \delta - N_4 u - N_8 r}{v} \\
N_8 &= \frac{-N_1 \delta - N_4 u - N_6 v}{r}
\end{aligned} \tag{13a}$$

The measurement matrix can thus be written

$$
\mathbf{h} = \left[\begin{array}{c|cccccccc}
\mathbf{X} & & & & \mathbf{0} & & & & \\
\hline
 & 0 & -\frac{u}{\delta}Y_4 & -\frac{v}{\delta}Y_6 & -\frac{r}{\delta}Y_8 & 0 & 0 & 0 & 0 \\
 & -\frac{\delta}{u}Y_1 & 0 & -\frac{v}{u}Y_6 & -\frac{r}{u}Y_8 & 0 & 0 & 0 & 0 \\
 & -\frac{\delta}{v}Y_1 & -\frac{u}{v}Y_4 & 0 & -\frac{r}{v}Y_8 & 0 & 0 & 0 & 0 \\
 & -\frac{\delta}{r}Y_1 & -\frac{u}{r}Y_4 & -\frac{v}{r}Y_6 & 0 & 0 & 0 & 0 & 0 \\
\mathbf{0} & 0 & 0 & 0 & 0 & 0 & -\frac{u}{\delta}N_4 & -\frac{v}{\delta}N_6 & -\frac{r}{\delta}N_8 \\
 & 0 & 0 & 0 & 0 & -\frac{\delta}{u}N_1 & 0 & -\frac{v}{u}N_6 & -\frac{r}{u}N_8 \\
 & 0 & 0 & 0 & 0 & -\frac{\delta}{v}N_1 & -\frac{u}{v}N_4 & 0 & -\frac{r}{v}N_8 \\
 & 0 & 0 & 0 & 0 & -\frac{\delta}{r}N_1 & -\frac{u}{r}N_4 & -\frac{v}{r}N_6 & 0
\end{array}\right] \qquad (13b)
$$

where **X** is an 8 x 8 diagonal matrix with diagonal elements equal to the corresponding elements of the state vector. Then for the computation of the Kalman filter gain:

$$
\mathbf{H} = \left.\frac{\partial \mathbf{h}}{\partial \mathbf{x}^*}\right|_{\mathbf{x}^* = \hat{\mathbf{x}}^*}
$$

6.4 Filtering

The filter must be modified to account for the additional terms included in the processes above. In order to estimate the prediction error covariance and hence the Kalman gain, $\mathbf{A}^*$ should *incorporate the entire matrix* $\mathbf{F}^*$:

$$
\mathbf{A}^* = \left[\begin{array}{c|c} \mathbf{A} & \mathbf{D} \\ \hline \mathbf{0} & \mathbf{I}_8 \end{array}\right] \qquad (14)
$$

The matrix **D** can then be obtained in a similar way to the discrete control and disturbance matrices and is then given by:

$$
\mathbf{D} = (e^{\mathbf{F}(t)T} - \mathrm{I})\mathbf{F}(t)^{-1}\mathbf{E} \qquad (15)
$$

The Kalman gain matrix, which now has dimensions 16 x 16, is computed as shown by Gelb [11].

7. CONTROL AND GUIDANCE

The theory of an optimal multi-variable control system has been developed to control simultaneously position and velocity of the vessel, and tested in simulation by Burns [13]. Deviation from the desired values were corrected by operation of the rudders and main engines. The cost function **(J)** is based upon the summation of the weighted errors over some time interval, perhaps over one stage of the voyage. In addition to minimise the errors in the output parameters, the optimal controller must also attempt to minimise the control effort, that is to minimise rudder and main engine activity. The cost function is normally stated in the following quadratic terms:

$$\mathbf{J} = \int_{t_o}^{t_1} \{ (\mathbf{x}-\mathbf{r})\ \mathbf{Q}\ (\mathbf{x}-\mathbf{r}) + \mathbf{u}\ \mathbf{R}\mathbf{u} \}\ dt \qquad (16)$$

where **r** is the desired state vector and **Q** and **R** are usually diagonal matrices, with the values of the individual elements reflecting the importance of the parameters being controlled.

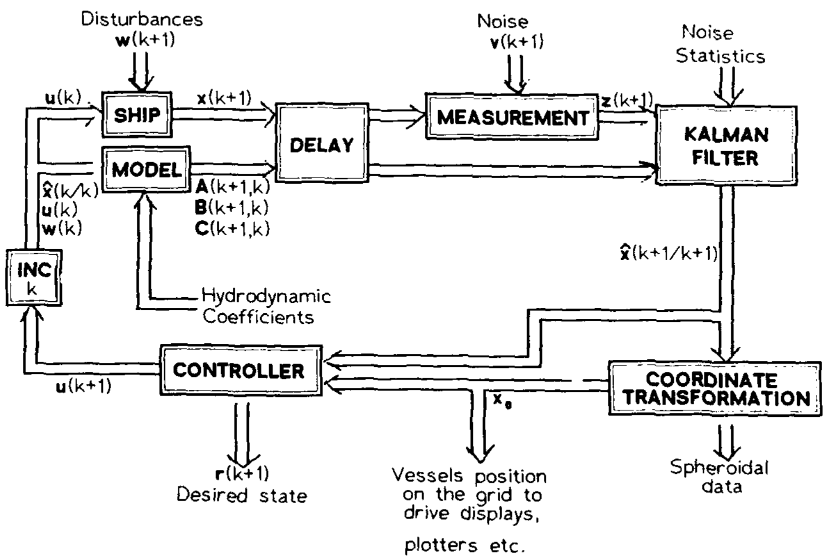

Figure 3. The Complete Integrated Navigation and Control System

An initial requirement of the controller is the desired state **r** at each sample time. This is obtained by entering a series of waypoints into the computer. In practice waypoint position is entered through the keyboard using either a cursor on the chart display driven by the arrow keys, or by typing in co-ordinates using the alpha-numeric keys. The program assumes that each pair of waypoints alternately define a straight line followed by a curve. Thus taking the first waypoint as the starting point, the second is the "wheel over" position at the start of the arc required to reach waypoint three. On reaching this point, the vessel is required to be on a steady course to waypoint four which is the next "wheel over" position and so on. With each waypoint either a speed for that leg of the passage or an estimated time of arrival is entered, so the desired state of the vessel can be computed at each sample time prior to starting the voyage. The overall integrated navigation system is shown as a block diagram in figure (3)

8. RESULTS AND CONCLUSIONS

Data sets used in earlier work were rerun using the filter algorithm with system identification. The overall track plot for a passage in to Plymouth showed a significant improvement. Part of a typical plot is shown in Figure (4), from which it can be seen that the filtered track follows closely the true position of the vessel. Figures 5 and 6 show the identified system coefficients. The rudder terms Y_1 and N_1 are seen to be noisy. These terms would be expected to reduce to zero when travelling in a straight line and increase during the use of rudders in a turn, which is seen to occur. Further noise is probably due to noisy rudder measurements. Y_4 and N_4, the surge terms are close to zero. These terms influence the turning characteristics with speed and over the 6 to 7 knot speed range used during the trial have little influence.

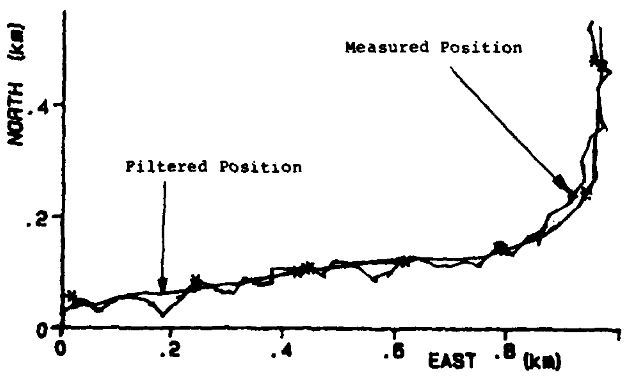

Figure 4. Comparison of Measured, Filtered and True Positions.

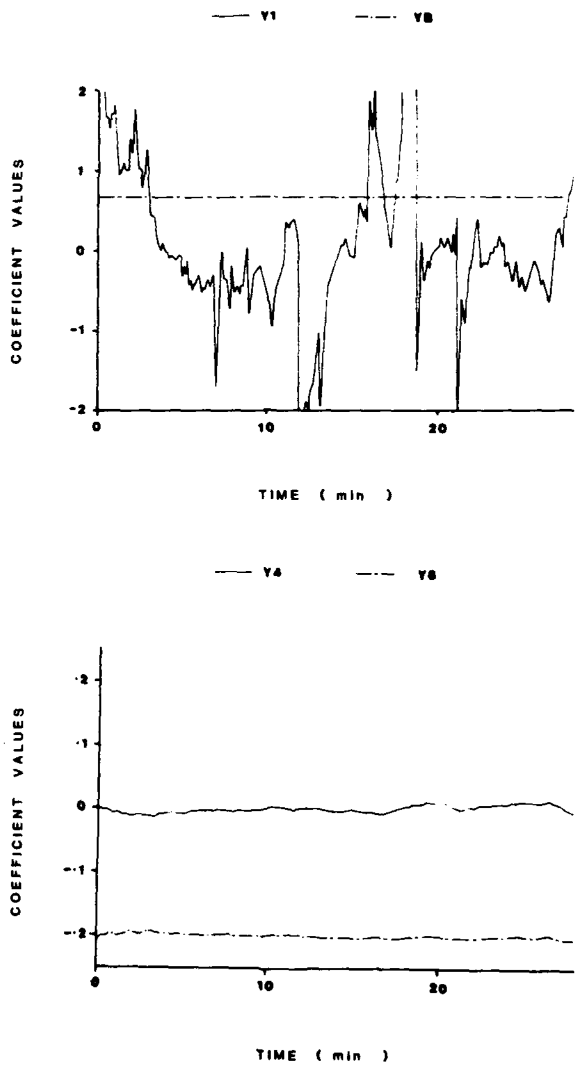

Figure 5. Sway System Coefficients.

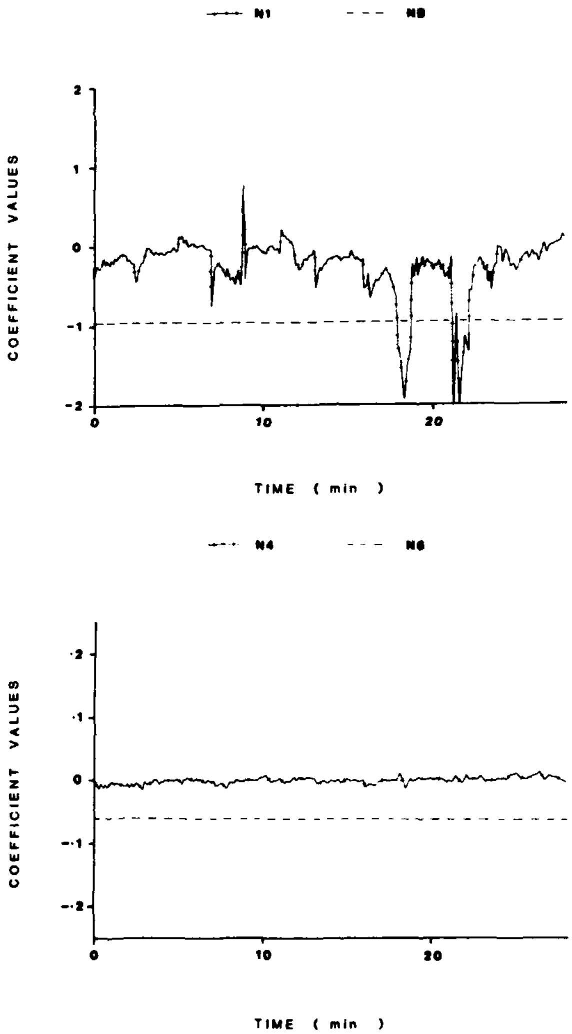

Figure 6. Yaw System Coefficients.

A technique to overcome coefficient inaccuracies and variations by incorporating them in to the state vector has been introduced. Trials were undertaken for sway and yaw terms only as these were considered to be the most inaccurate and widely varying, but the method can also be applied to the surge terms. Trials to this end are now being undertaken. Resulting track plots of filtered position showed the vessel to remain within 20 metres of the demanded track. The filtering algorithm in use is intended to cope with random errors only, and fixed errors must be evaluated and either removed prior to filtering, or an allowance must be made for them. In this way the noise reduction achieved is a better assessment of performance. The ability of the system to maintain a position central to the noise of the position fixing system, in this case a Decca Navigator was used because it gave the best coverage of the approaches to Plymouth at the time the trials were undertaken , demonstrated that the filter was producing accurate outputs of displacement in the three degrees of freedom considered. It was shown previously [14] that inaccuracy in one, or all, of these outputs led to drift from true track. As values for velocity are fed back into the modelling process, any inaccuracy in their estimates leads to cumulative errors in the displacement outputs. The turn rate does however remain noisy and an improvement could be achieved by the use of a gyro input, which was not available in the test vessel. Finally the filtered output was fed to a control algorithm. Optimal control theory was used to establish the control parameters to maintain the vessel on track, in both along-track and across-track directions.

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AUTOMATIC BERTHING BY THE NEURAL CONTROLLER

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1. ABSTRACT

The neural network controller for the berthing problem of the ship is discussed in this paper. The three-layered neural network is used to shape the controller and the weights and threshold of each unit are determined by the error back propagation algorithm with the pre-obtained teaching data. The controller has two neural networks which are used in near and far fields respectively, based on the precision required in each field. The controller is presented on the personal computer, and simulations to examine the performance are made on it. In spite of many theoretically inarticulate particulars, simulations show the prospective capability for the berthing control.

2. INTRODUCTION

The berthing is one of the most difficult manipulation of the ship. As the speed is small and disturbance due to winds and currents become relatively big, control devices are not so effective any more. However, very precise control is necessary especially for not colliding the ship to the berth. As the ship motion and control effectiveness is very difficult to represent in terms of the differential equation, the conventional design method for the feedback controller is not easily applicable for this problem(1).

In spite of difficulties, the human operator is very successful to make a safe berthing. The captain determines the control outputs to the ship by processing data such as the velocity, acceleration, distance between ship and berth, winds, currents, environmental restrictions and others as input. It could be expressed as the very complicated input-output relation between ship's state and the applicable control.

Recently, the neural network is applied to various kinds of engineering problems. In the field of the letter recognition, the neural network gives good results. The neural network provides a letter according to the pattern. Similarly, the ship's state is taken into the neural network controller as a pattern, and the network provides the control. The network makes a device to change the state into control which is made by the human operator at present.

In this paper, the neural network berthing controller for the 154,000-ton tanker is presented. Although there are several applications (2-5) of the neural network to the ship control, it has not been applied to the berthing problem. The neural network used here is still primitive and only the basic berthing patterns are illustrated. However, the simulation shows the prospective ability of the neural controller for the berthing.

3. THE BERTHING AND THE NEURAL NETWORK(6, 7)

3.1 The berthing procedure

The berthing procedure is summarized in Figure 1. The ship approaches to the berthing spot in a slow approaching speed. The ship reduces the speed and changes the course first by rudder and later by side thrusters. The ship must stop at the berthing spot with almost zero position and heading errors. Actually, the lateral speed should be small enough not to damage both the ship and the berth. This is the most typical and basic control for the berthing. If there are winds and currents, the control would be more complicated.

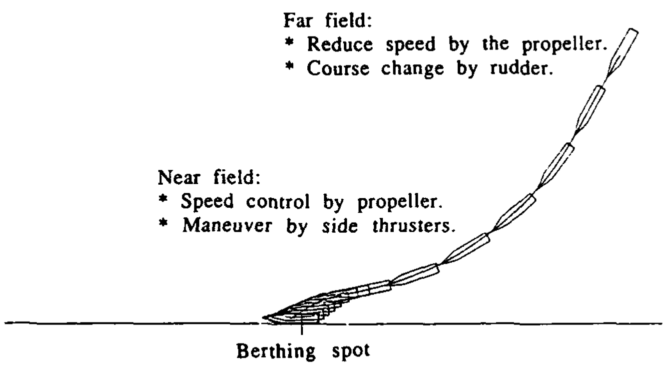
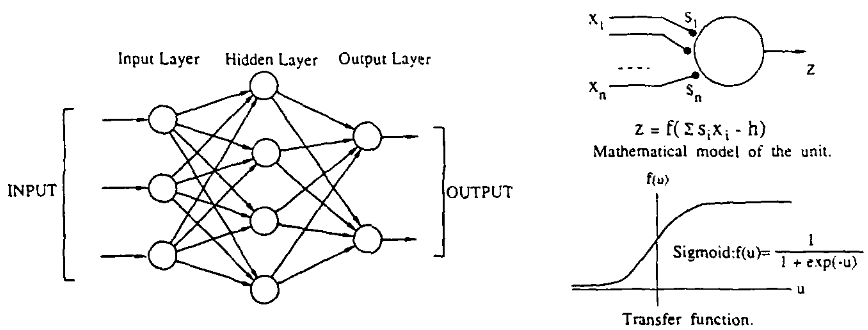


Figure 1. Berthing procedure.

3.2 The neural network

a. Configuration and units. The typical neural network is shown in Figure 2(a). Of course, more complicated network can be used. The input is a state of the ship and output is the control for the ship. The neural controller gives the control according to the state of the ship. Each unit has its own input-output characteristics represented by weights of the connection, s_i, thresholds, h, and transfer function as shown in Figure 2(b). Input to the unit is expressed in the weighted sum of the inputs from the connected upstream units and the threshold. Output signal is determined by the nonlinear transfer function to the input. Once the weights and thresholds are determined, the neural controller provides the control output according to the ship's state.

b. Learning. Weights and thresholds in the network are determined by learning the teaching data. Teaching data are carefully collected set of the input-output relations which the neural network should follow. Weights and thresholds are determined to minimize the error defined by the output difference between the teaching data and neural network output to the same input. The process is called learning. It is not necessary to learn all the data the ship may face, the neural controller will have the ability to interpolate or extrapolate if it has learned enough data. Some algorithms are proposed for this purpose, the error back propagation is applied in this paper. The error back propagation is an iteration method similar to the method of the steepest descent as summarized in Figure 3. The error is defined in Equation (1). Weight increment at the (p+1)th iteration is shown in Equation (2). The weight can be obtained from the output layer to upstream units. If the type and size of the network and teaching data are given, the procedure to shape the network is rather clear. What type and size of the network, what the teaching data should be are the biggest problems to be solved. They should be determined from the nature of the problem and precision required for the network. There is no advisable guide for the problem. In this paper, simple three-layered network is used and the size of the network is determined by the resolution requirement for the teaching data as described in the following section.



(a) Three-layered network.

(b) Mathematical model for the unit and the transfer function.

Figure 2. The neural network.

Error : $$E = \frac{1}{2} \sum_{i} (d_i - o_i)^2 \qquad \cdots\cdots\cdots (1)$$

Weight increment at the (p+i) th iteration :

$$\Delta W_{j\ i}^{k-1\ k}(p+1) = \eta\, \delta_i^k\, o_j^{k-1} + \alpha\, \Delta W_{j\ i}^{k-1\ k}(p) \qquad \ldots\ldots(2)$$

Where

$$\delta_i^k = (d_i - o_i)\, f'(i_i^k) \qquad \cdots\cdots(3)$$

for output layer , and

$$\delta_i^k = \left(\sum_n \delta_n^{k+1} W_{i\ n}^{k\ k+1} \right) f'(i_i^k) \qquad \cdots\cdots(4)$$

for middle layer .

<u>Notations</u>

d_i : Teaching data of i–th unit of the output layer.
o_i : Neural network output of i–th unit of the output layer.

i_i : Neural network input of i–th unit of the output layer.

$w_{j\ i}^{k-1\ k}$: Weight of connection of j–th Unit in (k–1) th layer and i– th unit in k–th layer.

o_j^{k-1} : Output of the (k–1) th unit of j–th layer.

α . η : Acceleration factors.

f , f ': Transfer function and its derivative.

Figure 3. The error back propagation algorithm.

4. THE NEURAL CONTROLLER FOR BERTHING

In this section, the neural controller for berthing is described.

4.1 154,000 ton tanker

The neural controller for the 154,000 ton tanker is presented in this paper, as the dynamics of the type ship in slow speeds were obtained in detail by model experiments by Kose et al[8]. The principal particulars of the ship is summarized in Table 1. The ship has bow and stem thrusters in addition to the propeller and the rudder. To describe the motion of the ship in very low speeds, many mathematical models are proposed. In this paper, the mathematical model proposed by Kose et al[8] was employed. The detailed discussion on the equations are described in APPENDIX.

4.2 Composition of the neural controller

<u>a. Phases 1 and 2.</u> The area where the neural controller works is shown in Figure 4. The area is divided into far and near fields from the berth. In the far field called Phase 1, the ship is controlled by the propeller and the rudder. On the contrary, in

HULL	type	Tanker
	Lpp	262m
	B	45m
	d	15m
	Δ	154,000 ton
	Cb	0.827
PROPELLER	Diameter	7.3m
	Pitch ratio	0.607
	Number of blades	5
RUDDER	Area	72.81m ^{2}
	Aspect ratio	1.709

Table 1. Principal particulars of the ship.

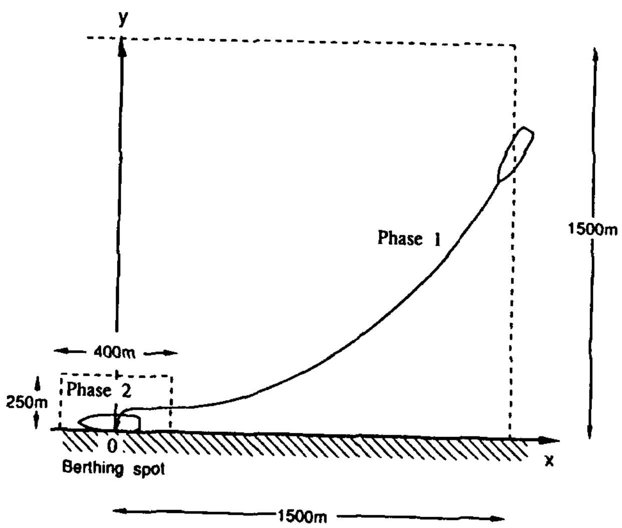
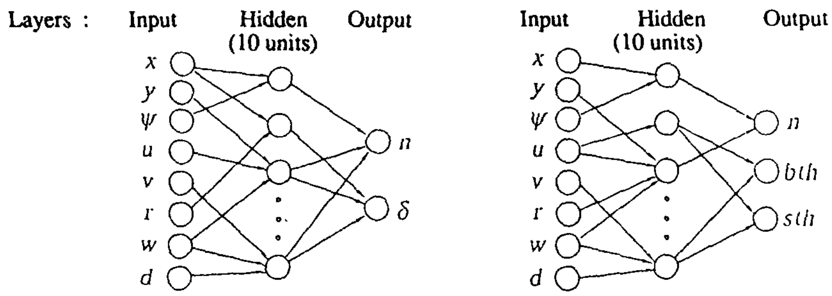


Figure 4. Control area and coordinates.



(a) The Phase 1 controller

(b) The Phase 2 controller

Notations

(x , y) : position of the ship, Ψ : Heading of the ship
(u , v , r) : Linear and angular speeds with respect to body fixed cords.
(w , d) : Wind speed and direction., n : Propeller rps. , δ : Rudder deflection.
bth : Bow thruster force. , sth : Stern thruster force.

Figure 5. Configuration of the neural controller

the near field called Phase 2, two side thrusters are mainly used and supported by the propeller. As the field becomes bigger, the error at the berthing spot may become bigger. If one controller is used in whole field, a big network may be necessary to achieve sufficient accuracy. However, if the field is divided into two parts, two moderate sized networks will suffice.

b. The neural controller. The three-layered neural network is used as shown in Figure 5. The input layer includes eight units, that is, the position of the ship, x and y, the heading, ψ, linear and angular velocities, u, v and r, speed and direction of the wind, w and d. As for the output, the propeller rps, n, the rudder deflection, δ, for the Phase 1, the propeller rps, n, the thrust of the bow and side thrusters, bth, sth are for the Phase 2.

c. Hidden layer sizing. Presently, there are no instructive guidelines to estimate how many hidden units are necessary. In this paper, the number of hidden units is determined as follows. The sigmoid transfer function is used and it is considered continuous form of binary function. As the outputs of hidden units are nearly binary, N hidden units can represent 2^N different patterns in the hidden layer. Therefore the number of hidden units which can distinguish P patterns is $\log_2 P$. The maximal number of teaching data used in the Phases 1 and 2 is 130. The number of the requested hidden units is eight, for $\log_2 130 = 7.02$. Ten hidden units are thought to be enough in both Phases 1 and 2.

4.3 Teaching data

Teaching data are obtained by the simulation on the personal computer NEC PC-9801 RX with using the simple manual controller. The manual controller was connected through the A/D converter. The manual controller has four volumes which correspond with the propeller, the rudder, and two side thrusters. One of authors made teaching data by himself.

a. Phase 1 teaching data. Figure 6 shows the Phase 1 teaching data. In the Phase 1, the initial velocity is fixed 5 kt, and no wind is assumed. Here it is requested that the heading of the ship is as parallel to the berth as possible, and the velocity is about 1 knot when the ship gets into the Phase 2 in order to achieve a good control in Phase 2. The time history of No.1-3 is shown in Figure 6(b). Circles in the time history and the trace show the points where the teaching data is obtained.

b. Phase 2 teaching data. Figures 7 and 8 show the teaching data for the Phase 2 controller. In Figure 7, the traces and the time history of No.2-6 teaching data are shown. The initial velocity is 0 kt in Nos.2-1 to 2-3. In Nos.2-4 and 2-5, the ship started from the same positions, but the initial velocities are 1 kt in No.2-4 and 2 kt in No.2-5. No.2-6 and 2-7 start from the same point with initial velocities 1 kt and 2 kt respectively. In Figure 8, teaching data concerning the wind are shown. The wind speed is 20m/sec and two directions are obtained. Teaching data are basically in the constant interval in time, however, data are more densely obtained near the points where the control is abruptly changed. Although teaching data can be obtained, it is still questionable whether the quantity and quality of teaching data is sufficient or not for the problem.

Teaching data are categorized into three cases as shown in Table 2. Case 1 is for Phase 1, and Cases 2-A and 2-B are for Phase 2. The case numbers will be used in the discussion in the next section.

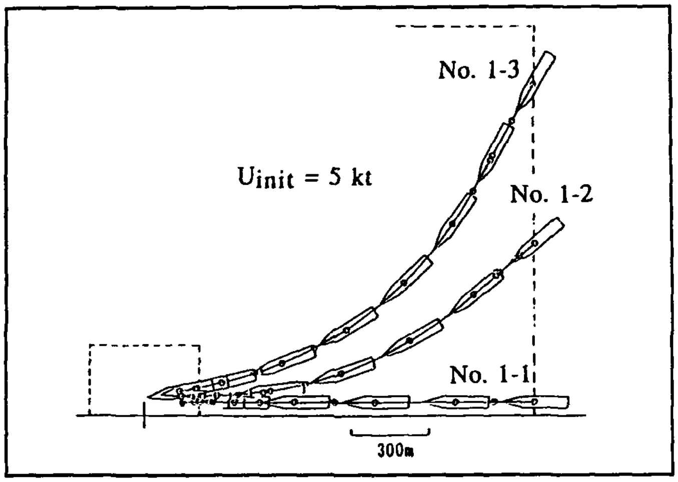
4.4 Learning

The error back propagation algorithm is used here for learning, and the main frame computer HITAC M680/682 is used because of the huge number of iterations in the algorithm. To study the effect of the number of hidden units, neural networks with 10, 20 and 30 hidden units are examined. As a result, no difference in terms of the convergence error are observed in three cases. The network with ten hidden units is considered sufficient in both Phases 1 and 2.

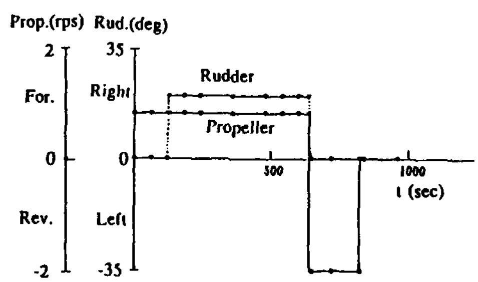
5. SIMULATION RESULTS AND DISCUSSIONS

5.1 Performance of the neural controller

The capability of the neural controller is shown in Figures 9(a) and (b). The network was composed by the Cases 1 and 2-A teaching data . Wind effect is not taken into account. The neural controller starts from the point A and ship's speed is 5 kt.

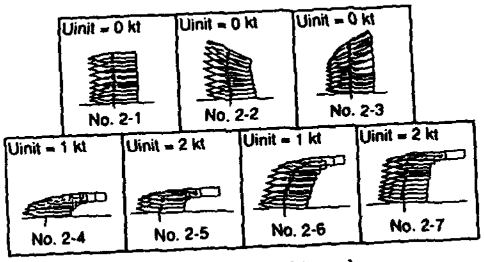


(a) Traces of teaching data.

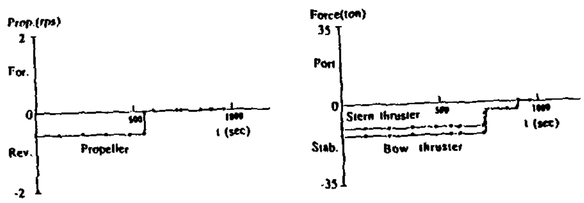


(b) Time history of the No.1-3 teaching data.

Figure 6. Teaching data for the Phase 1 controller.

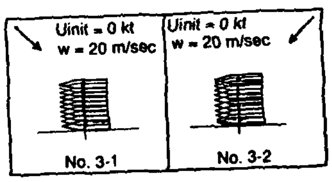


(a) Traces of teaching data.

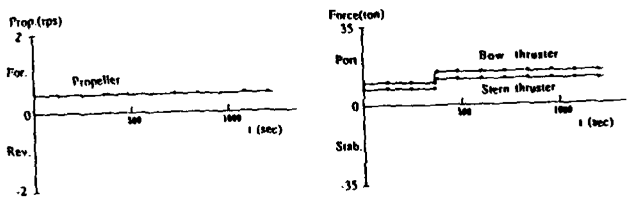


(b) Time history of the No.2-6 teaching data.

Figure 7. Teaching data for the Phase 2 controller.



(a) Traces of teaching data.



(b) Time history of the No.3-1 teaching data.

Figure 8. Teaching data concerning the wind.

Case No.	Teaching data No.
1	1-1, 1-2, 1-3
2-A	2-1, 2-2, 2-3, 2-4, 2-5, 2-6, 2-7
2-B	2-1, 2-2, 2-3, 2-4, 2-5, 2-6, 2-7, 3-1, 3-2

Table 2. Cases of teaching data.

Indices A to D in Figure 9 show starting point, propeller reverse, phase change and berthing point. In Figure 9(a), initial conditions are strictly same as No.1-3 teaching data. In Figure 9(b), initial conditions are between Nos.1-2 and 1-3 teaching data.

In Figure 9(a), it is rather natural for the ship not to follow the exact trace of the teaching data as shown in Figure 6, for the controller has been composed not only by No.1-3 teaching data but also others.

In both cases, the ship goes further than the aimed stopping point. This may be because that the propeller rating is increased just before the reverse to follow the abrupt change of the propeller. It gives unnecessary speed increase for the ship. If the change of the propeller is less abrupt or smooth, the controller may be more successful for the stopping point control. Moreover, it is experienced that the increase in propeller rating just before reverse depends on how the teaching point was selected near the propeller reverse point. In general, if more teaching points are available near the change, the less increase could be obtained by the neural controller.

Figure 9(b) shows fairly good interpolation capability of the neural controller.

5.2 Wind effect

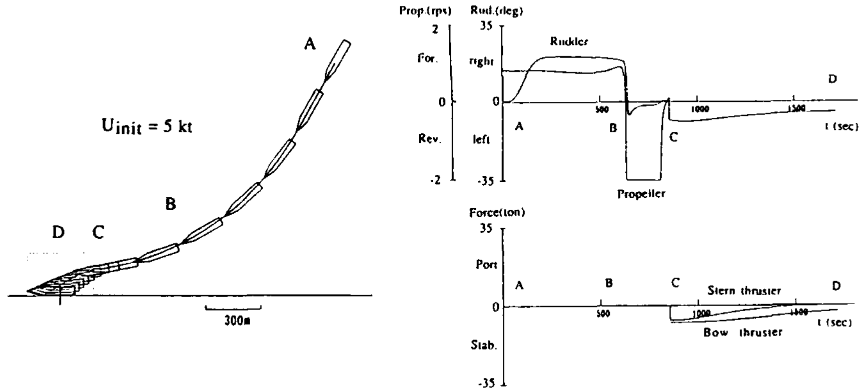
In Figure 10(a) and (b), the control capability to the constant wind is illustrated. The wind comes from 45degrees right forward in the simulation. The neural controller used in Figure 10(a) learned the Case 2-B teaching data. This includes the effect of the 20m/sec wind from 45degrees right forward and right rearward. In Figure 10(b), the controller was composed by the Case 2-A data which excludes the wind.

In Figure 10(a), the controller is successful to lead the ship to the berth. The wind gives the speed toward the berth and side thrusters are used in the opposite direction to reduce the speed by the wind. In Figure 10(b), the controller cannot take the wind effect into account and the ship collides to the berth. It is clearly observed that the capability varies according to the learning data.

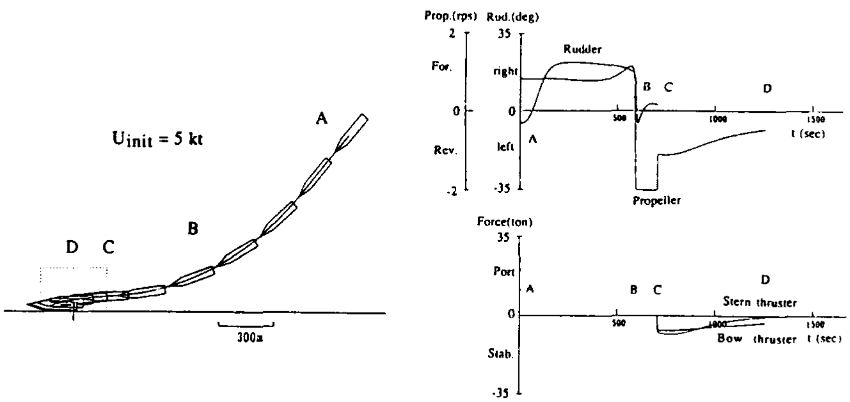
Actually, the controller used in Figure 10(a) is not capable to manage many situations, for it was made only by two wind conditions. There should be much more wind cases to be learned for the controller to be effective also to the wind.

5.3 Extrapolation capability

The neural controller has a certain capability of the interpolation. The interpolation here is the capability to form the control between teaching data. The neural controller may have capability of extrapolation to some extent. In Figure 11, the extrapolation capability was examined. In this case, the neural controller is made by Case 2-A teaching data only in the Phase 2 field. In Figure 11(a), the ship starts from

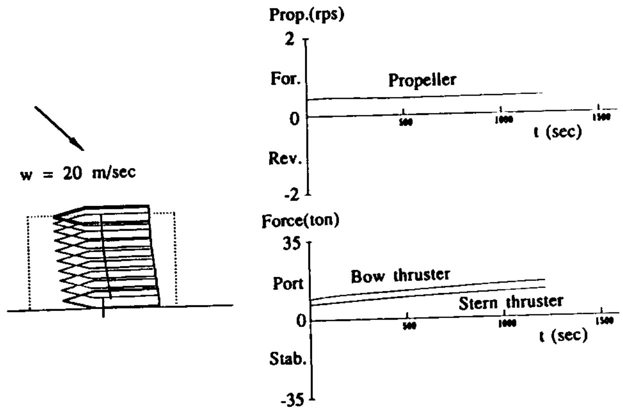


(a) Example 1 : Initial conditions are identical with teaching data.

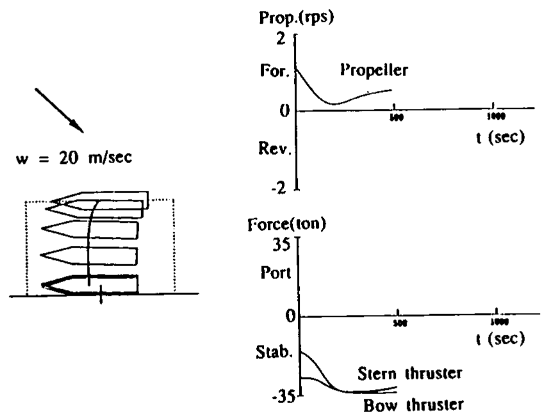


(b) Example 2 : General case.

Figure 9. Control by the neural controller.

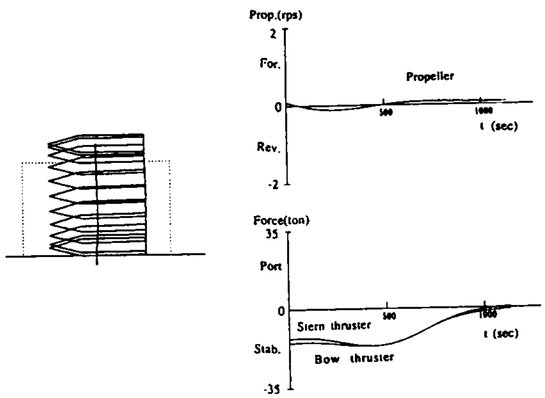


(a) With learning.

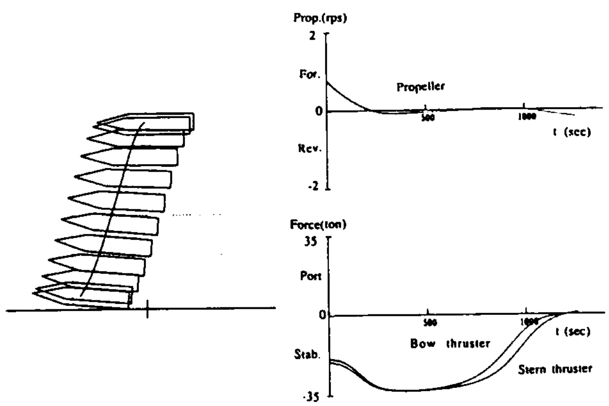


(b) Without learning.

Figure 10. The effect of the wind.



(a) Successful extrapolation.



(b) Failed extrapolation.

Figure 11. Extrapolation capability.

a little outside Phase 2 field and the controller also starts working from the same point. In this case, the controller can give an appropriate control for the ship. In Figure 11(b), the starting point from the berth is twice as far as the field length from the berth. In this case, the controller is not successful. As shown in Figure 11, the neural controller is sometimes successful and sometimes unsuccessful to the extrapolation. It is not clear until how much extent the extrapolation is available. The control by the extrapolation is not reliable. The sufficient quantity of teaching data should be used to make the neural controller working only by the interpolation.

6. CONCLUDING REMARKS

The three-layered neural controller is applied to the berthing problem. Based on the accuracy consideration, two neural controllers are used in far and near fields respectively. The neural controller at present can provide appropriate control for the berthing. The effect of the winds and currents are not sufficiently included in the present controller.

Several discussions on the inter- and extrapolations are made. The neural controller has a capability of the interpolation and it can be furnished by the sufficient teaching data. On the contrary, the extrapolation is essentially not reliable. The field which the neural controller covers should be included in the interpolation field.

The neural controller itself has very complicated nonlinear input and output relations. And it has profound ambiguity such as the size and type of the network, transfer functions, teaching data and so forth. In this paper, the size of the network is determined by considering the number of patterns to be distinguished.

In this research, the applicability of the neural controller is shown by the simulation with using the most basic prototype neural controller. Both the mathematical investigations and the application development by trials and errors of the network are desired to give a design method of the neural controller.

7. ACKNOWLEDGEMENT

Authors would like to express their most gratitude to Professors Hisaaki Maeda, Tamaki Ura and Keiji Kawachi at the University of Tokyo for their instructive discussions and encouragement.

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APPENDIX

A-1. Equations and coefficients

Many mathematical models of the ship motion have ever been proposed. In this paper, the mathematical model proposed by Kose[8] was employed. The coordinates are shown in Figure A-1. The equations are:

$$(m+m_x)\dot{u} = (X_{vr}+m_y)vr + X_{uu}|u|u + X_{vv}uv^2/U + X_e$$

$$(m+m_y)\dot{v} = -m_x ur + Y_v Uv + Y_{vv}|v|v + Y_r r + Y_{ur}ur + Y_{vvr}v^2 ru/U^2 + Y_{vrr}vr^2/U + Y_e$$

$$(I_{zz} + J_{zz})\dot{r} = N_{uv}uv + N_r r + N_{rrr}r^3 + N_{ur}ur + N_{vvr}v^2 r + N_e$$

Xe = Xp + Xr + Xw
Ye = Yr + Yt + Yw
Ne = Nr + Nt + Nw

- m : Mass of the ship.
- m_x : Added mass with respect to the x axis.
- m_y : Added mass with respect to the y axis.
- I_{zz} : Moment of inertia with respect to the z axis.
- J_{zz} : Added moment of inertia with respect to the z axis.
- u,v : Velocities with respect to the x and y axes.
- U : Absolute velocity.
- r : Angular velocity with respect to the z axis.
- X_e,Y_e : External forces with respect to the x and y axes.
- N_e : External moment with respect to the z axis.
- Xp : X-component of the external force by the propeller.
- Xr,Yr,Nr : External force and moment components by the rudder.
- Yt,Nt : External force and moment components by side thrusters.
- Xw,Yw,Nw : External force and moment components by the wind.

Forces and moments by propeller, rudder and wind are described in the following. And non-dimensionalized coefficients in the equations are shown in Table A-1. The non-dimensionalization by velocity was not used because the speed becomes almost 0 at the berthing. Here the gravitational acceleration and L_{pp} were used.

A-2 Thrust generated by propeller

The thrust generated by propeller is given by these equations :

$J = v_0/Dn$
$v_0 = v(1-w)$
$K_t = T/\rho D^4 n^2$

- v_0 : Advancing velocity of the propeller.

D : Diameter of the propeller.
n : Propeller rps.
v : Velocity of the ship.
w : Coefficient of the wake.
T : Thrust generated by the propeller.
ρ : Density of the sea water.

The relation between J and K_t is shown in Figure A-2. This is the result of the propeller test, so the actual thrust is T(1-t) where t is the coefficient of thrust reduction.

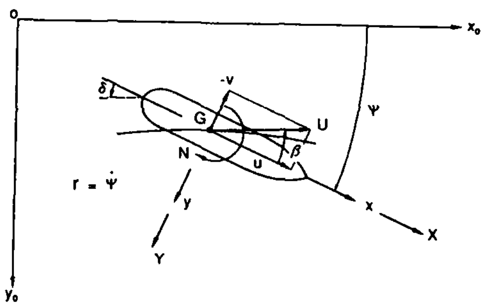

Figure A-1. Coordinates for equations.

Xuu*	-1.263×10^{-3}	Nrr*	-8.848×10^{-3}
Xvv*	2.947×10^{-3}	m*	1.633×10^{-2}
Xvr*	7.957×10^{-3}	m_x*	1.029×10^{-3}
Yv*	-2.700×10^{-2}	m_y*	1.110×10^{-2}
Yr*	1.525×10^{-3}	Izz*	1.361×10^{-3}
Yvv*	-4.200×10^{-2}	Jzz*	1.184×10^{-3}
Yur*	5.143×10^{-3}	w	0.364
Yvvr*	7.573×10^{-3}	t	0.218
Yvrr*	-4.680×10^{-3}	ρ_w(kg/m^3)	1.025×10^{3}
NrZ*	-1.687×10^{-4}	ρ_A(kg/m^3)	1.225×10^{0}
Nuv*	-8.000×10^{-3}	g(m/sec^2)	9.807
Nur*	-1.774×10^{-3}	A(m^2)	8.394×10^{2}
Nvvr*	-3.188×10^{-3}	B(m^2)	2.399×10^{3}

w : Wake factor
t : Thrust reduction factor
ρ_w : Density of sea water
ρ_A : Density of air
g : Gravity acceleration
A : Frontal projection area
B : Side projection area

Table A-1. Coefficients.

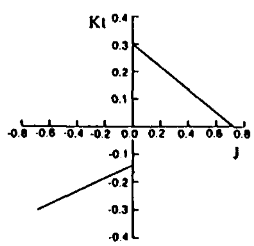

Figure A-2. Kt vs. J.

A-3 Force generated by the rudder

The force generated by the rudder is represented by following equations :

$F_n = 0.5\rho A_R U_R^2 \sin\alpha_R * f_\alpha(\Lambda)$

$f_\alpha(\Lambda) = 6.13\Lambda/(\Lambda+2.25)$

$(U_R/U_p)^2 \approx 0.467(K_t/J^2) + 2.667$

$U_p = (1-w)u$

F_n : Normal force on the rudder.
U_R : Inflow velocity to the rudder.
U_p : Inflow velocity to the propeller.
α_R : Angle of attack of the rudder.
Λ : Aspect ratio of the rudder.
u : Velocity of the ship.

A-4 Effect of the wind(9)

The force by the wind is given by the following equation :

$C_R = R/(0.5\rho_A U_w^2(A\cos^2\phi + B\sin^2\phi))$

R : Force by the wind.
U_w : Velocity of the wind.
ρ_A : Density of the air.
ϕ : Relative direction of the wind.
A : Frontal projection area.
B : Side projection area.

Relations C_R vs. ϕ, α vs. ϕ and a/L vs. ϕ. are shown in Figures A-4, A-5 and A-6 respectively.

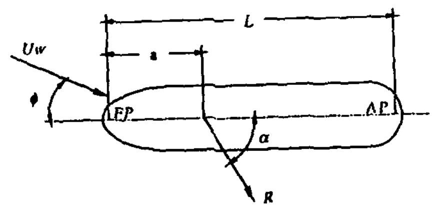

Figure A-3. Effect of the wind.

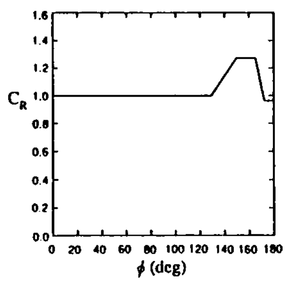

Figure A-4. C_R vs. ϕ.

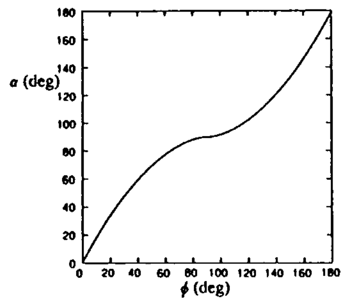

Figure A-5. α vs. ϕ.

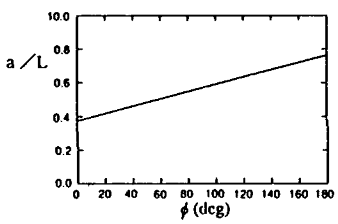

Figure A-6. a/L vs. ϕ.

Knowledge Based Systems within Damage Surveillance and Control

by John A Glen
and Iain M Ritchie
YARD LTD

1. ABSTRACT

This paper describes the results of a project undertaken by YARD LTD for MOD to provide a demonstrator of the feasibility of using Knowledge Based Systems (KBS) as a decision support aid within the damage control area. The project has been motivated by the requirement for future improved decision support to the Damage Control Officer (DCO) to counteract the effect of reduced manning levels and to increase damage control effectiveness.

Fire and smoke damage in a single zone of a typical frigate was selected as a representative application. The zone contains a Machinery Space, Ship Control Centre, Magazines and various other compartments and is sufficiently large to consider the effects of fire, smoke and heat spread and to provide scope for multiple damage incidents. The damage sensor fit in each compartment can be varied.

The design and implementation of the demonstrator EXpert Damage Assessor (XDA) is based on the strategy of modelling the tasks the DCO is faced with and how he solves them. The knowledge base contains a detailed representation of the information with which the DCO reasons, including knowledge about compartments, physical links and connections between compartments, the damage sensors and other relevant ship systems, the status of damage and consequences of damage responses.

The damage scenario is generated on a remote data entry facility (RDEF) using graphical representations of the ship layout and damage surveillance sensors. The RDEF is networked to XDA and allows a predefined scenario to be generated and input to XDA. The scenario can be changed during a run in response to advice on actions provided by XDA

The paper describes the main features of XDA and demonstrates how XDA responds to a typical damage scenario.

The principal conclusion is that KBS can assist in assessing a damage incident using remote sensing of damage data, and advising on priorities for action and providing the operator with information on the ship systems etc. relevant to the context of the damage incident.

2. INTRODUCTION

In this paper we describe some of the results of a study to establish the feasibility and effectiveness of using knowledge based systems within damage control on a fighting ship. The principal topic is the description of a demonstration system which has been used to assess the feasibility and effectiveness of KBS in Damage Surveillance and Control (DSAC).

The paper is structured as follows. In Section 3, we discuss why knowledge based technology can be expected to impact on damage control. We give some general reasons and include a brief description of the results of other studies undertaken within the UK which gave further evidence of the expected benefits. We also indicate how this earlier work relates to the present study and we note how some of these strands have developed. In Section 4 the selection of the application is discussed and its scope and user interface requirements are briefly described. Section 5 goes over the features of XDA : its design, some details of the models and knowledge base used and the user interface. This is followed in Section 6 by a mainly pictorial section which takes the reader through a damage incident and its assessment by XDA. The final section gives our conclusion for this work. An appendix is included which gives an outline of the stages of the development lifecycle for KBS used within YARD in order to place the present study within the experimental stage of that lifecycle. A list of abbreviations is given in Section 11

3. THE POTENTIAL OF KBS WITHIN DAMAGE CONTROL

The potential value of KBS technology within Damage Control arises from its ability to collect and process large amounts of information using knowledge gained from experts in a stress-free environment.

A subject as complex as DSAC inevitably has many difficulties associated with the successful implementation of damage control procedures. However, given sufficient time,full information and adequate resources, an MEO could effectively select the most effective procedures for the problems with which the ship is faced. Problems arise when these actions are required with deficient information and limited resources under pressure of time and other environmental pressures.

These difficulties manifest themselves in:-

- problems of communication, including the reliance on voice communication from remote sources and within the SCC, and the reliance on personnel to convey information.
- problems of assessment, including the difficulty of assessing the actual damage state, the threat to compartments from the fire, the priority for action and the full consequences of an action.
- problems of vulnerability, including the possibility of an untenable state of the SCC and the loss of DSAC personnel.

The solutions to these difficulties are not straightforward, but they do all relate to the collection, storage, processing and distribution of information and expertise. In this context, there is scope for much more extensive use of advanced information technology, in particular KB technology and User Interface technology, to assist with some of these functions. The work reported in this paper has investigated the feasibility and benefits of KBS as a decision aid.

3.1 Previous work relevant to KBS in DSAC

At the start of the project there had been some previous work as to how KBS might be exploited in the area of damage control.

(a) Feasibility Studies. MOD(PE) had previously commissioned feasibility studies on the Application of KBS within the Ship Control Centre (SCC). The recommendations from all of these is that there are substantial benefits to be gained from the use of such technology in a variety of roles in the SCC.

The possible application areas of KBS in the SCC are addressed in reference 1. Focussing on DSAC the principal benefits identified include:-

- an improvement in the speed and accuracy of damage reporting
- a reduction in the information processing demands on SCC personnel
- assistance in the trend towards integration of MCAS and DSAC systems
- a higher degree of damage control readiness
- an improved training facility
- more efficient control of machinery and resources
- facilitation of the proposed reduction in manning levels.

A further report on Systems and Methods for Future DSAC (Reference 2) concludes that by the application of modern technology it is possible and practical to improve DSAC facilities beyond those currently in service. Particular reference is made to the advantages of introducing KBS to DSAC. Additionally, the authors point towards the use of advanced MMI to fully exploit the benefits of KBS.

The report also highlights the often ignored need to integrate at an early stage the requirements of the user in the design of the KBS. The user interface should not be considered after design of the KBS.

(b) An Expert System for Damage Control. A thesis on An Expert System for Damage Control (reference 3) provides a review of expert systems and damage control and of software and hardware for expert systems, a description of the implementation of a prototype damage control expert system and an estimate of the size, in terms of the number of rules, of a full damage control expert system.

The principal conclusions of the report are that the use of expert systems to produce a damage control advisor is feasible and desirable and that the full system should be implemented as a forward chaining rule based system. This demonstrator is built as a forward chaining system for two principal reasons : namely, it allows for the iterative, on-site development of the rule base by the expert and it is an appropriate reflection of the problem faced in providing damage control advice. More specifically the author states that:

> "since the damage control advisor would be expected to follow the route of the damage control incident, which could not necessarily be forecast, the forward chaining strategy of moving from the data toward the overall goal is most appropriate." (p.9)

In our work we chose to tackle the problem of representing reasoning strategies and knowledge representation formalisms used in a complex problem such as damage control by using a suitable software architecture. This architecture is known as a blackboard architecture (reference 4) and is recognised as being a basis for dealing with such problems in real time systems (see Section 5.1).

(c) The Stateboard as Input. Many authors stress the importance of maintaining the primacy of the stateboard as a display facility. It provides a central source of information on the status of the ship which in this form can be relocated should the need arise. Dorey's work (reference 5) demonstrates how the the use of the stateboard as an input device could form part of a damage control information system which would help overcome some of the problems in current damage control practice. Indeed he suggests that further benefits could be gained if it was extended to provide input to an expert system for damage control.

Dorey used a digitised stateboard in order to provide the inputs to a damage control position (HQ1) with the two main repair posts. In this way all positions were fed the same updated information while removing the need for verbal communications. Dorey's work indicated that this technique dealt very efficiently with fixed format data such as stateboard information or equipment status reports. A small scale version of a digitised system, linking the ANBCDO in HQ1 with the command in the Operations Room is currently being evaluated by the Royal Navy at sea.

(d) Damage Control Retrieval System. Knowledge engineering requires considerable effort collecting and organising knowledge. This knowledge includes information about the ship, ship's systems, and the expertise used in detecting and controlling damage. Much of this knowledge is factual and encyclopaedic.

Work on this area is being done for the computer assisted damage control data retrieval system This system is required to provide fast retrieval and display of damage control information. More specifically, it provides a database about the ship and its compartments.

The shipwide data contains:-

- Watch and Quarter Bills
- Shipwide disposition of fixed and portable NBCD equipment
- Ship stability information
- X,Y,Z,A and M Closure details
- Jettison Bill
- Gas Drench guidance
- Electrical Storage Breaker Book
- Siting of gas-bottle stowages.

The data for compartments includes:-

- Compartment name, location marking and frame numbering
- Details for isolating electrical supplies to the compartment
- Details for isolating fluidic supplies to the compartment (e.g. fuel, hydraulics, water, etc.)
- Electrical Dependencies
- Fluidic Dependencies
- Main electrical supplies routed through the compartment
- HP and LP fluid supplies routed through the compartment
- Factors affecting boundary cooling of the compartment
- Ventilation isolation
- Smoke Clearance and control
- Flood Removal
- Fire fighting hazards
- Layout details and neighbouring compartments.

The systems also provides facilities for incident logging, including:-

- the type of incident
- time of initial report
- time of containment
- time of completion
- location mark.

It was recognised that it would be profitable to coordinate these developments, incorporating the data retrieval system within the KBS to allow access to this extensive encyclopedia of DSAC knowledge from the Demonstrator.

4. SELECTION OF THE APPLICATION.

Following consultation with MOD and YARD specialists in DSAC it was decided that Fire and Smoke Control on a naval ship should be the focus of the KBS demonstrator. The reference area within the ship would be a single zone containing a Motor and Gear Room, Ship Control Centre, magazines and various other compartments. This area is suitably varied to provide a range of possible damage scenarios. It is also sufficiently large to consider the effects of fire, smoke and heat spread, and to provide scope for multiple incidents, while not being so large that effort is wasted in duplication.

The model of the ship contains a more extensive sensor fit in the compartments than is currently the norm. Sensor fit is discussed in Section 5. The other relevant ship's systems are similar to those of modern frigates, including an HPSW system for fire fighting, Ventilation systems, Smoke curtains etc.

4.1 SCC DSAC Personnel

It was decided that the KBS demonstrator should be a decision aid targetted to the DCO. To give some context to this decision a brief description of the SCC DSAC personnel is now included.

Overall responsibility for the ship lies with command. DSAC personnel in the SCC co-ordinate all damage control activities and provide command with a current picture of the status of the ship and ship's systems. The principal DSAC personnel are:-

- The Action NBCD Officer (ANBCDO), usually the MEO,
- Damage Control Officer (DCO) usually a non-engineering branch junior officer,
- Electrical Damage Officer, usually a senior Chief Petty Officer,
- Propulsion/ Auxiliary Systems Officer, usually a senior Chief Petty Officer,
- An NBC Protection Officer's Assistant, usually a senior Chief Petty Officer,
- 2 Incident Board Operators.

It is the MEO's responsibility to assess the implications of damage to the ship, relay and receive information to and from command and decide on priorities for damage control action.

Response to damage to the ship follows the general sequence of:-

- Detection - the initial notification that damage has occurred
- Immediate Action - in most cases involving the implementation of pre-planned procedures
- Assessment - collection of information to build up an overall picture
- Containment - to limit the spread of damage
- Priorities - considering the overall demands, decide on the best allocation of resources
- Restoration - restore the ship to maximum availability.

The wide variety in time, location and type of events that can occur, means that such a formulation of the problem is inevitably a generalisation. Any of these tasks can involve a series of complex steps.

The demonstrator currently provides support to each of these activities to a greater or less extent.

<u>4.2 Scope of XDA</u>

It was not the intention to provide a full scale demonstrator. Rather, in keeping with approach suited to this early experimental stage in a KBS lifecycle (see Appendix), the requirements of the demonstrator were constrained as follows.

It was assumed that none of the bulkheads are breached during the incident. Modelling breach of bulkheads would require dynamic modification of the model of the ship's layout.

Detection and containment of fire and smoke would be the sole aim of the demonstrator. There would be no requirement to consider MCAS status, stability or the possibility of flooding in deriving fire-fighting actions.

There would be no requirement to implement a realistic model of fire and smoke spread within the demonstrator. Although such models exist they are currently rudimentary and lack the necessary accuracy. Information gained from sensors therefore provide greater accuracy at the present time although fire models may in future bridge the gap after sensors had suffered damage and could no longer be relied on

The required sensor fit for efficient use of KBS in DSAC was as much of interest as the use of KBS itself. Therefore it would be acceptable to assume a sensor fit which is more extensive than the current norm. In addition to the number of sensors employed, some latitude was taken in the types of sensor used. These were not those which are currently fitted, but are restricted to types which are available or will shortly become available. The level of sensor fit can be varied

It was assumed that no damage would be sustained to the sensors themselves. The problem of sensor validation has been addressed in other studies undertaken by YARD (reference 6).

Only fire-fighting equipment within the current fit could be assumed. No automatic initiation of fire-fighting would be necessary. The key requirement is to offer advice.

To summarise, the program should be able to:-

- monitor and collect remote sensor information
- reliably interpret this information to give an overall assessment of the damage situation
- provide advice on appropriate actions.

<u>4.3 The User Interface</u>

It was recognised that the design of the user-system interface is a critical factor in demonstrating the feasibility of KBS in DSAC. However good the rule base and inferencing mechanisms, the effectiveness usability and user acceptability of the system would be to a large extent dependent on the effectiveness of user-system interaction. The study has not fully analysed these problems but does identify user interface aspects needing attention.

5. WHAT XDA CAN DO

In this section the principal features of XDA are described, in some cases including a brief discussion of issues raised in selecting or implementing the features.

In keeping with the experimental nature of the demonstrator, the implementation has used much of the functionality of the AI development environment. This has meant that a complex software program has been rapidly developed using the facilities offered by the development environment. A next stage would involve developing a full scale system, probably re-engineered on a platform more suited for delivery

The main features are

- principle of the underlying design
- model of the ship structure
- model of individual compartments
- relationships between compartments
- model of sensor values
- ship systems
- simulation of sensor values and the ability to alter sensor fit
- fire and repair party reports
- continuous data input
- the rule base
- the validation of the rule bases
- the fire model and reasoning about single and multiple incidents
- the user interface
- the integration of DCDR.

A description of the response of XDA to a multiple fire incident is given in the next section. These two sections taken together should provide the reader with a clear understanding of XDA. Detailed functional description is not given.

5.1 Principles of the underlying design

In attempting to solve any complex problem experts use a range of problem solving techniques, in addition to their domain knowledge. Different procedures are most appropriate in different situations. For example, the methods used by the expert in the initial interpretation of active sensors are different from those he adopts to plan fire fighting actions.

The design and implementation of XDA is based on a model of the tasks the expert is faced with in damage control and the strategies he employs to solve them. In addition to providing a principle for design activity, this will lead to improved performance and be more acceptable to users.

Based on our previous experience of KBS in real time systems, we decided to use a blackboard architecture with separate processes being used to implement components of the architecture. In a blackboard architecture a set of sub-domain experts (knowledge sources) operate on a common data area (the blackboard), in this case the models of the ship and of fire, revising and updating the blackboard as they see fit. Such an architecture is recognised as being suitable for continuous, real time data. Furthermore the inherent modularity in the design, with separate knowledge sources, accommodates (a) a structured approach to knowledge acquisition, (b) the addition of new functionality in any future developments and (c) the future maintenance of the knowledge base.

5.2 The Model of the Ship and Ship's Systems

Constructing a demonstrator showing the feasibility of KBS techniques for damage control on ships requires more than knowledge about how to interpret damage situations and how to prescribe appropriate fire fighting actions. To demonstrate the full potential of KBS it is essential that a sophisticated and flexible model of the ship is a part of the demonstrator. Such information is a central part of the knowledge possessed by, or available to, a DCO when dealing with a damage situation.

The knowledge base in this demonstrator contains a powerful representation of the appropriate features of the ship, including:-

- knowledge about the compartment
- the relationships between the compartments
- the damage status of the compartments
- the sensors and the relevant ship's systems.

This model is currently equipped to cope with a considerable expansion in the scope of the possible damage scenarios. It is also straightforward to incorporate other features of the ship, relating either to the ship's systems or the process of reasoning about the damage situation. Additionally, the specific representation principles used in its construction are easily generalisable for use in other ships.

5.3 Model of Ship Compartments

The zone of the ship represented in the knowledge base is described in terms of ship compartments. All of the compartments are represented as being members of the class "Compartments". They are in turn subdivided into members of Compartments on a particular deck. The use of structured inheritance allows the assignment of properties relevant to all compartments, by assigning the property to the class. This makes it economical to input compartment information, and straightforward to reason about all compartments. The information in the slots are statements about the compartment e.g. the criticality of the compartment or the extent of heat threat to which the compartment is subject, or relationships with other units such as the adjacent compartments or the compartments' smoke sensor.

These slots contain information which is fixed under all circumstances such as

- the compartments adjacent to this one
- the ventilation systems in the compartment
- the type of the compartment
- the sensors in the compartment.

and information which may change a number of times in the course of a damage scenario such as

- the probability of a fire in the compartment
- the status of the ventilation systems in the compartment
- the assessed priority for fire fighting action for the compartment.

Such data is used for reasoning about the state of the ship and the requirements and progress of damage control.

5.4 Relationships between Compartments

An important feature of the model of the ship is the physical relationships between the compartments. A damage control operator, or in this case a damage control advisor, needs to be aware of which compartments are adjacent, above and below all of the compartments. If a fire has started in a particular compartment the system must know which compartments are threatened by the fire and how to get to the compartment.

To this end a compartment has slots listing the compartments which are adjacent on the same plane, above and below it. These are available to the system when considering, for example, which other compartments are threatened by a fire in a particular compartment. A general mechanism is available to construct this slot information from co-ordinate data describing the boundaries of compartments

5.5 Model of Sensors

The model of the ship used in XDA uses a more extensive sensor fit than is the practice in current build ships. The sensors providing damage control information to the KBS cover:-

- smoke
- ambient heat
- flame
- boundary temperature
- door status
- ventilation system status.

The smoke, ambient heat, flame, and boundary temperature sensors give values indicating the extent of the particular problem. For example, the smoke sensors have the values "no smoke", "light smoke", "medium smoke" and "heavy smoke".

A qualitative representation such as this reflects human expert thinking and knowledge representation in KBS, and should not be seen as a poor substitute for a more precise numerical representation. It is a very powerful and appropriate method.

The sensors for door status indicate whether the door is open or closed. The ventilation system sensors show whether the particular ventilation system is running or stopped.

5.6 Ship's Systems

The model of the ship contains a limited number of the fire fighting facilities normally available on the ship. A relevant subset of the HPSW and ventilation systems are included. This allows the possibility of smoke spread and clearance by the ventilation system, and also for the selection of the most appropriate fixed fire-fighting system to tackle the problem.

The ventilation system in this zone includes:-

- Machinery space supply and exhaust
- Air treatment units
- Air filtration units
- Supply fans
- Exhaust fans.

The HPSW system consists of:-

- Machinery space sprayers
- Magazine sprayers.

5.7 Simulation of sensor values and the ability to alter sensor fit

XDA has the facility to alter the sensor fit prior to running scenarios, in order to assess the performance of the system with different levels of sensor information. This setting of sensor fit is controlled from the Remote Data Entry Facility (RDEF).

The RDEF is a separate system on which a user can set the values of sensor data in each compartment in accordance with a pre-planned scenario for a damage incident. The user sets the values using an interactive display of compartments and sensors and sends the data to XDA. It is essential that the user maintains a consistent model of the fire. This facility implements a simple simulation of the sensor system which communicates with XDA.

5.8 Fire and Repair Party Reports

XDA uses both sensor information and FRP Reports as the basis for damage assessment. XDA offers the facility to input simulated personnel reports about the fire and *smoke damage status of compartments.* This is done by pointing at the compartment icon in the ship display and selecting the required menu item.

All data, sensor and personnel reports, contribute to the damage assessment process. Entry of either type of data is sufficient to initiate assessment. In XDA, much as in the real situation, FRP Reports take priority over sensor data.

5.9 The Rule Bases

We give here a brief summary of the rule bases used in XDA and their inputs and objectives. XDA contains the following knowledge sources, represented either as rule classes or LISP procedures:-

Fire-damage-status-rule use fire sensor data and FRP fire reports about a compartment to conclude the fire-damage-status of the compartment.

Smoke-damage-status-rule use smoke sensor data and FRP smoke reports about a compartment to conclude the smoke-damage-status of the compartment.

Fire-model-rules are used to maintain the units representing the fire. They use the damage-status and physical relations of compartments.

Smoke-threat-rules use the fire-damage-status and the smoke-damage-status, physical relations and ventilation systems to determine the smoke-threat to a compartment.

Heat-threat-rules use the fire-damage-status and the smoke-damage-status and physical-relations to determine the heat-threat to a compartment.

Compartment-concern-rules use the fire-damage-status and the smoke-damage-status, heat-threat, smoke-threat and compartment-type of a compartment to conclude the concern-level associated with a compartment.

Priority-rules use concern-level and compartment-value to conclude the priority-for-action on a compartment.

Boundary-cooling-rules use the damage-status, heat-threat, accessibility of compartments to advise on boundary cooling of a compartment.

Ventilation-system-restart-rules use the assessed-fire-model to determine whether the ventilation system can be restarted.

Fixed-fire-fighting-system-rules use the assessed-fire-model and the ship-model to advise on the use of fixed fire fighting systems.

5.10 Validation of Rule Base

A rigorous approach to the development and testing of the rule bases was used. The rule bases for XDA were documented in a structure and format that permitted the MOD to assess the rules without use of the demonstrator. Changes to the rule bases and the addition of further rule bases are documented in the same manner. This document was maintained throughout the project as a public record of the current state of the rule base. It provides a degree of visibility and clarity, together with a basis for verification not easily achieved with the coded representation.

The generation of the paper version of the rule base was assisted by the use of an intermediate form of representation where the rules were summarised in tabular form. This method began by identifying the the objectives of the rule base. These are matched in a matrix with the possible values of the range of input variables. This makes it relatively straightforward to specify the combinations of input variables that combine as a rule to give each conclusion. Once complete, each row of the matrix is in effect a single rule, with translation to the 'English' paper representation of the rules a straightforward task.

5.11 The fire model and reasoning about incidents

In handling multiple damage incidents, the evaluation of damage threat for one incident must take account of others. XDA takes account of the context of a damage incident in determining the threat posed by the incident and in deciding the level of action required.

This is achieved by the use of an explicit model of the fire(s) held by XDA. The fire-model-maintainer-process and the fire-model-assessor processes are dedicated to updating units representing the current fire damage believed to be affecting the ship. This representation of the fire includes properties such as the affected-compartments, fire-incident-boundary, smoke-threatened-compartments and the heat-threatened-compartments. By combining this with various compartment properties relating to fire damage, such as fire-damage-status, smoke-damage-status, concern-level and source-of-concern, XDA can successfully discriminate between the affects of different incidents and prioritise the need for action accordingly.

5.12 The user interface

XDA has been provided with a user interface equivalent to that needed by an operator.

(a) User control. The user has a high degree of control over the display of information in XDA. The displays of the fire representation or the advice will not change unless the user initiates the change. The user is primed when the screen display is not current.

(b) Ship Displays. There are two displays of information on ship status, the Ship Layout Window and the Ship Status Panel. The compartment icons in the Ship Layout Window can be pointed at to select menu items for DCDR access and FRP report inputs. The Compartment Status Panels in the Ship Status Window include information on the sensor values and on the FRP Fire and Smoke reports.

(c) Fire Representation and Advice. An extensive display of XDA's current view of the fire(s) is displayed upon request in the Fire Fighting Advice Window. The operator can interact with this display at the compartment and the fire level, allowing access to advice on boundary cooling, smoke and heat threat, the use of fixed fire fighting systems and the DCDR emulation. All fire fighting advice is displayed in the lower half of the Fire Fighting Advice Window.

(d) DCDR A DCDR emulation is provided for a limited set of compartments. This is accessible from the compartment icons in the Ship Layout Window and the fire representation. It has a similar layout to the DCDR, with a central display and menu buttons down the side allowing access to specific information. Menu items are selected by mouse.

5.13 The integration with the DCDR

The focus of attention in XDA is less about providing advice about fighting fires and more about providing a detailed assessment of the fire situation. This reflects more accurately the role of the DCO, fire fighting being the responsibility of the team at the fire. A DCDR emulation in XDA provides much of the information supporting a DCO's activities. All DCDR information is accessed with the mouse through the compartment icon in either the Ship Layout Window or the Fire Image in the Fire Fighting Advice Window. The DCDR information is displayed on a alternative screen display. Details of the DCDR have been given in Section 3

6. XDA RESPONSE TO A DAMAGE INCIDENT

In this section we describe the response of XDA to a damage incident using photographs of the XDA screen with an extended caption.

6.1 The XDA desktop

Figure 1 shows one deck of the ship fire zone display in the Ship Layout Window (top left), Ship Status Window (top right), Software Engineer's window (bottom right), Fire Fighting Advice Window (bottom middle) and the Intermediate Reasoning Window (above bottom left).

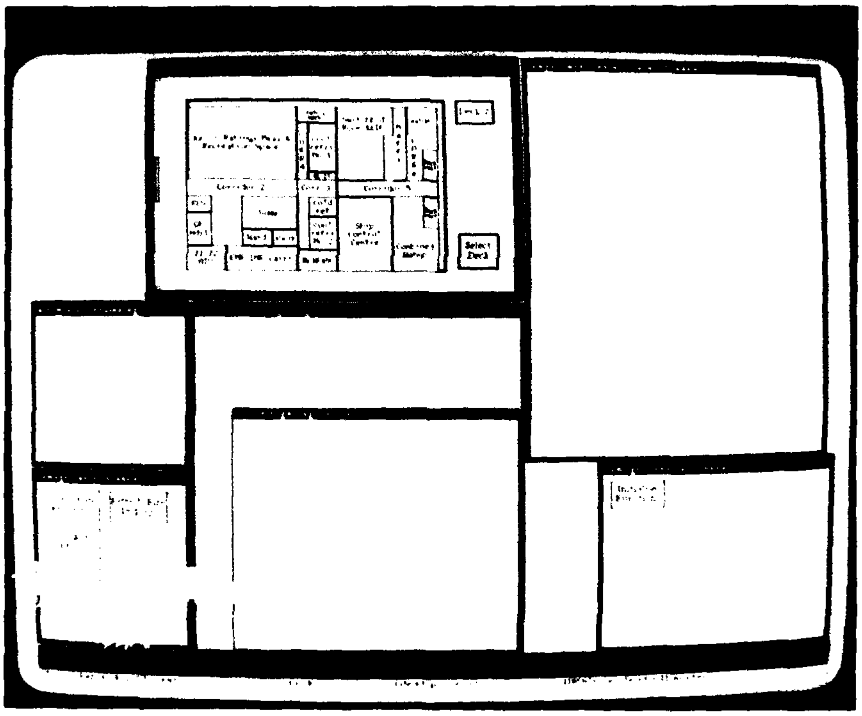

Figure 1. The XDA desktop

6.2 RDEF : Sensor value simulation

From RDEF an initial sensor fit is defined by setting smoke, heat, fire, boundary and door sensors as available or unavailable. The RDEF is used by the person responsible for developing the simulation of a fire/smoke incident and is run independently of XDA. As shown in Figure 2,the data file can be sent at any time to a buffer in XDA by selecting the Set Values menu. An XDA process reads the buffer.

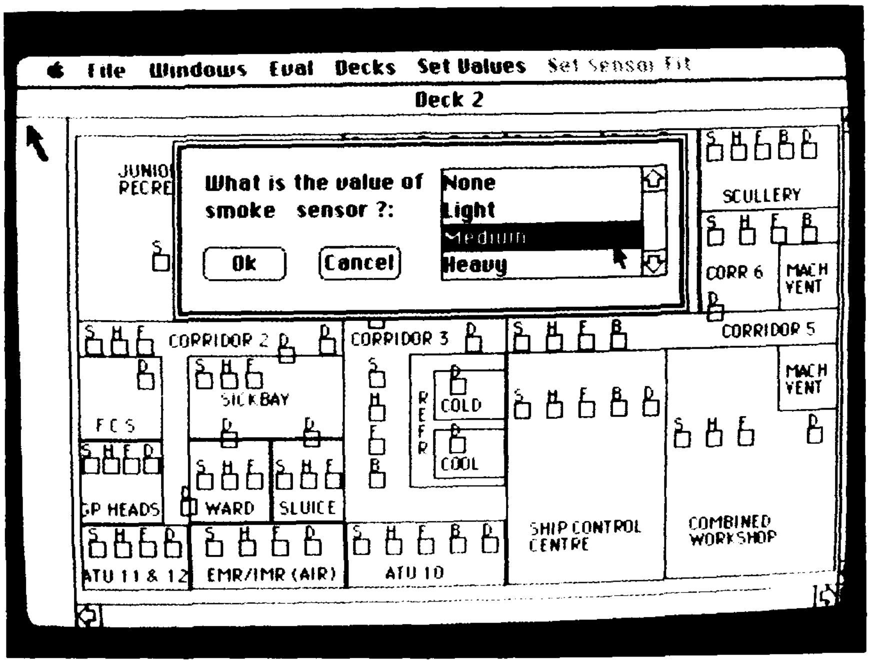

Figure 2. RDEF display and interaction

6.3 First indications of Fire 1

Data has been sent from RDEF. XDA correctly interprets it as a large fire in the recreation space with smoke spread outside. Figure 3 shows the sensor values displayed in the compartment sensor status window, grouped by compartment.

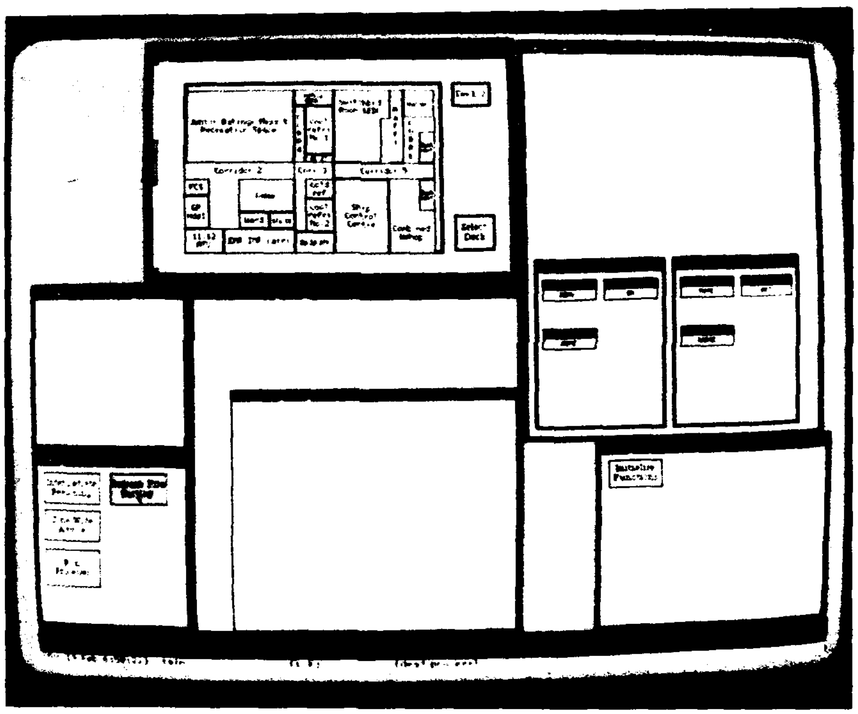

Figure 3. First indications of FIRE 1

6.4 The user asks for advice

A second fire develops. There is a fire in the SCC and in the corridor outside. This shows up (see Figure 4) as a second fire icon labelled FIRE 2

At this stage the user can ask for advice by selecting either the FIRE icon or the compartment icon. Advice covers zones fires and compartments. Zone advice advises on smoke control. Fire wide advice advises on boundary cooling, use of fixed systems, display of location, size and source of smoke and heat threats. The user has previously selected advice on heat threats from the pop-up menu obtained by pointing at the icon for FIRE 1. The heat threats are displayed, sorted according to the size of the threat. The diagram shows the selection of compartment advice which is given via the DCDR.

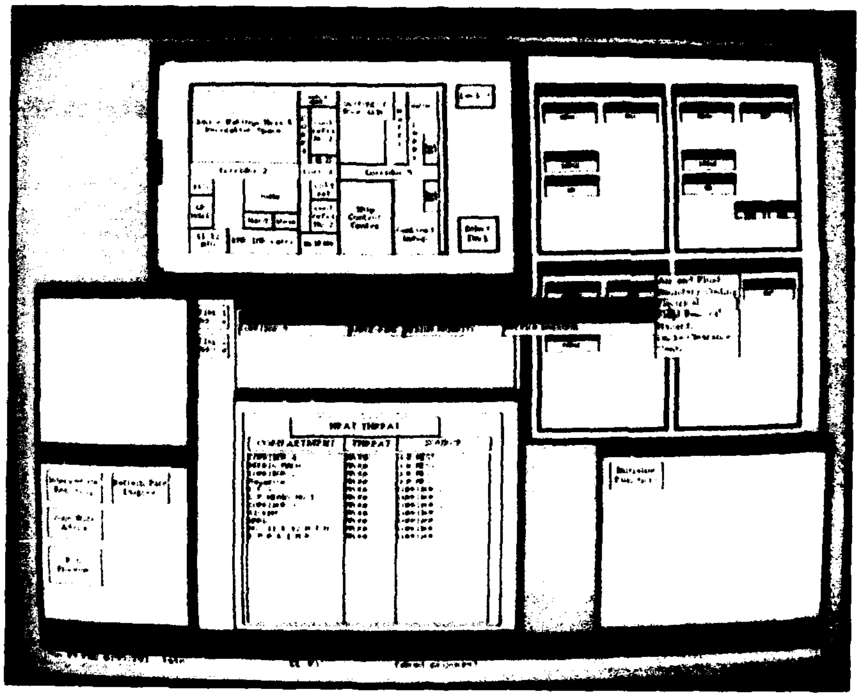

Figure 4. Information by compartment

6.5 DCDR Access

The DCDR can be selected via the ship layout, with the operator controlling the selection options. Alternatively, if the operator accesses the DCDR as shown in Figure 6.4 via the compartment icon in the Fire Fighting Advice Window, XDA will select the appropriate part of the DCDR encyclopedia (Figure 5) to display information related to the incident thus simplifying the operators task.

Figure 5 shows the SCC and the operator is selecting additional information from the selection buttons.

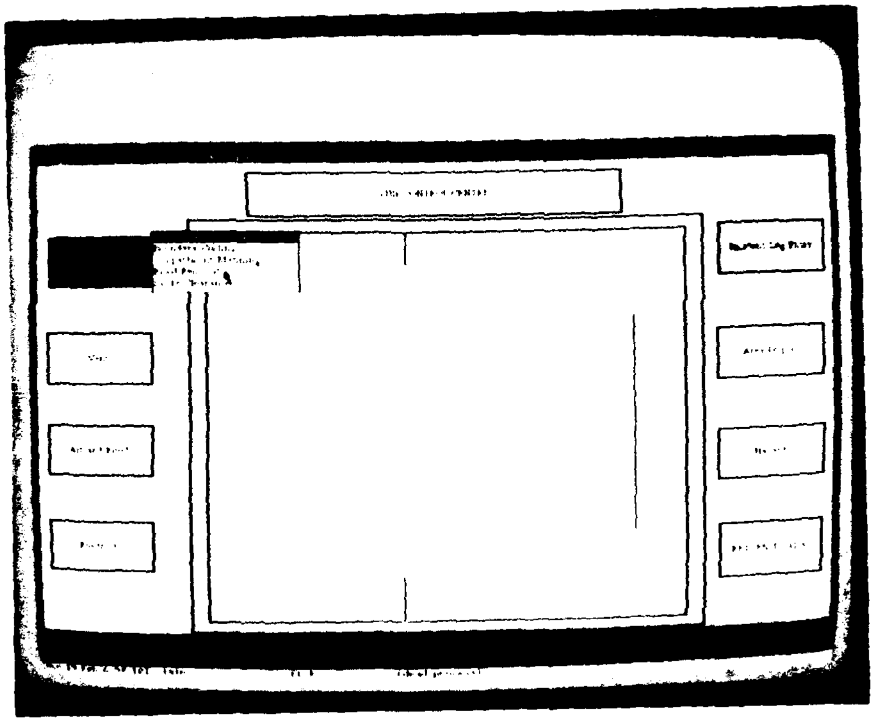

Figure 5. DCDR layout

6.6 Merged Fires

FIRE 1 and FIRE 2 have merged. XDA has deduced this and shows in Figure 6 a single, more complex fire as FIRE 1. Figure 6 also shows the operator inputting a FRP Report via the Ship Layout.

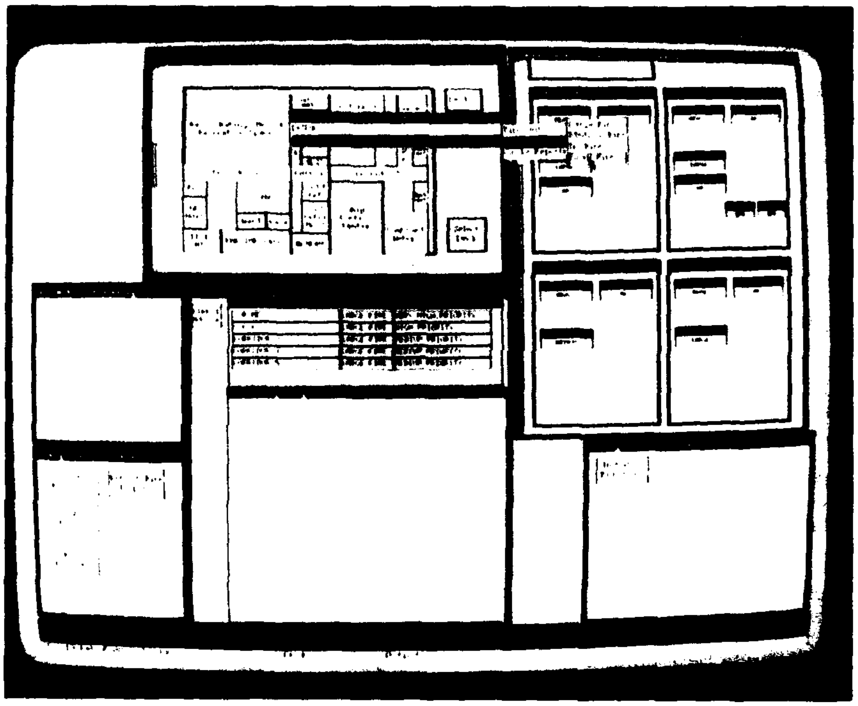

Figure 6. Merged fires and FRP Report input

7. CONCLUSIONS

7.1 Benefits of the design of XDA

We estimate that about 90-95% of XDA could be re-used in future developments which might include extension to further zones, longer term damage incidents, other damage categories (*flooding, structural damage* etc) or alternative uses than as a decision aid to the DCO, such as a training aid or sensor set evaluation.

The basis of this estimate is that such developments would involve revision of the user and hardware interfaces, extension of the ship model or the extension, amendment or addition of knowledge sources.

The modularity of the design has been an important principle which allows for the relative ease with which extensions to XDA could be made. This, in tandem with the use of a blackboard architecture allows the system developer to add new functionality in the form of new subdomain expertise or knowledge sources which do not impact substantially on the overall system. The modularity also allows the decoupling of representation from the functionality of the knowledge sources. the designer is free to select the appropriate method of representation, including algorithmic or computational methods (e.g. for stability), for the particular activity. Furthermore the specification of the functionality of each knowledge source, its implementation and its testing and maintenance is assisted by the modularity.

7.2 The operation of XDA

The assessment of XDA has shown it to be robust, although there are a number of operational difficulties which arise from its prototype nature and the features of the development environment.

A useful screen area has been made available for advice and assessment, however, the optimum way of displaying ship layout for a complete ship rather than a single zone needs careful consideration as will the means of displaying sensor information from a large number of compartments.

The use of pull down and pop-up menus is thought to be an acceptable means for controlling the presentation but the design will need to ensure that the options available to a user at any stage are clear to even an inexperienced user in a stressful situation.

The rule base continues to need enhancement and refinement which will come through wider use and further testing. However XDA is able to recognise multiple incidents, show the boundaries of each incident and provide an assessment of the compartments which are threatened by fire and smoke and recommend priorities for action on incident affected compartments.

7.3 Full implementation

XDA assumes the availability of a large number of sensors throughout the ship. In a true ship installation it is likely that there would be far fewer sensors fitted, primarily due to the cost of installation and maintenance and the limited extra information provided. Also in developing XDA, a basic assumption has been that the data provided by sensors is reliable, whereas in a true damage incident sensors would fail and either inaccurate data would be provided or a loss of data would occur. In both these situations of additional uncertainty a knowledge based approach can be used to interpret with reduced information.

The validation of the rule base would have to be addressed prior to a ship installation. It would not be feasible to trace a path through all possible combination of events to which XDA would respond. The experience gained to date suggests that the use of a staged development approach as outlined in the Appendix together with the modularity of the software architecture will provide an approach to validation.

8. ACKNOWLEDGEMENTS

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10. APPENDIX : The Knowledge Based System Lifecycle

A KBS is implemented in software but a conventional software lifecycle is not appropriate primarily because of the difficulties of specifying the knowledge based elements of the system in advance of design and implementation. Furthermore there are often technical issues regarding the methods for representing knowledge and for reasoning with that knowledge which must be resolved through prototyping and incremental development.

The development of KBS software should progress through the following stages.

a) A Preliminary Study Stage. The potential application is considered with particular attention to its suitability for KBS techniques.

b) An Experimental Stage.The feasibility of the KBS is confirmed and a number of decisions concerning Knowledge representation, reasoning mechanisms and architecture are taken. A representative sub-domain is selected for implementation trials. The software requirements for the next stage, the Prototype Stage, should be identified.

c) The Prototype Stage. This is the first full scale implementation of the KBS addressing the complete domain. The objective of this phase is to evaluate the KBS functions before developing an operational system. The prototype will be developed iteratively, each cycle involving some modification of the knowledge base. The user interfaces should be well designed. The hardware interfaces should simulate the operational inputs-outputs so that the evaluation can be carried out using realistic data.

d) The Operational System Stage.This consists of integrating the KBS in the target environment. Software engineering methods should be used. Maintenance procedures must be established in particular regarding modifications (amendments to, additions to, or deletions from) the knowledge base.

Within each stage a suitable method of work which ensures an appropriate set of documentation should be put in place. YARD uses a development model for knowledge engineering within each stage which provides visibility of progress and ensures quality of results.

The system described in this paper is at the experimental stage, but has been developed using appropriate software engineering principles.

12. ABBREVIATIONS

AI	Artificial Intelligence
ANBCDO	Action NBCD Officer
DCO	Damage Control Officer
DCDR	Damage Control Retrieval System
DSAC	Damage Surveillance and Control
FRP	Fire and Repair Party
KBS	Knowledge Based System
MCAS	Machinery Control and Surveillance
MEO	Mechanical Engineering Officer
MOD	Ministry of Defence
NBCD	Nuclear, Biological, Chemical, Damage
PE	Procurement Executive
RDEF	Remote Data Entry Facility
SCC	Ship Control Centre
XDA	EXpert Damage Assessor

GENERIC CONTROLLER CARD SET FOR ADVANCED CONTROL SYSTEMS

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1. ABSTRACT

This paper describes the use of the Generic Controller Card Set (GCCS) as the nucleus of the Navy Universal Digital Electronic Controller (NUDEC) in advanced systems. A NUDEC system provides both hardware and software to implement control algorithms for advanced systems such as: variable geometry inter-cooled regenerative (ICR) gas turbines, electric plant load scheduling, power scheduling for propulsion and pulsar weaponry, or platform stabilization in rudder roll steering systems. Central control, distributed control, pre-processing, post-processing, and levels of redundancy and fault tolerance can be achieved with Central Processing Units (CPU's), Multi-function Controllers, memories, and smart Input/Output (I/O) modules. NUDEC also contains the processing and memory capacity to implement artificially intelligent (AI) expert systems for more capable advance control systems. Comprehensive module level Built-in-Test (BIT) is also supplied to diagnose and report module or system level failures.

2. INTRODUCTION

With the advent of advanced system architectures in Naval combatants and support ships, control systems will be required to operate within a high speed multi-tasking environment. These control systems will dictate the use of high speed, real time processors to analyze machinery sensor data, resolve intricate control algorithms, and return the required control signals. Advanced control system modules will be required to operate as central control elements for processing common algorithms and performing supervisory duties as well as distributed dedicated processing elements to effect fast data manipulation and fail safe checks. These systems must also be highly reliable, cost effective, and easy to maintain. The NUDEC system is based on a high level open architecture bus protocol (IEEE 1296, Intel's Multibus II iPSB) for interagent communications and the implementation of primitive data buses to perform dedicated I/O control. Thus NUDEC delivers the necessary centralized and distributed processing paths to meet the requirements for managing these advanced systems. The modules comprising the NUDEC system are format "E" Standard Electronic Modules (SEM) developed as standards under the GCCS program. These modules incorporate all of the reliability features of the SEM program, contain a complete function on a card, and incorporate module level BIT circuitry and algorithms to perform on-line diagnostics and fault logging.

3. BACKGROUND

There are three major elements that comprise the NUDEC system: the bus backplane, the card cage/thermal dissipation system, and the GCCS modules including system unique signal conditioning (S/C) modules.

3.1 Bus backplane

The bus backplane is a twenty four slot multiple bus interconnect structure comprised of a single Intel parallel system bus (iPSB), two Intel local bus extension (iLBX II) buses, and a power interface/distribution system. Four of the slots are reserved for SEM E power supplies, or as an electrical interface for other types of power supplies. The power distribution system may contain as many as four different source voltages and three distinct ground returns within the backplane. Module slots are connected together to form a twenty module general communication iPSB protocol backplane on which any of the GCCS modules can communicate. At each end of the iPSB backplane, five slots are connected to form two iLBX II protocol high speed direct CPU to memory interfaces. A group of pins in each slot is reserved for the system user. None of these pins are connected, so all connections between modules in this region require wire wrapping. The primitive address/data buses (Local/Dual Port) in a NUDEC system will reside in the user defined area. This bus allows general purpose communication initiated by a Controller module to memories and/or I/O modules. The user defined area will also contain the S/C interconnects to I/O modules, RS-422 interfaces, and cabling to/from the NUDEC.

3.2 Card cage/thermal dissipation

The card cage/thermal dissipation system holds the backplane, GCCS, and S/C modules in place and dissipates the heat from the modules, format "E" modular power supplies, and backplane. Thermal management for the NUDEC system utilizes a conduction cooling scheme for heat dissipation. The heat generated by active components on the electronic modules is conducted through the module frame to the guide rib area. Wedge lock module retainers clamp the module guide rib against the card cage rails, thereby providing a low thermal resistance path between the module guide ribs and the card cage. Heat conducted into the card cage frame is removed by heat exchangers located in the rails. The heat exchangers transfer the heat to cooling air supplied through a fan/duct assembly.

3.3 GCCS modules

The GCCS consists of "building block" modules that can be configured to meet a wide variety of controller applications. The standard modules contain a complete specific function and an iPSB protocol bus interface. Resident hardware and firmware on all modules assists in system, module, and component fault detection and isolation. The CPU module is built around a 32 bit processor and coprocessor core for high level data processing and floating point math capability. Resident high speed pipe-lined memory allows the CPU module to operate efficiently and minimizes off card accesses. In dedicated control scenarios the Controller module is a lower cost option to the CPU module. The Controller's resident non-volatile memory allows user defined efficient dedicated control tailored to the application or low level data processing to augment a CPU. In addition to Multibus II applications, the module can be used alone or with I/O modules in applications that do not require an iPSB interface. Analog to digital (A/D), digital to analog (D/A), and discrete I/O (DIO) are the present I/O modules. Application flexibility for the system I/O is accomplished by varied operational mode capability, iPSB bus master interface, and primitive bus communications to the Controller module through a dual port memory. This memory is accessed by the Controller module on the Local/Dual Port bus interface. The random access memory (RAM) and erasable programmable read only memory (EPROM) modules provide additional scratch pad or program storage. The memories communicate with the CPU module using the iLBX II bus and to the Controller with the Local/Dual Port bus. They also act as global memory on the iPSB bus and can communicate with any of the processing or I/O modules. System unique S/C modules are used to condition inputs from sensors and loads to levels appropriate to the I/O modules, and to condition outputs from the I/O modules to levels appropriate to the system. These modules produce the specific level shifting, scaling, or drive required for each application that would not be appropriate on a general purpose module.

4. CONTROL HARDWARE ARCHITECTURE

The versatility of the backplane and GCCS module set affords NUDEC with an efficient architecture for implementing high complexity controls. The multiple bus backplane supplies the interconnect structure for modules, distributes power, and interfaces signals to/from the control system. The iPSB bus allows high speed real time communication for centralized control to transpire. A centralized processing module is able to efficiently receive sensor data and transmit control data through messages across the iPSB bus to/from other modules. The iPSB bus also promotes an atmosphere in which distributed processing can occur. Tasks can be segregated into dedicated fast ata manipulation or pre-processing routines and performed by additional processor or I/O modules. Pertinent information can then be passed by messages across the bus to the central control module(s). With the iLBX II buses, multiple CPU's are able to share fast common memory and perform parallel processing on intricate control algorithms for quicker resolution. A NUDEC system will contain a mix of GCCS modules (processors, memories, and I/O) to perform the specific control function. The processor modules will handle system housekeeping and maintenance functions and supply control algorithm solutions from sensor data gathered by the I/O modules. Memories will maintain the storage area for system algorithms, any nonresident processor specific routines, CPU operating systems, and system level maintenance routines. I/O modules are divided into two types: GCCS I/O modules and S/C modules. Machinery sensor data is transmitted or received by I/O modules and passed from/to other GCCS modules within the system.

4.1 Processing

The two processing modules in the NUDEC system are the CPU and Controller. They are responsible for obtaining sensor data from I/O modules, interpreting the data, solving control algorithms, and returning operational commands to the machinery. In advanced control systems, communication with other equipment or control systems will be necessary for integrated control. Direct or indirect communication with external equipment or systems requiring periodical or on demand updates is possible with the NUDEC processing modules. RS-422 interfaces produce a point to point communication capability or they can be placed in a master/slave arrangement. Advanced control systems will also be required to perform self diagnostics and operate with diverse recovery scenarios. In conjunction with data and control processing, GCCS processors may also be tasked with the collection and processing of module fault data for system use. This fault information is automatically generated in each of the GCCS modules by resident on-line hardware and firmware and if possible stored in non-volatile and iPSB accessible memory. Bus and system level diagnostics can be implemented with the processing modules to aid in system fault detection and recovery. The fault recovery could be a simple safe shut down of the system, switching to a degraded mode of operation, or a full reallocation of the system resources to maintain full operational capability. To perform effectively in a centralized control system a processor will be required to handle all system housekeeping functions, solve all control algorithms, communicate with data gathering modules and memories, and act as the central clearing house for all control activity. The GCCS processing modules can handle any system housekeeping necessary to maintain a logical flow of data within the system. These modules communicate to the other agents (memories modules or I/O modules) by various methods and on multiple bus paths. Module initialization, module configuration, and fault information is located in and accessed by the iPSB bus using the interconnect space protocol which uses an eight bit single transfer of data between modules. The module's host processor is not involved in or interrupted by the module to module interconnect data transfer. Memory communications may be conducted on the iPSB and iLBX II buses by a CPU module, or on the iPSB and the Local/Dual Port buses by a Controller module. A distributed control system requires processor modules to perform dedicated processing and control algorithms, communicate with other processing agents, share common memory space, and control dedicated I/O. A Controller module with its resident user memory is programmable for dedicated control and data processing. Its implementation of the Local/Dual Port bus allows independent control of I/O resources and memory data in conjunction with the iPSB global memory and I/O resources. Both processor modules can communicate with each other or with I/O modules using unsolicited message passing on the iPSB bus. In the unsolicited message protocol, a single 32 byte data packet is transferred. The CPU's can communicate using iPSB solicited messages which transfers multiple 32 byte data packets with a single bus arbitration.

4.2 Memory

The RAM and EPROM modules provide mass data storage for NUDEC systems. EPROM modules will contain the non-volatile memory used by CPU modules for operating systems, system BIT routines, and control programs and algorithms. Any additional non-volatile data and firmware required by Controller modules that is not contained in the resident memory will reside on EPROM modules as well. The EPROM modules may also be used for storage of I/O module programs for download by a Controller or CPU module. All temporary data storage in a NUDEC system will be in RAM modules when on board processor memory space is insufficient. Both memory modules are dual access capable with an iPSB bus interface, and another dual function interface that can be connected to an iLBX II bus or the Controller module's primitive Local/Dual Port bus. This multiple connection capability allows one memory type to service an entire system, thus reducing system cost and complexity. Up to four memory modules can be connected to a single CPU module across the iLBX II bus. To facilitate high speed multi-processing applications two CPU modules can be connected to as many as three memory modules on an iLBX II bus. In addition, data may be passed from Controller or I/O modules directly to the memories via the iPSB bus, instead of directly passing data messages to a CPU module. This allows a CPU module to directly access data from several sources across the high speed iLBX II bus as the data is needed. One of each type of memory module can be connected to a Controller module on the Local/Dual Port bus to expand the module memory or for use instead of the on board user memory. This high speed multi-access capability enhances a NUDEC system's ability to control advanced systems.

4.3 I/O

The GCCS I/O modules (discrete I/O, A/D converter, and D/A converter) are the interface to the external world from a NUDEC system. Each module performs a single specific function for one or more processor modules, and thereby supports the versatility and fault isolation capability necessary for high complexity control systems. Multiple signal types can be controlled by a single I/O module with the use of signal conditioning modules. These signal conditioning modules are used to level shift, scale, or increase the drive power for the signals to/from the I/O modules. System fault detection and isolation is unaffected by the addition of signal conditioning modules, since any I/O module can control and test all S/C modules to which it is attached. This on-line testing is conducted so that it will not affect the operation of the system, and if a fault is detected, the I/O module will report the fault to the system test handler. All of the I/O modules can be accessed across the iPSB bus and/or the Controller module's Local/Dual Port bus to further increase reliability and capability. The DIO module contains ninety-six off/on (zero Volt/five Volt) signals which can be used to control/monitor switches, etc. For added versatility, these signals can be software configured in groups of eight as either inputs or outputs. The A/D module has 32 channels for converting analog input signals into digital data that can then be forwarded to one of the processing modules for interpretation. The D/A module has 16 channels on which digital input data from one of the processing modules can be output as analog signals. Both the A/D and D/A modules have pin programmable voltage ranges to increase versatility, or a voltage level outside these ranges can be scaled for acceptance by a signal conditioning module. In addition to the pre-programmed operational modes of each module, all of the I/O modules can be loaded at the user's discretion with pre-processing programs to condition the data before transmission to the processing modules. This additional feature allows the burden of signal processing to be distributed throughout the system.

5. CONCLUSION

Since Navy platforms will increase in complexity to meet both the low and high level threats of the future, ship control systems must provide a high speed multi-tasking environment to exploit the capabilities of emerging technologies. These control systems will require high speed, real time processing capability to analyze sensor data, apply the data in intricate operational algorithms, and return the required control signals. Advanced control systems must have high data throughput, quick response times, and levels of redundancy and fault tolerance. These systems must also be reliable, cost effective, and easy to maintain. The Navy Universal Digital Electronic Controller is able to meet all of the Navy requirements for control systems, now and in the future. It gives the flexibility and speed in control and data processing that high complexity systems require. The ease of implementation, the built in redundancy, and the high level of testing and fault isolation in a NUDEC allows the construction of a wide range of high complexity control systems.

END NOTE

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ENHANCED **P R O P U L S I O N C O N T R O L** BY USING AN

ADVANCED ENGINE CONTROL SYSTEM

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1. ABSTRACT

Propulsion Control has a major importance among the different fields of Ship Control. Many complex Propulsion Control Systems (PCS) have been developed in the past. Most of them are exposed to the same problem: The interface between the PCS-computer and the conventional equipped propulsion engines, with their mechanical governors, pneumatic actuators and parallel cabled sensors, restrict the efficiency of the entire system.
MTU, known as a manufacturer of Diesel engines and Gas turbines cleared away these restrictions for its own and other PCS by developing a computerized Engine Control System (ECS), which covers all engine-related control functions and offers an adequate interface to the Propulsion Control System. In addition an Integrated Load Profile Recorder supplies the PCS with informations about "Life Cycle Consumption".

The paper contains a treatise of the various tasks of the Engine Control Systems the different approaches of the interface to the superior PCS and new "Propulsion Control" features. The advantages of the combination of ECS and PCS are shown in 3 different examples:

- speed boat with four shaft FPP-propulsion
- corvette with two shaft CODAD-CPP propulsion
- frigate with two shaft CODOG-CPP propulsion.

2. INTRODUCTION

The Propulsion Control System incorporates all components required for propulsion plant control and regulation. The main element is the Remote Control System (RCS), which performs all of the important control functions automatically. It relieves the operating personel of such tasks as configuration, control and supervision of the propulsion plant. Furthermore, incorrect control processes are eliminated to a great degree and the propulsion plant condition is diagnosed continuously. These tasks are fulfilled by the RCS in conjunction with the engine mounted subassemblies such as sensors, actuators, etc. (Fig. 1).

Electrical and functional connection of the RCS to the engine peripheral equipment is extremely difficult due to the large number of interfaces involved. The technical possibilities and operational reliability of the PCS are therefore limited.

The solution to this problem, as discussed in this paper, avoids direct connections between the RCS and the engine peripheral equipment by interposing the Engine Control System which performes the engine and gearbox specific control functions (Fig. 2)

3. CONVENTIONAL PCSs AND THEIR DISADVANTAGES

3.1 Matching to the various types of sensors and actuators

There are no binding standards for sensors and actuators. As a result the manufacturers of diesel engines, gas turbines, gearboxes, propellers, etc. employ a great variety of different types of actuators and sensors. The necessity of matching the system to this conglomeration of subsidiary equipment makes RCS standardization extremely difficult. Sensors with different functional sequences require modification of the RCS interface circuitry. The software must also be adapted to each type of sensor, particularly in the linearization and normalizing sub-routines.

Adaption to the actuators is even more difficult as two additional factors, i.e. power range and the dynamic characteristics, must be taken into consideration. The latter is especially critical for actuators are to be operating in "closed-loop control" since the available datas are in many cases insufficient regarding the dynamic characteristics.

3.2 Signal transfer by parallel wiring

Many signals have to be transmitted between the RCS and the propulsion machinery. Figure 1 shows the best known version. To date this has been accomplished by parallel wiring using the "one conductor one signal" principle. Continuously increasing PCS complexity leads to more conductors, and connectors, that means a rise of costs and a reduction of reliability.

3.3 Insufficient flexibility and stability of mechanical or mechanical-hydraulic speed governors

Conventional centrifugal governors are difficult to calibrate. Many times the adjustment repeatability is poor and heavy long-term adjustment drift is to be expected. This undesireable side-effect must be detected and rectified by the RCS. Adaptation of the governor parameters as a function of operational conditions is hardly to achieve, with such conventional governors which can, under certain circumstances, lead to an oscillating engine speed. Extensive RCS measures (anti-cyclic speed demand) are required to suppress such effects.

4. ENGINES AND THEIR ELECTRONIC CONTROL

Engine Control System have been developed not only in order to eliminate the problems described in the previous chapter but also to meet the precise control requirements inherent to the new-generation engines.

4.1 Diesel engines

a. Characteristics of state-of-the-art diesel technology

The last 8 years have brought about considerable advances in the development of fast-running, high-perfomance diesel engines. The specific power-to-weight ratio has been improved by some 30% without involving any appreciable change to the basic engine components or dimensions. This advance has been achieved by two innovations in the field of exhaust turbocharging, i.e.:

- sequential turbocharging, Figs. 3 + 4 and
- two-stage turbocharging in conjunction with sequential turbocharging.

The former allows a considerable torque increase, particularly in the medium speed range. The latter allows charge air pressures up to approximately 5 bar (gauge). In order to avoid impermissibly high combustion pressures due to these high charge air pressures, the engine compression ratio has been reduced. The resultant, initially poor, combustion characteristics in the idle and low-load operating modes have been returned to aceptable levels by a series of measures, the most important being:

- Cylinder bank cutout
  Only one bank of cylinders is supplied with fuel
- Charge transfer
  The air charge in the non-firing cylinders is transferred to the opposing (firing) cylinders during the compression stroke which leads to a temporary rise in the compression-ratio.
- Charge air preheating
  The intercooler is supplied with temperature-regulated engine coolant instead of seawater. As a result, the charge air is cooled in the high-load range and heated in the low-load range.

b. Engine Control System (ECS) for Diesel-engines

These new features of the advanced engine-technology require an electronic control system which additionaly must cover the conventional control requirements as speed governor, start and stop sequences. Therefore, an adequate technology was chosen: a microprocessor based hardware in a ruggedised casing in order to be mounted in the engine room. As shown in Figs. 5 and 6 the ECS-tasks are divided into governing-, controlling- safety- and diagnostic functions. The latter became more and more important during the recent years and is mostly named Built In Test Equipment or Integrated Test System. Fig.7. In addition to the current standard procedures for detection of malfunctions and hidden irregularities, this subsystem is capable of calculation and storage of life-data. Worthy of specific mention in this respect is the ECS "Running Profile Recorder". Fig.8. This is an array of digits covering the engine performance map (fuel rack position versus engine speed). This unit registers the number of seconds the engine operates in each power range. Provided the appropriate machinery-constructional datas are known this information can be used to calculate the life-cycle consumption details.

4.2 Gas turbines

Various types of gas turbines were prepared and installed by mtu for marine applications in the past. Even an ECS for gas turbines (ECS-GT25) has been developed . (Fig.9) This unit follows the philosophy of the ECS previously created for Diesel engines: to cover all control-, governor- and supervision functions as well as to communicate with the RCS by a serial link. Therefore the communication to the RCS involves only minimum effort even with CODOG propulsion system.

5. ACHIEVED ADVANTAGES

5.1 Interface simplification

The new-generation MTU Engine Control System (ECS) allows acquisition of all engine and gearbox measured data which are then standardized; the operational and limit values are calculated and stored in a data memory. This data pool is available to the superior RCS and, if necessary, to the Monitoring Control System (MCS). Data transfer is via physicaly separated, bi-directional data links or bus systems which, if required, are designed as redundant systems. To date RS-422 interfaces have been preferred; connection to an ETHERNET-bus is currently under test.

The roundabout route via pneumatic or hydraulic auxiliary systems is no longer necessary. Interface and data transfer problems have been eliminated. The amount of wiring required between the propulsion system components and the RCS has been reduced to approximately 10% of that originally required.

5.2 Storage and presentation of engine operating and diagnostic data

The simplified interface to the ECS has the advantage that all engine-related data and the "Load Profile Recorder" integrated into the ECS have access to the RCS, and MCS, master data bases located in the main control room or on the bridge. All data are permanently stored in these data bases and are prepared to be displayed either on a screen (Fig.10) or dialogue unit.

5.3 PCS improvement possibilities

As a matter of principle it is possible to say that, due to the intelligent ECS systems the performance capacities for modern propulsion systems have been increased considerably.

Here are a few examples:

- Optimum power matching of several shaftlines (see 6.1).
- Power matching during course change operation (see 6.1).
- Optimum power matching for DAD systems by simple changeover from master mode (speed governor) to slave mode (fuel injection governor) (see 6.2).
- Schedule map correction as a function of static and dynamic power limitation due to:
  - Intake air temperature according to ISO 3046/1
  - Seawater temperature according to ISO 3046/1
  - Fuel temperature
  - Charge air pressure

  (see 6.3).
- Optimization of acceleration, i.e. load acceptance control with optimum torque development (e.g. CPP propulsion Fig.11).

  Fig.11 shows, the acceleration characteristics of a PCS with and without "load control". In the case of propulsion systems without ECS the lack of reliable signals often means that only time-dependent specified setting commands can be given to the propulsion engine and the CPP. The result is not sufficient. Either the acceleration ramp is very slow or it is adjusted to normal conditions. But this approach would lead to an overload situation if a change appeared in enviromental conditions, i.e. hull fouling, increased displacement, high ambient temperatures etc.. The maneuver is never matched to the best conditions. In the case of MTU propulsion systems, the ECS supplies the RCS with a qualified signal which provides information on the power reserves available at all acceleration phases. This information is used for the calculation of propulsion engine speed and propeller pitch settings. This results in optimized acceleration and crash maneuvers which, irrespective of peripheral conditions, convert the maximum possible engine power into propulsive thrust.

- Torsional vibration monitoring with alarm initiation and Schedule map correction if alternating torque limit is exceeded (Fig. 12). Due to external influences on the propeller, or possible engine misfires, torsion vibrations may be created which can endanger the propulsion system components, especially the coupling. Fig. 12 shows schematically how the PCS reacts. Based on its "inside-information", the ECS calculates both the load torque and the alternating torque. If the alternating torque or the total torque, exceeds the permitted limit, the RCS change the "Demand" signals for engine speed and propeller pitch until the excessive torsional vibration (resonance point) is passed over. As far as possible, the ship's speed is kept constant during this procedure.

- Selection capability for optimization of various operational parameters, such as, for instance:
  - Noise reduction
  - Fuel consumption

5.4 Development and test simplification

Employment of the Engine Control System has considerable advantages not only for practival in-ship service but also in the development laboratory. When developing and testing PCSs it is not necessary for each and every analogue or binary value to be available as hardware.The serial data flow can be realized using an original ECS or an personal computer for simulation.

6. EXAMPLES

6.1 Speed boat with four-shaft FPP propulsion

The propulsion system configuration shown in Figs. 13 and 14 comprises four shaftlines each with a propulsion diesel, a revers reduction gearbox and and a fixed-pitch propeller. Each shaftline is controlled by an independent RCS using identical hard- and software. The number of control stands can be extended in accordance with the customer's options. Each propulsion engine is provided with its own ECS and is serial connected to the associated RCS. The RCS components are integrated into a star network and the information interchange from shaftline to shaftline is also via serial data links.

In addition to the standard PCS tasks, another advantage of the RCS/ECS constellation is worthy to mention. Actuation of a pushbutton allows any desired shaftline to be selected for "Single Control Lever" operation. Under cruise conditions this considerably eases ship's handling, in order to change to another propulsion stage the person in command merely has to operate one lever instead of four; synchronisation and matching of all shaftlines is assured by the RCS. The ECS provides the propulsion system with up-to-date performance and status data which facilitates precise load balancing between all four shaftlines. Propulsion engine overload due to incorrect control commands, failure of one shaftline, uncoordinated acceleration, or deceleration etc. are thus prevented. Even during course change , this function prevents unbalanced engine loading.

6.2 Frigate/Corvette with two-shaft CODAD-CPP propulsion

Fig. 15

The propulsion system configuration depicted in Fig. 15 comprises two shaftlines, each with two propulsion diesel engines, a reduction gearbox and a controllable pitch propeller. Each shaftline is controlled by an independent RCS. Each propulsion engine is provided with its own ECS.

Fig.15 roughly shows the interaction between an ECS per engine and the RCS as referenced to one shaftline. A particular advantage, inherent to this system, is the effective "Power Sharing".

Normally, in the cruise mode, only one engine is operative per shaftline. By pushbutton actuation in the control stand, this engine is designated as the "Master" engine and is automatically engaged. For the associated ECS this "Master" designation means that the engine governor must operate as a speed governor (Fig. 16 "Master Control Curve"). For higher speeds the second engine is required. Again by pushbutton actuation, the operator initiates full automatic second engine synchronization and engagement. On completion of this procedure the second engine ECS receives the designation signal "Slave" and switches the engine governor to the fuel-injection governor mode. (Fig. 16 "Slave Control Curve").

The fuel injection governor has the sole task matching the master engine load signal within the permissible speed limits. The loads per engine are thus exactly identical. This is of particular importance in high-performance applications as only so can the individual engine outputs be added together to produce the total power rating. Pre-selection of the "Master" or "Slave" engine is not necessary as the operator can freely select the "Master" unit under all operational conditions.

The design and concept of RCS and ECS guarantee precise load sharing, not only for static operational points along the propeller curve, but also for dynamic, or transient, procedures such as occur during acceleration and deceleration manoevers or in heavy sea conditions.

If the operator selects the "Single Control Lever" function, as described in 6.2 then, once again, he has the advantage of full control of the ship's propulsion system via a single control lever.

6.3 Frigate with two-shaft CODOG-CPP propulsion

Fig. 17

The propulsion system configuration depicted in Fig. 17 comprises two shaftlines each with a propulsion diesel engine, a gas turbine, a reduction gearbox with Self Shifting Synchronizing Clutch (SSSC) and a controllable pitch propeller. Each shaftline is controlled by an independent RCS. Each propulsion unit is provided with its own ECS. Design and operation of this PCS are identical to the previously described examples. Again, the efficiency of the RCS and ECS guarantees excellent handling with this propulsion system configuration.

Fig. 18 demonstrates one advantages of the interface simplification mentioned in 5.1 using the ambient temperature compensator as an example.

The ECS measures the power-relevant ambient temperature and transmits the measured value to the RCS. Dependent upon which propulsion unit is currently active, i.e. diesel engine or gas turbine, the appropriate functions are initiated to which the demand signals are then matched. For the gas turbine a coefficient is calculated from the manufacturer's performance map which, when multiplied by the temperature, produces a corrected demand signal. The ship's speed preselected by the operator in the control stand remains unchanged.

7. SUMMARY

The propulsion control is enhanced by the combination of the Remote Control System with an advanced Engine Control System. The following advantages are achieved:

- Increase of Propulsion Control performance
- Increase of Propulsion Control reliability
- Reduction of ingeneering efforts
- RCS-evaluation by simulated machinery under real time conditions.

Modern engine technology combined with state of the art electronic control offer a multitude of possibilities for layout and operation of power plants in order to provide optimized and reliable propulsion with full consideration of the technical specifications, safety requirments and economy aspects.

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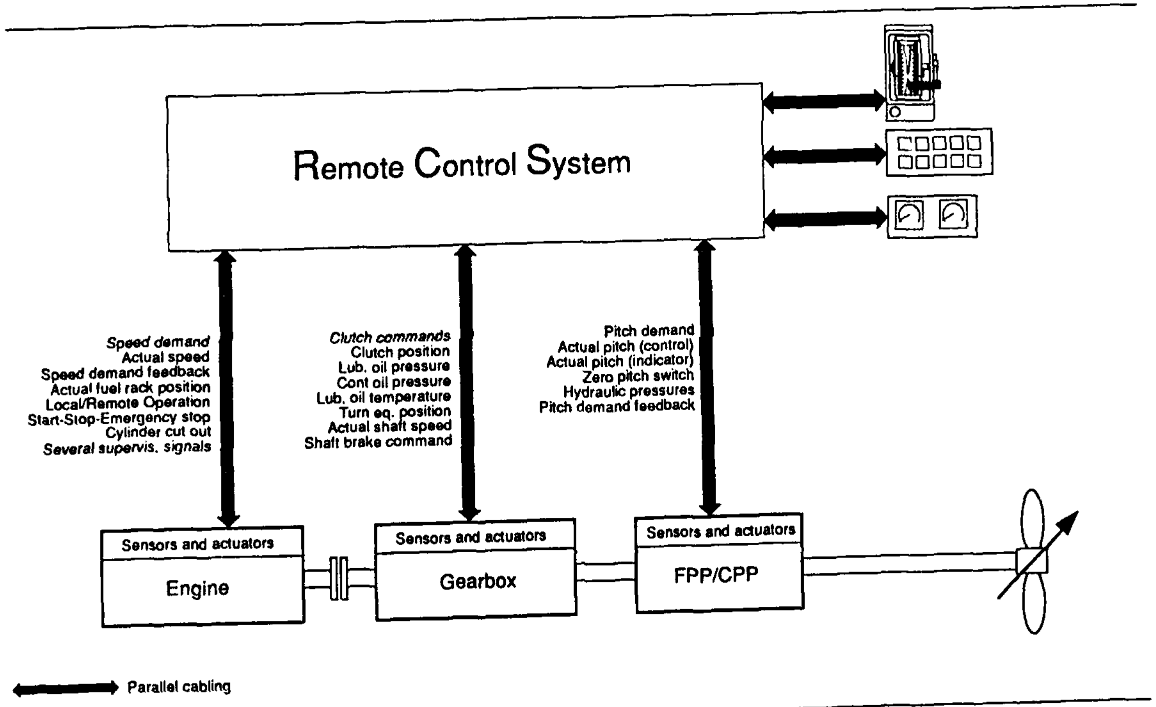

Conventional Propulsion Control Systems

Fig. 1

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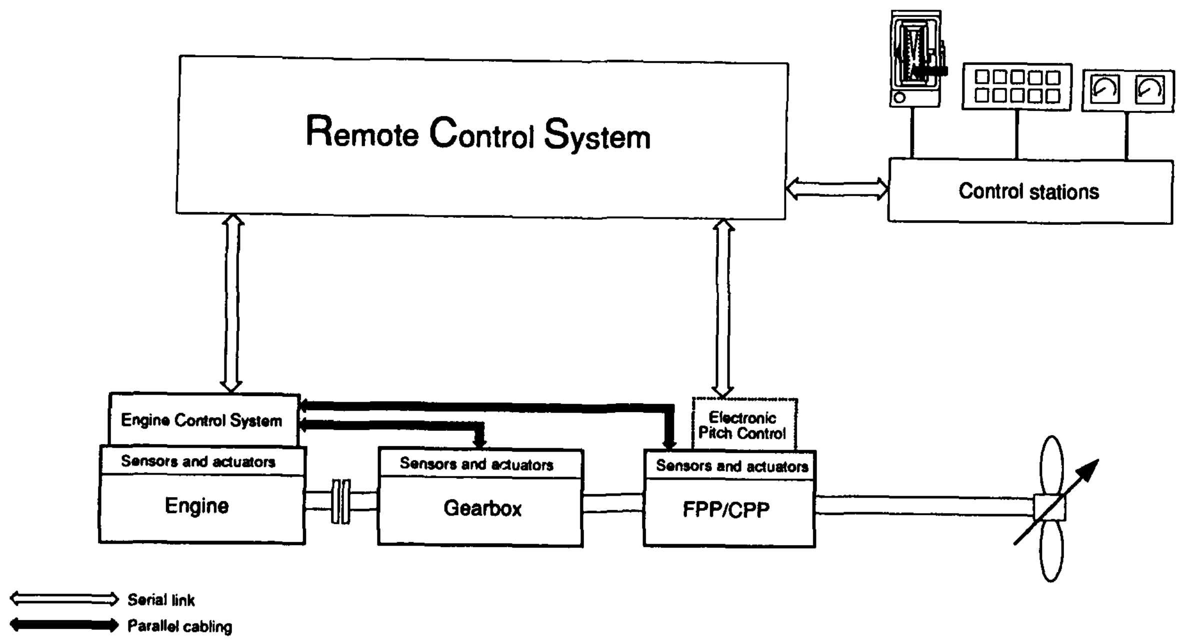

Enhanced Propulsion Control System

Fig. 2

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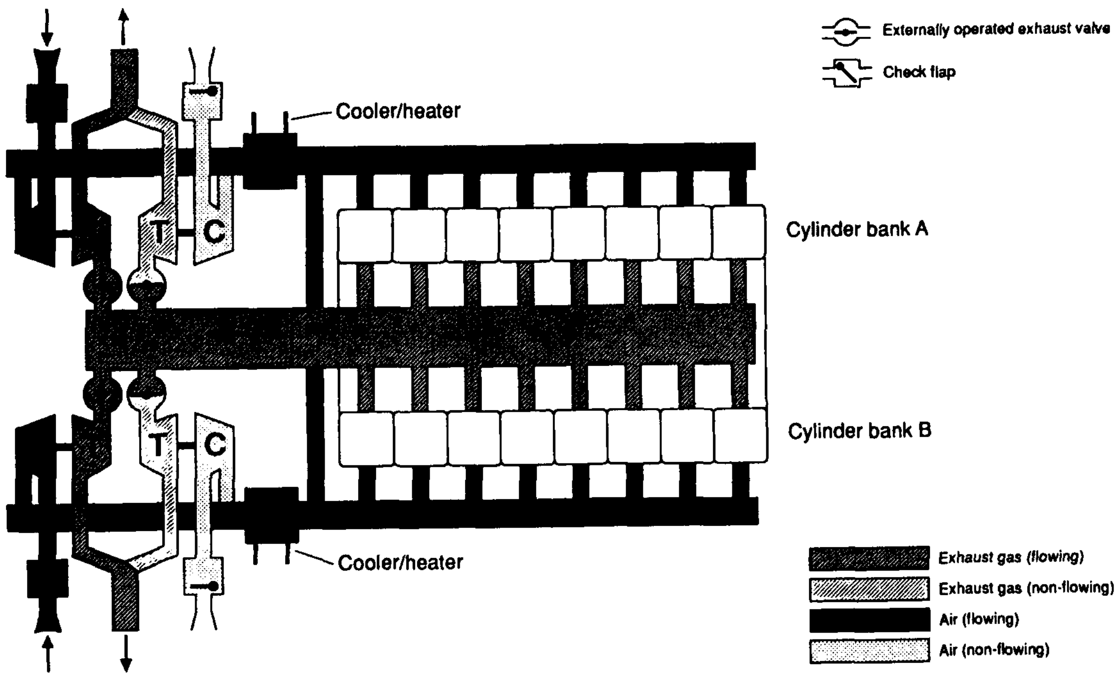

Sequential Turbo Charging

Fig. 3

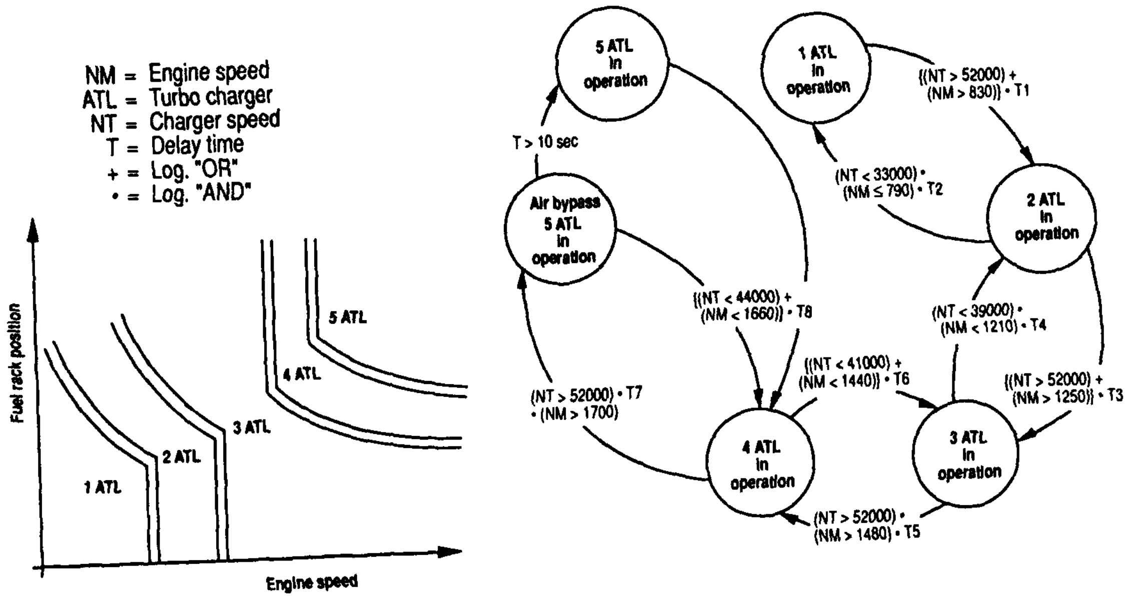

Fig. 4

ECS Turbo Charger Control

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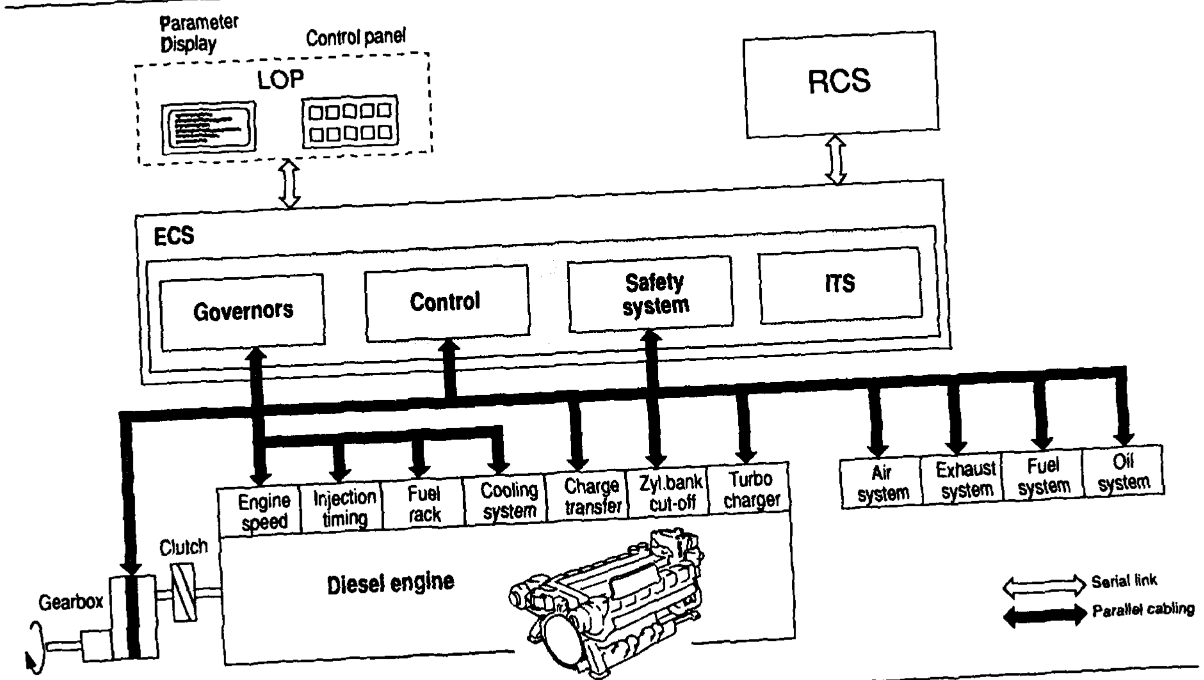
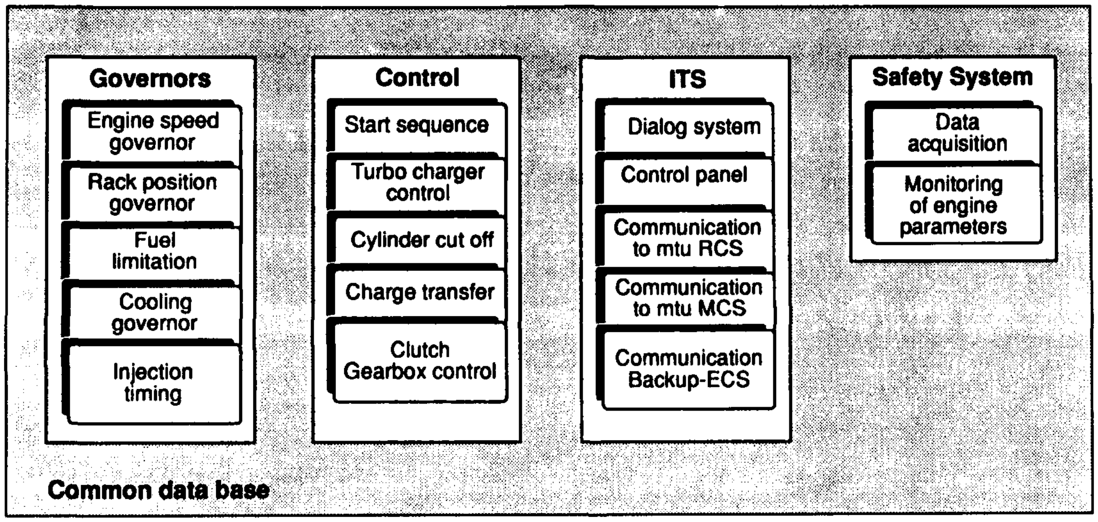


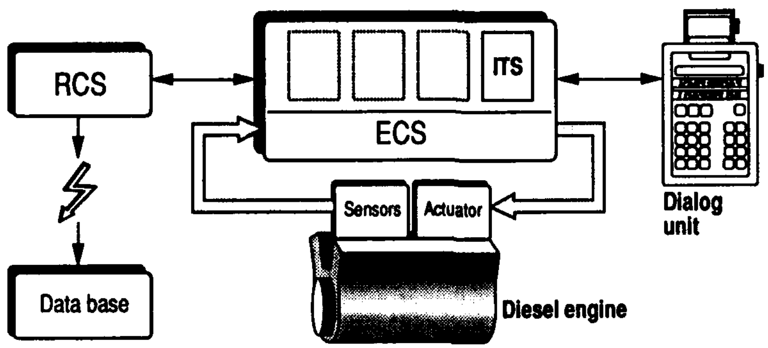
Fig. 5

Engine Control System (ECS) Overview



ECS Task Overview

Fig. 6



Detection of malfunctions by:	- Permanent selfcheck of the *Microprocessor System* - Test routines for peripheral devices - Plausibility check of sensor signals - Correlation of signals
Calculation and storage of events and life-data by:	- Counting and storing of the running profile - Calculation of the consumption of life-span - Storing of special events
Read-out and postprocessing by:	- Dialog unit - Portable host computer - Data base (factory or NAVY bound)

ECS Integrated Test System (ITS)

Fig. 7

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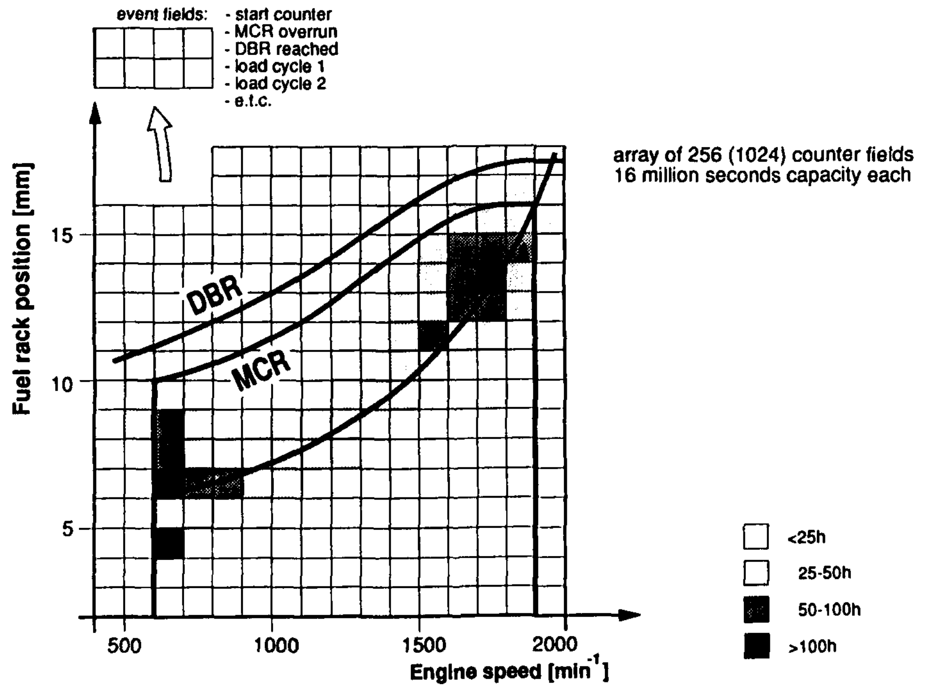

ECS Running Profile Recorder

Fig. 8

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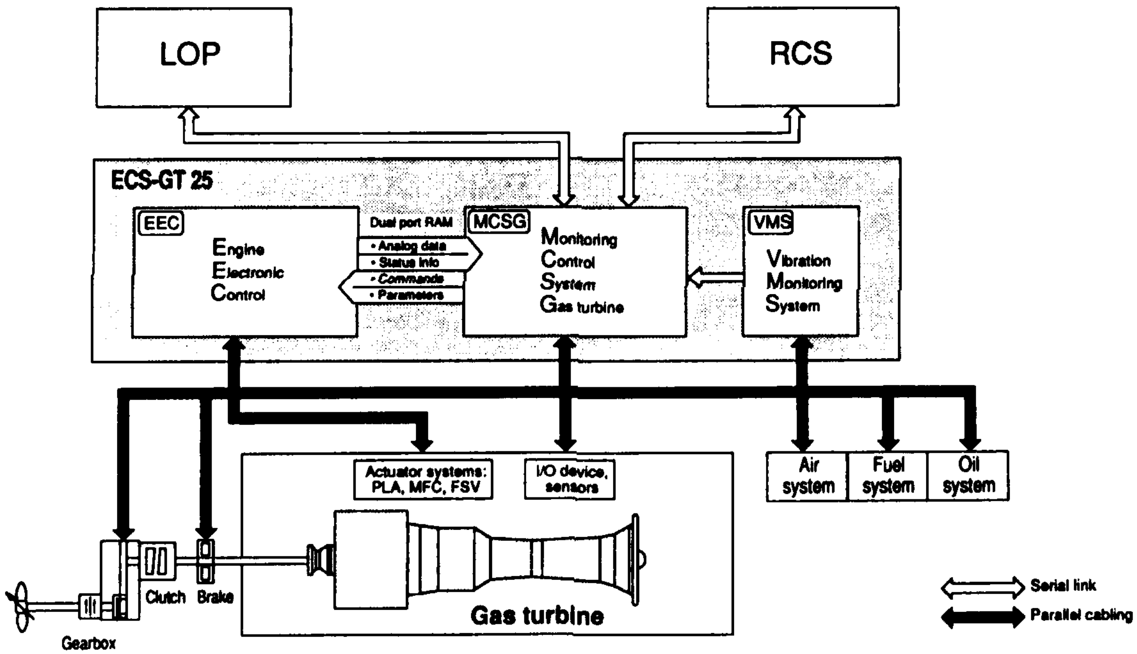
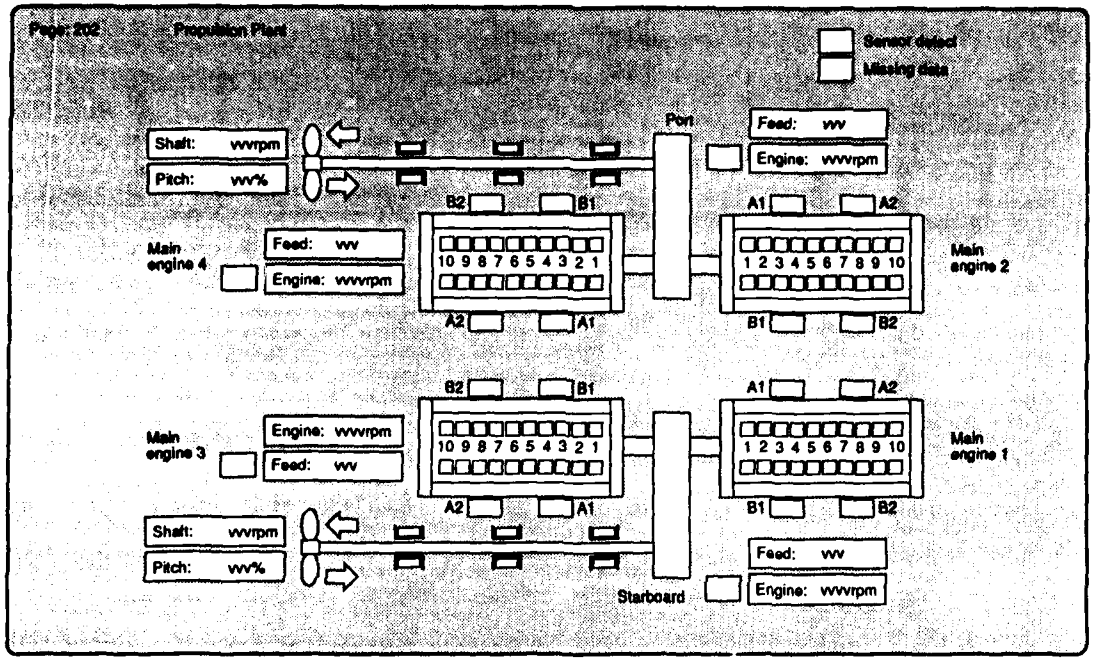


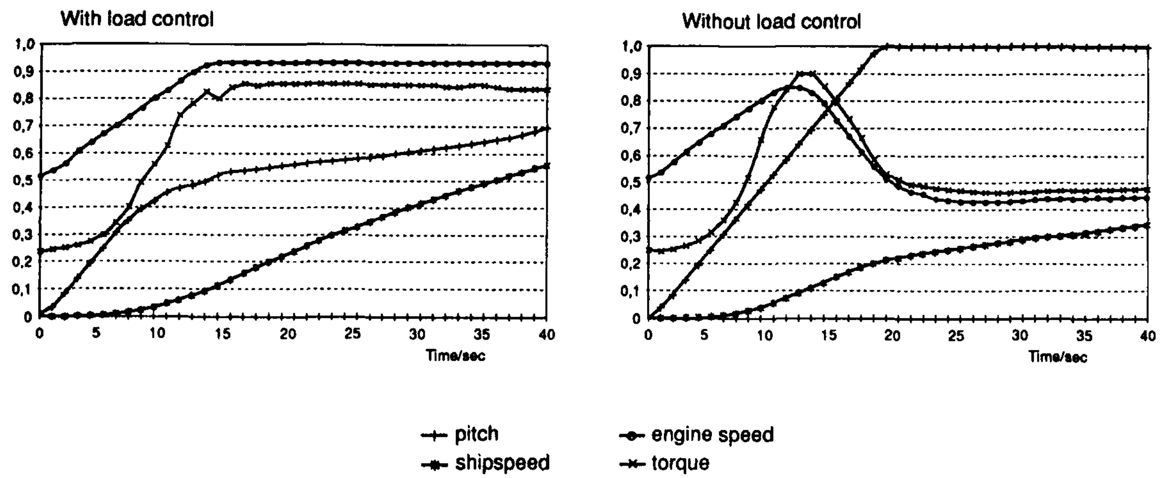
ECS-GT 25 Overview

Fig. 9



Screening of Process Data

Fig. 10



Acceleration Manoeuvre

Fig. 11

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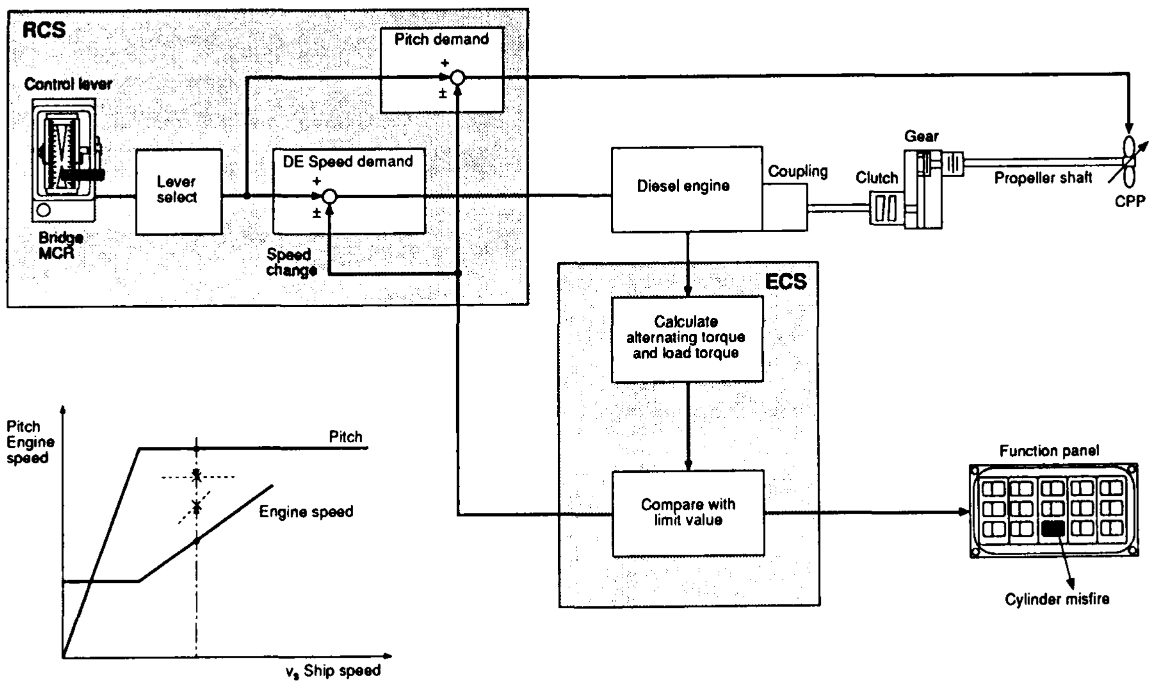

Cylinder Misfiring Safety Function

Fig. 12

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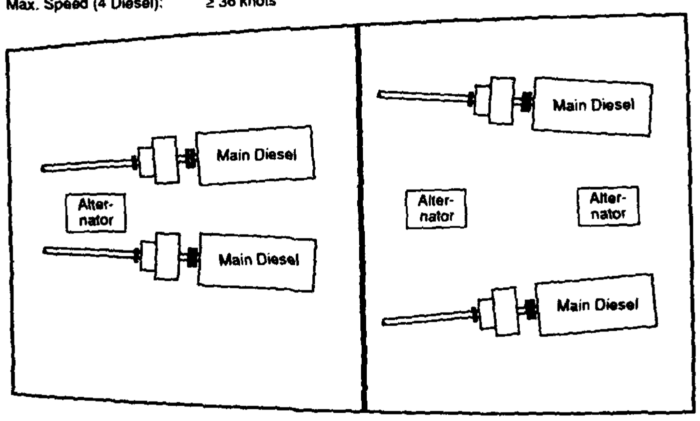
Main Data Propulsion Plant

Propulsion System:	4 Diesel Engines MTU 20 V 538 TB 93;
Output:	4 x 4,120 kW
Max. Speed (4 Diesel):	≥ 36 knots



170-ft-Patrol Boat

Fig. 13

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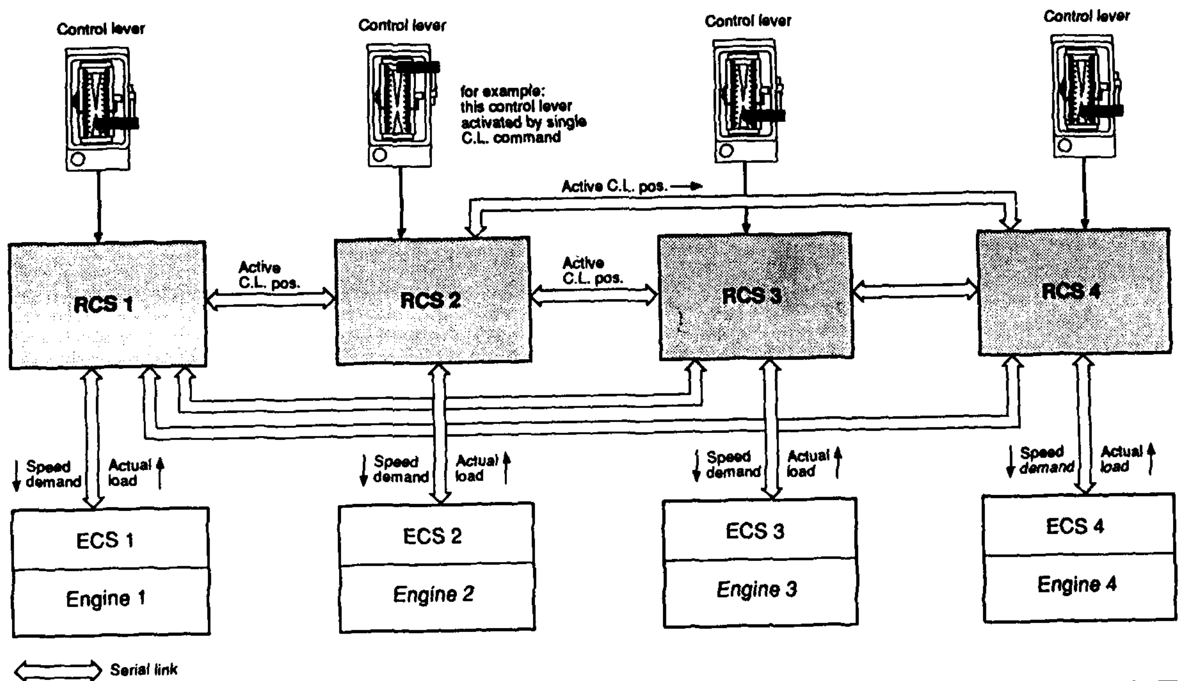

Four Shaft FPP Propulsion

Fig. 14

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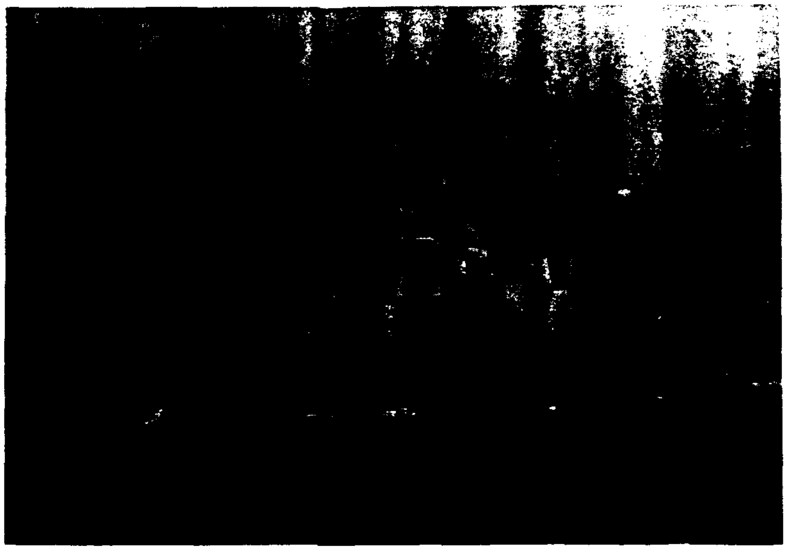
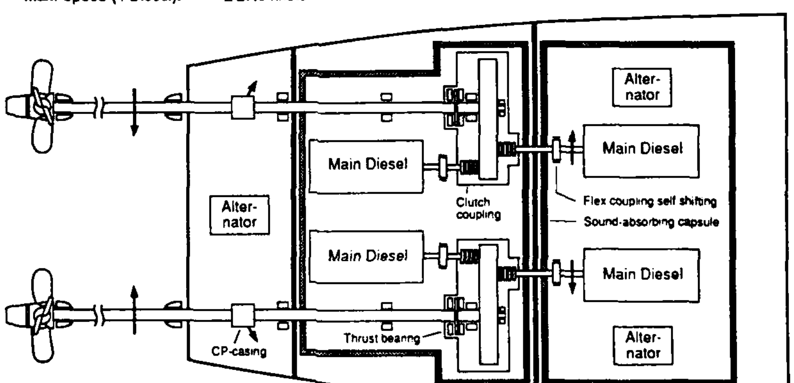


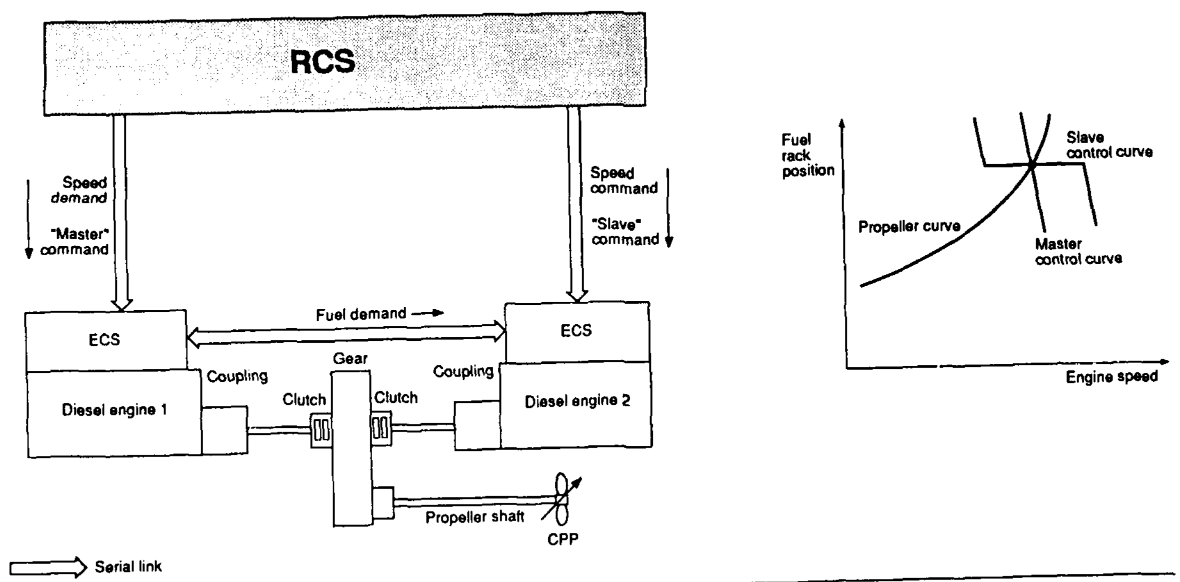
Main Data Propulsion Plant

Propulsion System:	4 Diesel Engines MTU 20 V 1163 TB 93;
Output:	4 x 6,120 kW
Cruising Speed (2 Diesel):	≥ 20 knots
Max. Speed (4 Diesel):	≥ 27.0 knots



CODAD Propulsion Plant

Fig. 15



CODAD-Power Sharing

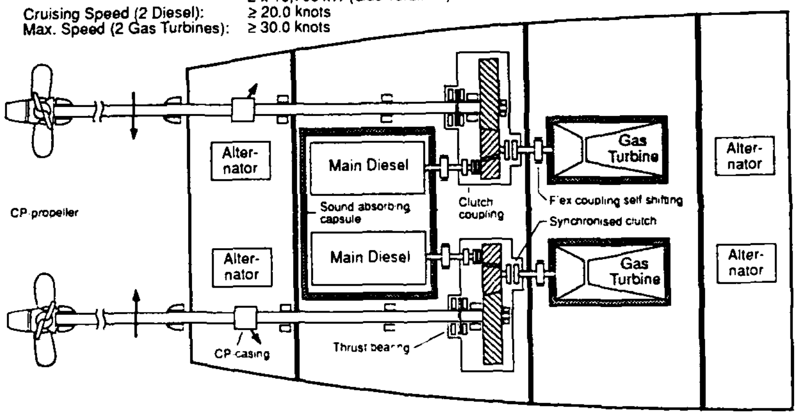
Fig. 16

MTU ELEKTRONIK

mtu Deutsche Aerospace

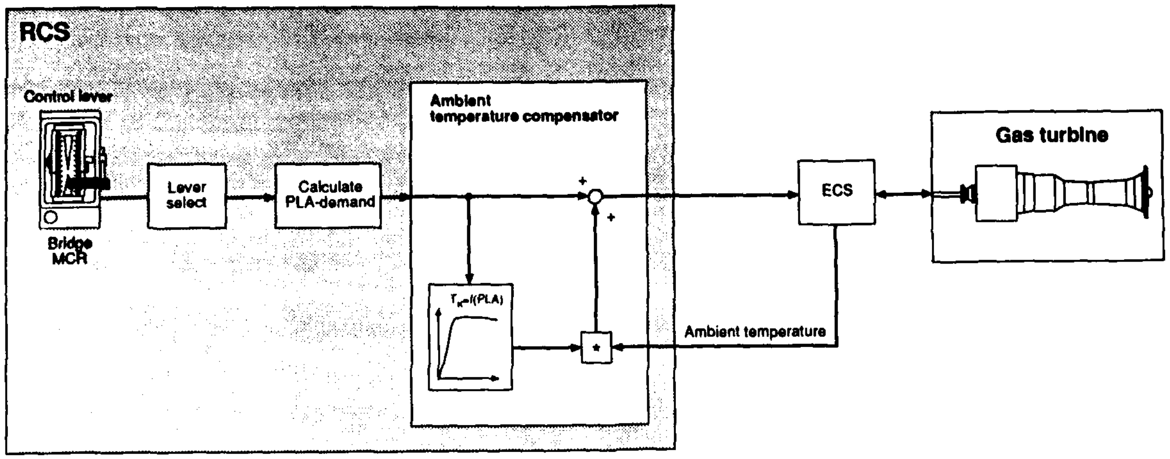
Main Data Propulsion Plant

Propulsion System:	2 Diesel Engines MTU 12 V 1163 TB 83; 2 Gas Turbines GE LM 2500-30
Output:	2 x 3,250 kW (Diesel) 2 x 19,700 kW (Gas Turbines)
Cruising Speed (2 Diesel):	≥ 20.0 knots
Max. Speed (2 Gas Turbines):	≥ 30.0 knots



CODOG Propulsion Plant

Fig. 17



Ambient Temperature Compensator Fig. 18

NEW CONTROLS FOR THE <u>POLAR STAR</u> AND <u>POLAR SEA</u> ICEBREAKERS

by Guy Hardwick
TANO Marine Systems, Inc.

1. ABSTRACT

U. S. Coast Guard polar class icebreakers **POLAR STAR** (WAGB 10) and **POLAR SEA** (WAGB 11) were built in the mid-seventies. The Coast Guard has experienced problems regarding reliability and maintainability with the original control system. The original system supplier is no longer in the marine controls business which has made spare parts supply a difficult task. Recognizing the need to improve the situation, the Coast Guard embarked upon a course to change out the controls, developing a specification in the mid-eighties.

TANO won a contract in 1987 to remove the existing control consoles from both ships and install new distributed microprocessor control and monitoring systems compliant with MIL-P-24423 as well as latest military technologies.

Several new control instruments were developed under this contract to meet the rigid temperature and vibration requirements experienced during icebreaking. This paper describes these new devices plus other unique features of this new control system, such as the trackball/CRT control inputs, and Ada software. The paper also discusses the trade-off studies made during the design process to achieve a high degree of both reliability and maintainability.

2. INTRODUCTION

The **POLAR STAR** and **POLAR SEA** icebreakers were launched in 1973 and 1975 respectively at Lockheed Shipbuilding in Seattle, Washington. These ships are 399 feet long and are the largest icebreakers outside of the Soviet Union.

Propulsion machinery consists of Diesel-Electric or Gas Turbine (CODOG) for three shafts with Escher Wyss controllable pitch propellers. There are six main propulsion diesel generators. Each shaft can be assigned either 1 or 2 main diesel generators to obtain either 3,000 or 6,000 hp per shaft while in the electric mode. Pratt & Whitney gas turbines (model FT4A12) provide 20,000 hp (continuous duty, 25,000 hp surge) for each shaft. Figure 2-1 shows the propulsion plant arrangement.

In diesel electric mode, ALCO diesel engines turn AC generators. The output is rectified to DC which drives Westinghouse propulsion motors which turn the shafts. In gas turbine mode, the free turbine output shaft drives a double-reduction gear, which is coupled to the propeller shaft, just forward of the DC propulsion motors.

The propulsion machinery is divided among five machinery spaces: Diesel Room No. 1 and 2, Gas Turbine Room, Motor/Gear Room, and Motor Room. The Motor Room contains the DC motor for the centerline shaft as well as the CP propeller hydraulic systems for all shafts.

The Engineering Control Center Console (ECCC) is located in the Engineering Control Center (ECC) directly above the Motor Room.

3. SITUATION ANALYSIS

The following is a brief overview of the system being replaced. The original monitoring and control system for these ships (built by Barber-Coleman) was a hybrid digital/hardwired design. Refer to figure 3-1. The propulsion control and monitoring was hardwired analog electronics. The control of the electric ship service and auxiliary systems was also hardwired. The monitoring of the auxiliary systems was done by a computer. This computer-based system provided for alarms on individual indicators, demand displays of analog parameters, and log printouts. A model KSR-33 teletype terminal was installed in the rear of the control console for running diagnostics. All ship's sensors were wired directly to the ECCC.

There are five propulsion control locations: primary control from the ECCC and remote control at the Pilothouse Console, Starboard Bridge-wing Console, Port Bridge-wing Console, and the Aloft Conning Station. The aloft conn is an enclosed, heated cubicle located on the mast at the 09 level. Access is internal through the mast structure. Propulsion and steering control can be transferred from the Pilothouse.

The throttle levers at the pilothouse were mechanically linked by push-pull cables to the levers at the port and starboard bridge-wing consoles. The pilothouse throttle levers sent analog electric signals to the propulsion control system in the ECCC.

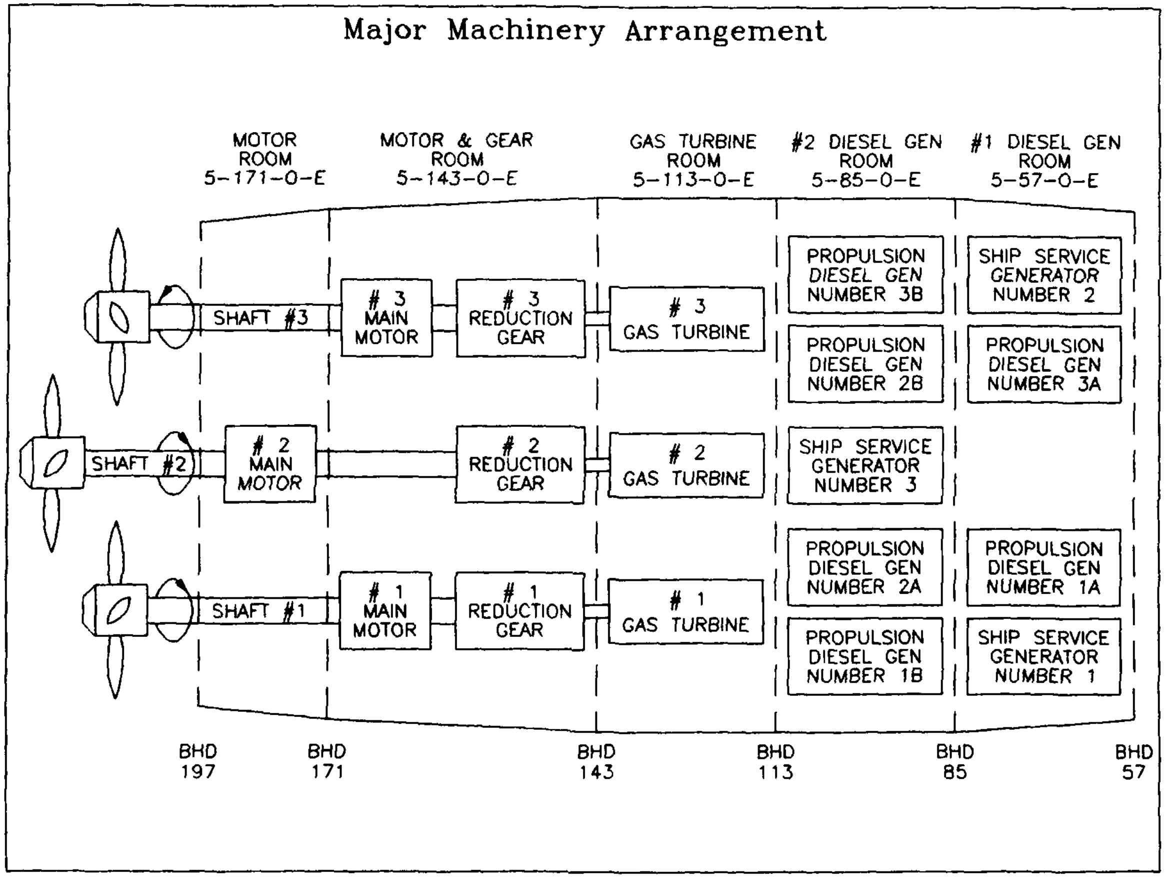


Figure 2-1. Major machinery arrangement.

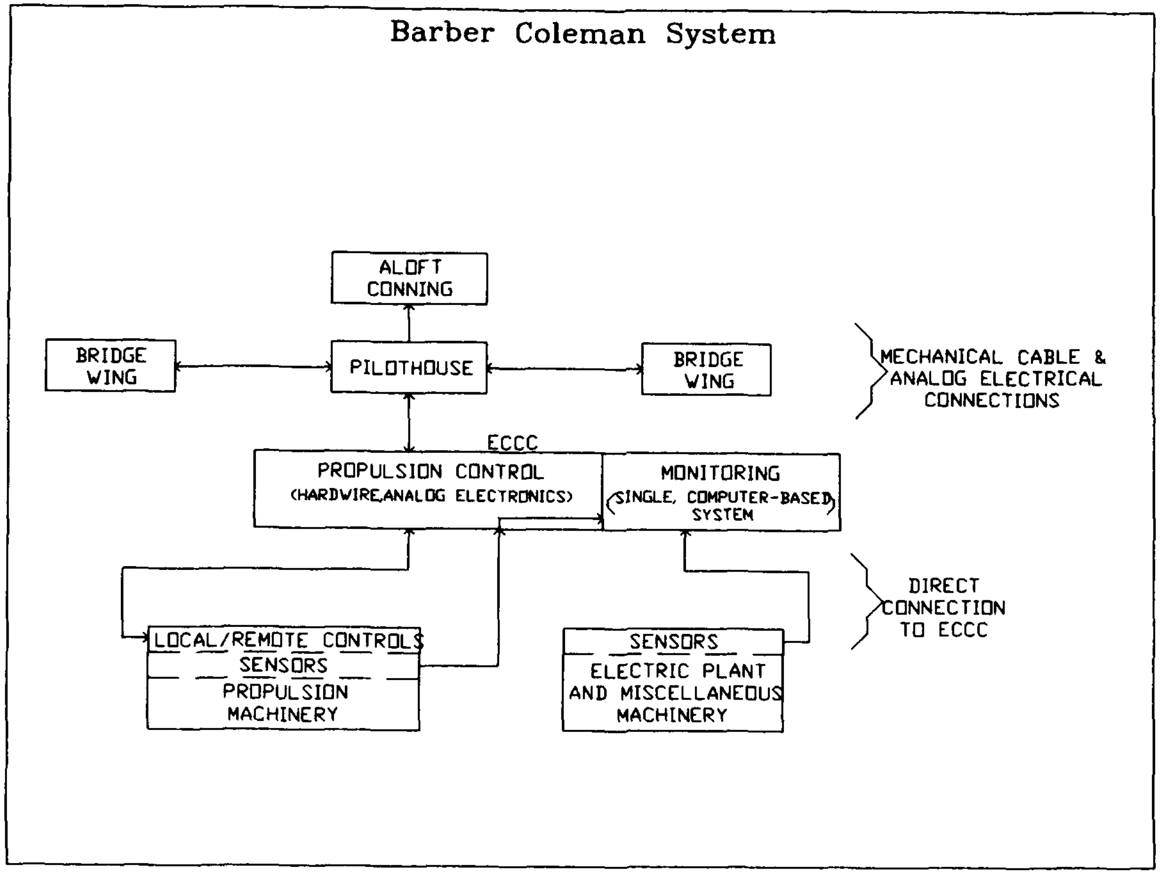


Figure 3-1. Barber Coleman System

4. NEW ARCHITECTURE

The new system is a distributed processing system incorporating five RDUs (remote data units). One RDU for each of the five machinery spaces (see figure 4-1). The system features nine militarized VMEbus processors using the Motorola MC68020 microprocessor. The contract required the use of a commercially available, industry standard processor bus using two-part backplane connectors. VMEbus and Multi-Bus II both met the contract requirements. TANO chose VMEbus based upon our usage of VMEbus on the U.S. Navy T-AO 187 series of ships, as well as our Ada programming experience with the Motorola 68000 series microprocessor. TANO elected to design our own family of militarized VMEbus modules because some features required (e.g. high-resolution graphics) were not available elsewhere at the time. We also felt that system configuration control could be better managed if we had design control over the processors.

5. RDUs

Each RDU contains a TANO VME-68020 microprocessor and signal conditioning electronics to acquire and send data to the sensors and actuators assigned to it. This system uses TANO's military qualified TDAC (TANO Data Acquisition and Control) sub-system which performs the signal conditioning and interfacing to the VMEbus processor. The TDAC sub-system has been used successfully on U.S. Navy LSD-41 Class ships and U.S. Coast Guard WMEC-901 Class cutters.

Each machinery space also has one or more local panels for visual and audible alarm indication. Since the machinery spaces on these ships are periodically unmanned, the local alarm acknowledge will automatically silence the audible horn or siren after an operator enterable time delay.

6. ECCC

The ECCC is comprised of a six section console, each section being 36 inches (91.4 cm) wide. For EMI protection as well as protection during shipboard assembly, each section is constructed as an individual deck-mounted console. The sections are bolted together and to a common base once in place. The construction also lends a high degree of independence between the functional areas of propulsion control, auxiliary control, and vital alarm system.

The ECCC contains four TANO VME-68020 microprocessors, one for each shaft, and one for the ship service electric plant and auxiliary systems.

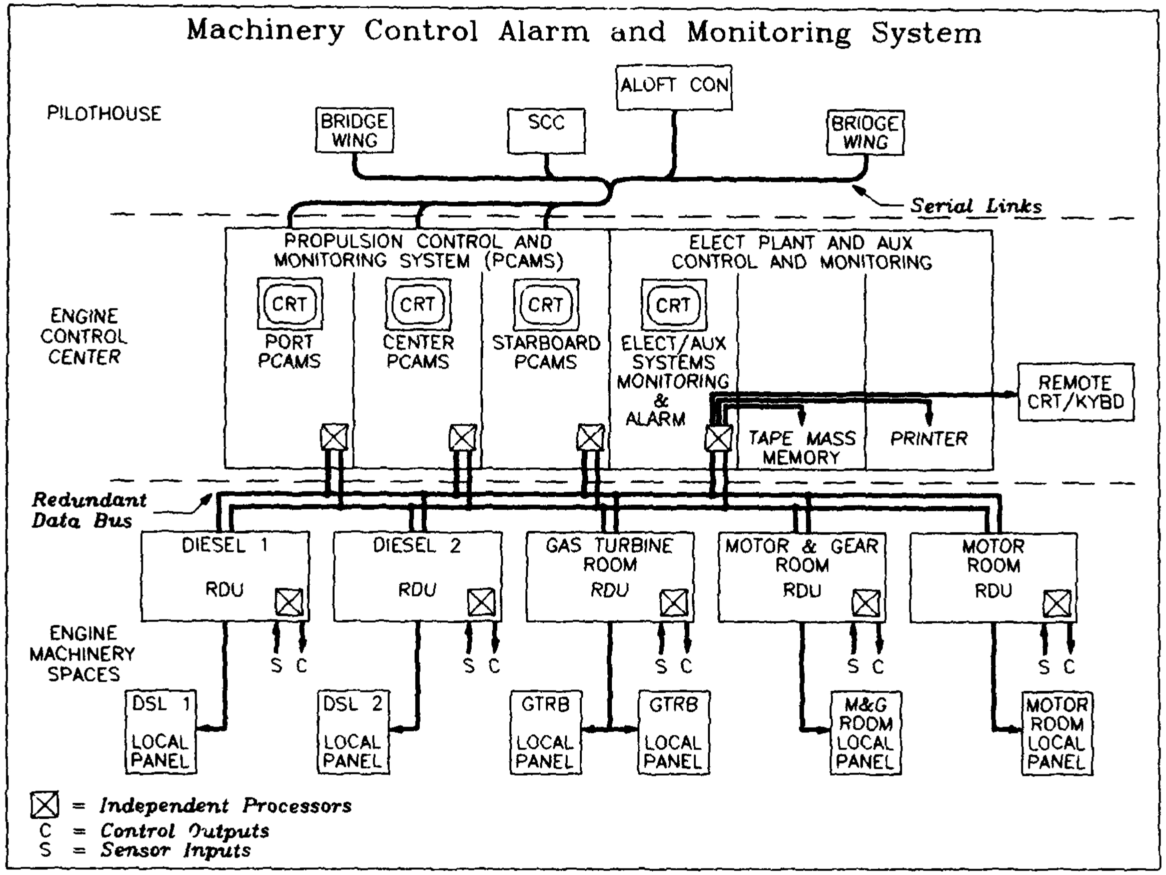


Figure 4-1. Machinery control alarm and monitroing system.

6.1 PCAMS

Three of the ECCC's six sections are devoted to PCAMS sub-systems (Propulsion Control and Monitoring System). There is a separate PCAMS for the Starboard, Port, and Centerline shafts. Each PCAMS is independent of the other: independent power input and distribution, redundant DC power supplies, VME processor, local interface electronics, CRT, LCD digital meters, throttle, trackball, etc. The operator can control and monitor the machinery dedicated to a given shaft or, in the case of diesel generators, assigned to that shaft (this ship system allows the operator to connect an alternate DG to any shaft DC motor drive). Except for nameplate legends, the three PCAMS units are identical hardware simplifying maintenance and logistics. Refer to figures 6-1 and 6-2.

a. **PCAMS CRT** The CRT's used on the PCAMS and the rest of the TANO system are military grade (MIL-E-16400) high resolution color monitors. The resolution is 800 x 600 pixels, non-interlaced. The CRT is fed by a TANO designed VMEbus video controller. The CRT screen is divided into four areas (see figure 6-3):

- o Central Display Area
- o Demand Display Area
- o Message and Alarm Area
- o Sidebar Menu Area

In addition, the system provides pop-up menus for specific purposes.

The normal PCAMS display is an overview mimic of the respective shaft showing the mode (GT or DG) and supporting systems. Refer to figure 6-4. An alarm within a primary system will lead the operator to a detailed mimic for that system to show the operator the cause for the alarm. See figure 6-5 for an example of a detailed mimic.

The operator can select any three analog parameters for continuous display (bar graph and digital format) at the top of the CRT screen in the area reserved for demand displays.

The sidebar menu changes with the central display. The sidebar, together with a trackball controlled cursor, allows the operator to activate soft-keys to enter commands to the system to bring up specific mimics. Detailed mimics allow the operator to change the state of most propulsion auxiliaries such as the CPP servo pumps.

Example: From the master mimic (figure 6-4), the operator would move the cursor to the "Pitch Servo" block and press the

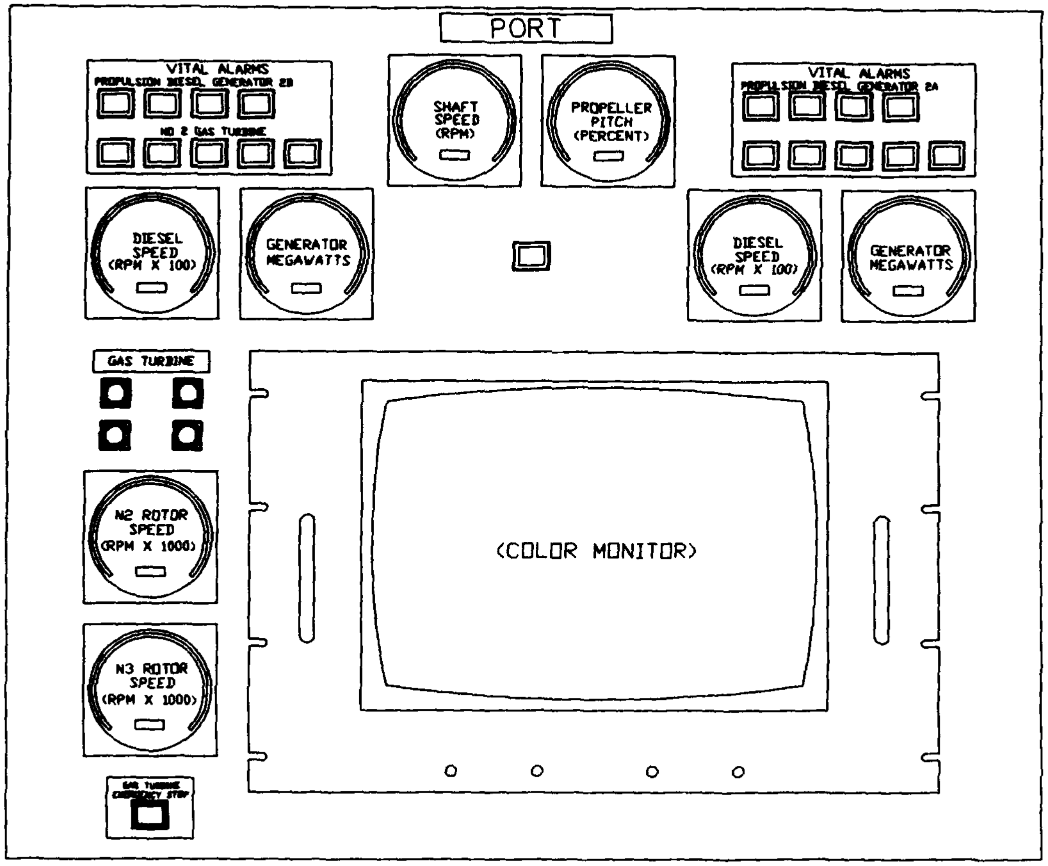


Figure 6-1. PCAMS upper surface.

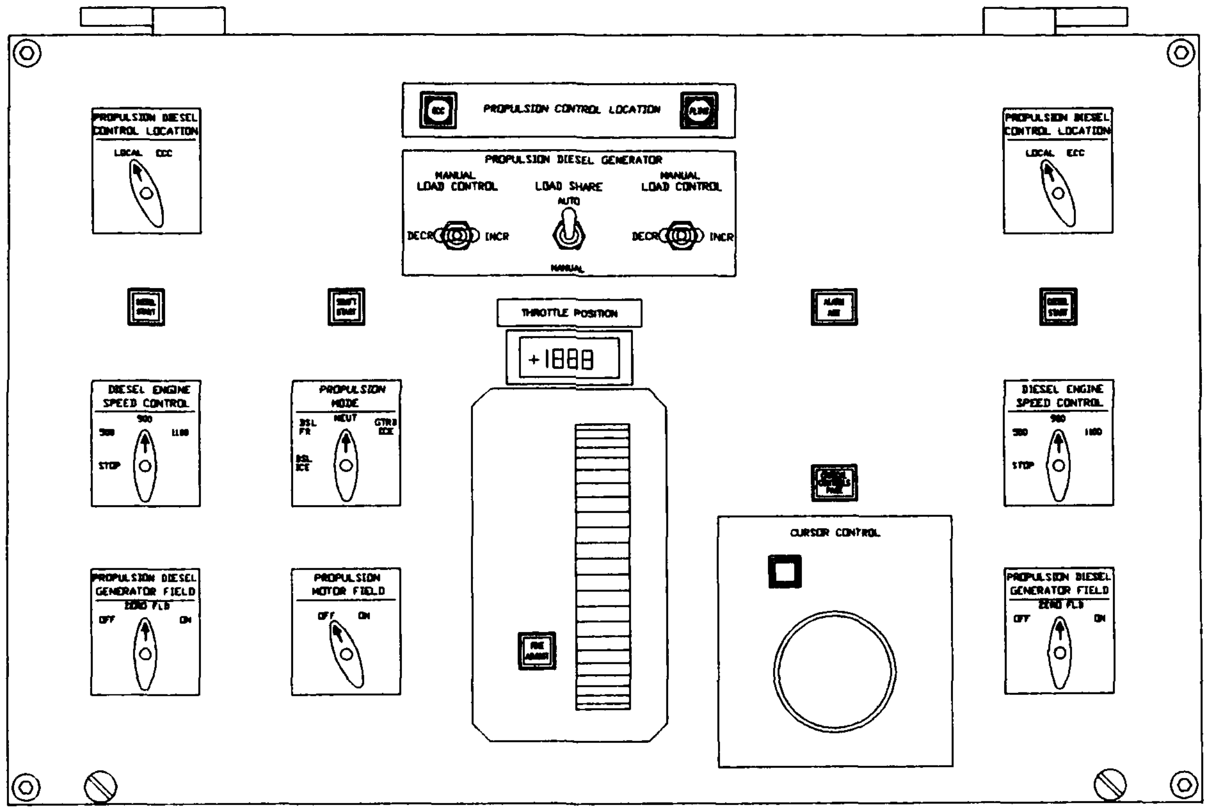


Figure 6–2. PCAMS control surface.

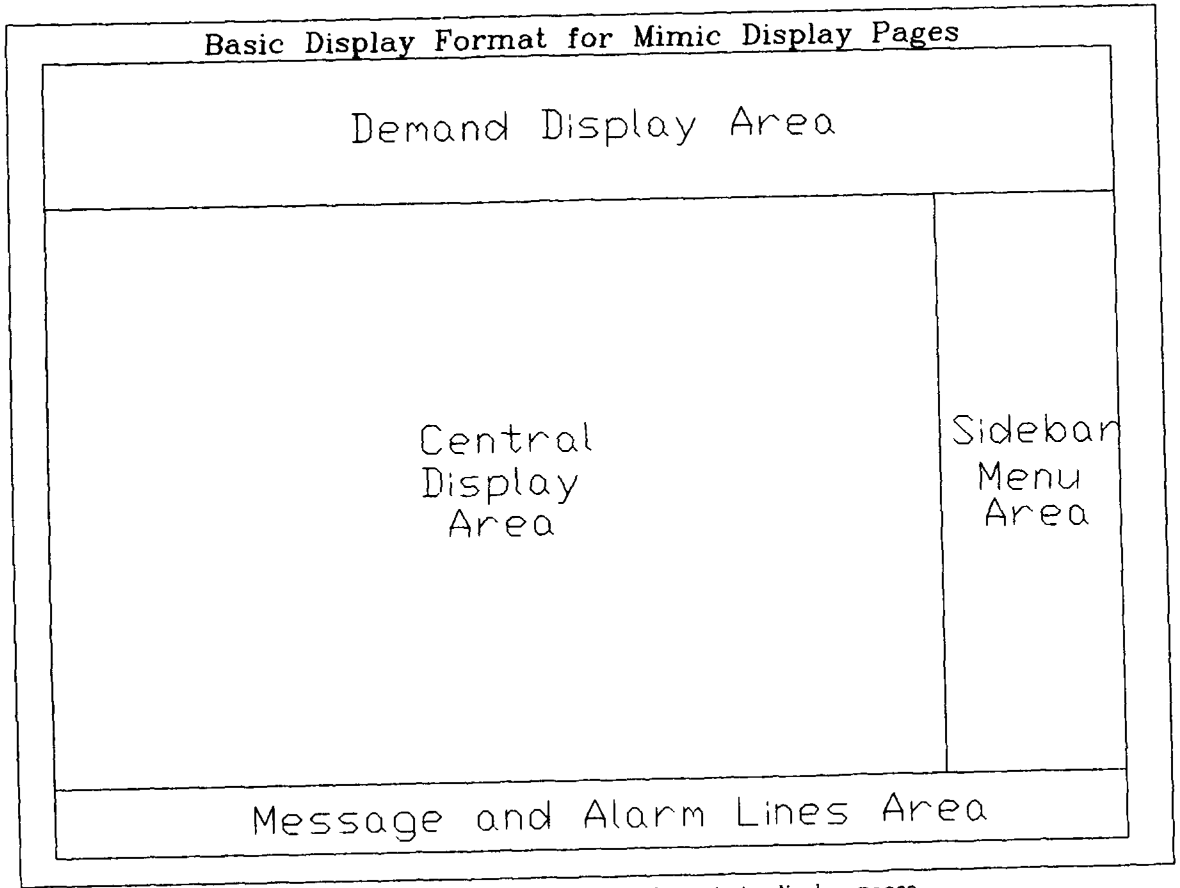


Figure 6-3. Basic display format for mimic display pages.

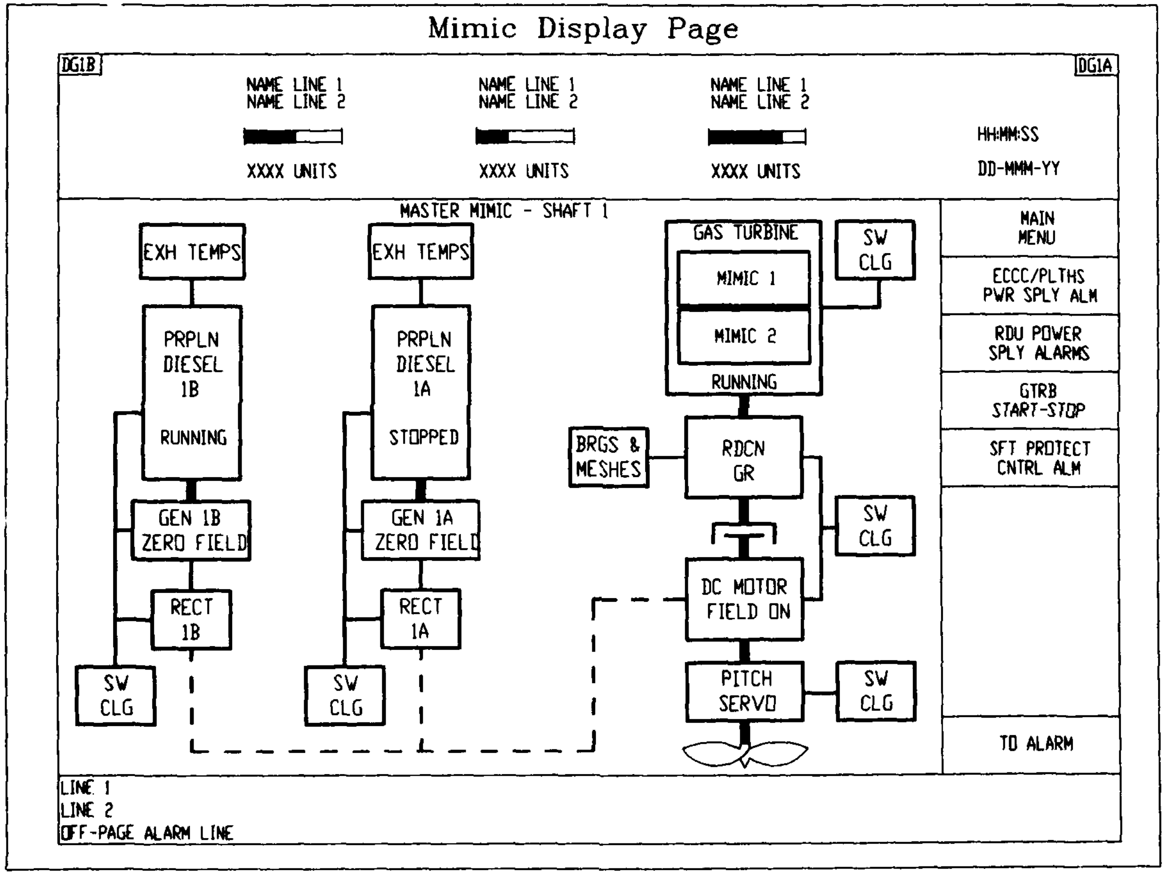


Figure 6-4. Master Mimic Display Page

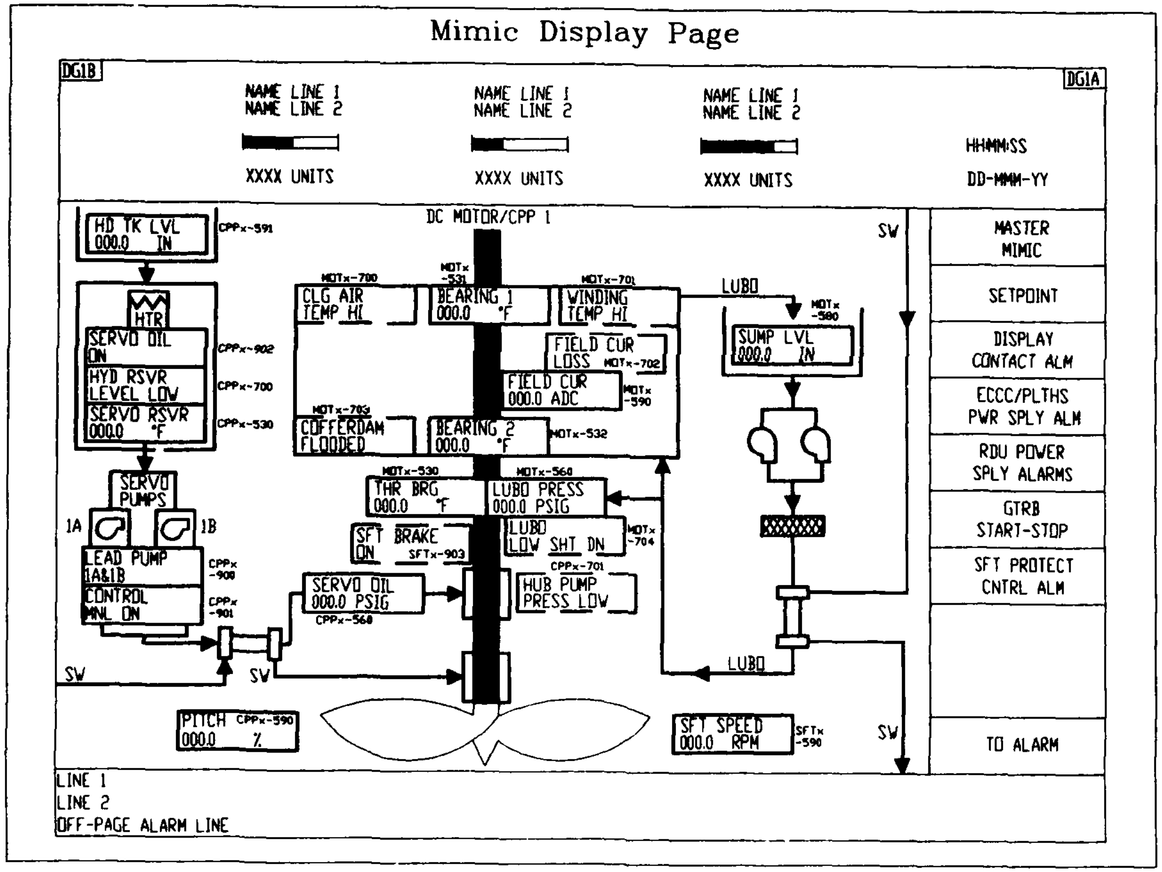


Figure 6-5 Mimic Display Page

SELECT pushbutton located adjacent to the trackball. The Main Motor/CPP mimic (figure 6-5) would appear. The operator would see the status of the CPP servo pumps. If the operator chose to change the status, he would move the cursor to the servo pump block and again press SELECT. A Pop-up menu (see figure 6-6) for the servo pumps would appear on the screen showing the operator which choices are available. By using the cursor and the SELECT pushbutton, the operator can change the pump's status.

Most pumps, valves, heaters and other propulsion auxiliaries are controlled through the CRT mimics by use of the trackball cursor and a pop-up menu. Those auxiliaries that are considered "critical" are also available (soft-key commands) on a Critical Controls Page which the operator can access through a dedicated pushbutton on the console.

6.2 MEPMAS

The auxiliary systems monitoring and control sub-system is called MEPMAS (Main Electric Plant Monitoring and Alarm System). The hardware elements for this sub-system are identical to the hardware items used in the PCAMS (CRT, trackball, VME processor, etc.) except that the MEPMAS also has a full size keyboard to allow the operator to perform system utility functions such as change setpoints and time delays, load new software from magnetic tape, and modify propulsion control variables.

In addition, the MEPMAS includes a second color CRT, keyboard, and trackball mounted into a deck mounted unit called the Watchstander's Terminal. The Watchstander's Terminal can simultaneously display different data/mimics than the ECCC mounted MEPMAS CRT. This unit can also perform as a back-up to the MEPMAS CRT/keyboard/trackball. The MEPMAS system also contains all of the PCAMS graphic mimic data in its database so that in the event of a failure of a PCAMS CRT, the MEPMAS can be set by the operator to display PCAMS mimics and allow the operator to activate PCAMS CRT controlled machinery.

7. LOCAL AREA NETWORK (LAN)

The nine VME processors communicate with each other over a redundant, high-speed (10 Mb/s) militarized Ethernet data network in conformance with ANSI/IEEE Standard 802.3-1985 and ISO International Standard 8802/3. (Ethernet was jointly developed by Digital Equipment Corp., Intel Corp., and Xerox Corp.) TANO designed the VMEbus LAN controller and the bus transceiver (node) to meet the military requirements for shipboard use.

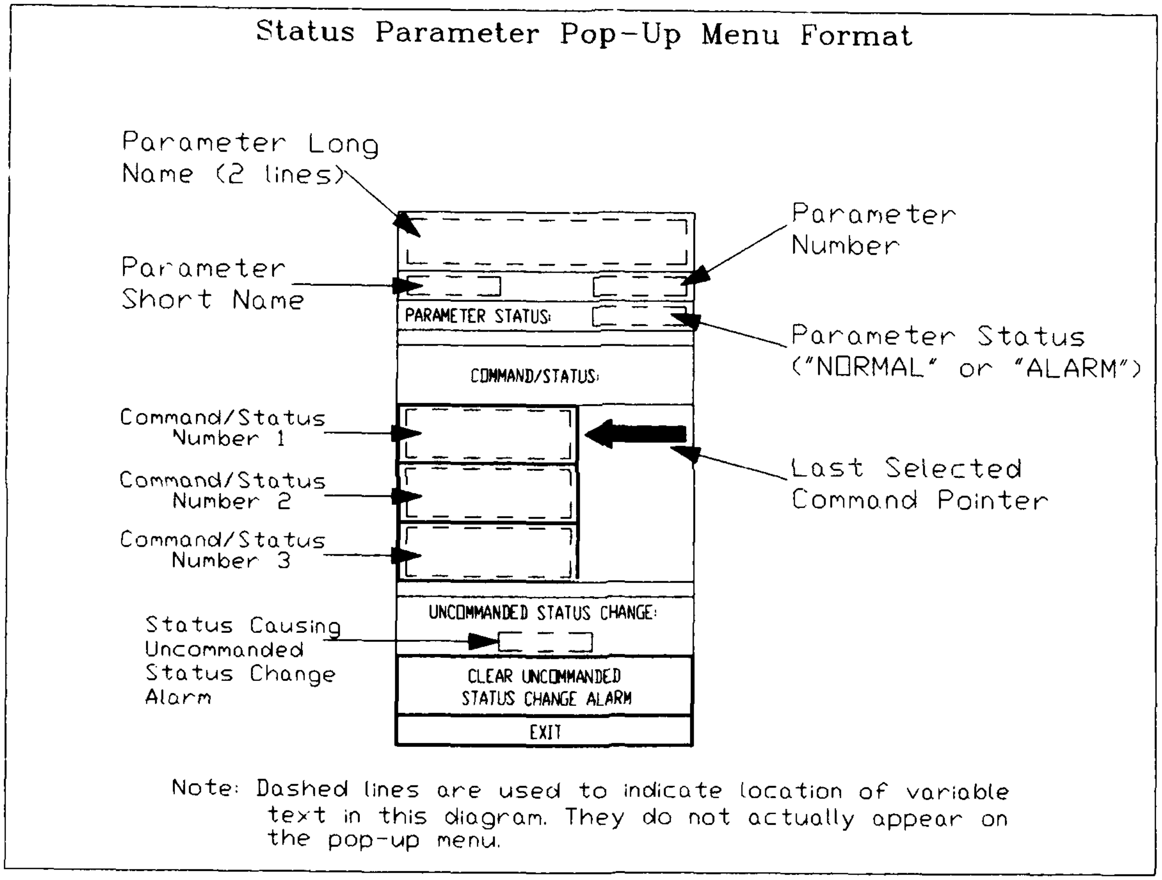


Figure 6-6. Status parameter pop-up menu format (commandable status parameters).

8. VITAL ALARM SYSTEM

The new control system contains an independent vital alarm system (VAS). Refer to Figure 8-1. The VAS is based upon a TANO designed microcontroller with Read Only Memory (ROM) based code. RAM memory is used for time delays which are operator changeable. The VAS has its own set of redundant DC power supplies and is not affected by a failure of the main control system. The VAS is linked to the MEPMAS to allow logging of vital alarm system events, to handle the man/machine interface for time delay changes, and to allow vital alarm annunciation of ECCC PCAMS or MEPMAS VME processor failure.

9. SOFTWARE

The language that was chosen for this system is Ada. TANO chose Ada due to previous success with Ada on a US Navy auxiliary oiler program.

9.1 Random Access Memory (RAM) Resident Code

An important software maintenance feature is the use of battery backed-up RAM in the VME processors. The RAM modules have an on-board battery to retain memory even when the module is removed from the system. The software is downloaded via the LAN to each of the nine VME sub-systems by use of the magnetic tape drive system linked to the MEPMAS processor. The system allows the logistics of spare RAM modules to be simplified and the number of unique electronic modules to be kept to an absolute minimum.

9.2 Software Modules

The following list describes the various Ada modules in the Polar Class system:

a. Serial I/O - contains utilities for configuring and communicating with devices connected to the TANO VMEbus Serial I/O board.

b. Database - consisting of predefined fields, Database is used to perform data acquisition, runtime calculation, and display.

c. Network - provides facilities to allow for general process-to-process communication over the LAN. In general, the LAN is used to communicate changes or exceptions. This reduces the network traffic reducing the possibility of data "collisions" and subsequent false readings.

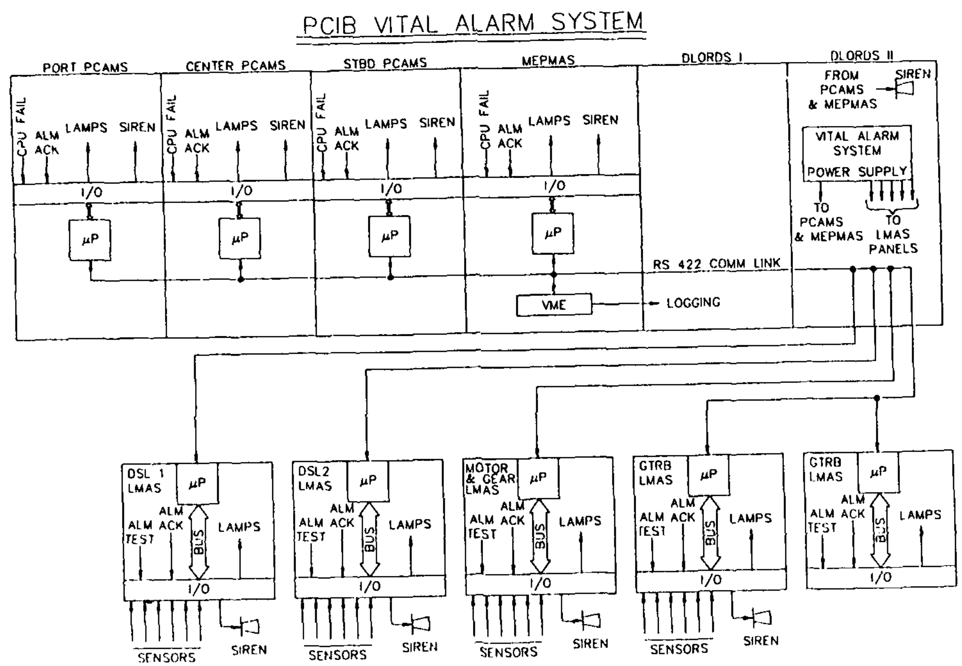


Figure 8-1 VITAL ALARM SYSTEM FUNCTIONAL DIAGRAM

d. Data Acquisition - scans raw data from RDU signal conditioning electronics (TDAC), checks for alarm and fault states, and sends output commands to external machinery through TDAC analog and solid-state relay outputs.

e. Display - provides facilities to create all of the mimic display pages, update the analog and status data displayed on a CRT screen, bring up the pop-up menu, and display setpoint values. A simple off-line facility gives the user the ability to create mimic layouts on a personal computer (PC).

f. Graphics - is designed to interface with the TANO VMEbus Video Graphic Controller. The Video board uses the Advanced Micro Devices AM95C60 graphic engine. Graphics provides routines for interfacing with the AM95C60 chip and a scaled down version of the GKS graphics command set plus some GKS_EXTENDED commands.

g. Propulsion Control - provides the various routines for controlling the shaft RPM and pitch, handling control location transfers, interfacing with digital throttles, gas turbine start-stop sequence logic, diesel generator load control, etc. All closed-loop control routines are confined to the processor that has access to the control inputs and outputs so as not to add a time phase lag because of multi-processor and LAN handling.

10. TRADE-OFF STUDIES

Several design trade studies were done during the course of the project to improve the system performance, reliability, or operability. A few are described here:

10.1 CRT Control

Perhaps the most significant trade study involved reducing the number of discrete motor/valve controls and indicators on the ECCC in favor of using software via the CRTs and trackballs. This had the effect of reducing the quantity of discrete panel mounted components thereby allowing the ECCC to be physically smaller and less intimating to the operator. Also, less hardware increases the reliability of the system with corresponding reductions in logistics/spare parts requirements.

10.2 Digital Meters

Another trade study involved the digital and circular bar-graph meters used in the system. The original specifications called for LED meters. Experiments with military-grade LED meters in and near direct sunlight showed that readability was not satisfactory. TANO proposed a liquid crystal display (LCD) meter that proved to be usable in all lighting conditions expected on the bridge of the icebreakers. The meters used on the ECCC are the same type (LCD) for logistics reasons.

10.3 Throttle Wheel

The Coast Guard asked that we eliminate the mechanical push-pull cables presently used on the bridge to link the ship control console (SCC) throttle levers to the bridge wing levers. We were also asked to keep the design as simple, rugged, and reliable as possible. In answer to this challenge, TANO developed the Digital Throttle Wheel (DTW) (see figure 10-1) which communicates over a RS-422 serial link to its corresponding PCAMS unit in the ECCC. The DTW has only two moving parts with no physical rotational stops and uses an optical encoding device. The design of the throttle device allows the operator to command the full range (from maximum astern to maximum ahead) while maintaining contact with the same point on the wheel. At pilothouse and aloft conn stations, the operator can simultaneously control three throttle wheels with two hands.

The throttle command setting is displayed in digital format on an LCD display adjacent to the throttle wheel. All control locations display the exact same throttle command setting. Control location transfers are inherently "bump-less" since all locations track the controlling location commands through the data links.

11. INSTALLATION CHALLENGE

This section discusses the engineering challenges to install the new system (size and placement of RDUs, size of ECCC, etc.) The contract required that TANO remove and replace the control system while the ships are docked and the crew is aboard.

11.1 RDUs

The RDUs had to be sized to fit through existing passageways. The approach taken was to divide the RDU into functional boxes of manageable size. Each RDU consists of:

a. Power Box containing the redundant DC power supplies and EMI filters,

b. Electronics Box containing the TANO VME-68020 processor and TANO Data Acquisition and Control (TDAC) electronics,

c. I/O Box(s) housing the field termination modules and signal conditioning circuits.

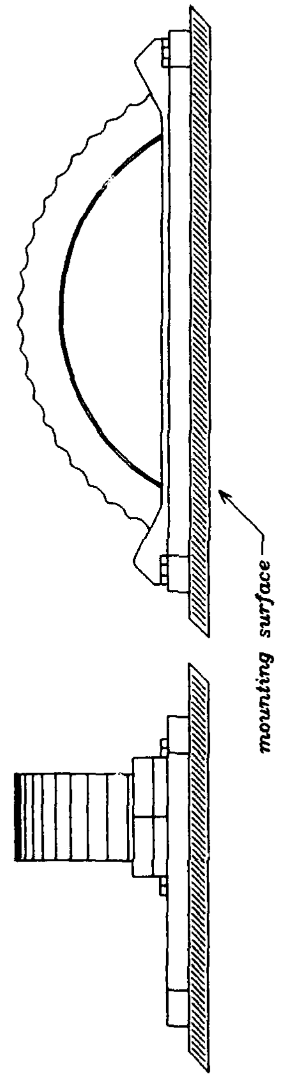


Figure 10-1. Throttle wheel.

The boxes are mounted as close to each other as possible and inter-box wiring is protected by means of EMI shielded, splash-proof, stainless steel wire ways.

Existing sensor cables were removed and new low-smoke cables installed from the sensors to the RDUs. Cabling from RDUs to the ECCC do not transit other machinery spaces to limit system degradation due to a casualty in any one machinery space.

11.2 ECCC

The ECCC, as previously mentioned, has the appearance of having six sections. Actually, the ECCC has twelve sections. Each major section (Port PCAMS, Stbd PCAMS, MEPMAS, etc.) is composed of a front and rear section bolted together. This was done to allow easier transit of sections into the control room.

All wiring enters the ECCC from the top surface of the console since the space below the ECCC is the Motor Room machinery space (not allowed to run wires through a machinery space that do not originate or terminate in that space).

12. SUMMARY

As this paper is written, the Polar Star Class (400 WAGB) control system is undergoing first article qualification testing. Installation of the first ship system is scheduled for November of 1990.

The following is a recap of some of the features of this advanced system:

- Distributed processing,
- MC68020 militarized VMEbus processors (quantity 9),
- Redundant militarized Ethernet Local Area Network,
- Ada software,
- High resolution 19-inch (48 cm) color CRTs (quantity 5),
- Trackballs and advanced "soft-key" CRT control design provide greater reliability and commonality of hardware,
- Liquid Crystal Display digital and bargraph meters for readability in bright light,
- LED lamps in lieu of incandescent in status/alarm indicators for reliability,
- Advanced throttle wheels providing precise digital control for three shafts at five different locations,
- Built and documented to military standards (MIL-P-24423),
- Monitors and controls approximately 1,000 analog and digital parameters.

The new TANO control system meets the needs for high reliability and improved maintainability for military environments. In addition, this design lends itself to easily adding future upgrades such as adding additional sensors or incorporating on-board operator training.

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(3) "IEEE Standards for Local Area Networks: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications", The Institute of Electrical and Electronics Engineers, Inc. , 1986

(4) "The Ethernet, A Local Area Network, Data Link Layer, and Physical Layer Specifications, Version 2.0", Digital Equipment Corp., Intel Corp., Xerox Corp., 1982

(5) Irene Wang, "Polar Class Icebreaker Software System Overview", TANO Marine Systems, 1990.

(6) "VMEbus Specification Manual", Motorola, Inc., Revision C.1, 1985

AN INTEGRATED RUDDER CONTROL SYSTEM
FOR ROLL DAMPING AND COURSE MAINTENANCE

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1. ABSTRACT

A Rudder-Roll Stabilization system is described in this paper. The system is microcomputer based and contains an adaptive Kalman filter, an adaptive course-keeping autopilot, high-gain turning regulators and an adaptive roll damping regulator. Roll measurements made onboard a minelayer, an attack craft and a passenger vessel show that the roll reductions obtained with the ROLL-NIX system, are of the same order as those which can be expected with an active fin stabilizing system. If the requirements on roll damping are extremely high, ROLL-NIX and active fins can be used at the same time. The ROLL-NIX system is in service on several ships including both naval and merchant ships. Both operational experience and the results of tests are presented.

2. INTRODUCTION

During recent years, interest in Rudder-Roll Stabilization (RRS) has increased rapidly. Advanced, adaptive filter and control algorithms for roll damping, course maintenance, turning and track-keeping are easily implemented in microcomputers. On many types of ship the RRS technique gives roll reductions in the same order as active stabilizing fins.

The application of rudder roll stabilization systems has moved to include merchant and commercial vessels along with the well documented applications aboard naval vessels. Common among the characteristics desired in these newer applications is the need or desire to maintain the vessel's top speed, maximum draft, and fuel efficiency. In short, the characteristics of RRS systems highly valued for naval applications are important for merchant and commercial applications as well.

The process of introducing sophisticated control algorithms to vessel steering systems makes obvious the need and opportunity to address other areas of the ship's steering processes. In particular, areas traditionally kept separate and distinct aboard ships such as rudder movement, autopilot, course planning, charting, and navigation, may now be integrated in a manner consistent with the real needs of the bridge crew. This new reality is possible by means of the integrated circuit microprocessor. Complex control algorithms based upon sophisticated algorithms can now be implemented reliably in small packages.

The ROLL-NIX system is an example of the application of this new technology; it provides a sophisticated rudder roll stabilization algorithm for the realization of its primary mission, roll damping. In addition, however, its ancillary systems: autopilot, precise turning regulator, and course keeping alarms provide substantive support to the vessel's steering activities on the bridge. Possibilities extend well beyond what is presented in this paper. Our intent is to show that careful holistic planning can yield a significant advance in the state of the art by integrating several systems previously kept separate and using the shared knowledge to substantially improve a ship's operations.

2.1 *Review of RRS*

The concept of utilizing the rudder for the purpose of stabilizing a vessel against rolling has been known since ancient times by seafarers. The interest for designing an automatic control system for RRS started around 1970. See Cowley and Lambert [1]. The first sea trial attempts performed in U.K. were not always successful [2], [3], [4], mainly due to the fact that simple control systems based on analogue techniques were used.

In the beginning of the eighties, very interesting and promising results were obtained in USA by Baitis and co-workers [5], [6]. A survey of RRS in the U.S. Navy is given in [7].

The RRS developments in Holland are summarized in [8], [9] and [10]. A Danish RRS-system is described in [11].

The development of the Swedish system ROLL-NIX started in 1984, see [12] and [13]. The first commercial ROLL-NIX was installed in 1987. By the end of 1990, the number of installed ROLL-NIX systems will be in the range of 10 to 15.

2.2 Integration of RRS and Autopilot

Since the steering gear and rudder system is used both for ship maneuvering and roll reduction, the integration of RRS and autopilot functions into a single control system is of crucial importance. This has been discussed in many papers, see e.g. [2], [3], [8], [13], [14] and [15].

2.3 Organization of Paper

Section 3 describes the ROLL-NIX system. The system design includes the Kalman filter, the autopilot, the turning regulator and the roll damping regulator; each are reviewed. A description of the hardware implementation is given in Section 4. Experiences from sea trials are given in Section 5, and a summary of operational experiences can be found in Section 6. The conclusions are summarized in Section 7, followed by the acknowledgements and references sections.

3. THE ROLL-NIX SYSTEM

SSPA started the development of ROLL-NIX in 1984. Presently, in 1990, more than ten systems are running on ships around the world. There are ROLL-NIX installations on many different ship types, e.g.:

- attack craft
- mine layer
- coast guard cutter
- rescue vessel
- passenger vessel

The compiled experience of ROLL-NIX in operation covers more than eight years (April 1990). The system is certainly well-proven and the installations provide their respective ships significant reductions in roll. ROLL-NIX is designed for use together with standard steering gear and rudder systems. Normally the maximum rudder rate is between 3 deg/s and 10 deg/s when two pumps are used at the same time.

A photograph of the complete system is shown in Figure 1. The size of the computer unit is 0.6 x 0.22 x 0.4 m and of the control panel 0.375 x 0.17 x 0.12 m. The total weight is only 25 kg.

3.1 System Design

The ROLL-NIX system contains:

- Adaptive Kalman filter
- Adaptive course-keeping autopilot
- High-gain turning regulators

- Adaptive roll damping regulator

The course and speed signals to ROLL-NIX are taken respectively from the ship's course gyro and speed log. Both the rudder position and the position of the helmsman's wheel are also obtained so that the ROLL-NIX function can be provided while the ship is being steered manually. The roll rate is measured with a built-in solid state rate gyro. A block diagram of the system is shown in Figure 2.

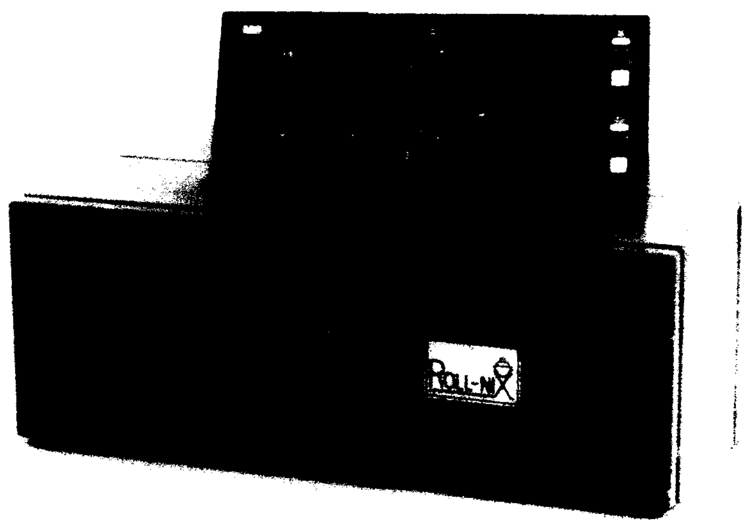

Figure 1. The ROLL-NIX system.

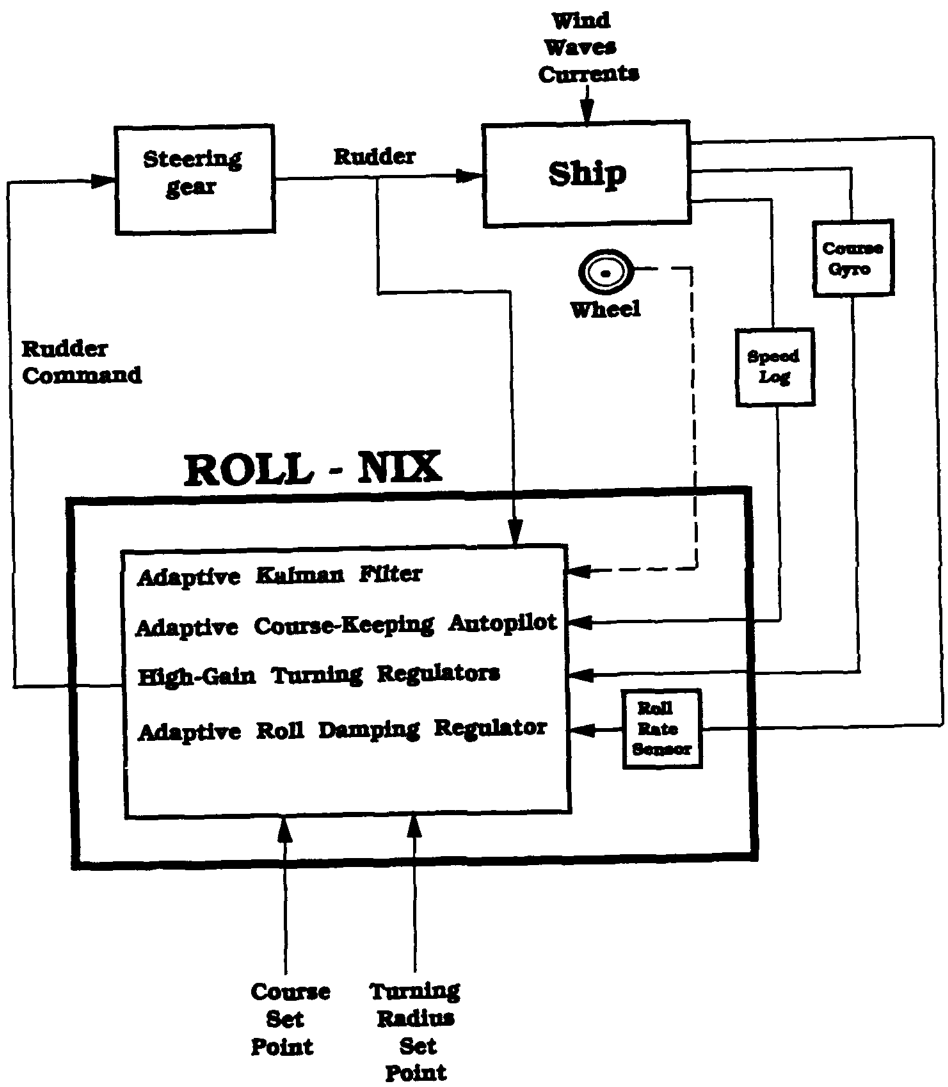

Figure 2. ROLL-NIX block diagram.

3.2 Adaptive Kalman Filter

The signal from the roll rate sensor is processed by an adaptive Kalman filter. Smooth estimates of the roll rate, the roll acceleration and the roll frequency are obtained and fed to the roll damping regulator.

3.3 Adaptive Course-Keeping Autopilot

The adaptive autopilot is used for steady state course-keeping and minor turns, i.e. course changes less than about ten degrees. The self-tuning regulator concept, see [18], is the basis of the autopilot. A detailed description is given in [16] and [17].

The main feature of the autopilot is its completely adaptive control algorithm. This means that the controller is automatically adjusted when the wind and wave conditions vary, or the trim and load conditions of the ship are changed. The autopilot always controls the vessel in a way that optimizes fuel consumption.

3.4 High-Gain Turning Regulators

A set of high-gain turning regulators is used in the ROLL-NIX system for precise and controlled turns. The regulators are described in [16] and [17].

The operator enters the required turning radius using a button on the control. He starts the turn by moving the joystick in the desired turn direction. (See Figure 1.)

3.5 Adaptive Roll Damping Regulator

The roll damping regulator is designed in such a way that a prediction of the ship's roll motion is calculated based on the Kalman filter estimates. From these estimates a control signal is generated for counteraction of the roll motion. The regulator is adaptive and designed for optimum roll damping when the maximum rudder rate is in the minimal range of 3 to 10 deg/s. The inclusion of roll motion prediction assures that an excellent roll damping is achieved even though the maximum rudder rate is less than 10 deg/s.

The adaptive roll damping regulator is designed for use during steady state course-keeping and normal turns. During tight turns or evasive actions the roll damping regulator is automatically switched off.

4. HARDWARE IMPLEMENTATION

ROLL-NIX is implemented as a system of modular subsystems interconnected by an industry standard bus, the VMEbus standard. This structure has supported the design, prototyping, field testing, and manufacturing production of this system for all of its phases to date. The advantages of this approach include:

- Availability of components from many sources.

- The ability to include custom components or interfaces on an interchangeable plug-in module basis.

- Ability to perform most field service operations at the module level as opposed to the circuit diagnosis level.

- Convenience in upgrading of either the algorithm(s) or addition of new features.

The following sections discuss the hardware components of ROLL-NIX in this modular context.

4.1 The Microcomputer System

VMEbus equipment is readily available from several commercial sources. Equipment enclosures that meet the size, ruggedness, and esthetic requirements for use on a ship's bridge where space is becoming an increasingly precious commodity, however, are more sparsely available. The enclosure chosen for ROLL-NIX contains two sets of hinges to allow access to both the front and rear of the VME backplane and modules via the front door of the cabinet. This particular enclosure has the possibility of being completely sealed (watertight) to NEMA 12 specifications if a heat exchanger was used rather than the presently used forced air cooling.

a. VMEbus microcomputer. The microcomputer module is a Motorola MVME101 single board system. Additional modules, an analog - digital - analog conversion module, a battery backed RAM module, and I/O interface modules complete the system.

b. Control panel. The control panel connects to the system via an I/O module which provides isolation and cable driving circuitry (see Figure 1). The panel is thus mounted separately at a site convenient to the helm. The production version of the panel has been carefully designed to be convenient for the professional operator. Buttons, levers, and indicators have been arranged for clear and concise communication between the operator and the system.

c. Roll-rate sensor. The roll-rate sensor, a solid-state gyro, is not significantly affected by translational velocities or accelerations. This means that it may be mounted nearly anywhere provided that its axis of rotational sensitivity is parallel with the ship's axis of roll. This convenient property allows the sensor to be mounted in the system cabinet as a module. Provision has been made in the sensor module for mechanical adjustment of the sensor's axis to achieve parallel alignment with the ship's axis of roll.

d. Tuning of the system. Best performance of the ROLL-NIX system is achieved by adjusting or tuning several parameters which optimize the model of the ship's roll damping to actual measured characteristics. In addition, several ship's model parameters used by the autopilot, precise turning regulator, and alarm algorithms must be made available to the system. A set of adjustment programs and diagnostic procedures are accessible via a connector on the system's panel. The system is tuned by connecting a portable terminal to access the interactive adjustment program. The coefficients and parameters are stored and recalled from the battery backed RAM portion of system memory.

e. Cabinet and power supply. Excepting the control panel, all system modules and interfaces are enclosed in the computer cabinet. Included there is the power control circuitry and a modular commercially available power supply for the provision of the standard DC voltages required by VMEbus systems.

4.2 Interfaces to Vessel Systems

The ROLL-NIX system incorporates individual I/O interface modules for connection to other shipboard devices and systems. These modules provide electrical isolation as well as the data formatting capability needed to acquire or dispense data in forms useful to all devices so connected. The following sections describe the principal interfaces and some of the optional interfaces:

a. Steering gear interface. Depending upon the type of steering control used by the ship, non-follow up or full-follow up, the steering control interface board is selected and configured. This includes input from a rudder position sensor and the ship's wheel.

b. Gyro compass interface. An interface to gyro compass signals, or optionally to a flux gate compass if a gyro compass is not available, is provided. As an option, a visual readout of heading can be provided to a point close to the ROLL-NIX control panel.

c. Optional interfaces. Interfaces to course planning systems attached to SatNav or GPS are available on a custom order basis. The ability to interface with other equipment makes possible increased integration of bridge operations.

5. EXPERIENCES FROM SEA TRIALS

The performance of roll damping systems has been measured in different ways over the years. From the scientific point of view, the obvious approach is to measure the roll angle with and without the roll damping system activated during exactly the same conditions. The significant roll angle $\Phi_{1/3}$ or the rms value is then calculated, and the percentage reduction obtained with the roll damping system is calculated as:

$$\text{Reduction (\%)} = \left[1 - \frac{\Phi_{1/3} \text{ (with roll damping)}}{\Phi_{1/3} \text{ (without roll damping)}} \right] \times 100 \qquad (5.1)$$

This is the method used in this paper for discussion of the roll damping performance of ROLL-NIX. For comparison, the typical reduction in roll motion, calculated by (5.1), is 50-70% for active fin stabilizers. LLoyd [19] (p 349) claims that for active fin systems "Reductions in rms roll motion of at least 50% are usually possible in moderate waves with a well designed system".

Sometimes another method is used, especially for active fin systems, to estimate the roll reduction with a roll damping system. A Wave Slope Capacity (WSC) is calculated and a typical roll reduction is obtained for a very special case, namely completely regular sea and synchronized control. A typical roll reduction for active fins, calculated in this way, is in the range of 80 to 90%. If the same method is used to calculate the roll reduction obtained with a RRS-system, almost the same figure, in the range of 80 to 90%, is obtained.

It is important to remember that a roll reduction calculation done in this way does not reflect what will happen under irregular sea conditions. It does not consider, for instance, the quality of the control system.

5.1 Roll Decay Test

In order to design a good RRS-system for a specific ship it is important to get information about the ship's roll dynamics. A simple approach is to move the rudder in a sinusoidal way with a frequency close to the ship's roll frequency, and record both rudder angle and roll. This method gives a rough estimation of how much damping can be achieved with a RRS-system, since such a system works exactly the other way around.

The test described above can be extended in such a way that the rudder is moved to zero when the ship is steadily rolling, or for comparison, the RRS-system is activated instead of moving the rudder to zero. An example of this type of test is shown in Figure 3.

It can be concluded for this type of ship, a passenger vessel 60 m long, that the ROLL-NIX system is very effective, at least when the ship is rolling close to the ship's own roll frequency.

Table 1. Summary of measured roll reductions with ROLL-NIX (see (5.1)) for the minelayer HMS Carlskrona (L = 105 m).

Test No.	Sea state	Wave direction [deg]	Speed [knots]	Roll reduction
1.1	4	90	15	40%
1.2	4	50	15	50%
2.1	5	50	17	41%
2.2	5	130	14	45%
2.3	4	90	16	68%
3.1	5-6	20	14	33%
3.2	5	30	14	46%
3.3	6	70	15	47%
3.4	5	40	13	40%

Wave direction: 0 degrees = astern seas.

5.2 Minelayer HMS Carlskrona

The minelayer HMS Carlskrona of the Royal Swedish Navy got the *first commercial* ROLL-NIX installation. This system has been in operation for almost three years. The roll damping performance with ROLL-NIX has been measured in different sea conditions and at different ship speeds using (5.1). A summary is given in Table 1. It can be concluded that in normal conditions a roll damping in the order of 40-50% is achievable with ROLL-NIX, but the maximum roll reduction obtained was as much as 68%.

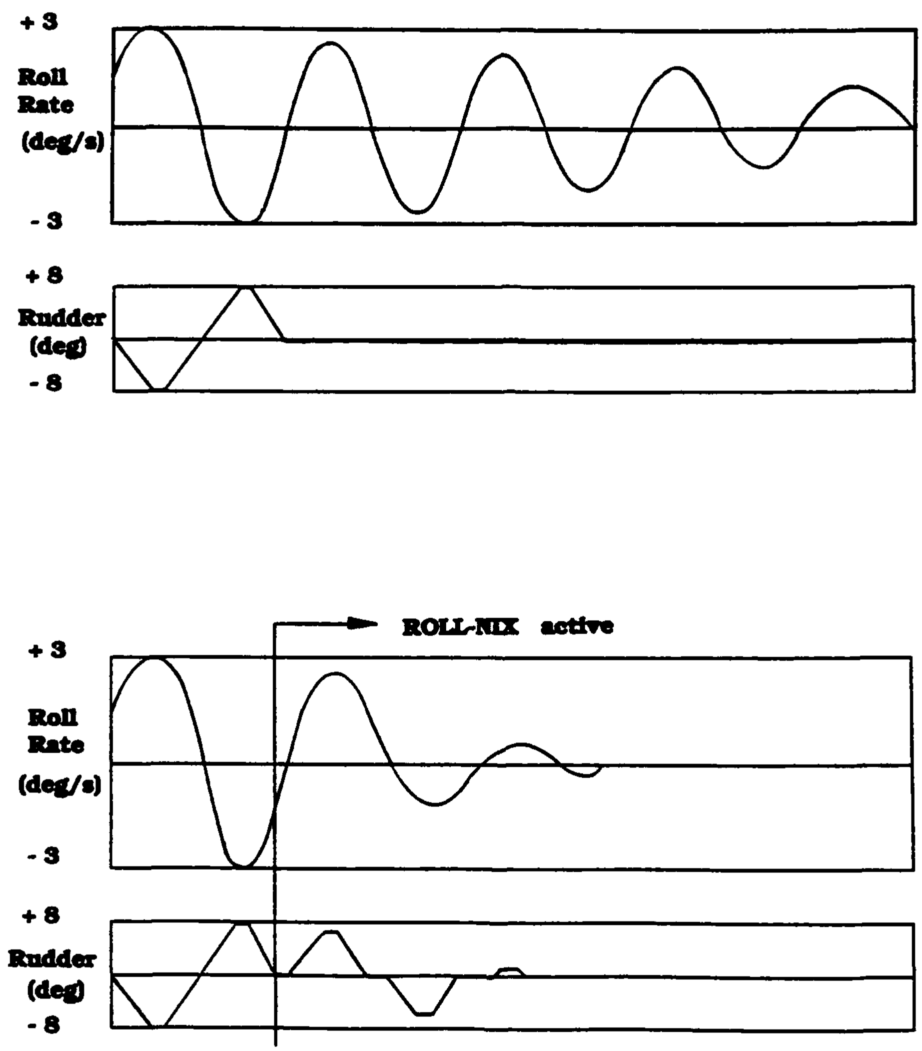

Figure 3. Roll decay test in calm seas with and without ROLL-NIX on a passenger vessel (L = 60 m) at a speed of 16 knots.

Figure 4 shows the ROLL-NIX performance in beam seas at a speed of 16 knots, resulting in a roll reduction of 68%. More results from HMS Carlskrona are given in [12] and [13].

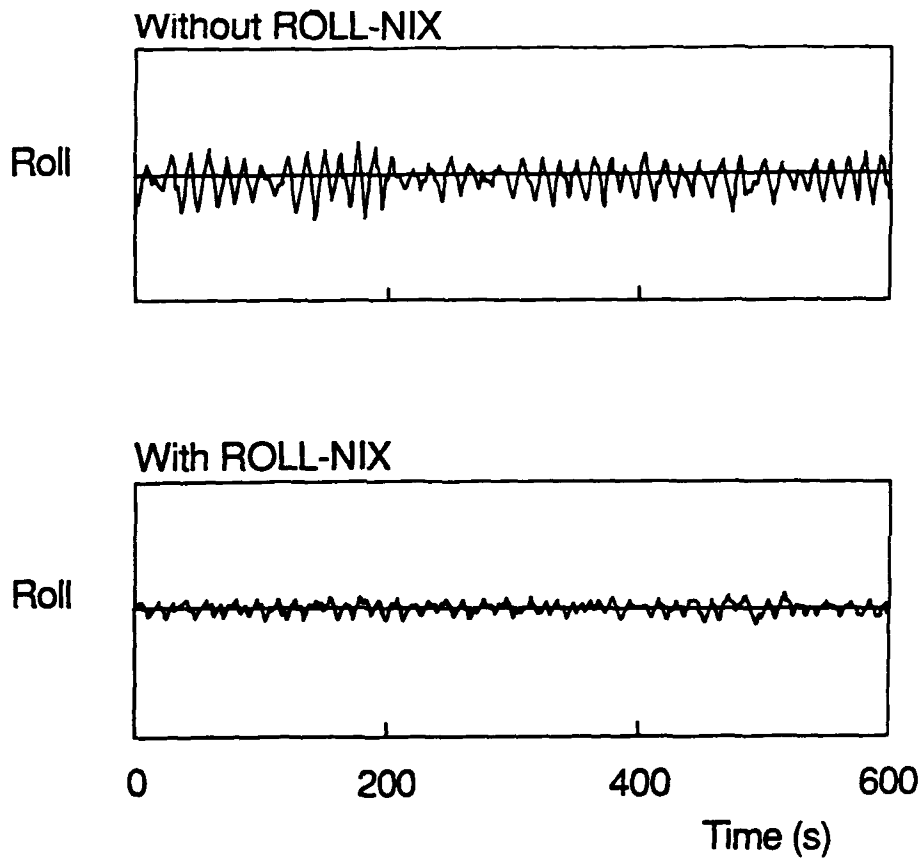

Figure 4. Results from sea trials with the minelayer HMS Carlskrona (L = 105 m) at a speed of 16 knots and in beam seas (4 Beaufort). The significant roll angle was reduced by 68% with ROLL-NIX (see (5.1)).

5.3 Attack Craft

Measurements with and without ROLL-NIX roll damping have been carried out with an attack craft (L = 35 m) of the Royal Swedish Navy. Normally, a roll reduction in the order of 45-55% was achieved with ROLL-NIX, but at 27 knots and in stern quartering seas (4 Beaufort) the reduction was 58%. Figure 5 shows this result. The roll and heading angles were recorded during the trial, which was carried out with manual control of the heading. The helmsman stated that it was easier to keep the ship's course when ROLL-NIX was active. This is clearly shown in Figure 5, where the course deviations from the experiment are smaller with ROLL-NIX than without.

More results from the attack craft trials are given in [12] and [13].

Table 2. Summary of measured roll reductions with ROLL-NIX (see (5.1)) for different ship types.

	Length [m]	Ship speed [knots]	Maximum rudder rate [deg/s]	Maximum roll reduction with ROLL-NIX	Average roll reduction with ROLL-NIX
Minelayer	105	13-17	8	68%	40 - 50%
Attack Craft	35	27	8	58%	45 - 55%
Passenger Ship	120	19	9	56%	45 - 50%

5.4 Passenger Ship

A series of trials with a passenger ship (L = 120 m) were also carried out. At a ship's speed of about 19 knots and in different wave conditions ROLL-NIX reduced the roll in average with 45-50%. One result is shown in Figure 6, where the roll reduction with ROLL-NIX is 56%.

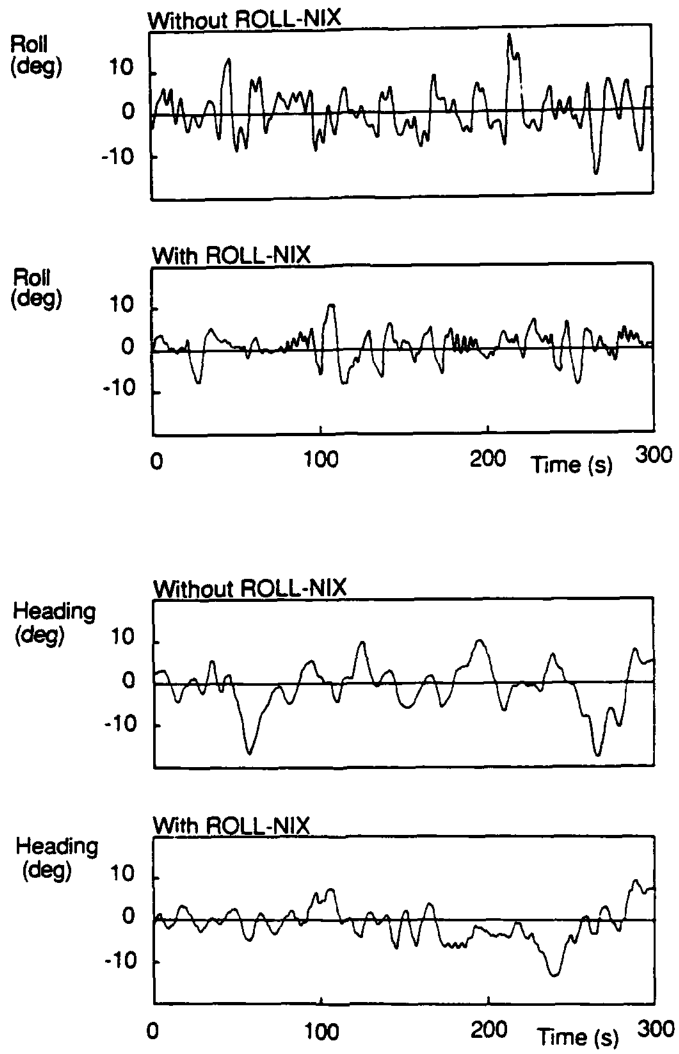

Figure 5. Results from sea trials with an attack craft (L = 35 m) at a speed of 27 knots and in stern quartering seas (4 Beaufort). The significant roll angle was reduced by 58% with ROLL-NIX (see (5.1)).

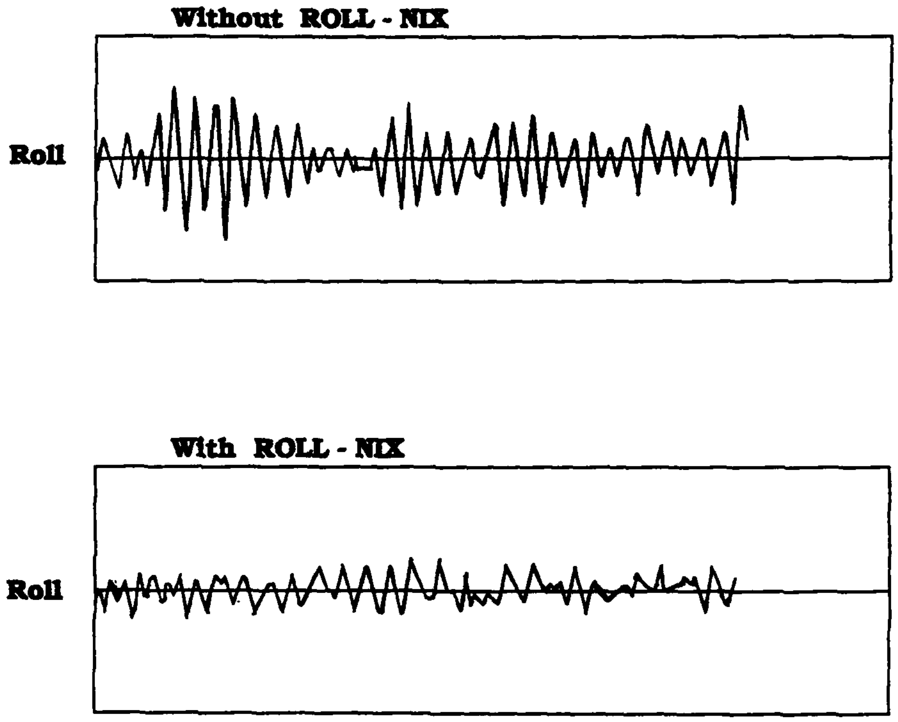

Figure 6. Results from sea trials with a passenger ship (L = 120 m) at a speed of 19 knots and in beam seas. The significant roll angle was reduced by 56% with ROLL-NIX (see (5.1)).

5.5 Summary of Results

The measured roll reductions with ROLL-NIX are summarized in Table 2. The average roll reduction for the three ship types (minelayer L = 105 m, attack craft L = 35 m and passenger ship L = 120 m) is in the order of 40-50% and the maximum roll reduction in special sea conditions between 56% and 68%. These roll reductions are very close to the reductions that would be expected from an active fin stabilizing system. Computer simulations carried out show that, if the requirements on roll damping are extremely high, ROLL-NIX and active fins should be used at the same time.

6. OPERATIONAL EXPERIENCES

The compiled experience of ROLL-NIX in operation is summed to more than eight years (April 1990). Problems with the ROLL-NIX equipment are extremely unusual, since the system's hardware components are very reliable.

The control pane. (see Figure 1) is designed with a very convenient man-machine interface. The operators are in almost all cases very pleased with the appearance and functional layout of the control panel.

In order to get an estimate of the percentage use of ROLL-NIX on a typical naval ship, the time in use was measured on HMS Carlskrona by the ship's officers during the winter training cruise, 1987-88. The time of use is shown in Table 3. Notice that there are four different, possible combinations:

- ROLL-NIX : Roll Damping + Autopilot

- ROLL-NIX : Roll Damping + Manual Steering

- ROLL-NIX : Autopilot only

- Manual Steering (no ROLL-NIX)

Table 3. Time of use of ROLL-NIX recorded by the officers in command on HMS Carlskrona on the winter training cruise 1987 - 88.

ROLL-NIX			Manual Steering (no ROLL-NIX)
Roll Damping + Autopilot	Roll Damping + Manual Steering	Autopilot only	
29%	39%	14%	18%
82%			18%

Thus, ROLL-NIX was used 82% of the voyage time.

Commander Hallin, Captain of HMS Carlskrona during the winter training cruise 1987-88, has told about an interesting and significant occasion:

> "This particular occasion was when the ship was off the Dutch coast, bound for den Helder, with seas coming in from astern on the port quarter. I was resting in my cabin. The time was 04.00 hrs. Suddenly, I sensed that the ship had started to roll perceptibly, and I wondered what was going on. At once, I went up on deck and asked the officer of the watch what on earth was happening, and what the reason was for this sudden increase in the ship's rolling motion. I was surprised to receive the reply 'We have just switched off the ROLL-NIX. We need to have some data without ROLL-NIX working, to see how much damping can be achieved!' I think that that is the most illustrative experience I have had of the ROLL-NIX system to date."

7. CONCLUSIONS

Rudder-Roll Stabilization (RRS) is by now a very well proven technique. It is shown in the paper that an RRS system such as ROLL-NIX reduces the roll motion by 40-50% in average and up to almost 70% in favorable wave conditions. The results are verified by sea trials with a minelayer, an attack craft and a passenger vessel.

The ROLL-NIX system works with relatively low rudder rates. The maximum rudder rate required is in the order of 3-10 deg/r. This means that standard steering gears can be used, possibly with two pumps working at the same time.

When designing a rudder control system it is important to consider all the different tasks: course-keeping, turning and roll damping. Since the steering gear and rudder system is the only actuator used for all tasks, it is important in the design to integrate the control system as much as possible in order to obtain a good overall behavior. These considerations have been made in the ROLL-NIX system. In the future it seems to be very likely that almost all rudder control systems will contain at least these three tasks: course-keeping, turning and roll damping.

8. ACKNOWLEDGEMENTS

The authors are grateful to the Royal Swedish Navy and to the Defence Materiel Administration (FMV) of Sweden for their support and assistance.

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AUTOMATIC SHIP STEERING FOR SURVEY APPLICATIONS

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Naval Air Development Center

1. ABSTRACT

A real-time, computer-controlled, track-keeping system has been developed that very accurately steers a survey ship along a prescribed rhumb line track. Prior to this development, less accurate track control was achieved via conventional autopilot steering of a constant ship heading, in conjunction with manual conning corrections to compensate for track errors arising from environmental factors. The system consists of an Integrated Navigation System, a track-keeping interface, and the ship's autopilot. The navigation system computer integrates position data from continuous fix radio and satellite positioning systems, inertial navigation systems, and dead reckon aids to develop Best Present Position (BPP). The navigation computer receives a manual input of the prescribed rhumb line track specified by a position and heading angle, also commonly referred to as the Desired Ground Track (DGT). At prescribed equally spaced times, BPP is used to compute the distance that the ship is off track. The off-track distance is used to develop proportional and integral heading corrections, which are fed via the track-keeping interface to the autopilot. The autopilot accepts the correction signal as a bias to the DGT heading, resulting in the ship being steered toward the desired track.

2. INTRODUCTION

Survey ships that collect bathymetric, gravimetric, and magnetic data efficiently accomplish the data gathering objective by collecting the data along prescribed rhumb line tracks. This paper describes an operational computer-based track-keeping algorithm, installed aboard various survey ships, that computes heading corrections based on the ship's distance off track. A portion of the heading correction is transmitted to the ship's autopilot and apportioned over a number of increments between computations in order to gradually lock the ship onto the track. The track-keeping algorithm, described herein, requires high-quality BPP data, such as provided by continuous Satellite or Loran navigation aids. The control law is composed of Proportional and Integral components (PI controller), which are computed using the ship's off-track distance (DCT). Generally, the proportional component compensates for short-duration disturbances such as wind gusts, whereas the integral component compensates for persistent disturbances such as ocean currents. Closing velocity limitations were imposed to provide an alternative approach to conventional differential control.

3. FUNCTIONAL DESCRIPTION

Prior to commencement of the survey data acquisition process, the desired ground track (DGT) heading is set into the autopilot, and the helmsman steers the ship to the desired track, to within start-up tolerances, to initiate the ship's automatic track-keeping operations. The automatic track-keeping system provides the necessary corrections to steer the ship onto the desired track. Environmental disturbances such as wind, waves, and ocean currents, tend to drive the ship off track, and it is the function of the automatic track-keeping system to restore the ship to the desired track. The open switch position shown on the functional block diagram in Figure 1 indicates the ship steering control loop prior to the start of the survey line (open-loop operation). When the ship reaches the start-up tolerance of the track, automatic track control is activated by closing the switch, which adds the track-keeping control law to the steering control mechanization (closed-loop operation).

4. CONTROL LAW IMPLEMENTATION

The track-keeping equations shown in Figure 2 add proportional and integral heading compensation (PI control law) to the autopilot, as required. Switches 1 and 2, shown in Figure 2, provide a means of indicating the application status of the compensation described herein. A survey line is started when the ship is typically within 0.1 nautical miles of the track. To prevent excessive integral compensation accumulation, resulting in undesirable overshoot of the track, only proportional compensation is applied (switch 1 is closed and switch 2 is open) until the ship is within 0.1 nautical mile of the track, at which time integral compensation is added (switch 2 is closed). To further minimize the possibility of overshoot and ensure a smooth lock onto the track, no proportional or additional integral compensation is added to the autopilot when the ship's closing velocity exceeds 0.5 knot (i.e., switch 1 is opened when the component of the ship's velocity perpendicular to and moving toward the track exceeds 0.5 knot).

5. CONTROL LAW GAIN SELECTION

The proportional and integral gain constants K_p and K_i, respectively, were selected to yield a maximum permissible proportional heading correction of 15 degrees for a ship's off-track distance of 0.1 nautical mile from the track and an integral time

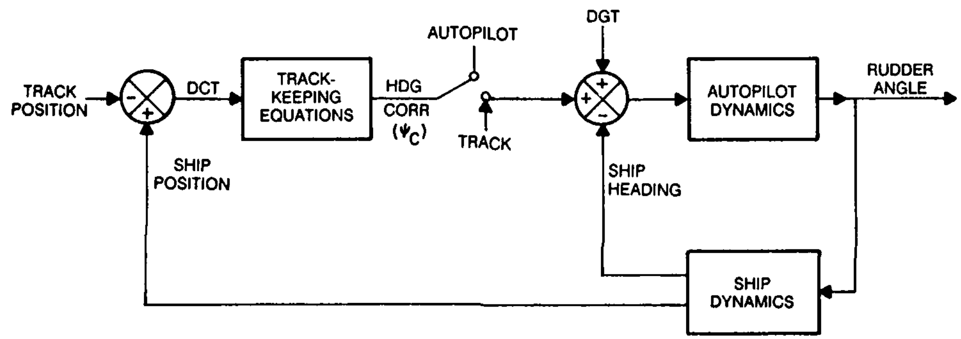
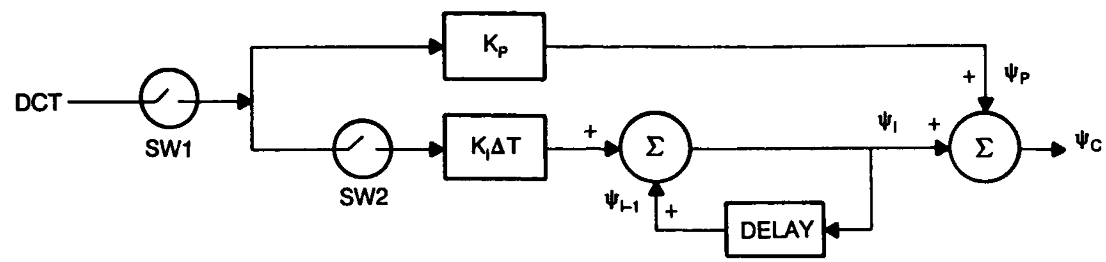


Figure 1. Automatic track-keeping system, functional block diagram.



TRACK-KEEPING EQUATIONS

$$\psi_P = K_P \cdot DCT$$

$$\psi_I = \psi_{I-1} + K_I \Delta T \cdot DCT$$

$$\psi_C = \psi_P + \psi_I$$

TRACK-KEEPING EQUATIONS DEFINITIONS

K_P: PROPORTIONAL GAIN
K_I: INTEGRAL GAIN
ΔT: COMPENSATION APPLICATION TIME INTERVAL
DCT: SHIP DISTANCE ACROSS TRACK

ψ_P: PROPORTIONAL HEADING COMPENSATION
ψ_I: INTEGRAL HEADING COMPENSATION
ψ_{I-1}: PREVIOUS INTEGRAL HEADING COMPENSATION
ψ_C: DGT HEADING COMPENSATION

Figure 2. Track-keeping control law equations, flow diagram.

(reset rate) T_{rr}, corresponding to a ship's nominal velocity of 15 knots. Using these notions, the gain development shown in Figure 3 indicates design values of 3 minutes for T_{rr}, and gain values of 150 degrees per nautical mile and 3000 degrees per nautical mile per hour for K_p and K_i, respectively. Using a reduced-order model of ship dynamics consisting of yaw and sway, rudder dynamics, and autopilot controller dynamics, application of Liapunov stability analysis techniques verified that the selected design constants yield a stable system.

6. PERFORMANCE SIMULATION

A ship motion simulation computer program featuring linear-state space models of the ship's sway, yaw, and roll motions; a non-linear surge equation to account for rudder, sway, and coupled yaw/sway drag; and autopilot and steering hydraulics models, was employed. Track-keeping algorithm performance was evaluated through simulations of the ship's response to various external factors driving the ship off track. The simulation assumed a ship velocity of 20 knots, a 3-knot ocean current crossing the track at 45 degrees, and a 0.5-nautical mile initial ship offset from the track. The maximum heading correction permitted was 25 degrees for 0.33 nautical mile, or greater, distance off track and 15 degrees, otherwise. The maximum incremental heading correction permitted was 2 degrees. Integral compensation updates were introduced only when the ship's distance cross track was 0.1 nautical mile or less.

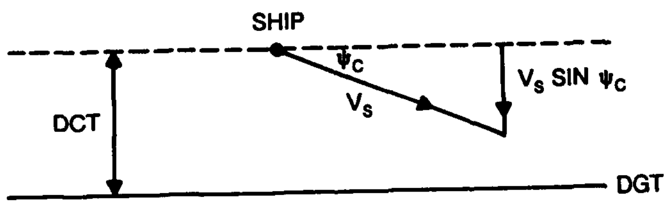
The autopilot heading correction, the ship's distance cross track, and PI control law graphs, depicted in Figures 4, 5, and 6, respectively, were generated from the simulation. The negative and positive constant slope portions in Figure 4 reflect time frames in which the theoretical PI control law correction exceeded the maximum 2 degrees per increment applied correction limitation. In Figure 4, the size of an increment is indicated by the vertical distance between successive plot symbols. The left and right flat portions of the graph, respectively, indicate a 25-degree maximum heading correction for the ship's off-track distance of 0.33 nautical mile, or more, and a 15-degree maximum heading correction, otherwise. Finally, the curved portion in Figure 4 indicates instances where less than maximum allowable incremental heading corrections were required.

Figure 5 reflects the ship's off-track distance in response to the combination of the applied heading corrections indicated in Figure 4, the ocean-current environment, the ship's initial offset from the track, and the ship's velocity. Due to the 2 degree per increment heading correction application limitation, the effect of the ocean current causes the ship to initially move farther away from the track, as indicated at the start of the run. As the heading correction application increased to the 25-degree limit permitted for offsets of 0.33 nautical mile, or more, the off-track dis-

$$K_P = \frac{\psi_{CMAX}}{DCT_I} = \frac{15°}{0.1\ NM} = 150°/NM$$

$$T_S = \frac{DCT_I}{V_S \, SIN\left(\frac{\psi_{CMAX}}{2}\right)} = \frac{0.1\ NM}{(15\ KTS)\ SIN\left(\frac{15°}{2}\right)} = 3\ MIN$$

$$K_I = \frac{K_P}{T_S} = \frac{150°/NM}{3\ MIN} = \frac{3000°/MIN}{HR}$$



V_S: NOMINAL SHIP VELOCITY

ψ_C: HEADING COMPENSATION ANGLE

DCT: SHIP DISTANCE CROSS TRACK

Figure 3. Proportional and integral gain selection.

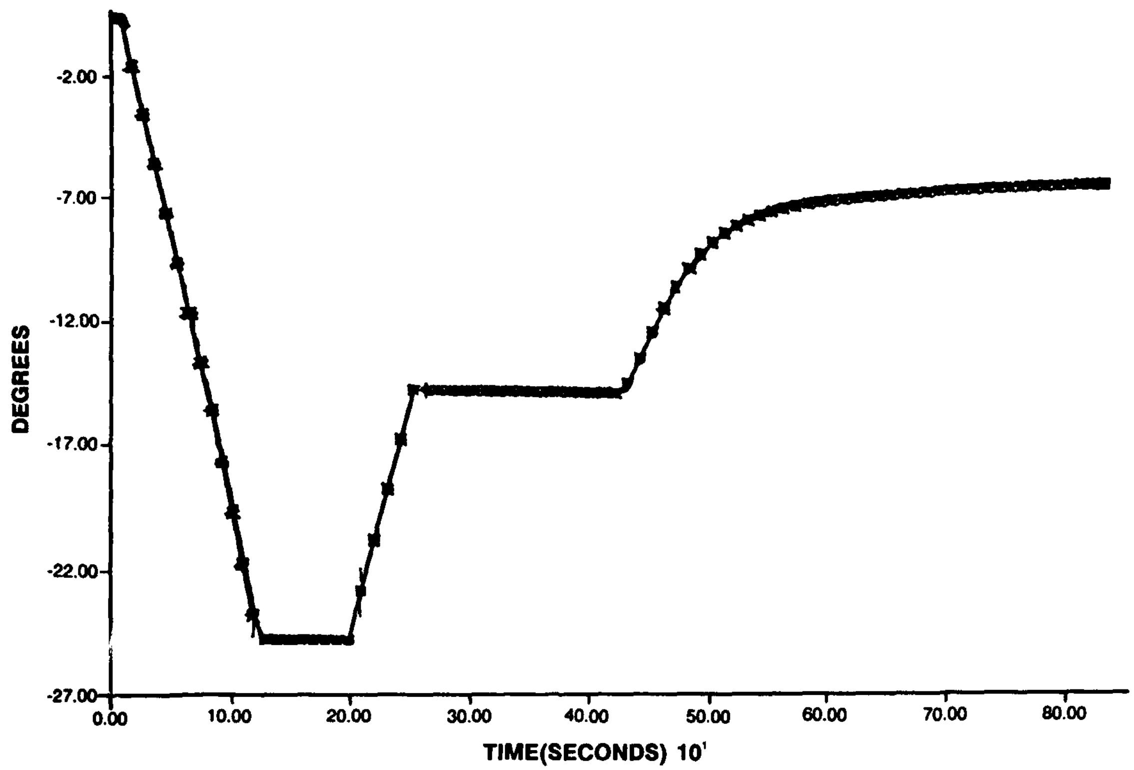


Figure 4. Simulation program autopilot heading commands.

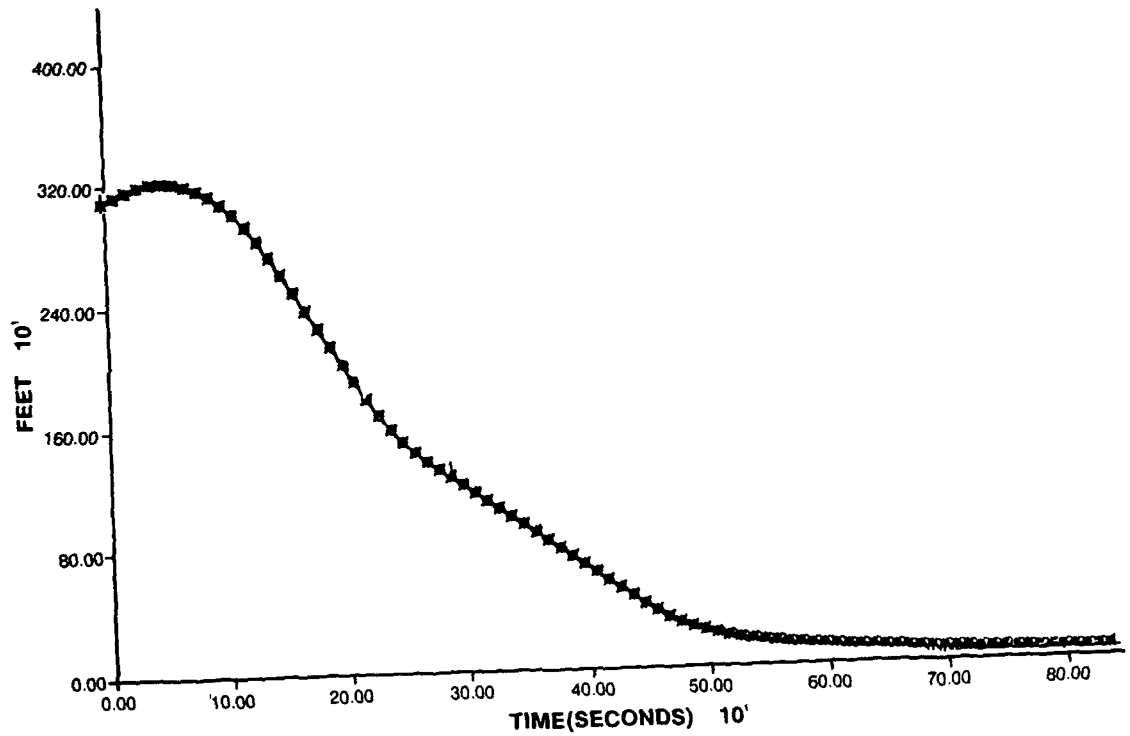


Figure 5. Simulation program ship off-track distance.

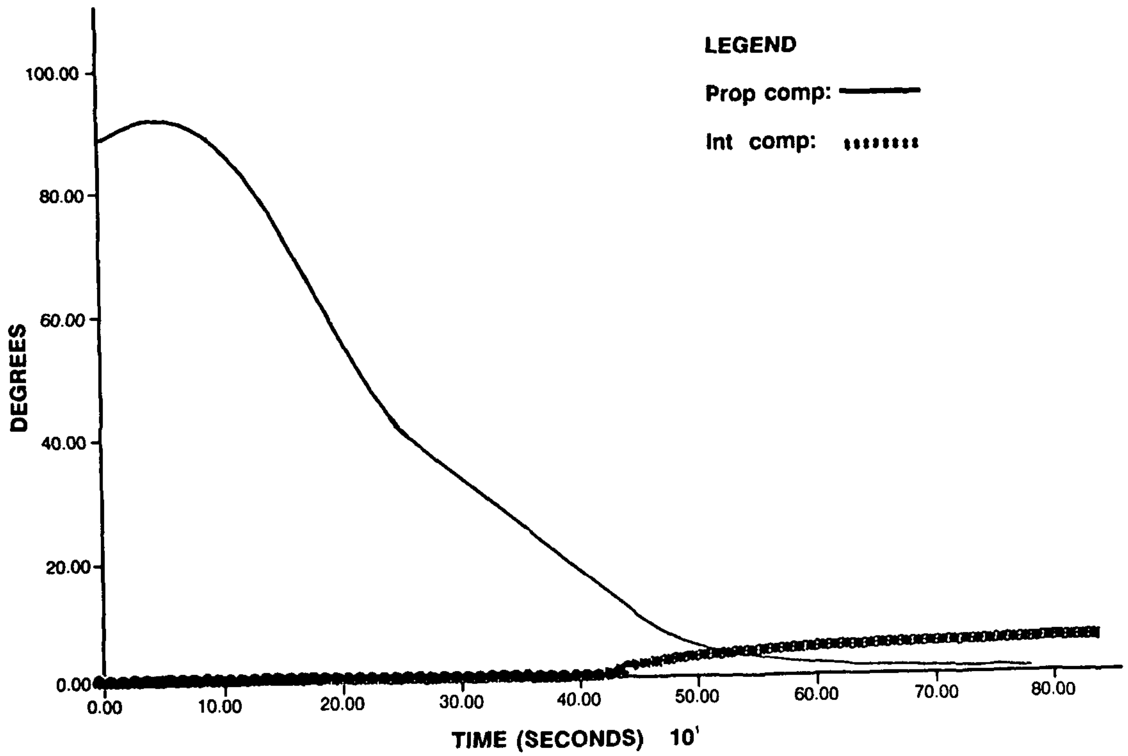


Figure 6. Simulation program proportional and integral components.

tance decreases rapidly. When the off-track distance falls below 0.33 nautical mile, the maximum heading correction application is reduced to 15 degrees, resulting in a corresponding decreased rate of ship movement toward the track. Finally, as the off-track distance falls below 0.1 nautical mile, the proportional heading correction gradually diminishes, while the integral compensation commences. Integral compensation builds up to the heading correction value required to compensate for the steady-state ocean current at the point of reaching zero off-track distance.

Figure 6 demonstrates the proportional and integral corrections generated by the PI control law. The proportional correction graph is identical in shape to the ship's off-track distance graph shown in Figure 5. In accordance with the correction application criteria discussed above, the integral compensation graph indicates zero values for the ship's off-track distances in excess of 0.1 nautical mile, and gradual accumulation to the value required to compensate for the ocean current, in the 0.1-nautical mile off-track distance range.

7. TRACK-KEEPING IMPLEMENTATION

The automatic track-keeping system was implemented on several survey ships with varying host computers and ship configurations as shown in Figure 7. The PI controller algorithm was hosted in the existing navigation computer, and an electrical interface was developed to handle data communications between the navigation computer and the ship's autopilot equipment. The track-keeping interface included digital-to-analog conversion functions and provided options for communications with two different types of host computers; namely, the AN/UYK-20 Navy Standard minicomputer and the HP-1000E commercial minicomputer. Figures 8 and 9, respectively, show the configuration of the track-keeping interface designed for the two types of host computers. Autopilot configuration modifications entailed incorporation of circuitry to add PI controller-derived heading corrections to the selected DGT heading. This permitted the autopilot system to function normally in all other respects so as to seek and lock onto a selected DGT. In this case, however, PI controller corrections cause the autopilot system to steer a rhumb line survey track.

Finally, sea tests were conducted to fine-tune design constants for each ship's implementation. The robustness of the design was evidenced by the fact that successful implementation was achieved with only minimal parameter tuning for ships with widely divergent characteristics.

8. CONCLUSION

Proportional and integral heading corrections derived from a ship's distance off track can be applied to the autopilot of a

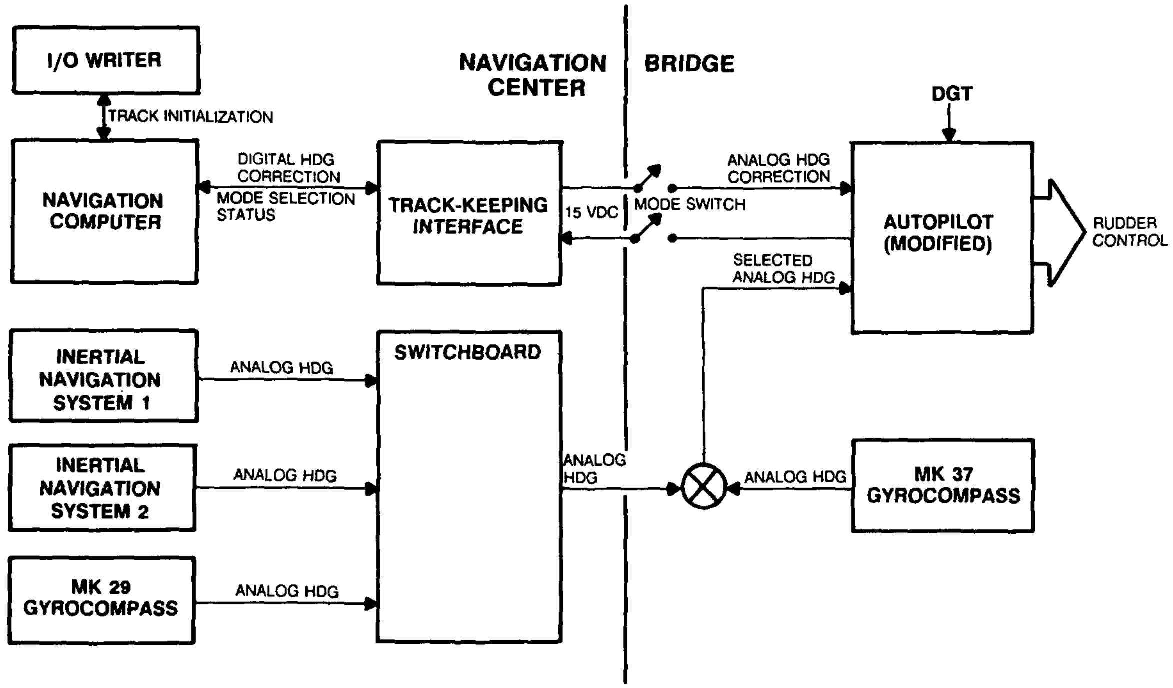


Figure 7. Track-keeping system integration.

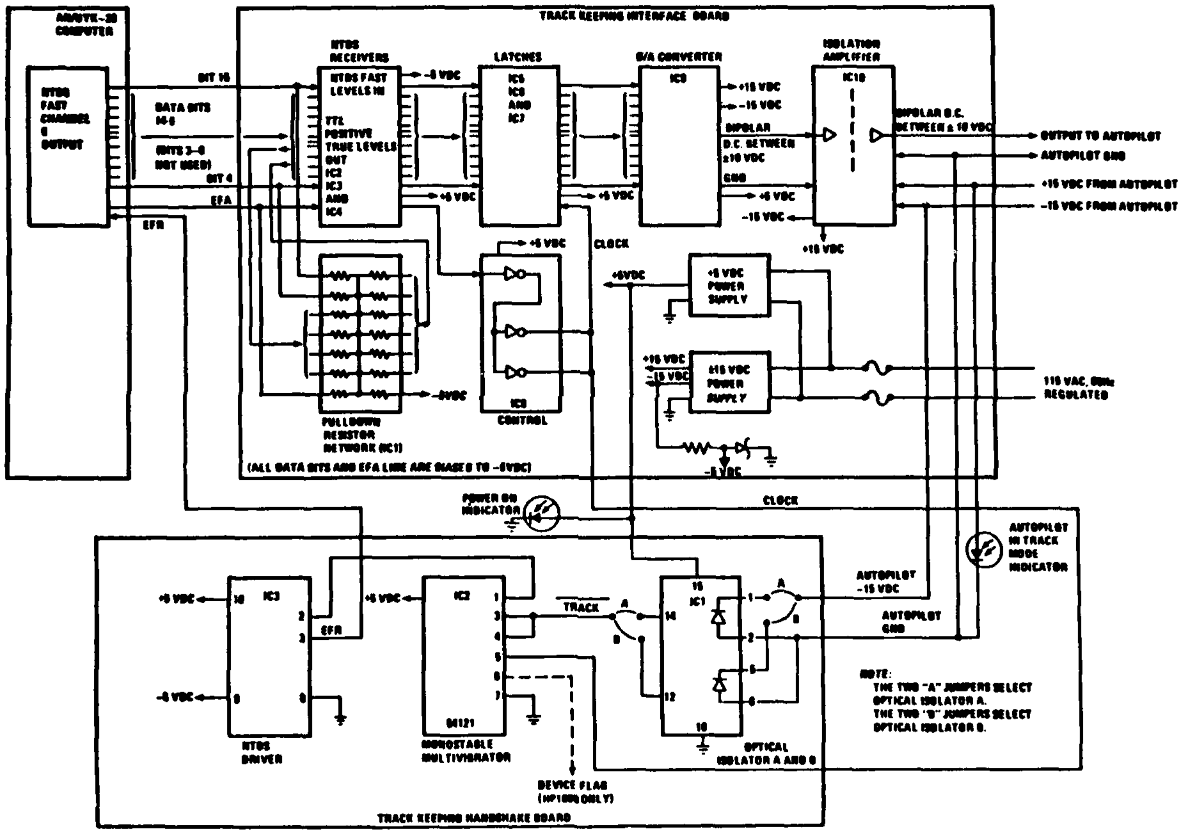


Figure 8. Track-keeping interface, functional block diagram, AN/UYK-20 configuration.

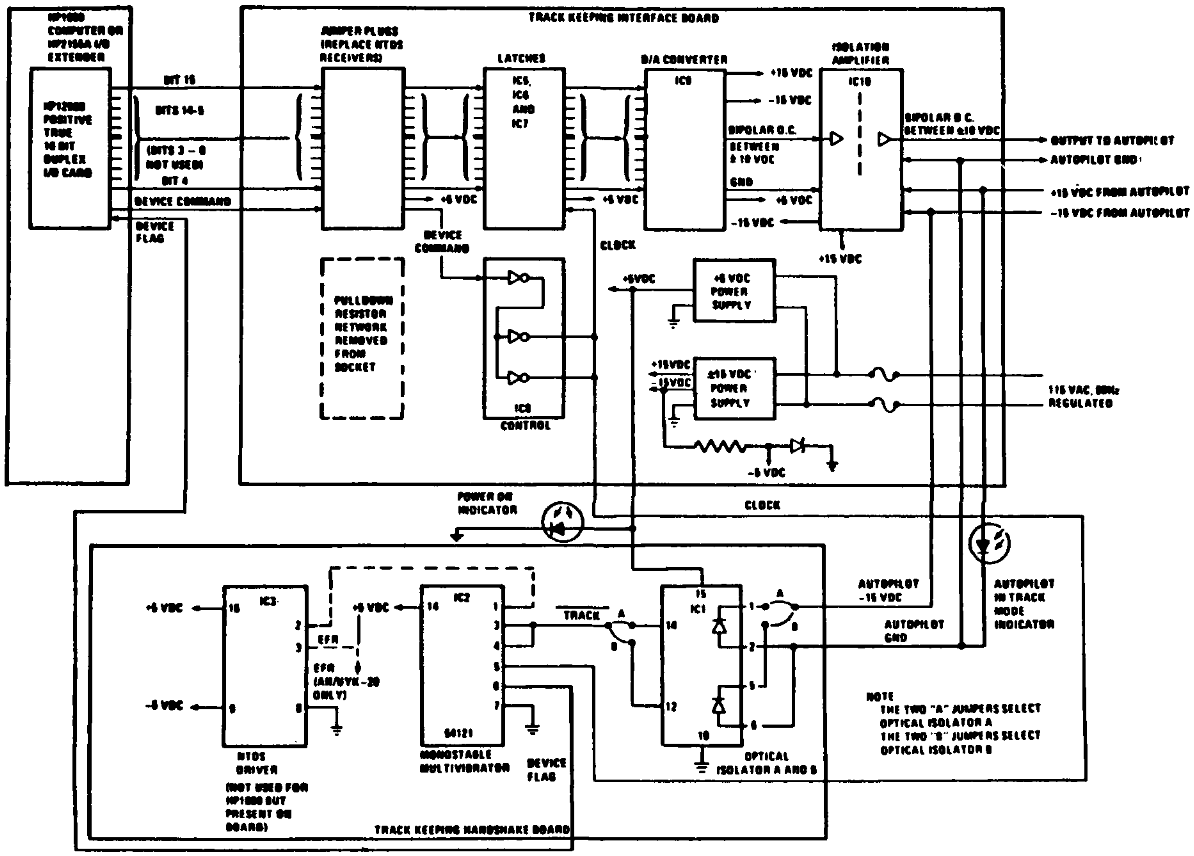


Figure 9. Track-keeping interface, functional block diagram, HP-1000 configuration.

survey ship to lock onto and precisely steer the ship along a prescribed rhumb line track, provided accurate continuous navigation data is available.

H_∞ MARINE AUTOPILOT DESIGN FOR COURSE-KEEPING AND COURSE-CHANGING

By

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Abstract

Over the last eight years the new H_∞ robust design techniques have been developed and are now finding application in industry. They enable systems to be designed with relatively low order models and the subsequent feedback system is robust in the face of variations in the system parameters. In marine system ship models are often poorly defined since it is usually too expensive to obtain tank test results or identification data.

The method can be extended to the design of roll stabilization, ship positioning systems and steering systems.

The objective of this paper will be to introduce the new approach and to detail the advantages of the robust design procedure. An autopilot design study will then be presented to illustrate the various stages of the design procedure and the performance which can be achieved.

Simulation is carried out using a single-input single-output ship model with non-linear steering gear with a H_∞ autopilot. It is shown that the H_∞ approach is a good feedback design tool for both the *course-changing* and *course-keeping* modes of the ship steering operation. In addition, the fixed H_∞ controller gives good robustness to parameter variations.

Introduction

The H_∞ design appro... duced by Zames (1981) provides a mathematical framework which is particularly appropriate for robustness studies and feedback controller design for uncertain systems. It is often the case that the likely modelling error can be pre-determined and the question then arises how best to design an optimal controller. An H_∞ design provides such a solution.

For marine applications, robustness to wind and wave disturbances must be achieved and these phenomena are presented by reasonably well-defined power spectra. Optimal rejection of these disturbances can be achieved by shaping the frequency response of the closed-loop transfer function.

Ship models are usually poorly defined since it is rare for exhaustive tests to be performed on scale models or on the actual vessels. A tolerance to the unmodelled dynamics is therefore required and this is provided by the H_∞ design procedure. Although this approach may not be the most appropriate for many applications, it does appear that the stochastic nature of marine systems and the poor models normally available make them particularly suitable for this type of problem. In this paper the ship steering problem is considered.

The ship steering control problem has received much attention over the years using several different control philosophies. Many autopilots which are based on modern control theory are adaptive - for example van Amerongen (1980) which uses the MRAS (Model Reference Adaptive System) approach of Landau (1979). Kallstrom et al (1979), Mort and Linkens (1981) use the STR (self-tuning regulator) approach of Astrom (1980). Another adaptive autopilot is that by Rios-Neto and da Cruz (1985).

The H_∞ fixed controller yields a feedback controller which is robust with respect to parameter variations. The purpose of this paper is to investigate the performance of a fixed H_∞ controller in the presence of nonlinearity from the rudder and parameter variations in the ship due to speed changes.

Both course-changing and course-keeping modes of operation are considered. In course-changing, the ship is required to follow a step change in desired heading with no overshoot or steady-state errors in spite of environmental disturbances such as wind and sea. In course-keeping mode, the controller is required not to actuate the rudder against the wave motion to achieve fuel economy and reduced rudder wear.

The course-keeping model of operation is achieved either by including the wave model as an output disturbance model and penalizing a particular term in the cost function or by frequency-dependent weightings in the performance index.

The paper is organized as follows: description of the modelling of the ship, rudder and disturbances in §2; derivation of the linear ship models and wave models for a number of different sea states in §3; description of the controller design and simulations for course-keeping and course-changing in §4 and §5 respectively.

1.1 *Ship coordinate system*

Fig. 1 shows the ship coordinate systems. The ship is depicted as a rectangular block. The origin is at the geometric centre of the ship. The ship velocity U has components u and v in the x and y directions respectively. Steering motion takes place around the z-axis which is vertically through the origin.

2. Marine System Model

Fig. 2 shows the linear discrete-time model used for the ship autopilot design. The ship is represented as $A^{-1}B$ where $B = B_k z^{-k}$ and k is a delay term. It is assumed at all times in this application that k=1. The yaw angle $\varphi = y$ is assumed to be identical to the ship heading and u is the control signal (demanded rudder angle). Wind is modelled as an input disturbance $A^{-1}C_d$ and wave motion is modelled as an output disturbance $A_n^{-1}C_n$. The controller (autopilot) is represented by $C_{fd}^{-1}C_{fn}$. The yaw angle φ must follow a demanded heading $\psi_r = r(t)$.

3. Ship and Rudder Modelling

3.1 *Ship modelling*

In this section, the modelling of the ship is considered. The ship is considered to be linear and time-invariant. The only factor which is assumed to affect the model is the speed U of the ship. Robustness with respect to speed variation is considered in detail in a later section.

In order to generate linear model of the ship, a standard procedure is followed which may be found for example in Zuidweg (1970). The following well-known transfer function model may be derived:

$$\frac{\psi(s)}{\delta(s)} = \frac{K}{s(1+s\tau)} \quad (1)$$

This transfer function represents the response of the heading angle ψ to small changes in rudder angle γ and was originally proposed by Nomoto (1957). Its simplicity renders it attractive for feedback controller design purposes.

3.1.1.1 *Speed variation*

The model parameters τ, k vary with the forward speed of the ship, U. If τ_1 and k_1 represent the ship parameter at speed U_1 then, at a speed of U_2, $K_2 = K_1^* U_2/U_1$ and $\tau_2 = T_1^* U_1/U_2$. This is obtained from Kallstrom (1979). Clearly, the gain K is directly proportional to the ship speed while the time constant τ is inversely proportional. The combination of both these variations with speed suggests a rather non-linear characteristic over the operating speed range of the ship. It is hoped that the fixed H_∞ controller will give good performance robustness over a range of speeds.

3.2 *Rudder dynamics*

In theory, it would be possible to simulate the ship with a linear feedback control law assuming that there were no limitations on rudder movement in terms of position and velocity. In practice, however, the constraints on the rudder movement are such that they must be included in the simulation study. This has been considered extensively in the marine literature. A model of the rudder could be as follows:

$$\dot{\delta} = \begin{cases} -\dot{\delta}_{max}(1-e^{(u-\delta)/\mu}) & \text{if } u-\delta > 0 \\ 0 & \text{if } u-\delta = 0 \\ -\dot{\delta}_{max}(1-e^{(u-\delta)/\mu}), & \text{if } u-\delta < 0 \end{cases} \quad (2)$$

The parameter μ is adjusted to give a rudder model response close to that of the real rudder. Fig. 3. shows the rudder rate as a function of the position error. The value of the parameter μ will depend on the moment of inertia of the rudder. Typical values will be in the range $3 \le \mu \le 10$. This model was taken from Rios-Neto and da Cruz (1985).

4. Disturbances

Environmental disturbances which any affect a ship at sea include wave motion, current and wind. High frequency wave motion is considered to be the most important disturbance ; current and wind may be considered to be low frequency disturbances which can be rejected by a control system relatively easily by the introduction of integral action (low frequency gain).

In some cases, it is necessary to actuate the rudder to counter disturbances due to the sea in order to achieve high accuracy in heading. This high accuracy is achieved, however, only at the expense of a very lively rudder action. This can obviously lead to deterioration of the rudder and steering gear and in addition a higher fuel cost will be incurred. It is important therefore to have two different autopilot strategies

(i) For high accuracy of heading and for good manoeuvring ability (course-changing)

(ii) For reasonable accuracy of heading in steady-state but with a less lively rudder action (course-keeping).

Under strategy (i), the feedback controller rejects disturbances due to wave motion, that is introduces high gain where the wave spectrum may be dominant. Under strategy (ii), however, it is important that the controller introduces low gain where the wave spectrum is dominant.

4.1 *Wind Modelling*

Wind has low frequency disturbance components which must be rejected by the control system- for example if a gust of wind causes a heading error then it is necessary for the rudder to actuate in an appropriate manner so that the heading error is corrected. The wind may be considered to be a d.c. disturbance for present discussions.

The magnitude spectrum of the wind disturbance model is therefore dominant at d.c. and low frequencies while having a low value at high frequencies. In order to achieve this type of spectrum, the wind is modelled by an integrator as follows:

$$d(t) = W_d\xi(t) = \left[\frac{0.03}{1-z^{-1}}\right]\xi(t) \quad (3)$$

Clearly $W_d(z = 1) = \infty$ and $W_d(z = -1) = 0.015$. Fig. 4 shows a magnitude bode diagram for the wind model.

4.2 ***Wave Modelling***

Modelling of the sea has received much attention in the marine literature. Wave amplitude spectra such as the Pierson-Moscowitz spectrum (Pierson and Moscowitz (1964)) and the ITTC spectrum which was introduced at the 12th International Towing Tank Conference (see for example Beukelman and Huijser (1976)) are well established. These spectra represent the frequency characteristics of the sea for different significant wave heights.

Modelling of the effects of the sea on a ship in terms of angular disturbance is rather more difficult. The ship is modelled as a rectangular block in order that relatively simple expressions may be derived for the forces on the ship in the x and y directions and for the torque about the z-axis. In the study of the autopilot, the forces in the x and y directions are neglected since only torque about that z-axis is relevant to steering.

Fig. 5 shows the block-shaped ship travelling at an angle μ with respect to the fixed q and r axes (see Blanke (1981)). The encounter angle $\chi = \mu - \psi$.

4.2.4 *Waves as an output disturbance*

In order that the wave disturbance may be included in the standard stochastic system description described in §2, it is necessary to model the wave disturbance as an output disturbance. In this way, it is possible to distinguish between the wind and wave disturbances in the H_∞ cost function.

A second order transfer function is used to model the waves as follows (see Jin and Grimble (1986) and many others).

$$W_w = \frac{X(3)\, s}{s^2 + X(2)\, s + X^2(1)} \tag{4}$$

The time series of angular accelerations on the ship due to waves is produced by driving W_w with a Gaussian white noise sequence.

In order to compute the coefficients of the transfer function W_w, a FFT is carried out on the time series of torques. This produces the angular acceleration spectrum. The coefficients X(1), X(2), X(3) are then computed using a standard least squares fitting program.

5. Ship and disturbance models

In this section, a ship model is introduced which will be used for simulation testing of the H_∞ autopilot. In fact three models will be derived; (i) Representing the ship at low speed, (6 knots), (ii) Representing the ship at high speed (16 knots), (iii) Representing the ship at an intermediate speed $\simeq$ (11 knots). 6 to 16 knots ($\simeq$ 3 to 8 m/s) is considered to be the speed range of the ship.

Three linear models were derived each representing different sea conditions. These models will be used when evaluating the course-keeping performance of the H_∞ autopilot. (i) Low sea conditions - the calmest sea which is modelled is Sea State 3 at a wave encounter angle of $\chi = 45^o$, (ii) high sea conditions - the worst possible sea condition is considered to be Sea-State 8 at a wave encounter angle of $\chi = 45^o$. This is an extremely rough sea. (iii) intermediate sea conditions - sea state 5 with an encounter angle of $\chi = 45^o$.

5.2 *Ship Model Parameters*

The three gains and time constant at three different speeds are summarized in Table 1 and the discrete-time model parameters are in Table 2. The frequency responses of the three ship models are in Fig. 6.

5.2 *Wave Model parameters*

Table 3 summarizes the three wave model parameter X(1), X(2), X(3) in equation (24) for Model 2 of the ship considered at three different sea conditions. These parameters were obtained using a spectrum fitting program and the angular acceleration times-series.

Table 4 lists the discrete-time wave model parameters. Fig. 7 shows the magnitude frequency responses for these three linear models.

6. H_∞ Course Changing Autopilot

In this section, an H_∞ controller is designed in order to yield good course-changing control action - that is in order that the ship follows a step change in desired heading quickly and with no overshoot. The wave disturbance term may be omitted from the cost function in this case. High gain may be introduced at the high frequency part of the disturbance spectrum if required by simply costing the tracking error signal. For this reason and for clarity of results, wave disturbance is neglected in the simulations in this section. Wave effects may be omitted since fuel economy is not the main criterion when manoeuvring.

6.1 *Ship frequency responses*

Fig. 4 shows a family of frequency responses of the ship. The ship is modelled as a first order lag with an integrator which gives a d.c. gain of ∞ and d.c. phase lag of 90^o. The gain rolls off at 20 dB/decade. The extra phase lag introduced by the integrator means that the phase becomes -180^o at high frequency.

6.2 *Wind frequency responses*

Fig. 3 shows the wind magnitude frequency responses. It has a similar response at low frequency to the ship but rolls off more rapidly at high frequency. This clearly shows the dominance of wind at low frequencies.

It will be necessary to introduce high gain at low frequency to reject wind disturbances. This high d.c. gain is introduced automatically if the wind model is included. An alternative method would be to omit the wind model from the equations and introduce integral action by means of the error weighting function in the cost index.

6.3 *Generalized H_∞ controller design*

In this section, a generalized H_∞ controller is obtained for course-changing (see Grimble 1987) and Fairbairn (1989) for details of the generalized H_∞ controller calculation).

The performance index (cost function) which is minimized is as follows:

$$J_\infty = \sup_{|z|=1} \Phi_{\varphi\varphi}(z^{-1}) \tag{5}$$

where $\Phi_{\varphi\varphi}(z^{-1})$ is the spectral density of the signal:

$$\varphi(t) = P_c e(t) + F_c u(t) \tag{6}$$

The criterion minimized is a weighted sum of the error and control signals. The weighting transfer functions P_c and F_c are chosen by the designer to trade off between stability robustness and performance. The weighting functions are expressed in polynomial form as follows:

$$P_c = \frac{P_{cn}}{P_{cd}}, \quad F_c = \frac{F_{cn}}{F_{cd}} \tag{7}$$

where $P_{cn}, P_{cd}, F_{cn}, F_{cd}, \varepsilon P_+$.

The GH_∞ optimal control law is summarized in the following theorem.

Theorem 1 (GH_∞ result)

The GH_∞ controller to minimize the criterion (5) may be computed by finding the minimum-degree solution (F,G,H,λ) where $F \varepsilon P_-$, $G, H \varepsilon P$, $\lambda \varepsilon R$ with respect to F of the following coupled polynomial equations:

$$FAP_{cd}\lambda + L_-G = P_{cn}CF^* \tag{8}$$

$$FBF_{cd}\lambda + L_-H = F_{cn}CF^* \tag{9}$$

where $L \varepsilon P$ is as follows

$$L = P_{cn}F_{cd}B - F_{cn}P_{cd}A \tag{10}$$

and factorize L as follows:

$$L = L_+L_- \tag{11}$$

where $L_+ \varepsilon P_+$, $L_- \varepsilon P_-$.

The GH_∞ controller follows as:

$$C_f = \frac{C_{fn}}{C_{fd}} = \frac{GF_{cd}}{HP_{cd}} \tag{12}$$

and the closed-loop characteristic polynomial $\rho_c \in P_+$ is given by:

Proof: Grimble (1987) and Fairbairn (1989).

Choosing $P_c = 1$ and $F_c = 0.1$ the generalized H_∞ controller is computed. The coefficients are in Table 6.

6.4 ***Simulation***

Simulations are carried out by solving the ship differential equation with the non-linear rudder model included. This is achieved by using a standard Fortran NAG library integration routine. A Fortran 77 simulation program, was developed which incorporated the NAG routine.

Ideal weather conditions are assumed- that is no wind or waves. The wave motion is neglected for course-changing as mentioned before. Wind disturbance in the form of a d.c. disturbance is considered in the next section.

The simulation data is as follows : simulation time = 200 seconds, rudder angle limit = $\pm 35^o$ rudder rate (max) = 5^o/s.

The response of the ship to a desired heading of 60^o is considered for an initial condition of $\psi = 0, \delta = 0$. (In addition all derivatives of ψ, δ are zero). The GH_∞ controller coefficients are in Table 5. The open-loop frequency response of the controlled system is in Fig. 8. It is clear that the gain and phase margins are excellent. Fig. 9 shows the time responses. It is slow due to the inertia of the rudder. Care must be taken not to try to move the rudder too fast or slew-rate limiting problems will be experienced.

6.5 ***Wind disturbance***

In this section the wind rejection property of the autopilot is considered. Wind disturbance will be considered to be a single gust which causes an error in the yaw angle.

The ship is considered to integrate the effects of a steady wind. That is a steady wind will cause a constant rate of turn. In simulation this is achieved by simply adding a ramp to the yaw angle ψ for a short period of time, for example 10 seconds. This simulates the effects of a maintained gust of wind for 120 seconds.

The demanded heading ψ_r was maintained at zero and the disturbance was introduced at T = 100 seconds. It is hoped that the rudder will actuate in such a manner as to return the ship to the correct heading.

It can clearly be seen from Fig. 10 that the wind disturbance causes an error in heading. However, the high gain at low frequency, introduced by the inclusion of the wind disturbance model in the cost function, reduces the error to zero. This disturbance rejection result will apply to other low frequency effects such as current and low frequency wave motion.

6.6 *Robustness with respect to speed variations*

In this section the robustness of the fixed controller with respect to model variations due to speed is considered. As mentioned in §2, the ship gain increases with speed while the time constant decreases.

The H_∞ controller calculated in the previous section for the intermediate speed of 5.42 m/s was tested in simulation with ship models representing speeds of 3 m/s and 8 m/s respectively, the corresponding parameters are in Table 1.

Ship speed = 3m/s (Fig. 11)

With a lower ship speed the ship gain is lower and the time constant is larger. With the same controller, it is expected that the closed-loop performance of the ship will be slower which is certainly the case in the first 30 seconds.

Ship speed = 8 m/s (Fig. 12)

With a higher ship speed the ship gain is larger and the open loop time constant is smaller.

Fig. 12 for the generalized H_∞ controller indicates that the response is almost unchanged from that of Fig. 9.

7. H_∞ Course-keeping Controller

In this section, a H_∞ controller is designed which will maintain the heading of the ship but will reduce the actuation of the rudder against the wave motion in order to save fuel and to minimize rudder wear.

In all cases, the demanded heading ψ_r is assumed to be zero since course-keeping is a steady state problem.

The wave motion is simulated in the time domain by means of equations (4). To reduce the number of simulation traces, only the extreme cases of Sea-States 3 and 8 will be considered.

The course-keeping controller is designed causing no wave model but using a frequency-dependent control weighting.

7.1 *Performance of course-changing controller*

In this section, the performance of the course-changing controller is considered when the ship is affected by wave motion.

It is clear from Figs. 13a , 13 b and 14a, 14 b for sea states 3 and 8 respectively that the tracking capability of the course-changing controller is excellent. This is achieved, however, only at the expense of a very active rudder. For Sea-state 3 the heading is maintained to an accuracy of around 0.05^{o} while the rudder activity is around 23^{o}. Under Sea-state 8 the heading is maintained to an accuracy of around 0.2^{o} while the rudder activity is around 7^{o}.

It is this rudder activity which must be reduced whilst maintaining reasonable heading accuracy.

7.2 *Controller design using frequency dependent weighting*

In this section the control signal weighting function F_c will be selected to minimize rudder activity at high frequency.

Consider the frequency responses of the three wave spectra in Fig. 7. It is clear that control weighting is necessary in the frequency range 0.1 to 1 rad/s.

It is desired to shape F_c such that it has a low value at low frequency and rising quickly in the range 0.1 to 1 rad/s and maintaining a constant value as $\omega \rightarrow \infty$.

Let F_c be defined as:

$$F_c = \frac{k_w f_1 s^2}{s^2 + f_2 s + f_3} \tag{14}$$

This is similar in form to the output disturbance model (4). However an extra s is included in the numerator to ensure a non-zero value of F_c as $\omega \rightarrow \infty$. Once sensible values have been chosen for f_1, f_2, f_3 then the k_w term may be adjusted as a design parameter.

With $k_w = 1$, suitable values for f_1, f_2, f_3 were determined to be $f_1 = 140.175$, $f_2 = 0.144$, $f_3 = 0.274$. Using the bilinear transformation, the following discrete-time control weighting function was obtained:

$$F_c(z^{-1}) = \frac{122.918 - 245.836z^{-1} + 122.918z^{-2}}{1 - 1.634z^{-1} + 0.874z^{-2}} \tag{15}$$

The frequency response of this weighting function is in Fig. 15.

The generalized H_∞ controller was determined. The parameters are shown in Table. 7.

Fig. 16a shows the yaw angle obtained with the course-keeping controller under Sea-state 3. The heading is maintained to an accuracy of around 0.2^{o} which is clearly worse than with the course-changing controller. However, the rudder activity has been significantly reduced to variations of around 0.15^{o}. A similar effect is obsered for Sea-State 8, (Figs. 17a and 17b). The heading error is around 0.3^{o} which is only slightly greater than with the course-changing controller. However, the rudder activity has been significantly reduced to around $0.3\ ^{o}$.

7.4 *Robustness with respect to speed variations*

In this section, the effect of speed variation on the course-keeping controller is observed; for clarity only Sea-state 3 will be considered.

It is clear from Figs. 18 and 19 that the high frequency movement of the ship is more pronounced at the higher speed of 8 m/s.

8. Conclusions

Two H_∞ autopilots have been presented : one for course-changing mode and one for course-keeping mode. The course-changing autopilot provides responsive control action for a good step response and to counteract the effects of disturbance due to the wind and waves. The course-keeping autopilot provides less accurate heading performance in the presence of waves but the rudder activity is significantly reduced.

The H_∞ autopilot design procedure provides very good stability robustness with little effort in selection of weighting functions.

Both autopilots have shown to be very robust with respect to speed variations. The ship considered, however, is not intended as a highly manoeuvrable craft and does not have a very large speed range. Modern warships have a larger speed range. Further work will be necessary to evaluate the robustness of the H_∞ autopilot with a larger speed range.

A very simple linear model of the ship is assumed in this paper. Furthermore the ship transfer function parameters are assumed to vary only with speed. However, they will vary also with other parameters such a with magnitude of rudder movement and with loading. In addition, the centre of gravity of the ship will almost certainly not be at the geometric centre because of asymmetry and loading. However, these complexities are not considered in this paper.

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John Wiley & Sons, Chichester.

Model	Speed (m/s)	K (1/s)	τ(s)
1	3	0.03	73.5
2	5.42	0.0542	40.6
3	8	0.08	27.5

Table 1 - Ship Model parameters

Model	Speed (m/s)	b_o $\times 10^{-4}$	b_1 $\times 10^{-4}$	b_2 $\times 10^{-4}$	a_1	a_2
1	3	1.014	2.027	1.014	-1.986	0.986
2	5.42	3.290	6.58	3.290	-1.976	0.976
3	8	7.127	14.255	7.127	-1.964	0.964

Table 2 - Discrete-time model parameters

Sea state	Encounter angle (°)	X(1)	X(2) ×10^{-2}	X(3) ×10^{-2}
3	45	0.602	6.471	3.171
5	45	0.566	0	6.616
8	45	0.521	19.068	22.990

Table 3 - Wave model parameters

Sea state	Encounter angle (°)	c_{no} ×10^{-4}	c_{n1}	c_{n2} ×10^{-4}	a_{no}	a_{n1}	a_{n2}
3	45	7.532	0	-7.532	1	-1.619	0.943
5	45	16.600	0	-16.600	1	-1.703	1.0
8	45	54.629	0	-54.629	1	-1.635	0.872

Table 4 - Discrete-time wave model parameters

Controller	F_c	C_{fno}	C_{fn1}	C_{fdo} ×10^{-4}	C_{fd1} ×10^{-4}	C_{fd2} ×10^{-4}
1	0.1	0.2899	-0.2829	30.0	2.7719	0.9538

Table 5 - GH_∞ Controller parameters

Controller	C_{fn0}	C_{fn1}	C_{fn2}	C_{fn3}	
2	-0.8394	2.1906	-2.072	0.7159	
	C_{fd0}	C_{fd1}	C_{fd2}	C_{fd3} ×10^{-4}	C_{fd4} ×10^{-4}
	-3.6875	7.1551	-3.475	-2.644	-2.413

Table 6 - Generalized H_∞ controller parameters

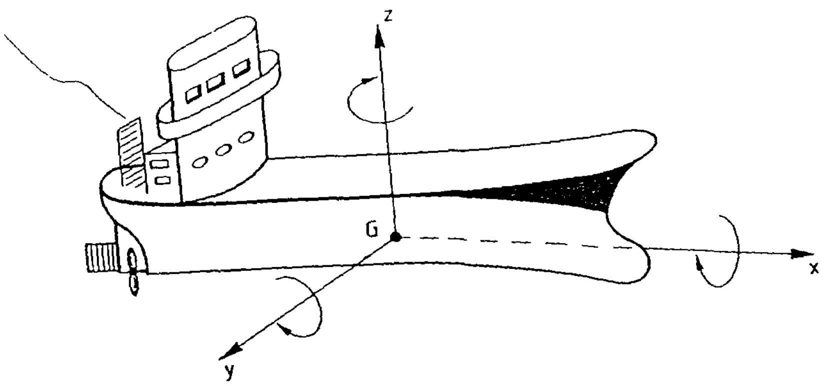


Figure 1 - Ship co-ordinate system

(due to van Amerongen (1982))

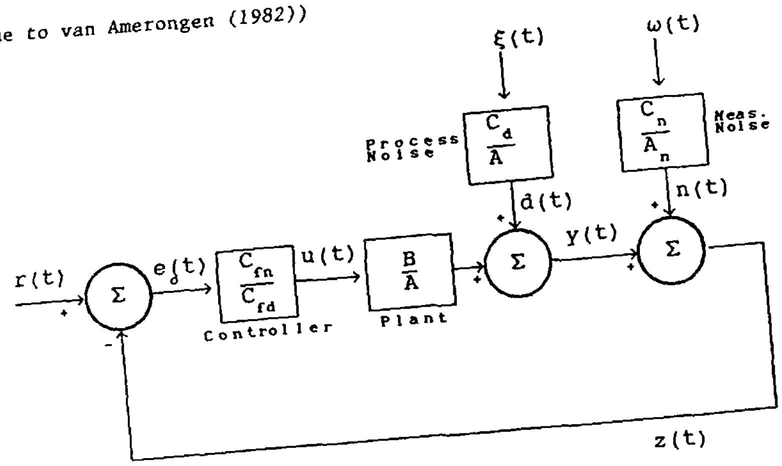


Figure 2 - Feedback system description

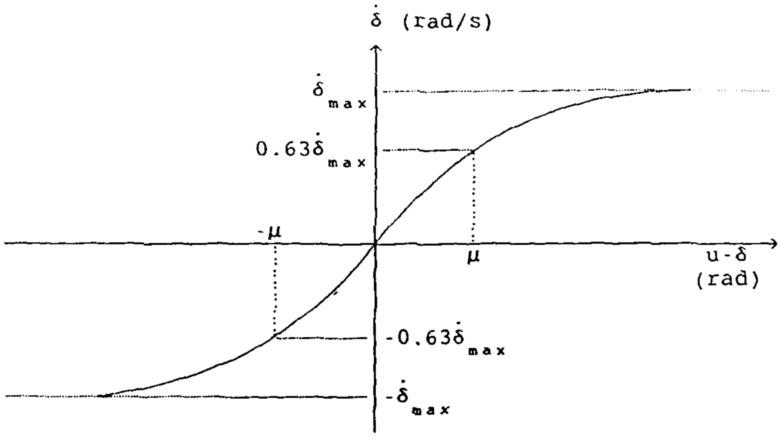


Figure 3 - Rudder motion model

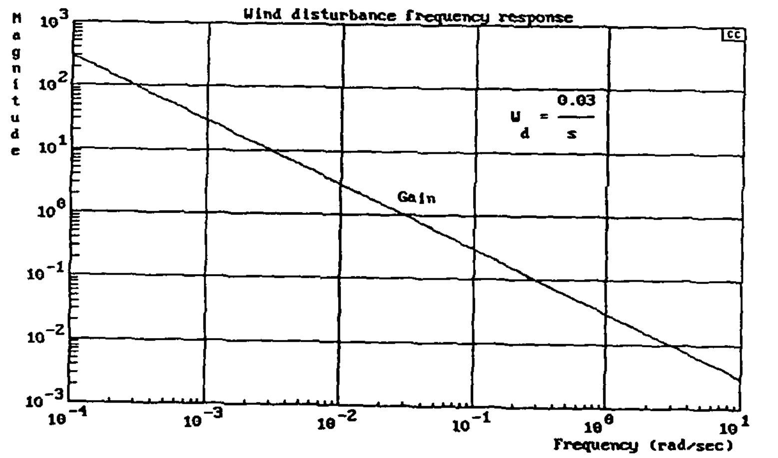


Figure 4 - Wind disturbance bode plot

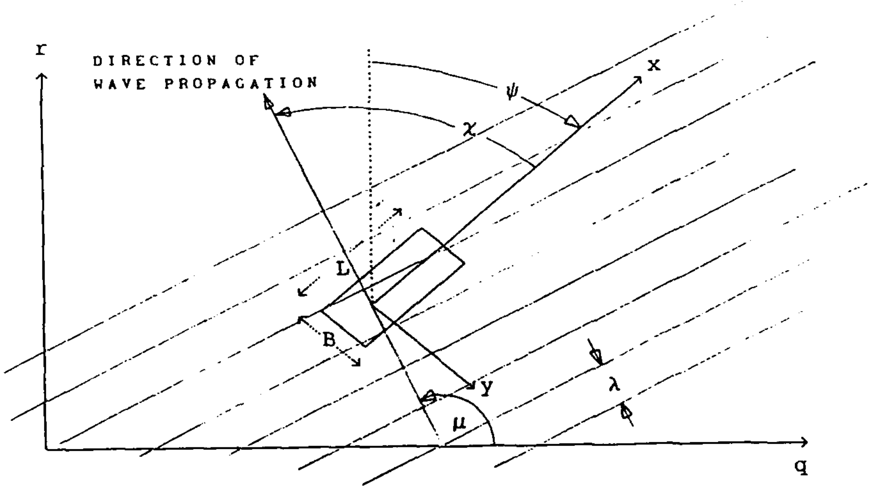


Figure 5 - Block-shaped ship in waves

(after Blanke (1981))

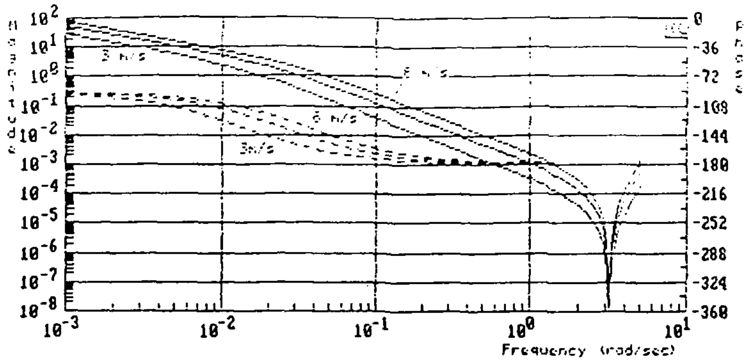


Figure 6 - Frequency response of ship models

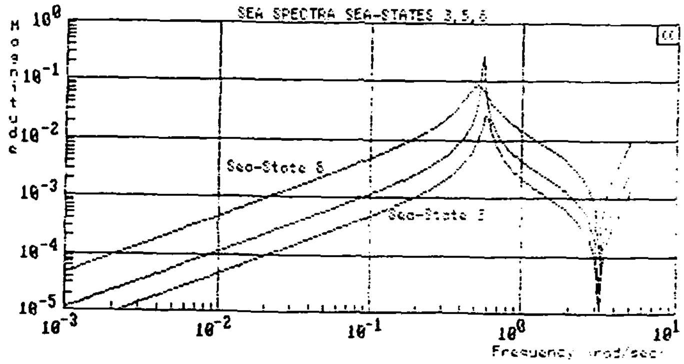


Figure 7 - Frequency responses of wave models

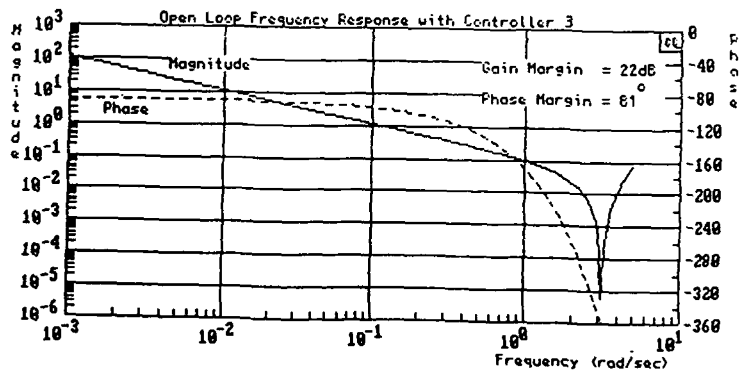


Figure 8 - Open-loop frequency response with Generalized H-inf

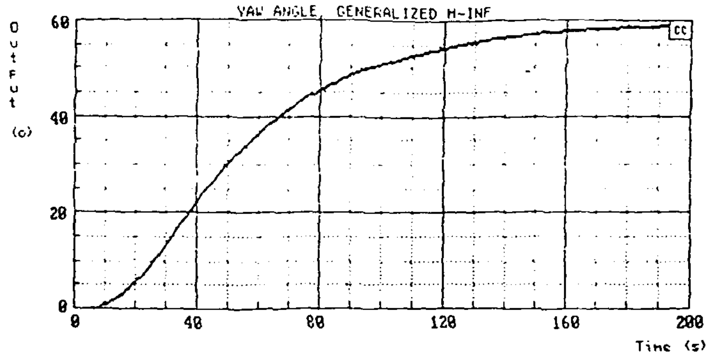
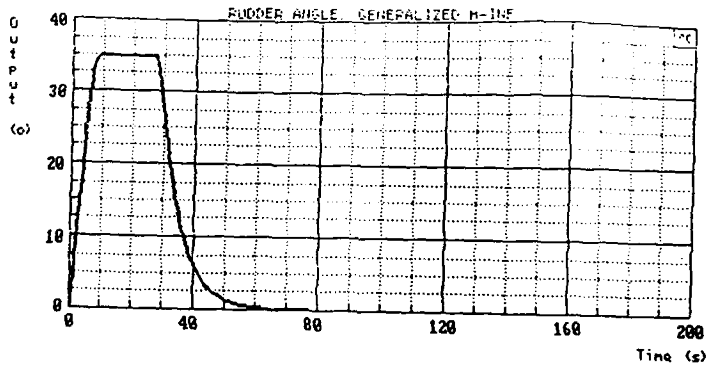


Figure 9a



Fi;ure 9b

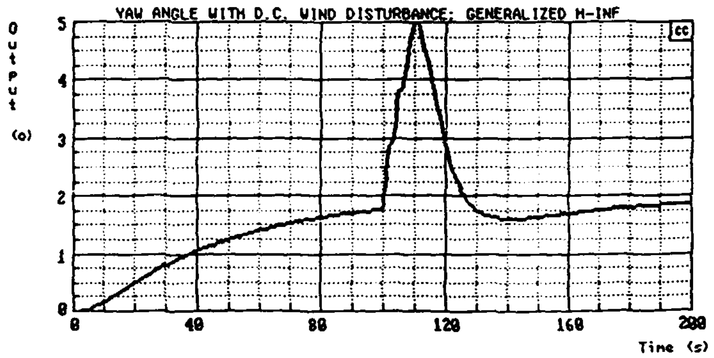


Figure 10

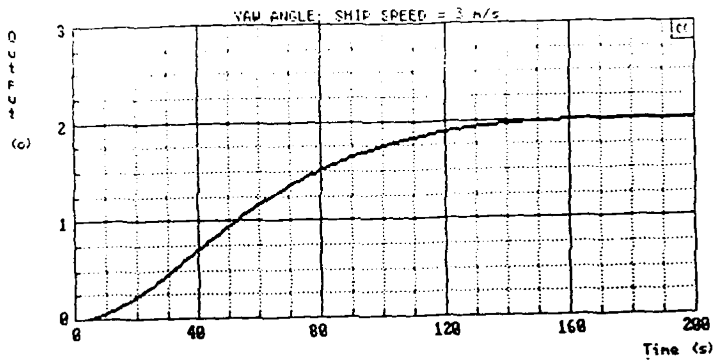


Figure 11

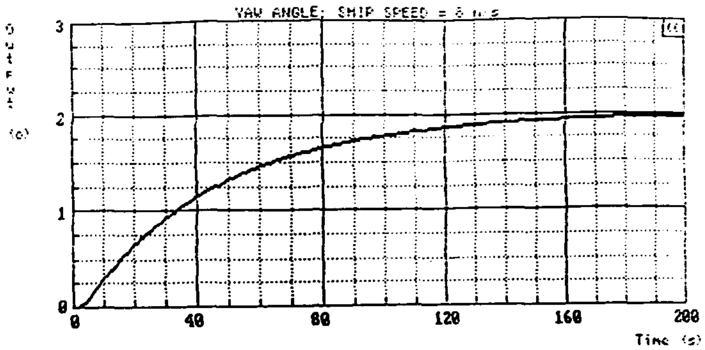


Figure 12

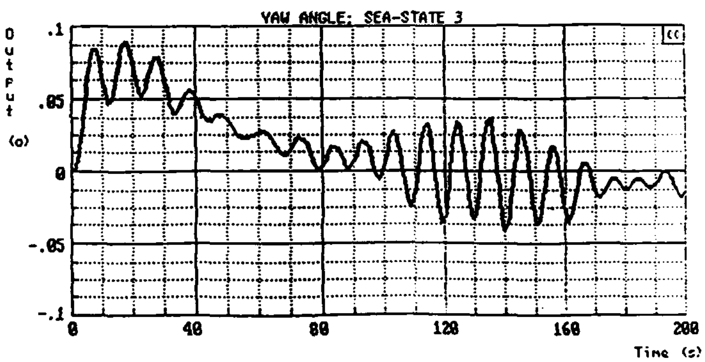


Figure 13a

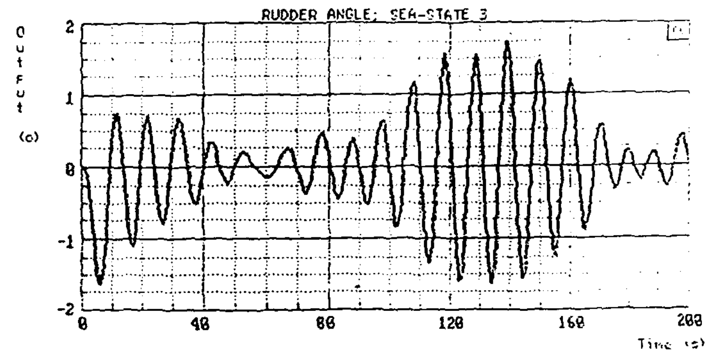


Figure 13b

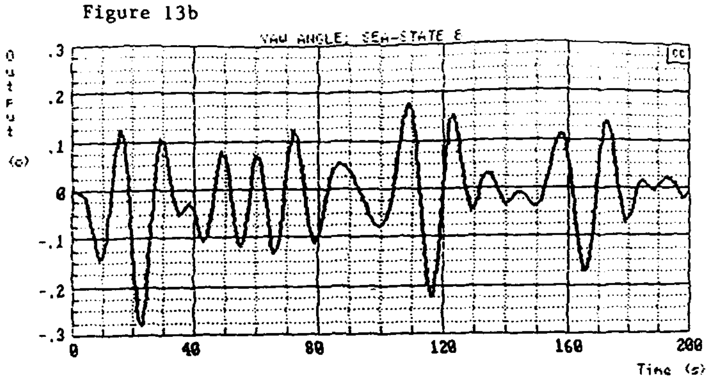


Figure 14a

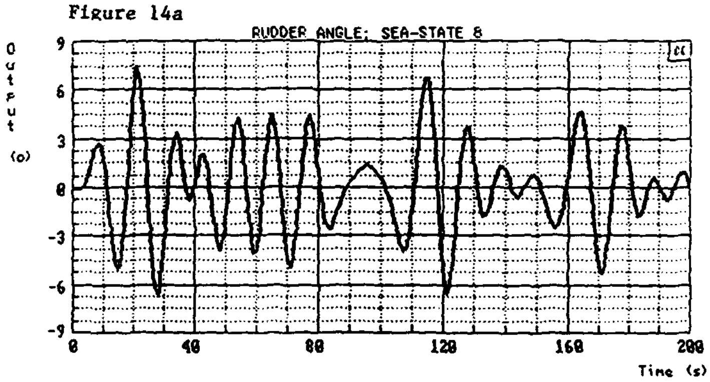


Figure 14b

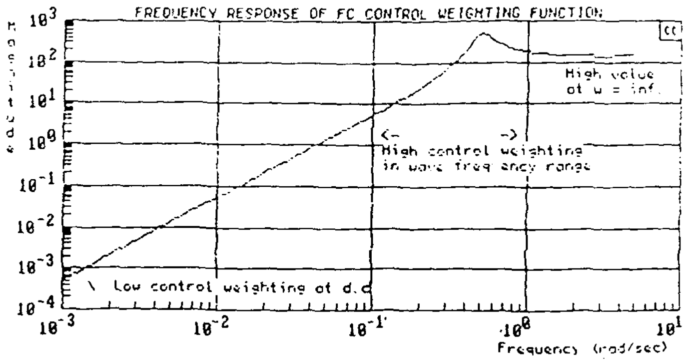


Figure 15

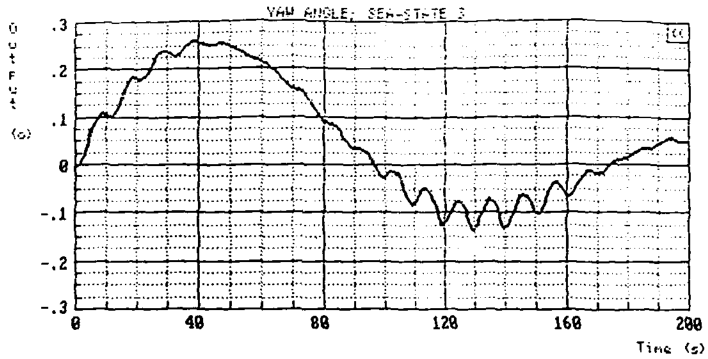


Figure 16a

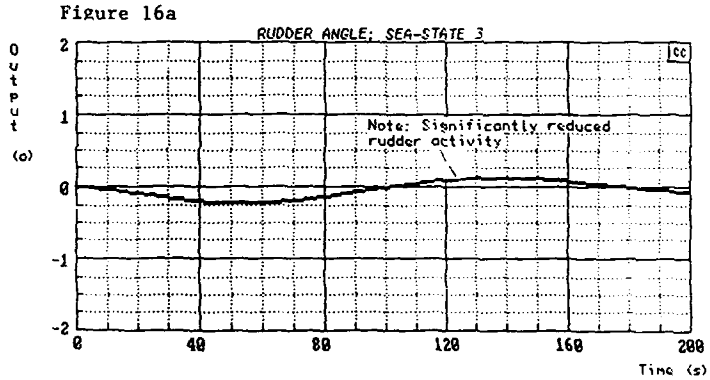


Figure 16b

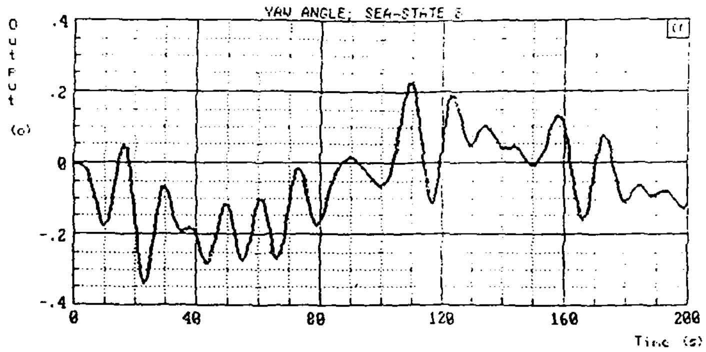


Figure 17a

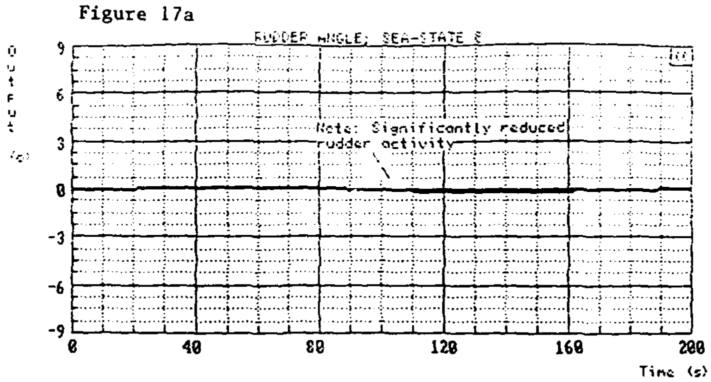


Figure 17b

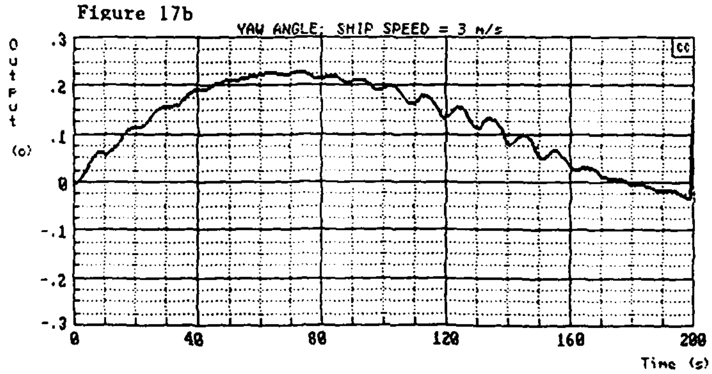


Figure 18

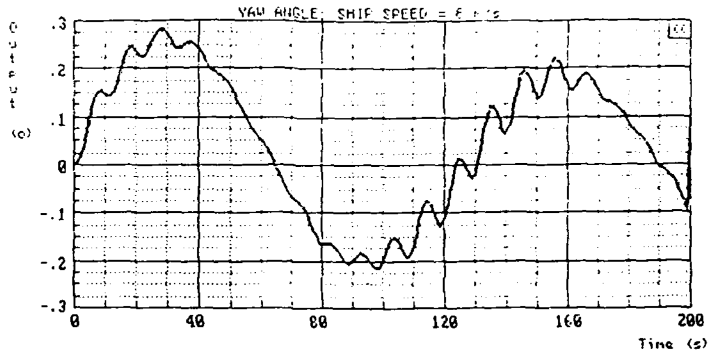

YAW ANGLE: SHIP SPEED = 6 m/s
Output
(o)
.3
.2
.1
0
-.1
-.2
-.3
0
40
80
120
160
200
Time (s)

Figure 19

COMPUTER AIDED DAMAGE STABILITY CONTROL IN THE M-CLASS FRIGATE OF THE ROYAL NETHERLANDS NAVY

by W. van Nes,
Royal Netherlands Navy
R. Moerman
Van Rietschoten & Houwens

ABSTRACT

Damage Control (DC) management needs information about the stability and buoyancy of the ship. This information is based on the integrity of the ship's hull and the loading condition and is the result of a number of calculations.

Up till now the required stability information was derived by the DC officer from standard damage stability data sheets, which are only available for a limited number of damage-, wind- and loading conditions. But in the M-class frigate the calculations are performed within the Integrated Monitoring and Control System (IMCS) which offers a user friendly man machine interface for all platform systems.

The Stability Calculation Module for the M-class IMCS consists of three functions:

a. Damage stability calculation: to derive actual state stability data and final state stability data if no DC counter-measure will be carried out. The system will also check whether the operational stability criteria will be met, i.e. if wind and roll movements are taken into account.

b. Damage stability evaluation: in order to evaluate the result of possible DC counter-measures. The operator can enter his proposed counter-measures into the system which will then calculate the new final state stability.

c. Stability indication calculation: in order to to derive a quick rough stability indication based on roll movements. This indication will be used if not all the required inputdata for the stability calculations are available or reliable, or if there are too many influencing factors such as severe damage, heavy icing or fire fighting waste water.

The Stability Calculation Module supplies the DC officer with the information he needs to make accurate decisions, with a minimum of manual input, and is operated as an integrated part of his platform management workstation.

1. INTRODUCTION

If we consider a navy vessel to be a system, the major system functions that can be distinguished are, in order of importance:

- to stay floating;
- to remain underway;
- to retain its mission.

The primary function, floating, is accomplished by buoyancy and stability. However, the buoyancy and the stability of the ship can be threatened by calamities such as a collision or a hit of a torpedo, a mine or a missile. To enable the damage control managers to deal effectively with these threats, the managers must be quickly provided with accurate and detailed information about the situation, so that they can counter the threats by taking appropriate active measures. Passive measures have already been taken in the design of the hull geometry and compartimentation as well as in the weight distribution on board.

Till now, the Damage Control (DC)-officer derived the stability information that he needed for decisions about weight distribution or about the appropriate counter measures in case of calamities, from standard damage stability data sheets, on which only a limited number of damage-, wind and loading conditions were described. On top of that, the described conditions were not the operational conditions, but were mainly the functionally required conditions as specified in the contract design.
With these datasheets, the DC-officer had to compile the actual stability situation by means of calculations, while also coordinating the damage control actions throughout the ship at the hectic location of the combined Ships Control Centre (SCC) and the NBC-and DC-headquarters. Also, the datasheets did not describe situations in which there occurs severe icing or an excessive amount of water caused by firefighting and boundary cooling. Experience on the USS Stark and, more recently, on the Scandinavian Star, has proved that the effects of these occurrences are of great influence in actual situations.

The M-class frigate is equipped with an Integrated Monitoring and Control System (IMCS). This system processes platform sensor input that is displayed on workstations in the SCC via which the operator can also enter commands for platform actuators. As the input for the stability calculations was already available in the IMCS, it was decided to integrate the stability calculations in the IMCS of the M-class Frigate.

In the M-class frigate, the calculations, which are based on a model of the ship and carried out within the IMCS, are performed in such a way that even complex situations can be analized. At the same time, the system also provides the necessary sensor input as well as an user-friendly man-machine interface in which the monitoring and control of platform systems and the stability management are integrated in such a way that the operator does not loose grip on the situation. This reduces the workload of the DC-officer and enables him to simultaniously manage damage control and stability. Although the stability calculation module is a decision support system, it is not an expert system.

2. THE M-CLASS INTEGRATED MONITORING AND CONTROL SYSTEM

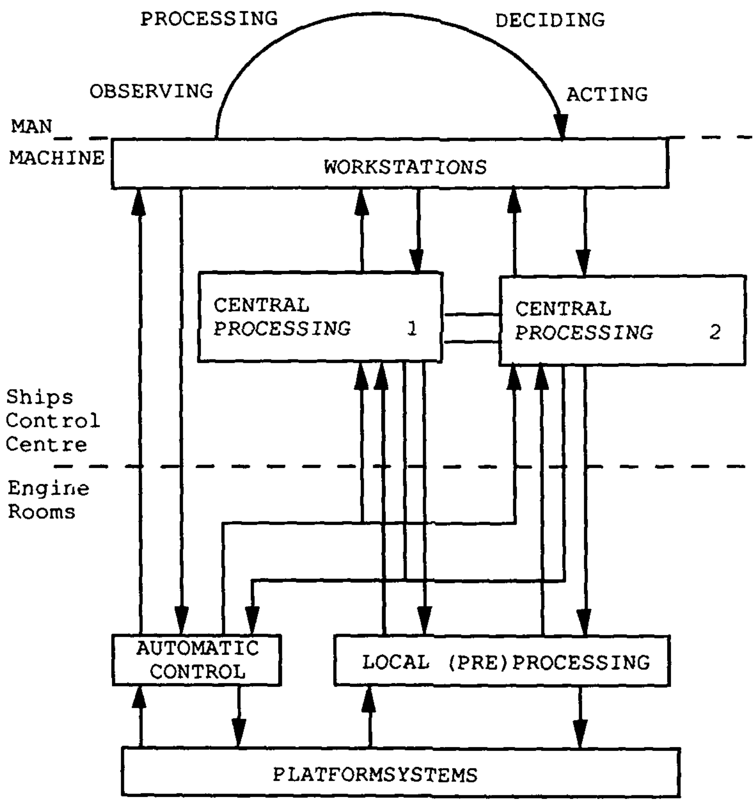


Figure 2.1 M-Class frigate IMCS configuration

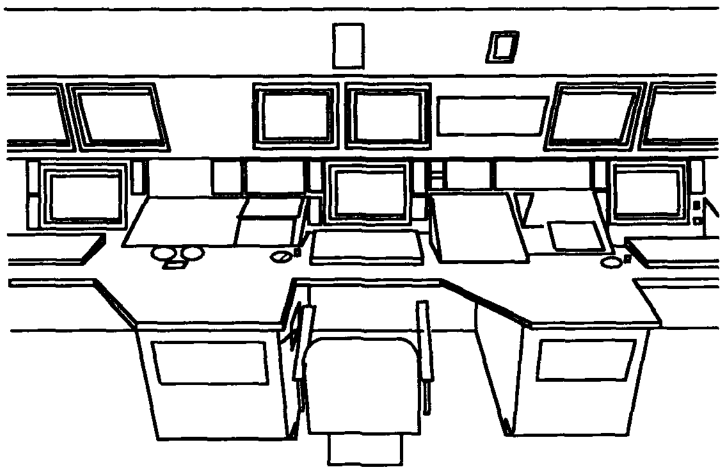


Figure 2.3 SCC Operator Workstations

For their monitoring and control tasks, the three platform operators can dispose of three VDU's. On one VDU, there is a display of an alarmtable which contains a list of the relevant alarms for that particular position. The operators can also request mimic VDU presentations from a set of mimics. Mimics are drawings of platform systems in which the current state of a system is represented. Furthermore, the operators may request several general information presentations concerning components or parts of platform systems on their VDU's. The DC operator may also use a set of DC plot presentations of the current situation in the ship. In these DC plot presentations, damage information derived from human observation is entered graphically through a workstation at the DC section station, or at the SCC. This information is integrated with the automatic sensor information. To avoid communication errors, the same presentations are available in the DC section stations, in the SCC and in the CIC. This information is also used as input for the damage stability calculations.

3. THE M-CLASS STABILITY CALCULATION MODULE

The M-Class Stability Calculation Module consists of three parts, as shown in figure 3.1:

The IMCS of the M-class frigate is a decentralized computer network which basically consists of four parts as shown at fig 2.1:

- the control units;
- the local processing units;
- the cental processing unit;
- the workstations.

The control units have the possibility to monitor and control a platform system independently. In the local processing units, which are located thoughout the ship in the vicinity of sensors and actuators, the sensor data is being processed and sent to the redundant central processing unit where the sensor data is processed further in order to get integrated information on system level. Operators can get a presentation of this system information on their workstations and they can also enter commands concerning a platform system by means of their workstations.

The workstations are placed in the SCC, in the Combat Information Centre and in the DC section stations fore and aft, as shown in fig 2.2. The DC-operator in the SCC has a three-VDU workstation and this also holds for the propulsion operator and the electrical operator as shown at fig 2.3. Both the DC-officer and the NBCD-officer have a single-VDU workstation and this also holds for the DC section stations. The commander in the Combat Information Centre also has a workstation but this workstation does not offer the possibility of entering commands.

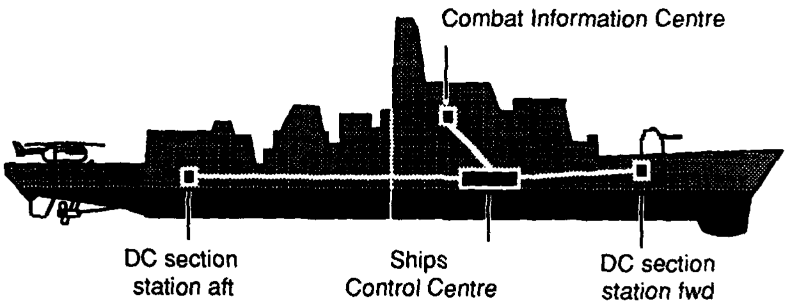


Figure 2.2. General location of the IMCS workstations in a frigate

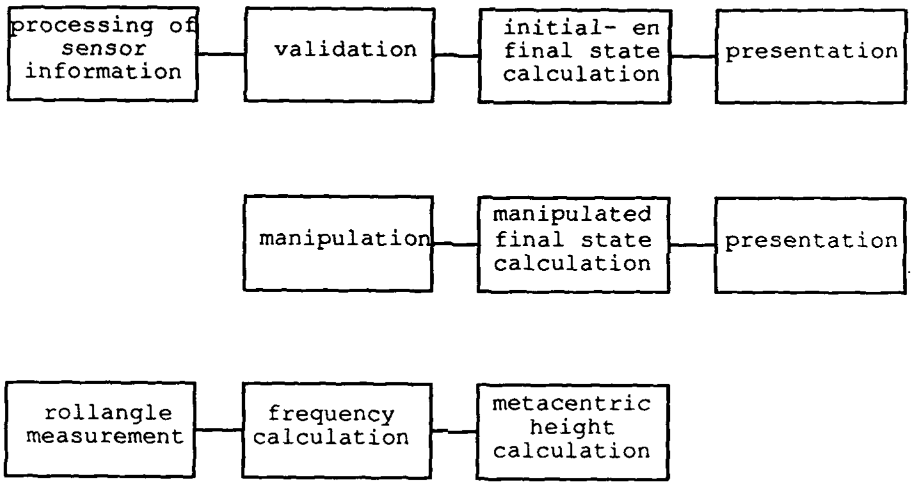


Figure 3.1 Overview of the Stability Calculation Module

- The calculation of the initial- and final state stability, based on the *current situation*. The initial state represents the condition of the ship at the moment of calculation and the final state represents the equilibrium condition of the ship that will be reached if no corrective actions are taken.
  These calculations can be divided into the following subsystems:

  - the processing of sensor data into platform information, this is a standard IMCS function;
  - the validation of automatic sensor input for the stability calculations by the operator;
  - the calculation of initial and final state stability;
  - the presentation of stability information;

- The calculation of the initial- and final state stability, based on the actual situation and a number of counter measures; the latter can be divided into the following subsystems:

  - the input of counter measures by the operator;
  - the calculation of final state stability with counter measures;
  - the presentation of stability information with counter measures;

- The stability indication calculation, producing the metacentric height, based on the roll movements of the ship.

4. VALIDATION

The results of a calculation are worthless if there is an error in the input of the calculation. In case of a decision support system, the system is only usable if the user trusts its output. If the DC officer does not trust the result of a stability calculation which is done by a system, the implementation of such a system has a negative effect on the performance of the DC officer instead of reducing his uncertainty about the situation, the system gives him one more reason to worry.
To make the stability calculation module a useful and powerful tool for the DC officer, the module offers a validation of the input-data that are used for the calculations. This enables the officer to maintain control of this module in such a way that it does not increase his workload.

The validation can be done by both the DC officer and the DC operator. The actions that can be performed to carry out the validation process are:

- For each (tank) compartment, the operator can decide whether the representation of the situation by the digital readout of the sensor is correct. If there are no sensors in in a compartment, or if the sensors are out of order, or it is decided that the representation is incorrect, the operator can enter a replacement value, based on actual, local observation. The operator can also change the value of the specific weight of the contents of a tank.

- For each (tank) compartment the operator can decide whether it is damaged. Information about damage is based on the plot symbols that are plotted on the DC plots by the repair units and on direct reports from his sectionleader. In case of damage, the compartment status "damaged" is entered into the system by the operator after which the stability calculation can be made.

- The operator can decide whether wind speed, wind direction and the heeling angle as are shown by the digital readout of the sensors, are correct. If the operator decides that the reading is wrong, the operator can enter a replacement value.

- When a sensor for which the operator has entered a replacement value works correctly again, it is possible for the operator to decide to remove the replacement value. To be able to see the difference between sensor-input and operator-input, the source is shown at any reading.

5. THE M-CLASS MMI PHILOSOPHY

The M-class frigate man-machine interface philosophy is based on "interfacing through presentations". This means that information for the use of operators can be retrieved from a predefined set of presentations and that input can only consist of adaptations which are entered by means of a presentation. As the stability calculation module is an integrated part of the IMCS, the "interfacing through presentations" is also implemented here. There are seven presentations defined for the stability calculation module:

- actual state stability presentation. This presentation contains the current dynamic values that are the input for the stability module. This presentation is used for the validation of the input;

- stability input presentation. This presentation contains the static values which were the input for the last stability calculation;
- initial state stability presentation. This presentation contains the initial state graph, which is a result of the last stability calculation;
- final state stability presentation. This presentation contains the final state graph, which is a result of the last stability calculation;

- manipulation presentation; this presentation contains the input values that were the input for the last stability calculation. This presentation is used for the input of the countermeasures that have to be evaluated;
- final state manipulation presentation. This presentation contains the final state graph which is a result of the last stability calculation based on the countermeasures that have to be evaluated;

- stability parameter presentation. This presentation contains the parameters for the stability calculation module that do not frequently change but that are affected by the use of the ship. Examples of such parameters are the displacement under standard loading conditions and the weight of ammunition.

A presentation request or a change in a presentation is not linked in any way to the start-command for the stability calculation. The operator may switch a number of times between stability presentations and other presentations before starting the stability calculation. It is also possible that part of the validation process is performed by another operator ("multi tasking"). To enable the operator to use the presentations in this way, he needs a simple and direct interaction that requires only a minimum of operator-action.

5.1. Presentation request

Because the presentation-request forms the start of every operator-action and because the request can be made in every possible situation, the operator can identify the presentation-group by means of a single function key on his functional keyboard. Examples of a presentation-group are: mimic presentations, stability presentations and DC plot presentations. For stability presentations there is a key marked "stability". After pressing this button, the operator is provided with a short menu of the possible presentations within the group. The menu will appear at the bottom of his screen and in this case, the menu will consist of the above mentioned presentations.
The operator can choose from this menu by indicating his choice with a trackball cursor or by pushing the concerning function key. The dialogue is finished by entering the "execute" command with a function key.

5.2. Operator input

The object of the operator input can indicated with a trackball cursor. When an operator has selected an object in this way, then the relevant information about this object is presented at the bottom of his screen, together with a menu of possible commands. A command can be selected by pointing it out with a trackball cursor or by pushing the concerning function key. If the object is a numerical value, the operator can enter a (new) numerical value with a numerical keypad.

6. ACTUAL STATE

With the actual state stability presentation, as shown in figure 6.1, the operator can perform the validation process, so that a reliable output of the stability calculation module is ensured. This presentation contains the input data for the stability calculation module

- for each compartment:
  - the relevant information that is required to enable the operator to identify the data;

- the identification code of the compartment,
- the name of the compartment,

• the basic status information;
  - the level of liquid in a compartment;
  - the specific weight of the liquid in a compartment;
  - the indication "damaged";
  - the source of the information;

• additional information as drawn on the DC plot presentations as "water level" and "damaged".
  - the heeling angle;
  - the relative wind speed;
  - the relative wind direction.

actual state stabiliteit informatie datum: dd mm yy tijd hh : mm

slagzij 5 graden BB
windsnelheid 15 knots
windrichting 25 graden over BB

compartiment nummer	damage geplot	lek actual state	actual state peiling	actual state soortelijk gewicht	ruimte benaming
1H10			0.000	0.000	kabelgat en bergplaats trossen
1H20			0.000	0.000	bergplaatsen bevo 3, bevo 4
1H30			0.000	0.000	bediening- en overlaadruimte 76 mm kanon
1H40			0.000	0.000	slaapverblijf 5, slaapverblijf 6
1J10			0.000	0.000	bergplaats bevo 2, ob instrumentenruimte 6
1J20			0.000	0.000	bergplaats bevo 5
1K10			0.000	0.000	bergplaats bevo 1
1K15			0.000	0.000	kettingbak
1K20			0.000	0.000	bergplaats 1
1K25			0.000	0.000	schacht
1L10	*	*	****	****	echolood ruimte voor
1L15			1.50	****	ruimte onder k dek voor sp 157
1L20			0.000	0.000	trimtank 1
1L30			0.000	0.000	trimtank 2
1M10		*	****	****	boegdome
1M20			0.000	0.000	baffle achter boegdome
2H10			0.000	0.000	slaapverblijven 7, 8, 9, 10, en omroephut
2H20			0.000	0.000	hutten onderoff.

Figure 6.1. The actual state presentation

The operator can alter the input data for the stability calculation module by selecting the item with the trackball cursor and by replacing it with a correct value. If he switches between several presentations in order to obtain situation information or to handle other problems, the altered input data remains stable. Eventually, when the operator agrees with the situation he has created in this presentation, he can start the stability calculation again by selecting the name of the presentation, followed by entering the "start" command.

7. CALCULATION OF INITIAL AND FINAL STATE

The stability calculation is devided into two separate, but identical parts:

- the calculation of the initial state; this is the condition of the ship at the moment that the calculation is made.
- the calculation of the final state; this is the equilibrium condition of the ship that will be reached if no corrective actions are taken.

7.1. Calculation of the initial state

The calculations are based on a mathematical model of the ship in the form of a number of polynomes. These polynomes have been precalculated with the hydrostatic package SIKOB for the hydrostatics of the hull and the compartment parameters as a function of (sensor) sounding values. The polynomes are stored in a database in the form of polynome coefficients and the required values are obtained by interpolation with the Hörner method.

The database also contains a number of other data items like parameters for positions of openings in the hull and on the bulkhead deck. The parameters for the calculation of the aerodynamic loads are derived from measurements on a model M-class frigate in a windtunnel of the Dutch Aerospace Laboratory (NRL). Both wind force and point of application have been determined.

The calculations consist of four parts:

- calculation of draught and trim;
- calculation of righting and heeling arms;
- calculation of the heeling angle;
- calculation of stability margins.

a. Calculation of the draught and trim

The validated sounding data will be converted to basic soundings, representing the liquid level that is independent of the heeling angle. Based on these basic soundings, the sum of liquid loads, momentums and the effect of the free liquid surfaces are calculated. The calculation uses curves which are stored in the database and are shown in figure 7.1. The weight of food supplies and ammunition is assumed to be proportional to the weight of the liquid loads and is considered to be a relatively static factor. As such, the weight of food supplies and ammunition is taken into account in

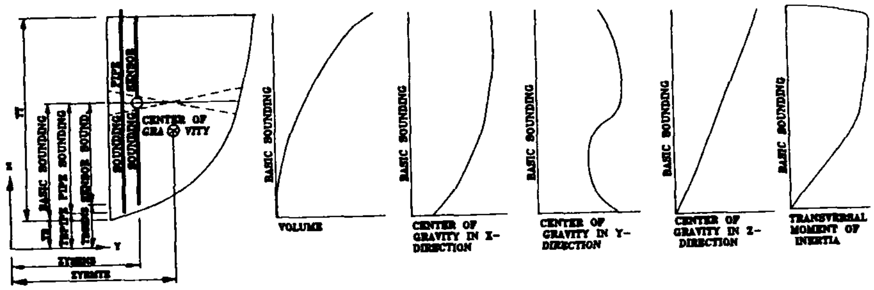


Figure 7.1 Curves used for calculation of compartment data

the calculations. Based on these loading conditions, the displacement, the center of gravity are calculated.

The draught and trim will be derived from the curves of the draught and of the longitudinal center of buoyancy as a function of displacement and trim, as is shown in fig 7.2.
The metracentric height will be calculated in the same way. (Also see 7.3)

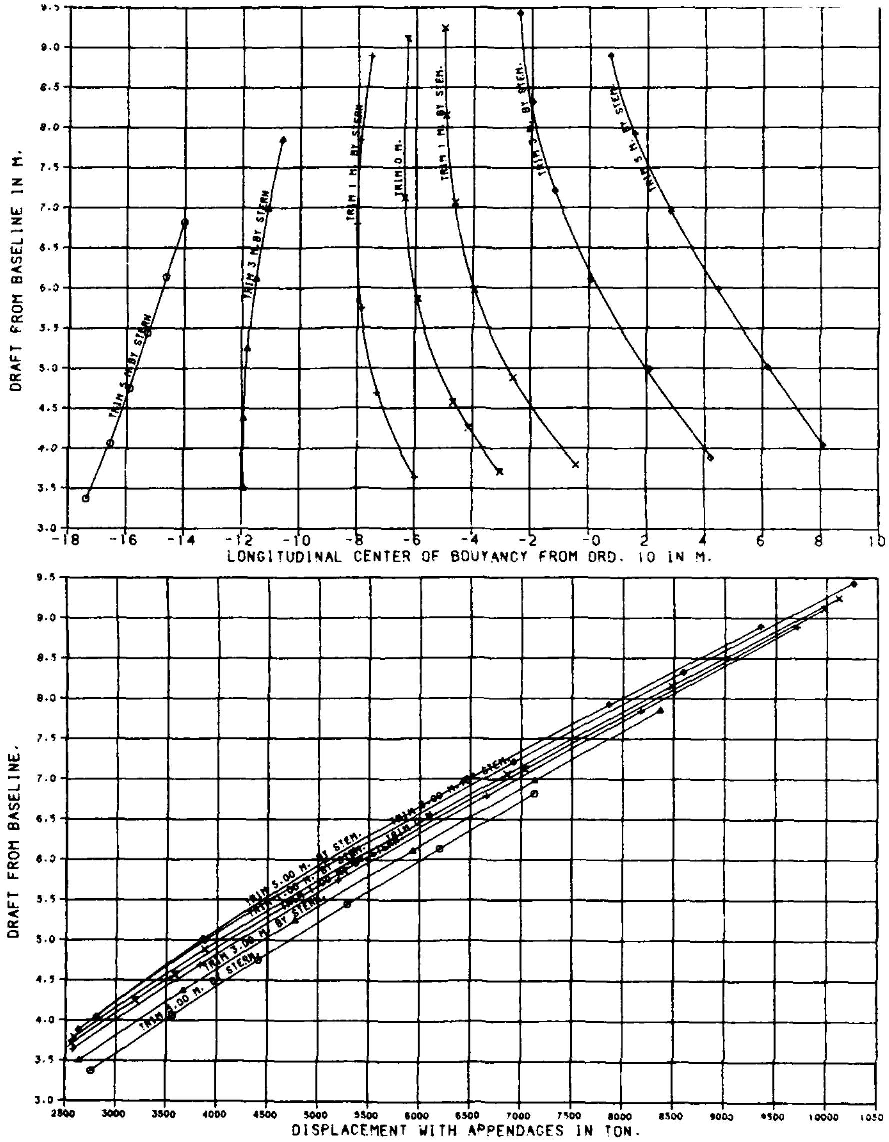


Figure 7.2 Curves used for calculation of trim and draught

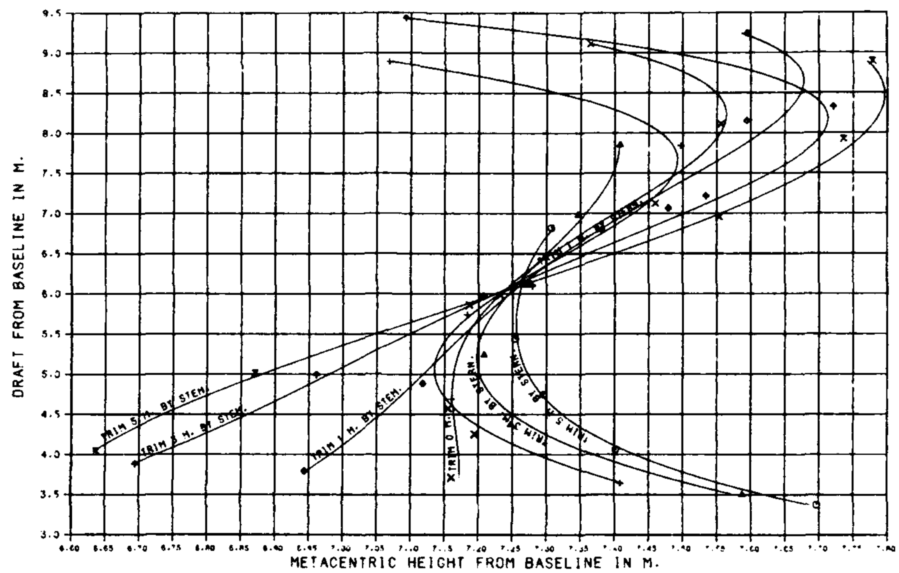


Figure 7.3 Curves used for calculation of matacentric height

b. Calculation of righting and heeling arms

The righting and heeling arms are calculated on the basis of the displacement, trim and the effect of the free liquid surfaces.

The arms that are calculated, are the arms of the righting and heeling momentum with the weight of the ship as a unit force.

The righting arm is the horizontal distance between the center of gravity and the center of buoyancy. The metacenterpoint is the point of intersection of the righting force and vertical centerplane. Crosscurves are used for the calculation of righting arms. The crosscurve equals NK * sin(PHI) and is stored in the database as a function of displacement and the longitudinal center of buoyancy. (Also see figure 7.4)
Based on the known displacement and the position of the center of gravity, the righting arms can be calculated with the crosscurve polynomes from the database. (Also see figure 7.5)

The heeling arm caused by free liquids is derived from the transversal momentum of inertia of the liquid surface, which is stored as a polynome in the database as a function of the basic sounding. (Also see figure 7.6)

The heeling arm caused by wind is derived from the relative wind speed and from direction data in combination with the results of the aerodynamic scale measurements that are stored in the database. The point of application of the reactionforce is assumed to be on half draught. (Also see figure 7.6)

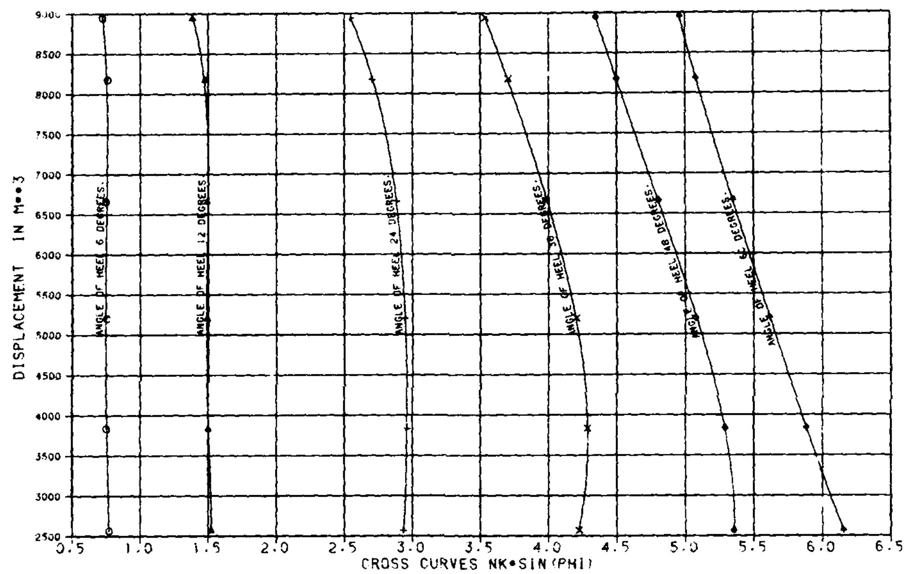
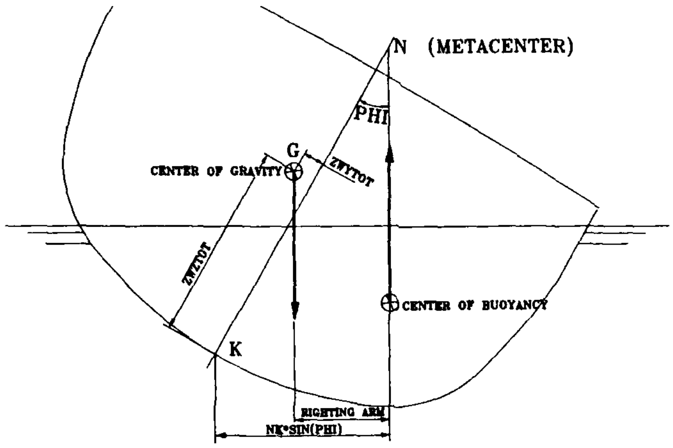


Figure 7.4 Cross Curves used for calculation of righting arms



CROSS CURVE = NK * SIN(PHI)

RIGHTING ARM = NK•SIN(PHI) − ZWZTOT•SIN(PHI) + ZWYTOT•COS(PHI)

Figure 7.5 Righting arms

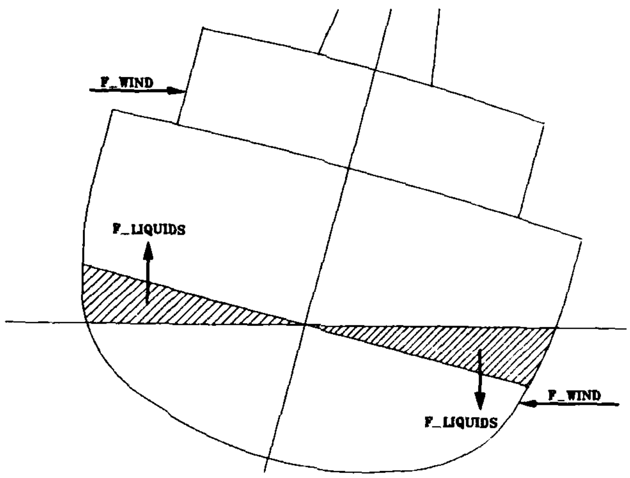


Figure 7.6 Heeling forces

c. Calculation of the heeling angle

The angle of heel can be derived by calculating the angle at which the righting arm equals the total of heeling arms.

d. Calculation of the stability margins

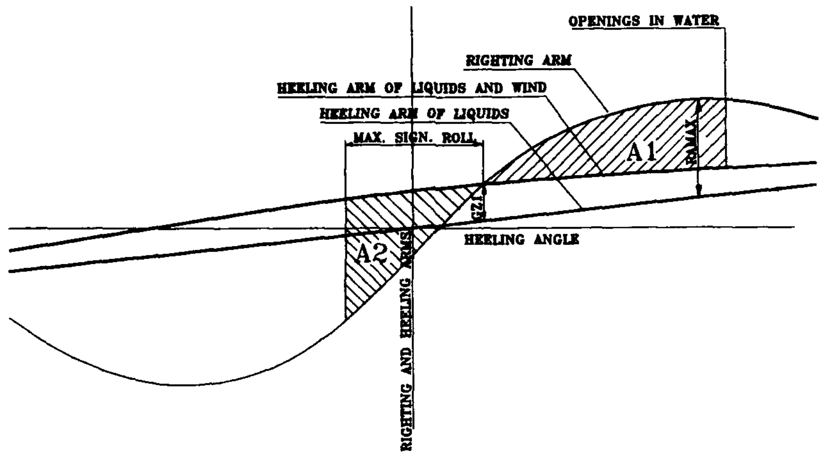
The buoyancy margins are expressed by freeboard which is derived by calculating the vertical distance from every opening in the ship's structure to the waterline and from a number of positions on the bulkhead deck to the waterline. The smallest distance is the resulting freeboard. The location of the positions used in the calculations is stored in the database.

Usually, stability criteria are based on the design criteria, so, the conditions in the damage stability data sheets are predefined and independent of environment. However, stability criteria are essential for survival under given circumstances in real-life situations. Therefore, the operational stability criteria that are used here, are based on Goldberg and Sarchin (5) and that resulted in the formulation of operational criteria that take the environmental conditions such as wind and roll movements into account.

The stability criteria that are used are:

- maximum significant roll angle;
- maximum wind arm;
- minimum metracentric height.

The allowable roll angle is limited by the angle at which the openings reach the water level during the roll movements of the ship. Besides that, the significant roll, which is a measure for the dynamic energy of roll movements, may not exceed the value that represents the potential engergy of the righting moment. This value is determined by the ratio of the size of the areas A1 and A2 and by the roll movement safety factor, as shown in figure 7.7.



MAXIMUM SIGNIFICANT ROLL AT A1/A2=1.4

GZ1/RAMAX < 0.6

MG > 0.05 M.

Figure 7.7 Righting and heeling arms as function of the heeling angle with tht operational criteria

The stability should be sufficient to withstand a gust of wind. Therefore, the ratio of the the arm caused by wind and the maximum achievable wind arm (RAMAX), as shown in figure 7.7, should be less than the wind safety factor.

The metracentric height should always be positive and should have minimum value.

In the M-class frigate the safety factor for roll movements is determined at 1.4, the safety factor for wind at 0.6 and minimum value for metracentric height at 0.05 meters.

7.2 Calculation of the final state

The final state stability calculations are based on the added weight method which results in an iterative process. A damaged compartment is assumed to be in open connection with the sea. This assumption leads to a final state situation in which the original liquid contents of the damaged compartment has disappeared into the open sea and the compartment is filled with seawater up to the known waterline. The tanksoundings of the flooded compartment are calculated with the draught trim and heeling angle of the last iteration. The difference in mass and momentum of the water in the flooded compartment is added to the mass and momentum of the ship. With the new displacement and new center of gravity and the total effect of free liquids, the new trim draught and heeling angle can be calculated and used for the next iteration.

The final state will be reached if the draught, trim and heeling angles do not alter more than a given tolerance.

8. PRESENTATION OF STABILITY INFORMATION

In the initial and final state presentations, the stability data is made visible to the damage control management. Primarily, this is done graphically and is supported by a small number of stability and buoyancy margins in a digital readout. If the margins do not meet the criteria, the operator receives a warning. Usually, naval constructors make stability data visible by presenting stability arms as a function of the angle of heel. This presentation method is also applied for the stability calculation module. In conventional stability data sheets, only the stability arms for one side are presented, showing the worst case. However, the results of the stability calculation module have to be shown to SB and PS for both angles, so as to give the operator a complete view of the situation. (Also see figure 8.1)

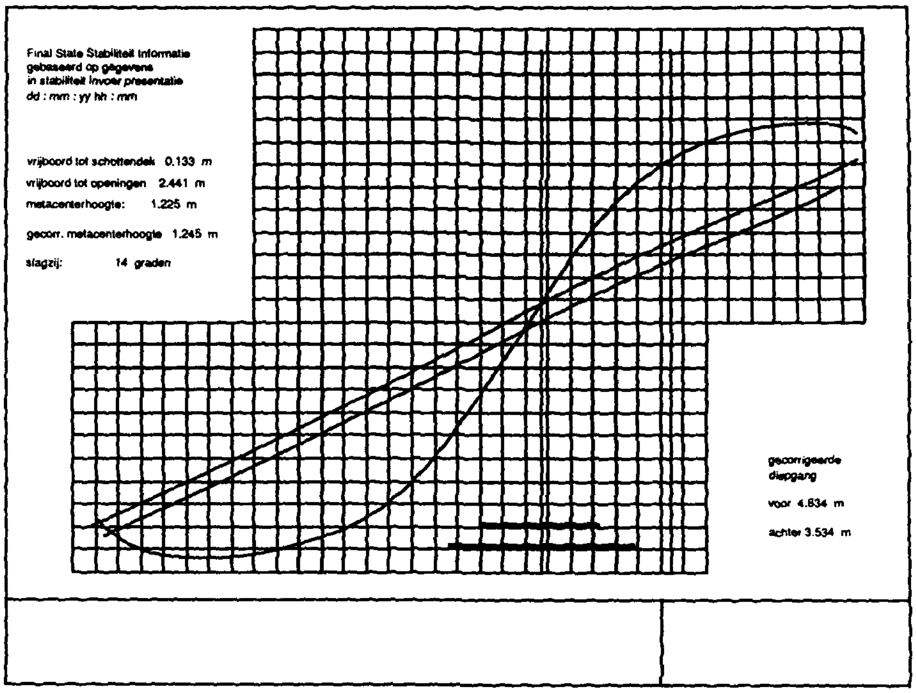


Figure 8.1. Initial state stability presentation

9. MANIPULATION

To assist the DC officer in his stability management tasks, an attempt has been made to provide solutions for damage stability cases with an expert system. The results of these attempts made clear that it took a long time to process the whole range of possibilities and that the results were unpredictable.
Therefore, an evaluation function has been added to the stability calculation module. This evaluation function is a powerful tool for the DC officer to evaluate the possible counter measures and it enables him to take adequate actions without delay. In this way, solely the damage control managers remain responsible for the actions that have to be taken.

By means of so-called manipulation commands, corrective actions and their effect on the ship's stability can be simulated by the stability calculation module. The aim of counter measures is to create a better stability and buoyancy. The actions that can be taken into account in order to reach this goal, are the actions that create:

- a heeling moment which reduces the heeling angle;
- a trimming moment which increases freeboard;
- a low position of the center of gravity which increases the righting moment.

For this purpose, the DC officer can enter four commands for each compartment into a presentation that is similar to the actual state presentation:

- ballast with seawater;
- transfer of liquid load;
- de-watering;
- counter flooding.

The manipulation function creates a manipulated set of compartment soundings and this set is used as input for a final state stability calculation.

10. STABILITY INDICATION CALCULATION

This calculation can be used if, due to exceptional conditions, no reliable calculation can be made. Exceptional conditions are, amongst others:

- severe icing;
- extreme wastewater problems due to firefighting;
- severe damage to the ships sections.

With this calculation the metacentric height can be derived from the roll movements of the ship using the known "pendulum formula". The circle frequency with the highest amplitude will be retrieved from the power density spectrum of rollmovements, as shown in figure 10.1. Then, the metacentric height will be:

$$GM = \frac{(I * \Omega)^2}{G}$$

In which:
GM = metacentric height;
I = transversal radius of inertia;
Ω = circle frequency;
G = acceleration of gravity.

Experiments have been carried out on board of the Standard-class frigates of the Royal Netherlands Navy. From these experiments an algorithm has been derived. This algorithm has proved to be very useful if applied in the process that leads to a reliable metacentric height.

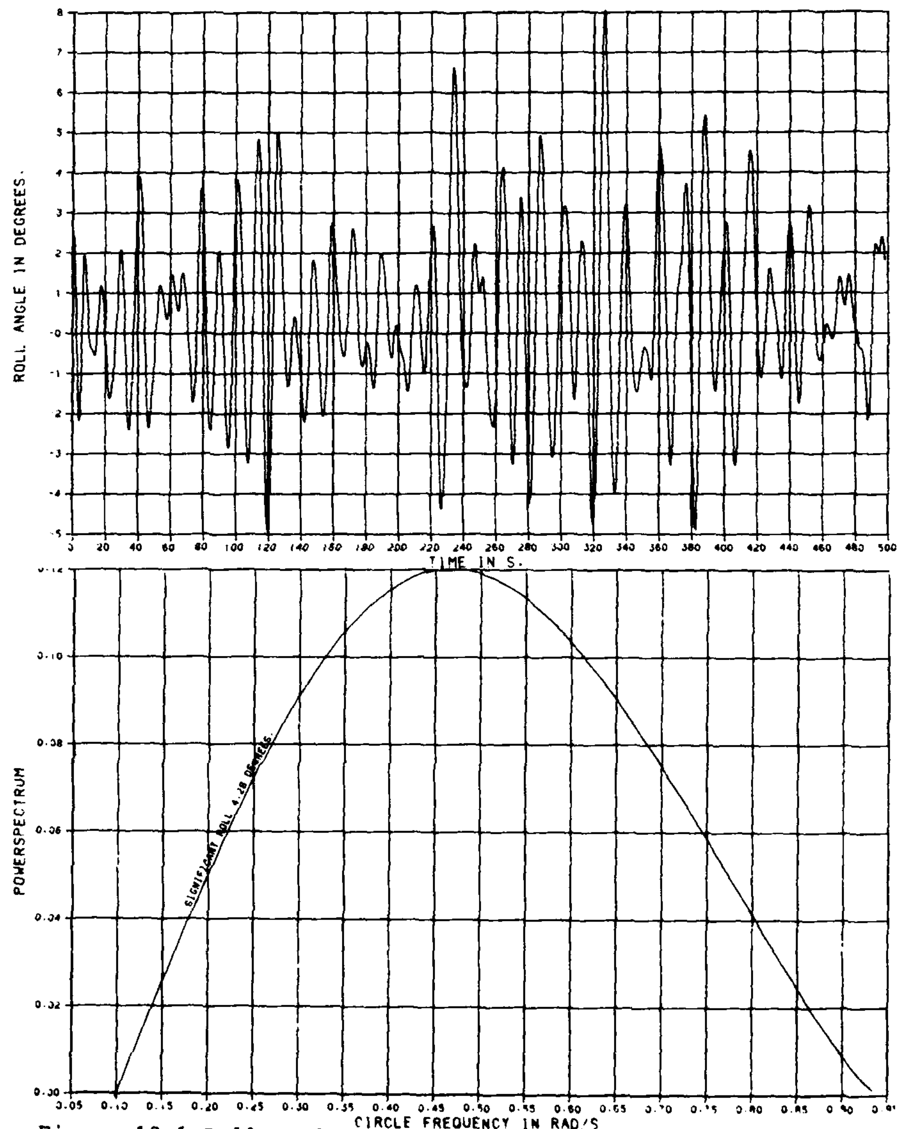


Figure 10.1 Roll angles as recorded and roll spectrum as calculated during the RNLN experiments

The reliability of this calculation depends on the processing of sufficient roll data and on the applied algorithm that was found during the experiments of the Royal Netherlands Navy . The reliability of this calculation is only influenced externally if the ship is sailing in following seas.

11. CONCLUSIONS

Integration of the stability calculation module in the Integrated Monitoring and Control System is necessary because through this integration it is possible to provide direct input from the many sensors and the automated integrated damage control plot facilities to the stability calculation model in order to reduce the workload of the DC-operator and the DC-officer.

Knowledge of the stability of ships is necessary for the operator.

The stability calculation module is a powerfull tool for the Damage Control management during Damage Control operations. Also, the stability calculation module is an important factor in the training of the technical staff as it enlarges the knowledge of stability and leads to a better understanding which, in their turn, result in quick and adequate corrective actions in case of calamities.

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FIGHTING HURT
COMBAT SYSTEM DAMAGE CONTROL

by David W. Geer
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1. ABSTRACT

Ships in war will be hit. Fighting hurt means post-hit firepower having a capability and reaction time that meets the requirements of the operational commander both for terminal defense and area defense/offense.

In order for the combat system to continue to fight after battle damage, ship control and auxiliary systems must provide uninterrupted vital services required for the combat system as well as protecting vital spaces. The capability to Fight Hurt involves both the physical and functional survivability of not only the combat system but the ship control and vital systems as well.

Emphasis is placed on the fact that people (ships crew) fight and save ships using the tools (systems, equipments, and procedures) that are provided them. Thus, every capability must have the fundamental purpose of providing a "force multiplier" to the crew by way of training, organizational coordination, fighting hurt procedures and decision aids, together with survivable system design. An evolutionary approach to improved survivability employing and expanding upon current highly successful and proven techniques is described.

2. INTRODUCTION

Fighting Hurt is the recovery of the combat system after battle damage by reconfiguration of surviving components to re-engage threats and provide terminal defense of the ship. Major physical damage is expected to the targeted ship as illustrated in figure 1. Because the combat system can not reasonably be hardened to withstand direct weapon impact or blast effects, the emphasis is placed on shock and fire "hardening", redundancy and separation, and thus survivable reconfiguration.

2.1 Post-hit Self Defense

The damage to the targeted ship's Vital Systems and Spaces must be minimized, magazine explosion precluded, and vital services sustained to the surviving combat system terminal defense systems and weapon launchers.

At the occurrence of battle damage, it is imperative that terminal defense systems be supported and restored as a high priority since the ship will be highly vulnerable to subsequent threat weapon salvos and raids.

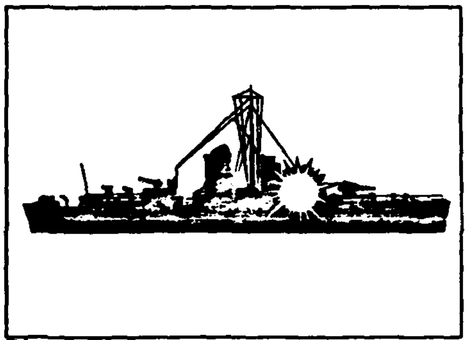


Figure 1
SHIP DAMAGE

The best shipboard damage control organizations and ship designs can be overcome by subsequent weapon hits. If the ship has been hit once, it is clearly targeted. Thus the ship's combat system must be prepared to re-engage incoming threats as rapidly as possible.

Figure 2 illustrates the need for rapid combat system recovery to engage multiple missile salvos or multiple threat targeting of the ship. Ships performing escort or convoy duties can be expected to be separated by 5 to 30 miles from other combatants. Thus, each ship must provide for its own defense against "leakers" penetrating the screen. Since enemy engagement doctrine typically specifies firing multiple missile salvos at a targeted ship, rapid re-engagement of subsequent missiles within the salvo interval is essential for survival.

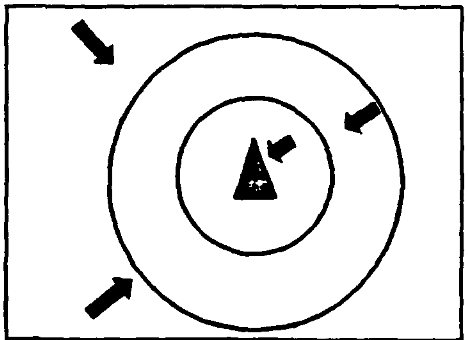


Figure 2
MULTIPLE WEAPON THREAT

2.2 Design for Damage

Ship combat system designs and procedures optimize pre-hit firepower. The design process and procedures are well defined and successful. However, ships in war must plan to be hit. This requires the extension of the design discipline to include post-hit firepower. Coping with battle damage requires immediate, total-ship coordination and prioritized restoral of vital systems and equipments. Command decision making and priorities must be based not only on the primary damage effects to the ship, but on the tactical threat and residual combat system capability.

The combat system dependency on the ship's HM&E systems and damage control organization is such that combat survivability requires integrated resource management of systems and personnel.

The relationships between all elements of the battle organization are the same both before and after battle damage, they differ however, in emphasis and manpower allocation as reflected in table I.

The evolution of a Fighting Hurt capability requires total-ship combat system / HM&E system survivability engineering. In the far-term, these changes would be implemented as total-ship threat reactive control system response, redundancy and dispersal of vital components, survivable connectivity, and automated decision aids. In addition, a long term commitment to revisions to ship procedures, doctrine, training, and organizational relationships is required.

Table I
CHANGING EMPHASIS

POST - HIT CHANGING EMPHASIS
• SUSTAIN / RESTORE ELECTRICAL POWER TO COMBAT SYSTEM
• SUSTAIN / RESTORE VITAL SERVICES
• PROTECT VITAL SPACES
• SUSTAIN / RESTORE WEAPON ENGAGEMENT

3. VITAL SPACES AND SYSTEMS

Fighting Hurt acknowledges that major physical damage will occur when the ship is hit. The statistics and assessments of battle damage from World War 2, Korea, Falklands, and the Persian Gulf are clear. Ships are seldom lost as a result of Primary Damage (direct blast effects), but rather as a result of Secondary Damage (the spread of fire and flooding into surrounding areas).

3.1 Vital Spaces

Vital Spaces are defined in the ship specifications and ship's damage control books as "those in which continued operation is essential for ship control, propulsion, communications, seaworthiness, and fighting capability". Table II lists representative vital spaces. The combat system vital spaces are located throughout the ship. Protection of combat system vital spaces together with propulsion, electrical and auxiliaries vital spaces is of paramount importance to post-hit fighting capability.

Within the context of total ship survivability, priority must be given to saving vital spaces. They should be clearly identified on decision aids and accorded the reaction time of response required to save the vital components contained within. One example will suffice; magazines. Magazines are vital spaces. Fire in the vicinity of a magazine is always accorded the highest priority; however, flooding and structural damage are not necessarily. In order to fight hurt, it is imperative that weapons be kept dry and debris cleared for weapon launch. Within each damage control zone of the ship, all vital spaces should be prioritized with respect to the ships current tactical situation and the type of damage sustained.

Table II
VITAL SPACES

REPRESENTATIVE VITAL SPACES

COMBAT SYSTEMS	PROPULSION / ELECT / AUX
PILOT HOUSE	CENTRAL CONTROL STATION
CIC	DAMAGE CONTROL CENTRAL
RADIO ROOM	ENGINE ROOMS
MISSILE LAUNCHERS	AIR CONDITIONING ROOMS
IC & GYRO	MACHINERY & PUMP ROOMS
POWER CONVERSION	AUX MACHINERY ROOMS
COMBAT SYSTEM EQMT ROOMS	STEERING GEAR ROOM
SEARCH RADARS	GENERATOR ROOMS
RADAR EQMT ROOMS	POWER SUPPLY / CONVERSION ROOM
CIWS CONTROL ROOMS	ELECTRIC LOAD CENTERS
CIWS MAGAZINES	
SONAR CONTROL/EQMT/COOLING	
NIXIE ROOM	
GUN DIRECTOR	

3.2 Vital Systems

The Vital Systems summarized at Table III are essential to the operation of not only the combat system, but the propulsion and auxiliaries, as well as the survival of the ship after battle damage.

While all vital systems are essential to the combat system and ship survivability, the effect of an interrupt varies, as reflected in the ships' Battle Short Doctrine. The range of time permissible for an interrupt to the combat system varies from milliseconds for electrical power to minutes for cooling or chilled water. Additionally, after battle damage, the effect of an interrupt can be catastrophic to certain vital systems such as the firemain, with men engaged in firefighting or magazine sprinkling due to fire.

Casualty reconfiguration of Vital Systems also includes reducing the demand (load) required by reduced capacity caused by damage. Electrical Load Shed is a prime example of the necessity to rapidly reduce electrical load in accordance with a predetermined and FLEXIBLE doctrine. Chill Water an example of the need to reduce heat load by reconfiguring the combat system over a period of minutes.

Table III
VITAL SYSTEMS

VITAL SYSTEMS

- ELECTRICAL POWER (400 HZ, 60 HZ
  - FIREMAIN
    - MAGAZINE SPRINKLING
    - AFFF
    - COOLING
  - CHILL WATER
  - OWN SHIP HEAD, ROLL, PITCH, SPE
  - WIND SPEED, DIRECTION
  - RUDDER ANGLE INDICATION
  - INTERIOR COMMUNICATIONS
  - VENTILATION / AIR CONDITIONING
  - COMPRESSED AIR

4. FUNCTIONAL SURVIVABILITY OF THE BATTLE ORGANIZATION

Fighting Hurt requires prioritized casualty and damage restoration. Everything can not be done at once. Primary damage by weapons can cause 25-40% personnel casualties on a destroyer resulting in a severe shortage of manpower. This can be especially significant in the area of critical technical skills.

The crew of a warship fights and saves its ship within the framework of the Battle Organization. The Control Positions within the Organization are connected by voice and data networks. Figure 3 illustrates a typical Condition I Organization.

The success of the organization depends in large measure upon the survivability of its interior voice and data links. The speed and completeness with which the organization can decide and act is

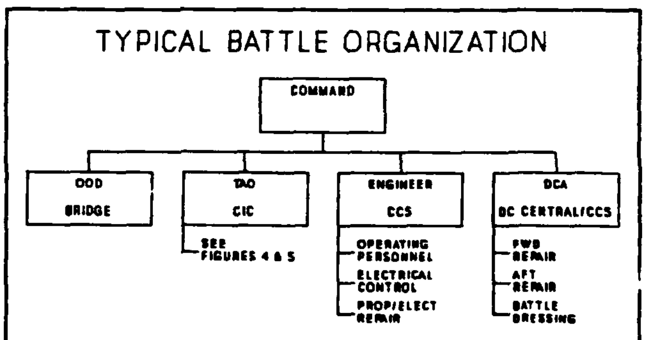


Figure 3
TYPICAL CONDITION I BATTLE ORGANIZATION

dependent on the information and displays presented to the decision makers at the control positions.

4.1 Typical Combat System Organization Deficiencies

The typical combat system organization reports directly to the Tactical Action Officer (TAO) as illustrated in figure 4. The organization that functions in this manner has the simplicity of each equipment group and its operators reporting directly to the warfare operators.

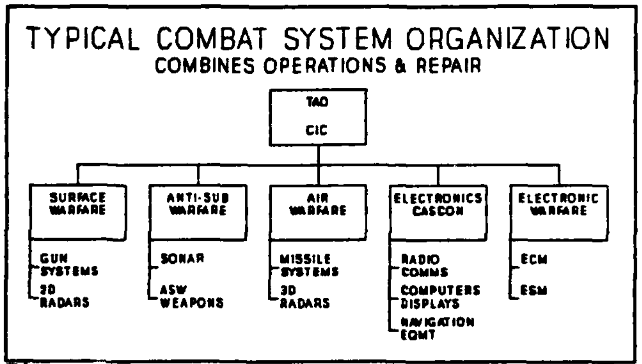


Figure 4
TYPICAL COMBAT SYSTEM
BATTLE ORGANIZATION

The battle damage problem with this organization is the Electronics Casualty Control (CASCON) group only communicates with the Electronic Technicians and the Data Systems Technicians. All other repair personnel report directly to their Warfare Officers and the Tactical Action Officer. The lowest common denominator for casualty and damage coordination is the Tactical Action Officer, not the Electronics Casualty Control Group.

In a battle action, the TAO and Warfare Officers are totally absorbed with the threat and tactical use of what remains of the combat system. Further, coordination with Engineering & Electrical Control and Damage Control Central is by each warfare area and Electronics Casualty Control; five different areas with potentially five different sets of priorities. During battle damage, the DCA and Engineer Officer are already saturated with voice and data communications within their own areas of responsibility. Further compounding the problem is the fact that no ONE in the combat system organization knows the complete status of the combat system to advise the Commanding Officer and TAO of remaining capability. The most serious deficiency is that there is no practical way for Command to set priorities for the reconfiguration and restoral of the combat system to engage the most threatening targets.

4.2 Alternate Combat System Organization

The deficiencies discussed above are being resolved aboard selected ships today as indicated in figure 5. There are two primary benefits to this organization: (1)the TAO and warfare officers concentrate of tactical use of weapons systems, and(2) a single decision maker prioritizes the reconfiguration and restoral of the entire combat to meet threats.

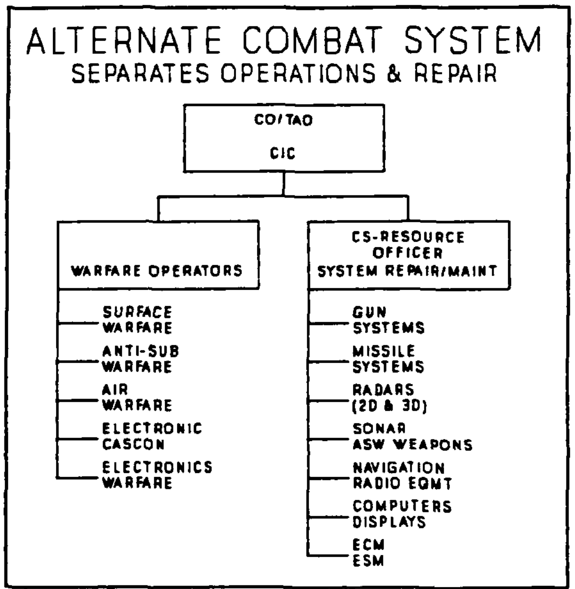


Figure 5
ALTERNATE COMBAT SYSTEM ORGANIZATION

The centralized combat system damage decision making is the functional equivalent of the DCA. With centralized decision making, more suitable facilities and decision aids can be (and are) provided. The facility is commonly called Combat System Maintenance Central (CSMC), although the same capabilities and communications could be established within the existing Repair 8 (combat system repair) organization.

Crucial to setting priorities for combat system restoral after battle damage is the complete understanding of the threat as seen by Command/TAO. This is accomplished within the organization shown in figure 5 by the Combat System Resource Officer (CSRO) standing in the vicinity of Command/TAO in CIC. The CSRO is supported by the CSMC organization and its decision aids physically located elsewhere in the ship.

Within the CSMC are dedicated maintenance and repair communications throughout the combat system that do not compete with tactical communications. Further, the CSMC maintains not only a combat system plot, but a set of vital systems, vital spaces, and damage plots equivalent to those maintained by the DCA.

5. SYSTEM / EQUIPMENT SURVIVABILITY

5.1 Hardening (Shock, Fire)

The common denominator of all high explosives is shock. If the combat system, vital systems and equipments, propulsion and electrical, and damage control systems are to be of any use after battle damage, they must be selectively shock hardened up to a predetermined set of thresholds for continued performance after survivable damage. The design for survival should address required residual capability required after both underwater burst shock and air burst shock.

Shock hardening of machinery such as engines and generators is more easily recognized than that of antennas, wave guides, and chill water piping. However, if the ship is to fight hurt, clearly defined hardening criteria for major equipment groups within the combat system must specify which components are expected to fail and define the alternate routing and dependency paths.

Fire "Hardening" as used in this paper is the time related resistance of vital equipments and systems to flame and high temperature. Data and voice communications together with electrical power distribution are prime examples of the need for fire hardening. Various fire resistant cable conductors and coatings are readily available for use aboard warships. Their use should be focused on vital circuits and data systems essential to post-hit firepower and survival. The value added of fire hardening is the lengthening of circuit and system use from 3-5 minutes to 20-60 minutes when exposed to flame.

The time gained from extending the use of fire hardened circuits/systems is during the initial minutes after the occurrence of damage, which is the most critical. Both the combat system and damage control organizations will benefit. Further, by retaining the vital capabilities, the damage may be rapidly contained and controlled such that the hardened vital circuits/systems will not be disrupted for the remainder of the ships transit.

5.2 Separation/Redundancy

Physical separation of vital spaces, systems, equipments, and connectivity is essential to battle damage survival. Destroyers, Frigates, and Cruisers in the 4000-9000 ton displacement range will be penetrated by the weapons and the high explosive/shrapnel effects will cover a predictable interior volume of the ship. Air bursts and underwater bursts also have predictable effects. Since the systems/equipments within the lethality range of the weapons will be destroyed, the only alternative is maximum feasible physical separation of redundant components.

Duplication of separated vital systems/equipments is essential to fighting hurt. Redundant components and paths must be physically separated to reasonably assure alternate paths for reconfiguration after damage.

In many cases, ships today have redundant systems that are virtually collocated (separation of a few feet or less), primary and alternate power supplies only available from one power panel or both power panels located in the same space, chill and cooling water systems that do not have sufficient bulkhead cutouts allowing casualty reconfiguration due to rupture.

The effect of redundancy on post hit mission capability is well illustrated by a ship having only one radio room. A hit in that space can eliminate tactical communications with the dispersed convoy or escorts discussed in section 2.1. An emergency radio communications capability is essential today and in the future for the same reasons it was standard practice during World War 2.

5.3 Reconfiguration After Battle Damage

After sustaining battle damage, the only reasonable method of reestablishing ship capability is to reconfigure around destroyed or damaged systems/equipments. In high threat environments, there is no time available to repair. The ship must be rapidly reconfigured; manually, mechanically, and/or electronically, to restore surviving capability. It is here, under extremely adverse conditions, that people within the Battle Organization discussed in section 4 will fight and save the ship using the tools that are provided them.

6. TRAINING TO SURVIVE

Fighting Hurt or Combat System Damage Control, is the ships' crew using the systems, equipments, and procedures provided them for the rapid recovery of the combat system by reconfiguration after battle damage. Training for battle damage requires voice and data communications and informed decision making throughout the battle organization shown in figure 3 and in particular within the combat system organization shown in figure 5.

The training must emphasize the fact that the post-hit threat will be more intense as discussed in section 2.1.

6.1 Training Realism

Figure 6 illustrates the requirement to realistically expose the total ship battle organization to the expected threat for their area of operations. By exposing the crew to the effects of self defense weapons detonating an incoming missile, the effects of anti-shipping missiles detonating within the ship, and torpedoes/mines exploding at the extremities of the ship, the crew gains knowledge of their ship and confidence in their ability to "handle" actual damage.

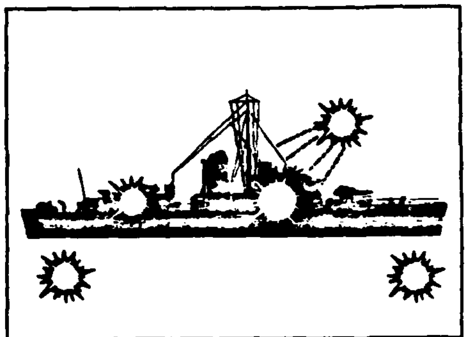


Figure 6
TRAINING FOR DAMAGE

Threat and damage realism is essential. This can be obtained from each navies estimates of weapons effects for their area of operation and applied to the specific configuration of the ship undergoing training. This can be done either manually or by use of computer models or both. Once the threat and weapon effects are determined, the actual damage expectancy is applied to ships drawings and verified by observation aboard the actual ship undergoing training. The training "battle problems" are then scripted in detail for the ship.

The training must emphasize *SURVIVABLE* battle damage while sustaining the threat to the ship. Experience has shown that only the early portion of the scenario up to the initial hit can be "scripted" in detail. The ships' crew must be allowed innovative responses. Additional threats must be disclosed and the ship required to successfully engage them. If the combat system fails to successfully engage incoming weapons, another "hit" must occur. In general, there is no UNIQUE solution to the problem. Thus, the training team conducting training must be capable of real time revisions to the battle problem. The most versatile method for training team response has been found to be VHF voice radio at the 4-5 watt level of power.

6.2 Design Benefits

One of the greatest benefits of realistic training, is that the manual actions in fact prescribe a design and control algorithm. The innovation and ingenuity of a ships crew provides invaluable insight into survivability of design and past design flaws. Capitalizing on this potential requires a close working relationship between the design community and the operating forces. If viewed in the context of "The Manual Implementation of the Future Automated System", shipboard survivability training can not only assist in design innovation, but serve to validate new doctrine, procedures, control position organizational requirements, display and decision requirements, and control "algorithms".

7. PAYOFF

The payoff, illustrated in figure 7, is improved combat system survivability. The probability of kill, Pk, of the combat system is shown decreasing from current firepower kill levels to that of mobility and hull levels. Ship and system/equipment design ultimately determine survivability.

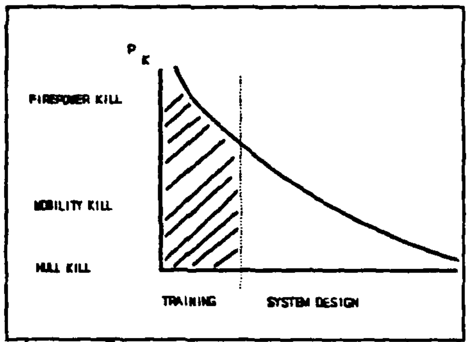


Figure 7
PAYOFF

7.1 Training

Training has proven effective in restoring the combat system to engage threats after sustaining simulated battle damage. Most importantly, Command decision making is significantly enhanced and thus the ability of Command to set priorities.

Prior to training, the various elements of the Battle Organization shown in figure 3 focused on their own areas of "doctrinal" responsibility. In short, they did not "communicate" at the total ship survivability level. With training, ships achieved a total ship perspective and were able to rapidly restore not only combat system capability, but vital systems essential to damage control, propulsion and electrical control throughout the ship.

7.2 System/Equipment Survivable Design

Training can only enable the crew to effectively use what is provided by the designers. Significant further increases in survivability can be achieved with "total ship system engineered" hardening, separation, and redundancy. With survivable reconfiguration, the potential exists to exploit numerous new and future weapon systems in a casualty mode of operation not requiring the use of vulnerable own ship radars.

8. CONCLUSION

Post-hit firepower having the capability and reaction time to meet the requirements of the operational commander can be achieved if the combat system and its supporting vital systems are designed for damage reconfiguration.

Over the near term, significant improvements can be made with existing assets through realistic total ship training and modifications to ships' doctrine.

In the long term, improvements in survivable design of systems and equipments may well extend combat system survivability to that of mobility and even beyond to that of the hull (depending on ships' weapons). Equal benefits can be achieved to propulsion and electrical systems as well as damage control systems through the application of this discipline. A close working relationship between the design community and the operating forces can capitalize on the "manual implementation of the future automated system". This manual implementation will provide a proven foundation for the "control algorithm" of the future automated survivable control system and its total ship resource display and decision requirements.

THE IMPLEMENTATION OF THE SHIP'S POSITION CONTROL SYSTEM FOR THE ROYAL NAVY SINGLE ROLE MINEHUNTER

by A M Burt
Vosper Thornycroft (UK) Limited

1. ABSTRACT

This paper describes the processes involved in the production of the Single Role Minehunter, Ship Position Control System (SPCS). The design, test, and trials periods are covered, the processes involved are explained and the steps taken to reduce risk described.

The SPCS was developed by Vosper Thornycroft Controls for the Royal Navy Sandown class of minehunters.

2. INTRODUCTION

Vosper Thornycroft Controls (VTC) is part of the Systems Group of Vosper Thornycroft (UK) Ltd and is primarily involved in the design and manufacture of control systems for Naval vessels.

The SPCS was designed for use upon the Sandown class of minehunters for the Royal Navy. Its purpose is to automatically control the vessel during minehunting operations, and to provide manual joystick and autopilot control functions.

The vessel is equipped with Voith Schneider Propulsors (VSP) that provide controllable vectored thrust, and a bow thruster. The vessel uses twin diesel engines for non minehunting operations and electric slow speed drives for minehunting.

This paper covers the techniques used to implement the design and the steps taken to simplify the tasks of testing, setting to work and sea trials.

The system was designed to meet a Naval staff requirement and was required to provide several different operational modes. The requirement was to produce a simple and easy to use facility to control the vessel during minehunting operations within set accuracy targets. This was intended to reduce operator fatigue and to enable accurate track following over an extended period and for a wide range of environmental conditions.

2.1 Manual Joystick

The system was required to provide a manual joystick mode, where a three axis joystick is used to control vectoring of the vessel thrusters. The joystick is fitted to the Quarter Masters Console (QMC), and a portable version can be connected at various positions around the vessel. Hover mode can be selected by operation of a pushbutton adjacent to the joystick. This hovers the vessel at that physical location until the pushbutton is operated again or another mode selected.

This mode will be used when berthing the vessel or when recovering and deploying the remote vehicle.

2.2 Track Keeping

Track keeping is the mode used for minehunting when following a search pattern. The Mine Warfare Officer (MWO) sets a plan to be followed into the Action Information Organisation (AIO) and the coordinates of the required waypoints of the track are then transmitted to the SPCS via the Weapon System Data Bus (WSDB). The SPCS then interprets these waypoints as a command to track keep, and indicates to the Quarter Master that the request to track keep has been received. The vessel is then automatically manoeuvred along the track between waypoints. Ship speed is also controlled by the Mine Warfare Officer and sent along the data bus with the waypoint data.

This mode is used for minehunting and classification operations. As a waypoint is passed the AIO updates the plan to ensure that the SPCS always has three waypoints in its memory; thus enabling the SPCS to automatically follow a tight circular path.

2.3 Hover

When the AIO sends only one waypoint or the last of a series of waypoints is reached the SPCS will automatically select Hover mode.

The SRMH is equipped with a small bow thruster that is adequate for all normal berthing operations of the vessel, but does not have sufficient power for hovering using traditional dynamic positioning techniques at all environments encountered during minehunting. In order to overcome this limitation three variants of the hover mode were developed to cater for the range of environmental conditions that the SPCS has to meet.

Hover by Dynamic Positioning with a command desired heading (Hover DP CDH) is used in low environmental conditions with no restriction on the ships heading. The CDH is set by the Mine Warfare Officer and is transmitted along the Weapon System Data Bus.

When operating in Hover-DP mode, priority is given to maintaining heading. The system calculates Northing and Easting position errors from the Hover point and the ship position. The Heading error is calculated from the desired Heading and the Ship Heading. The system takes the error information and processes it to produce pitch setting demands to the VSPs and speed demands to the BT in order to keep the ship at its Hoverpoint.

Hover by Dynamic positioning with a favourable heading (Hover DP FH) is used in higher environments than DP CDH. The favourable heading is determined by the SPCS as that which will minimise the effects of wind and tide on the vessel, this heading is termed the Favourable Heading. It is calculated by measuring the actual wind and tide, and then using a ship model to predict the bow thruster usage at various headings between wind and tide directions. The minimum is found by extrapolating between the sampled headings that produced the lowest bow thruster usage.

Hover using Position Control by Manoeuvring (Hover PCM) is used in environments up to the maximum suitable for minehunting. This mode uses the VSP to work against the environment to maintain the required position.

When operating in Hover PCM the ship will tend to move in the desired direction to correct any positional errors rather than moving laterally. Under steady conditions, the ship's heading is the Favourable Heading.

2.4 Autopilot

The SPCS implements a traditional Autopilot function using the same hardware as for the other automatic modes. The mode is selectable by the Quarter Master, and a desired ships heading entered. The SPCS then controls the VSP lateral pitch to maintain the desired vessel heading. VSP longitudinal pitch is set to full ahead and vessel speed is controlled by adjustment of the main engine speed.

The desired heading is adjusted at the QMC by means of increase and decrease pushbuttons until the desired heading is displayed on the plasma display, the operator can then enter the new heading into the controller.

A yaw limit and the usable steering pitch are also operator adjustable. The autopilot is based on a three term controller with a wind feed forward term.

2.5 Minehunting Under SPCS Control

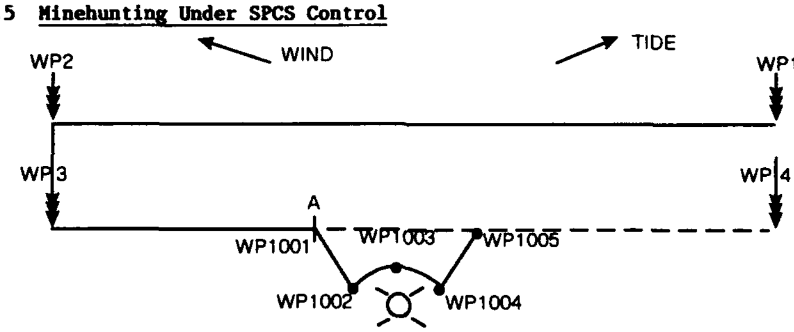


Figure 1 - Typical Minehunting Exercise

Figure 1 shows a typical minehunting exercise, and demonstrates how the automatic modes are used. The AIO transmits a pattern of waypoints, WP1, WP2 and WP3 to the SPCS and the system will select track keeping mode. When an artefact is detected (point A) between WP3 and WP4, the AIO will send a new plan of WP1001 and WP1002. The vessel will hover at WP1002 while classification takes place. Following further periods of classification at WP1003 and WP1004, the vessel will retreat to WP1005 for disposal.

All of the above operations will be carried out under automatic control of the SPCS. The Quarter Masters only duty is to monitor the vessel performance and to ensure that the selected hover mode is the most suitable for the actual environment.

3. SPCS DESIGN

There are three main sections to the SPCS design:

- The hardware design
- The software design
- The control algorithm design

3.1 The Hardware

The system is implemented using processors and interface cards from the VTC range of D86 PCBs, as already used on various other RN vessels; the T23 frigate, the T2400 submarine, and the Trident submarine; as well as other foreign naval vessels.

Special precautions had to be taken to protect the electronics from the harsh EMC environment encountered on board Glass Reinforced Plastic (GRP) vessels. This included fitting any vulnerable electronics within double screened enclosures, and the filtering of supply and signal cables.

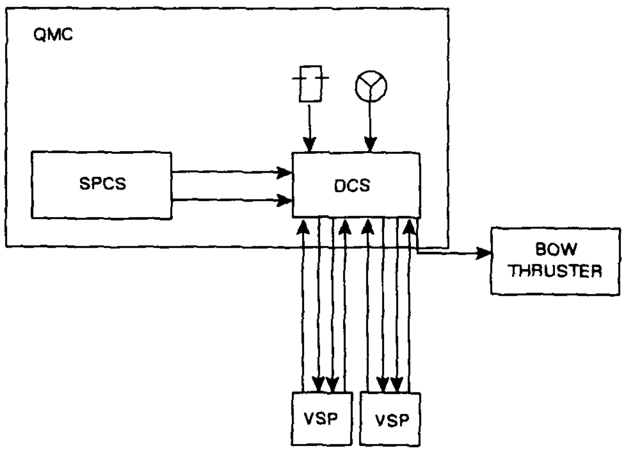


Figure 2 - System Interfaces with Propulsion Machinery

The SPCS system is housed within the Quarter Masters Console (QMC) and interfaces with the Direct Control System (DCS) also housed in the QMC and supplied by VTC. The QMC is mounted on the bridge. *Figure 2 shows* the arrangement and the interfaces with the Voith Schneider propulsors.

a. **SPCS** - The SPCS *consists* of one rack of electronics with all necessary power supplies, interfaces, and Man Machine Interfaces (MMIs) mounted in a console that forms half of the Quarter Masters console.

The MMI comprises a plasma display, a fallback display and all necessary pushbutton switches and indicators. The plasma display has a dedicated page for each mode that gives all the relevant data for that mode. Figure 3 shows the display for track keeping mode. Three status pages are also available to give further useful parameters.

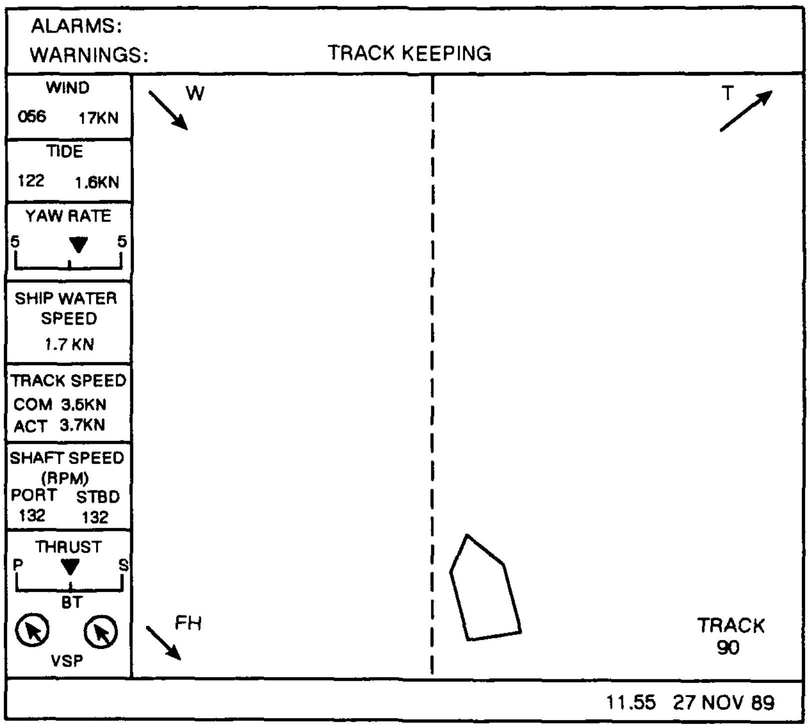


Figure 3 - Typical Plasma Display - Track Keeping

The fallback display provides sufficient information to enable the system to function correctly on failure of the primary plasma display, and consists of arrays of indicating lamps showing across track error, along track error, and heading error.

As most of the SPCS modes are fully automatic, the primary function of the MMI is surveillance, and alarms or warnings will be raised should any system or interface problems arise, as well as providing all relevant vessel and environmental data via the plasma display.

b. Direct Control System - The DCS is the normal method of controlling the vessel and provides independent longitudinal, and lateral control of the Voith Schneider propulsor pitch as well as bow thruster control.

The VSP pitch is controlled by hand levers and a helmwheel providing demands to dedicated electronics that implement closed loop control of the VSP actuators. The DCS interfaces with the propulsion systems are shown in Figure 2.

Each control loop is independent and was designed to achieve a high reliability. This was achieved by minimising the component count, component screening and the elimination of single point failures.

The inclusion of the high reliability control system was to ensure that vessel safety was not compromised by common mode failures. The transfer from SPCS control to DCS control can be achieved by the operation of a single mode select switch on the QMC.

The SPCS controls the vessel by the use of isolated analogue inputs in the DCS, so any SPCS failures will not affect DCS availability.

The main engine speed control and hence VSP shaft control also forms part of the DCS and is independent of the SPCS. Each engine speed is controllable by an array of pushbuttons that control the governor setting by means of a stepper motor. Setting the governor to minimum when the slow speed electric motors are running causes the automatic changeover of the Self Synchronising and Shifting (SSS) clutches.

c. Interfaces - Figure 4 shows the interfaces with the other ships systems and navigation aids. All positional data is received via the WSDB, as well as sonar positional data and system time.

The SPCS has been designed to function correctly with a variety of navigational aids, and the X Y coordinates are received from the AIO via the WSDB. Racal Hyperfix is the normal navaid used, due to its extensive coverage of UK coastal waters.

Ships heading, and wind direction are received via synchro interfaces. Wind speed is received via an analogue signal.

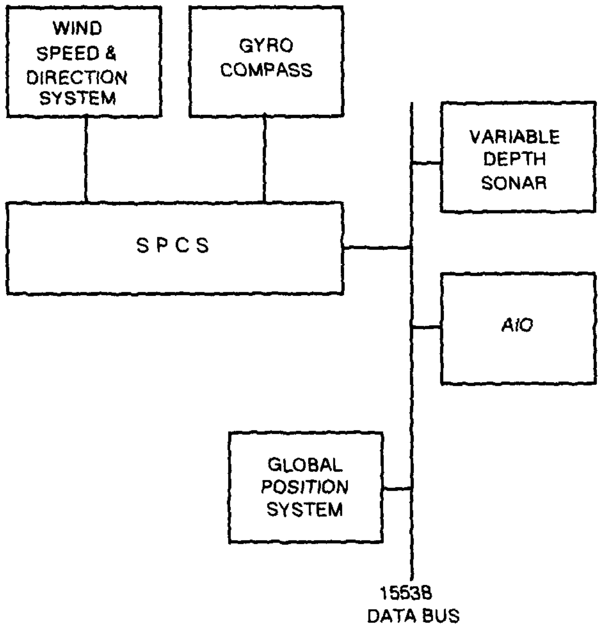


Figure 4 - SPCS/Navaid Interfaces

d. Correlation Electromagnetic Speed Log - Surge and sway ground and water speed are received via an RS422 link directly from the Correlation electromagnetic speed (CMS) log. This system has been developed in a military version by VTC for the SRMH. The system provides an accurate measurement of surge and sway ground speed by using ground tracking techniques. The CMS log also incorporates a electromagnetic log that provides alongships and athwartships water speed.

3.2 The Software

The application software was implemented using tried and tested standard VTC I/O modules. This use of proven software reduced risk and simplified the task of integration and test. The code is mainly written in CORAL 66 with assembler used where dictated by speed, and was developed within a Context environment.

Structured Analysis and Design techniques were used in the development of the system software. Rigorous testing of software modules was employed to reduce the integration time.

The application specific software consisted of code to handle control mode transitions; to handle the MMI and to call the relevant control algorithms. Functions such as the database management, I/O handling, and comms handling all used standard VTC modules.

The software incorporates extensive diagnostics and failure detection to simplify and speed up fault identification and repair.

3.3 The Control Algorithms

The development of the control algorithms was carried out by running a ship simulation on a μVax computer. The algorithms went through many design stages and took many forms before the final designs were settled upon.

Different control techniques for the algorithm designs were tested by coding them and then running them against the simulation. Stable hover and track keeping performance was then observed as well as performance in transient situations such as veering wind and tide conditions or turning at waypoints.

The use of Linear Kalman filters was investigated and while this offered good performance in linear or stable conditions, gave unacceptable performance in non-linear situations such as manoeuvring.

Eventually conventional three term controllers were found to be the most suitable robust option. After initial testing of the designs, the algorithms were coded in coral for inclusion into the system software. The designs were also included in a SPCS model within the simulation, the simulation was then used to evaluate the algorithm performance over the full range of environments and conditions.

Separate algorithms were developed for each operational mode; Autopilot, Track keeping, Hover DP and PCM, plan interrupt and ship emergency halt; as well as for the favourable heading calculation. The favourable heading module is used to calculate the best heading for hovering for the environment. This is achieved by calculating the Hydro, Aero and Sonar forces on the vessel for a range of headings between the actual wind and tide, and then calculating the required use of the bow thruster for that heading. The heading that gives the minimum use of the bow thruster is the favourable heading.

The algorithm gains and limits were then tuned and adjusted as the result of extensive simulation work.

Once the algorithm gains had been finalised, the system was subject to a full stability analysis. This involved analysis of the SRMH system without any controller and then adding the analysis for each controller. The analysis was carried out by examining the response of a linearised model of the system to small control inputs and disturbances. The results of the linear model analysis were compared with results from the non-linear model to ensure accuracy of the linear model. The linear model was then exercised over a wider range of environments in order to find any areas of instability. The stability analysis indicated that the SPCS would be stable across all required operating scenarios.

a. Fallback Modes - While the vessel will normally have all the required thrusters available for minehunting; the SPCS has been designed to operate with only one Voith Schneider Propulsor functional. This means that in most environments the SPCS can function with little or no loss of performance with only one shaft available.

The SPCS can also function with the shafts at different speeds again with little effect on performance. This flexibility means that the SPCS can make maximum use of the available propulsion prime movers.

Various navaids can be replaced by estimated data in the event of navaid failure. Thus loss of non-critical navaids will not mean total loss of the system.

b. Noise Limiting Algorithms - Provision has been made to limit the SPCS usage of thrusters in order to limit thruster noise. The noise limiting algorithms will be determined after noise ranging of the vessel and can be incorporated with no software redesign.

The algorithms will most likely limit the Bow Thruster and VSP usage to reduce the risk of cavitation.

4. THE SIMULATION

A complete ship simulation was developed by VTC and included Hull and Machinery models provided by the shipbuilder and the Ministry of Defence.

The simulation also included models of the SPCS, CMS log, AIO and WSDB, as well as a full environmental model. The simulation was enhanced and expanded as algorithm design progressed. This included the addition of enhànced graphical displays and monitors for the calculation of performance figures. The improved MMI greatly reduced the task of analysis of large quantities of trials results.

The primary purpose of the simulation was to accurately model the real operating environment of the system in order to establish the system functionality and to enable realistic testing of the system. This was carried out in order to reduce the setting to work time required on board the vessel.

The simulation was then used to form the basis for a system test facility, where the vessel, the ship interfaces, and the environmental conditions were simulated in order to functionally test the complete system.

The simulation was also used to define the effects of tuning the algorithms. Thus maximum and minimum values and the sensitivity of each parameter was determined before sea trials.

Various failure modes of ships equipment were simulated in order to test the fallback systems within the SPCS and the designs' ability to withstand degraded sensor performance.

5. TRIALS LOGGING FACILITY

As sea trials time was going to be very limited and due to the dynamic nature of the SPCS, it was important to make full use of all ship time. In order to achieve this and to ensure that any unexplained or transient phenomena were recorded a data logging facility was developed. The main functions of this facility are:

- The logging of internal SPCS parameters.
- The tuning of algorithm gains.
- The production of performance figures.

The facility was implemented using a μVAx computer connected via an RS422 link to the SPCS display processor. The display processor was then able to access the main SPCS database and supply the required parameters to the logging computer. The parameters to be logged can be selected from the logging computer and this selection passed to the SPCS, thus only selected parameters are passed down the data link.

Several parameters can also be logged from the port and starboard Machinery control and surveillance systems.

The data available to the logging facility are algorithm gains and limits, controller outputs, filter and navaid data, as well as SPCS mode and thruster information. Over three hundred different parameters are available for monitoring or tuning, of which any 100 can be logged at one time.

This facility is also used during system integration and test to log system parameters in order to troubleshoot faults when connected to a system on the test facility. The performance monitor is used to provide performance figures during factory acceptance tests.

Algorithm tuning is required to adjust the performance of the algorithms on board the vessel to give the desired performance. Thus the effect of inaccuracies in the simulation database can be minimised. Prior to sea trials the effect of algorithm tuning was tested on the simulation. Maximum and minimum safe levels for each gain were determined using the simulation. Thus the tuning of algorithms could be undertaken without affecting the system stability.

Once a parameter has been selected for display the facility can log it to a disk file for processing at a later date. This data can then be post plotted to give a permanent record of any trial or manoeuvre. An example of the plotted data is given in Figures 5 to 7. Figure 5 shows the vessel path during the logging period. The vessel position is plotted at regular intervals to indicate the vessel heading and at a scale that will not obscure the path. Figures 6 and 7 show various SPCS parameters throughout the logging period, thus enabling different parameters to be compared with each other at any time during the trial.

The output of each term of each three term controller can be examined to analyse the controller performance and give a guide to any tuning required.

6. HARBOUR ACCEPTANCE TRIALS/LINKING

The Harbour Acceptance Trial (HAT) and linking trials to various ship systems were carried out during the setting to work period. The purpose of these trials were to prove the functionality of the interfaces to other ships equipment and to ensure that the SPCS had been correctly installed prior to going to sea.

Due to the dynamic nature of the SPCS it was not possible to fully test the system with the vessel tied up alongside a harbour wall.

7. PRE SEA ACCEPTANCE TRIALS

Prior to the formal Sea Acceptance Trials (SATs) a period of setting to work and tuning at sea was made available and was referred to as the Pre SATS period. The aims of this period were to test each mode to ensure correct functionality; to gather data about the real ship to compare with the simulation models; to carry out tuning of the algorithms if required; to dynamically test the system; and to enable ships staff to familiarise themselves with the system prior to handover.

The Pre SATs period was split into several sections as determined by the ship part 4 trial programme. The first week took place off Portland in November 1989, and was characterised by extremes of environment. The first day was absolute calm followed by three days of gales. However the trials were a success with all modes functioned and the logging system proven.

The autopilot proved to work satisfactorily and the manual joystick in both local and remote modes was proved. Track keeping was tested and functioned correctly despite the very high winds; Hover testing was more limited as only the PCM mode could be used in the environment encountered.

Figures 5 to 7 show the results of a track keeping trial from the Pre SATs period. The vessel follows tracks of 170, 270,345, and 15 degrees. Figure 5 shows the vessel manoeuvring around the required track as well as plot information. Figure 6 shows various vessel parameters including wind and tide speed and direction. Figure 7 shows some of the track keeping parameters that were logged including track speed and direction.

A few minor interface problems were discovered during this week in both SPCS and ships interfaces and these were corrected prior to the second week when it was intended to fully test the Hover and Track keeping modes. These modes have to function correctly with and without the hunt sonar deployed and these tests were carried out off Rosyth in April 1990.

One of the objectives of the Pre SATs was to gather as much data as possible regarding the system and vessel performance. When a trial has been conducted satisfactorily it can then be rerun on the simulation in order to validate the simulation. Once the simulation has been shown to be accurate or any differences explained; the extensive simulation results become an accurate system performance definition, and future operational problems or changes can be tested against the simulation.

8. SEA ACCEPTANCE TRIALS

The purpose of conducting Sea Acceptance Trials (SATs) is to show that the system meets the customer requirements, and to demonstrate all modes of operation.

The system will be demonstrated by VTC to the shipbuilder and the Ministry of Defence at the same time. The total time allocated to the trials is four days of sea time. Due to the dynamic nature of the system and its inter-reaction with the the environment testing will be limited to that achievable in a few days. Hence no attempt will be made to conduct trials in different combinations of wind and tide, and the simulation results will be used to give more extensive results.

The SATs will include demonstrations of each control mode. Minehunting modes, track keeping and hover will be demonstrated with and without the sonar deployed. Performance figures will be calculated by the data logger computer with independent checking of navaid accuracy. The SATs are scheduled for completion in April 1990.

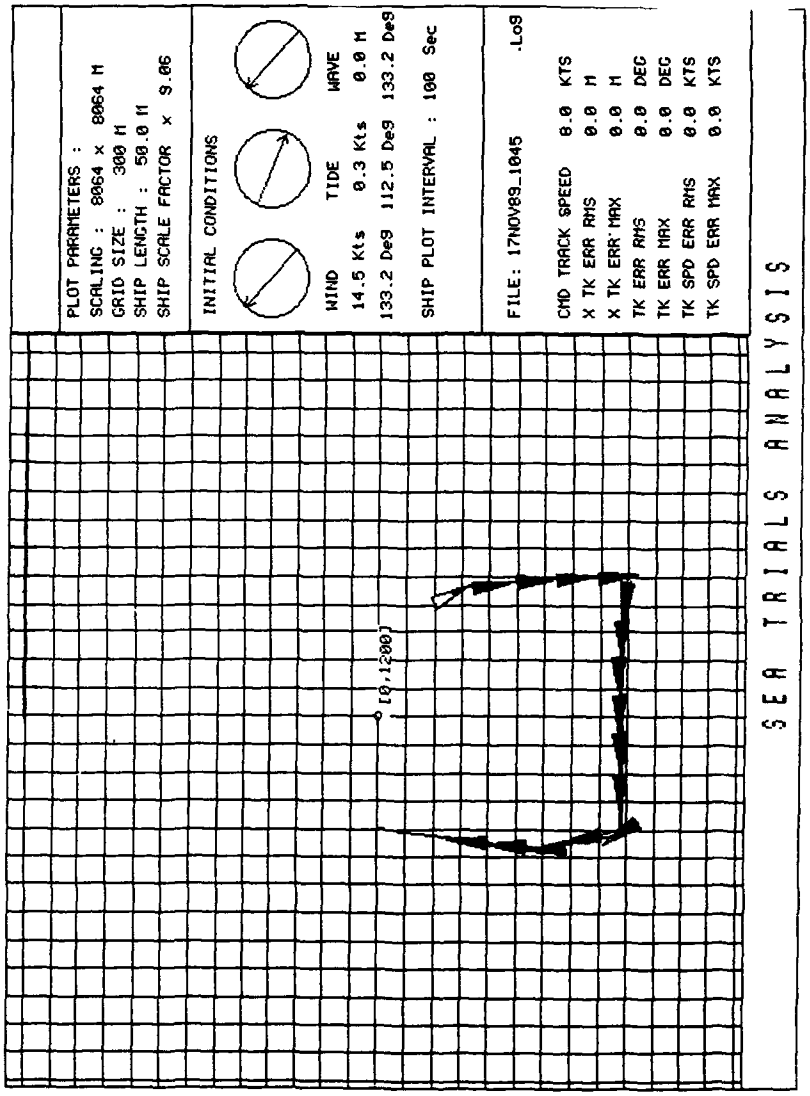
9. CONCLUSIONS

During system development several areas have been found where improvements can be made to enhance performance and it is hoped that these can be included in the near future. Work is also under-way to look at developing the algorithms for use on other similar vessels.

The SPCS has now been fully tested by the shipbuilder, and has proved its ruggedness and suitability for the harsh environment in which it will be required to operate.

The usefulness of extensive simulation work in the design and analysis stages of a project such as this has been proved. Without the ability to test algorithm design against a computer simulation the production of a working system would have been almost impossible. The total non-customer acceptance testing at sea for the SPCS system was eleven days during which the vessel was not always exclusively available for VTC use.

The inclusion of a fully automatic ship control system should greatly improve the overall minehunting effectiveness of the vessel; due to good predictable performance over a wide range of environments with minimal operator involvement.



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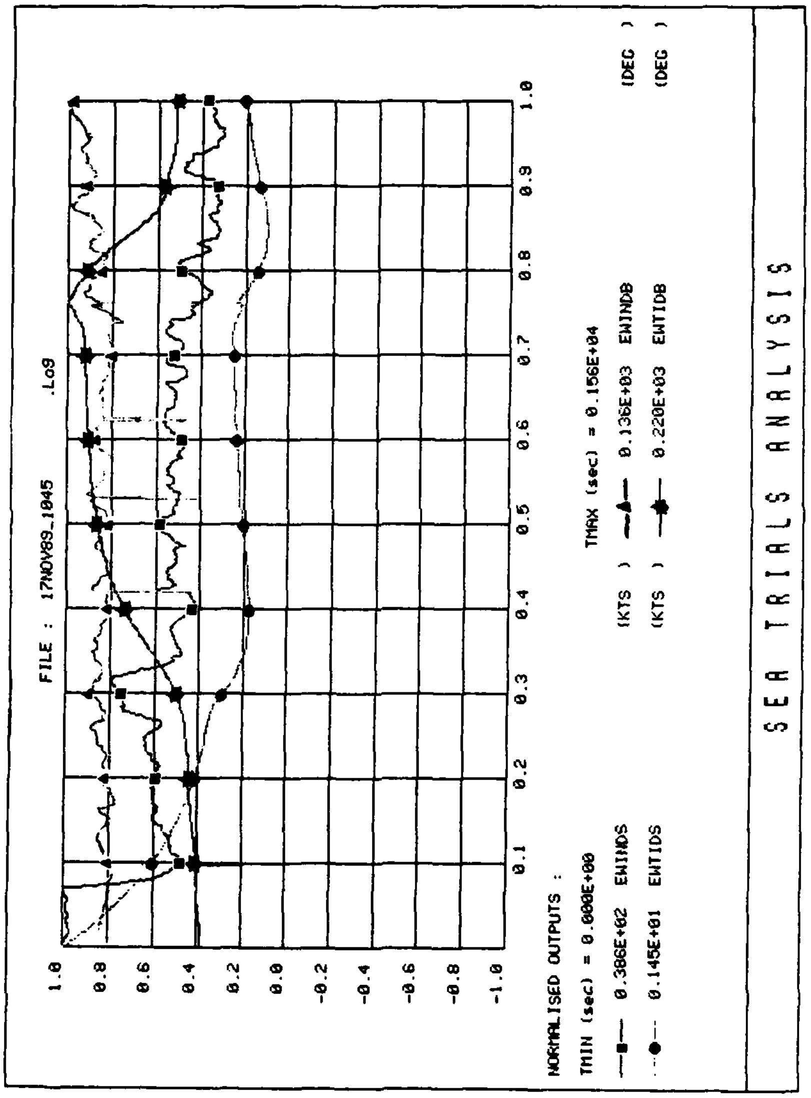
SEA TRIALS ANALYSIS

FIGURE 5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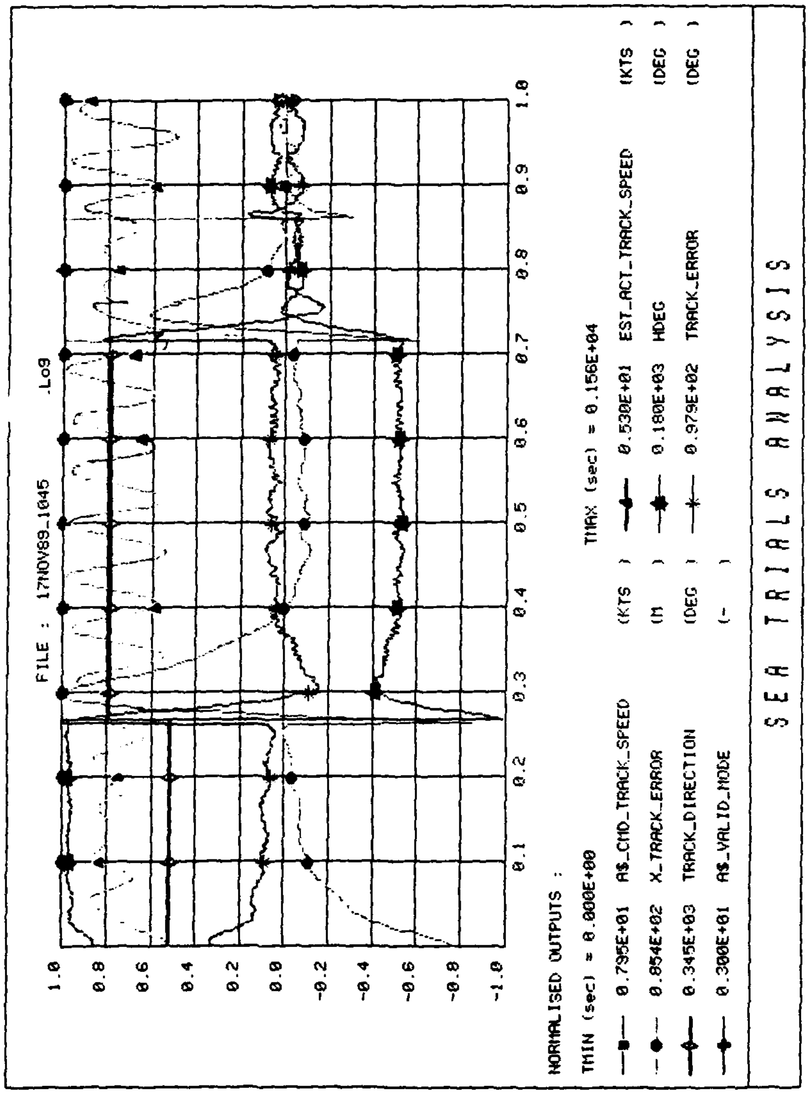
SEA TRIALS ANALYSIS

FIGURE 6



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0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
NORMALISED OUTPUTS :
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TMAX (sec) = 0.156E+04
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0.180E+03 HDEG (DEG)
0.979E+02 TRACK_ERROR (DEG)
SEA TRIALS ANALYSIS

FIGURE 7

THE DESIGN, DEVELOPMENT AND IMPLEMENTATION OF AN OPTIMAL GUIDANCE SYSTEM FOR SHIPS IN CONFINED WATERS

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1. ABSTRACT

This paper describes the design, development and implementation of a multivariable optimal control system for the guidance of vessels in confined waters. The work is part of an overall strategic programme to optimally guide a ship from port approaches at the start to port approaches at the completion of a voyage. During the pilotage phase, the cost function is weighted to minimise track, course and speed errors, whilst in the oceanic phase, it is weighted to minimise fuel and time.

A non-linear, discrete, time-varying ship mathematical model, validated with results from sea trials is embedded within an optimal filter which accepts raw data from the vessel's navigation instruments and passes best estimates to the optimal controller.

Results from simulation, model testing and full-scale sea trials are presented for manoeuvring modes, together with possible control strategies for open-seaway operation.

2. INTRODUCTION

Automatic guidance of ships has its origin near the beginning of this century, following the invention of the gyrocompass. Sperry (1) discussed the problems of automatic steering in 1922 and in the same year Minorsky (2) presented the basic theory for directional stability of automatically steered ships. Ten years later over four hundred of Sperry's autopilots had been installed on merchant ships throughout the world. Traditionally, ship autopilots are single-input, single-output systems designed to control the vessel's heading. Since proportional control tends to produce oscillatory response, and integral control is required to reduce errors due to environmental disturbances such as wind and waves, conventional autopilots use a proportional, integral and derivative (PID) control law as described by Bech (3). However, vessel response is sensitive to control parameter settings and more recent ship controllers are based upon the pioneer work of Honderd and Winkelman (4) in 1971 and Astrom and Wittenmark (5) in 1973, and employ adaptive algorithms to implement self-tuning autopilots.

The fundamental problem with existing ship autopilot control systems is that they are single dimensional, controlling one parameter only, whereas by its very nature a ship is a multidimensional system with many inputs, and many outputs that require to be controlled simultaneously.

By the use of multivariable system theory it is possible to describe the motion of a ship in several degrees of freedom. This enables the formulation of an optimal control policy that can view the global problem, and so minimise the errors in controlled variables according to some predefined order of priority. Expressed in another way, an optimal control system will seek to maximise the return from the system for a minimum cost.

Stochastic optimal control theory employs the separation principle to reduce a given optimisation problem into two subsequent problems whose solutions are known, namely an optimal filter in cascade with a deterministic controller. If a multivariable ship model has been identified, then the ship guidance problem can be expressed as shown in Figure 1.

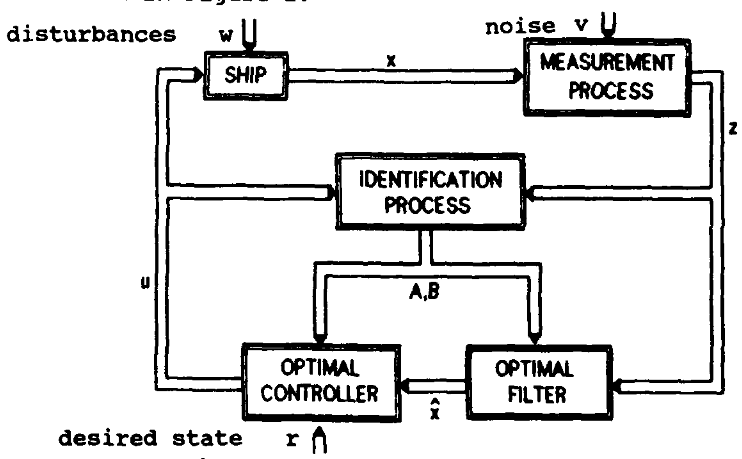

Figure 1. The Ship Guidance Problem

3. SHIP MATHEMATICAL MODEL

The Euler equations of motion in surge, sway and yaw are required for manoeuvring in confined waters (6), whereas the equations of pitch and heave are important in an open seaway (7). Since roll does not contribute significantly to added resistance, it has not been included. The equations for a five degree of freedom model are given below:

Surge Equation

$$m\dot{u} + mqw - mrv = X_{\dot{u}}\dot{u} + X_u(u+u_c) + X_{uu}u^2 + X_{uuu}u^3 + X_{vv}v^2$$

$$+ X_{rr}r^2 + X_{\delta\delta}\delta_A{}^2 + X_{\beta\beta}\beta^2 + X_{un}un_A + X_{nn}n_A{}^2 + X_{ua}u_a + X_{zz}z^2$$

$$+ X_{\theta\theta}\theta^2 \qquad (1)$$

Sway Equation

$$m\dot{v} + mur = Y_{\dot{v}}\dot{v} + Y_v(v+v_c) + Y_{\dot{r}}\dot{r} + Y_r r + Y_{nn}n^2{}_A + Y_{vvv}v^3$$

$$+ Y_{rvv}rv^2 + Y_{nn\delta}n^2{}_A\delta_A + Y_{nn\delta\delta\delta}n^2{}_A\,\delta^3{}_A + Y_{\delta vv}\delta_A v^2 + Y_{va}v_a \qquad (2)$$

Heave Equation

$$m(\dot{w}-qu) = Z_{\dot{w}}\dot{w} + Z_w w + Z_z z + Z_\theta\theta + Z_q q + Z_\beta\beta + Z_\zeta\zeta_a \qquad (3)$$

Yaw Equation

$$I_z\dot{r} = N_{\dot{v}}\dot{v} + N_v(v+v_c) + N_{\dot{r}}\dot{r} + N_{nn}n^2{}_A + N_{vvv}v^3 + N_r r$$

$$+ N_{rvv}rv^2 + N_{nn\delta}n^2{}_A\delta_A + N_{nn\delta\delta\delta}n^2{}_A\delta^3{}_A + N_{\delta vv}\delta_A v^2 + N_{va}v_a \qquad (4)$$

Pitch Equation

$$I_y\dot{q} = M_{\dot{q}}\dot{q} + M_q q + M_\theta\theta + M_z z + M_w w + M_\beta\beta + M_\zeta\zeta_a \qquad (5)$$

Steering Gear

$$\dot{\delta}_A = \frac{1}{T_R}\delta_D - \frac{1}{T_R}\delta_A \tag{6}$$

Main Engine

$$\dot{n}_A = \frac{1}{T_N}n_D - \frac{1}{T_N}n_A \tag{7}$$

The fin dynamics are not taken into account. Equations (1) to (7) can be arranged in the state matrix vector form:

$$\dot{\mathbf{x}}(t) = \mathbf{F}(t)\mathbf{x}(t) + \mathbf{G}_C(t)\mathbf{u}(t) + \mathbf{G}_D(t)\mathbf{w}(t) \tag{8}$$

where,

$$\mathbf{x}^T = (\delta_A\ n_A\ x\ u\ y\ v\ \psi\ r\ z\ w\ \theta\ q) \tag{9}$$

$$\mathbf{u}^T = (\delta_D\ n_D\ \beta) \tag{10}$$

$$\mathbf{w}^T = (u_c\ v_c\ u_a\ v_a\ \zeta_a) \tag{11}$$

The corresponding discrete solution is:

$$\mathbf{x}((K+1)T) = \mathbf{A}(T,KT)\mathbf{x}(KT) + \mathbf{B}(T,KT)\mathbf{u}(KT)$$

$$+ \mathbf{C}(T,KT)\mathbf{w}(KT) \tag{12}$$

4. CONTROL LAW

The quadratic performance criterion for an optimal tracking system is:

$$J = \int_{t_0}^{t_1} \{(\mathbf{x}-\mathbf{r})^T\ \mathbf{Q}\ (\mathbf{x}-\mathbf{r}) + \mathbf{u}^T\ \mathbf{R}\ \mathbf{u}\}\ dt \tag{13}$$

Q and **R** are diagonal matrices and the values of the individual elements reflect the importance of the parameters being controlled.

In a track-keeping situation for example, elements q_{55} and q_{66} (that relate to y and v) are required to be heavily weighted so that the majority of the control effort is expended in reducing cross-track error. When steaming in an open seaway however, elements q_{44}, q_{99} and $q_{11\ 11}$ (that relate to forward speed, heave and pitch) should be emphasised for fuel economy.

It can be shown (8) that constrained functional minimisation yields the matrix Riccati equations:

$$\dot{\mathbf{W}} = -\mathbf{W}\,\mathbf{F} - \mathbf{F}^T\mathbf{W} - \mathbf{Q} + \mathbf{W}\,\mathbf{G}\,\mathbf{R}^{-1}\,\mathbf{G}^T\,\mathbf{W} \qquad (14)$$

from which the optimal control law becomes:

$$u_{opt} = -\mathbf{R}^{-1}\,\mathbf{G}^T\,\mathbf{W}\,(\mathbf{x}-\mathbf{r}) \qquad (15)$$

or,

$$u_{opt} = \mathbf{S}(\mathbf{x}-\mathbf{r}) \qquad (16)$$

where the feedback matrix is

$$\mathbf{S} = -\mathbf{R}^{-1}\,\mathbf{G}^T\,\mathbf{W} \qquad (17)$$

5. COMPUTER SIMULATION

5.1 Simulation in Port Approaches

The study vessel used in the simulation was a 150 m long car ferry of displacement 14,400 tonnes. Linear and non-linear hydrodynamic coefficients were obtained from towing tank tests on a 3.4 m long model of the ferry, conducted at the National Physical Laboratories, Teddington, and values substituted into equations (1), (2) and (4).

Figure 2 shows a simulated approach of the ferry into the Port of Plymouth at a forward speed of 7.717 m/s (15 knots) with no wind or tidal disturbance effects. The

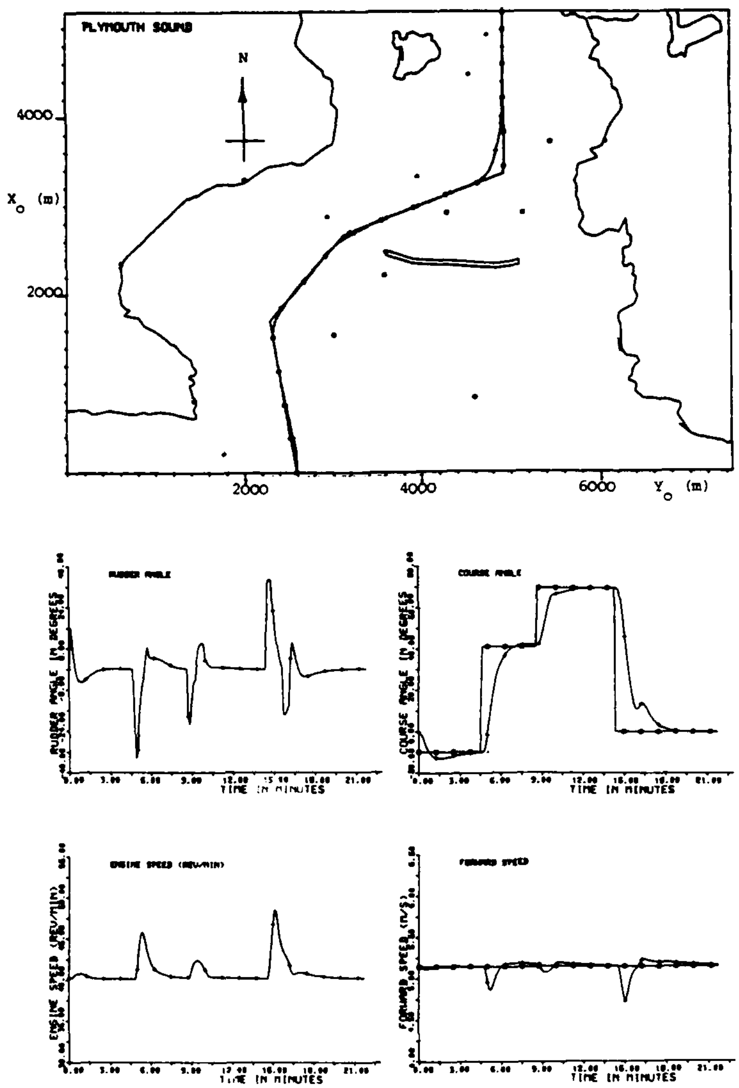

Figure 2. High Speed Simulated Passage into Port of Plymouth with no Disturbance Effects.

controller parameters are set to provide the following emphasis:

a) track control,

b) course control,

c) speed control.

As a result, at each way-point the vessel pulls quickly onto the new track, but in doing so incurs errors in both course and speed.

In Figure 3, the vessel approach speed is 5 knots 2.572 m/s (5 knots) and it is being subjected to a force 8 wind and 2 knot tidal stream both from a south-westerly direction. It can be seen here that the vessel is being dragged off track although maximum control effort is being applied. This indicates the limiting condition of safe operation of the control system.

5.2 Simulation in a Seaway

When a vessel is moving in a seaway its increased motion, particularly in pitch and heave, produces additional resistance and hence a loss in forward speed.

Figure 4 shows the response of the study vessel to a Pierson Moskowitz sea spectrum for a significant wave height of 4.573 m (15 feet). As a result of pitch and heave motion the forward speed of the vessel reduces from the initial 7.717 m/s calm water value to 5.8 m/s.

If bow and stern control fins are fitted to the vessel, it is possible to adjust the control action by computing a feedback matrix with reduced emphasis on track control, but increased weighting on pitch and heave. Figure 5 illustrates the effect of such control action for the same sea-state, where it can be seen that the pitch and heave are significantly reduced and here the final forward speed is 6.75 m/s. This represents a fuel saving of 24.7% based on power requirements.

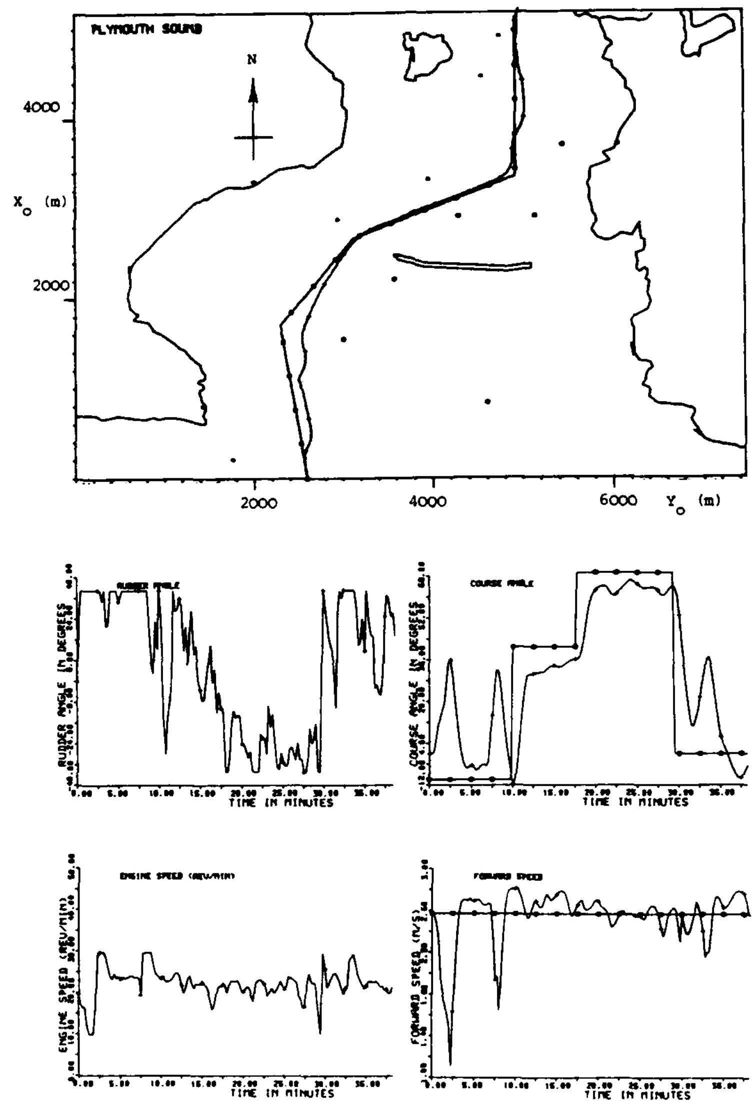

Figure 3. Low Speed Simulated Passage into Port of Plymouth in the Presence of Wind and Tide.

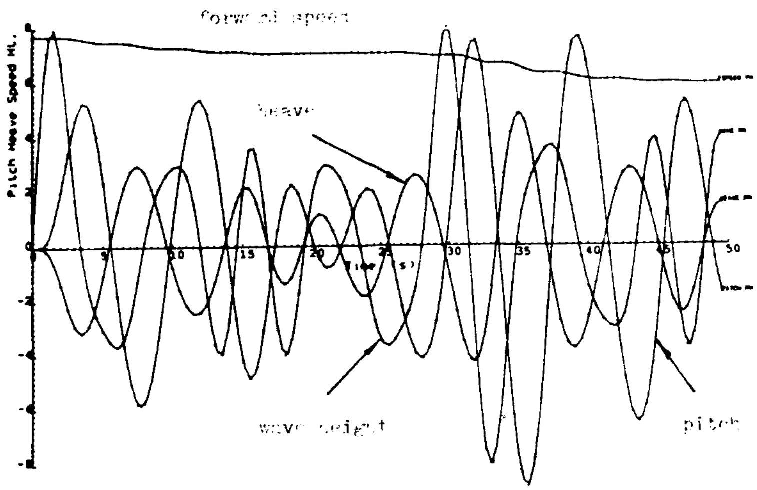

Figure 4. Study Vessel Simulated Response to Pierson Moskowitz Sea Spectrum.

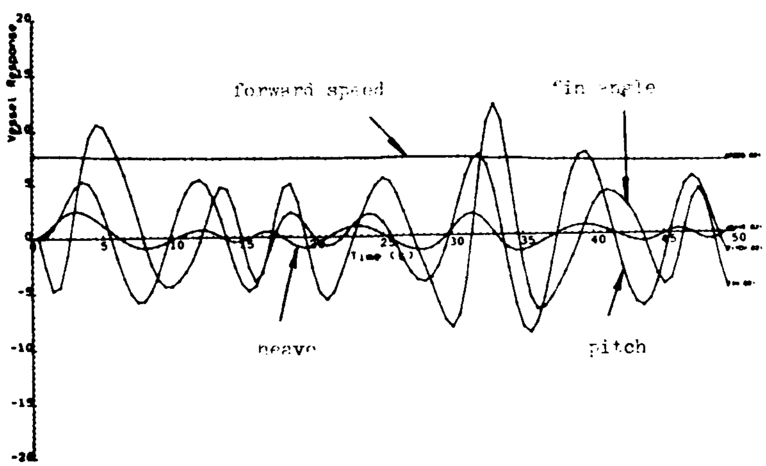

Figure 5. Simulated Effect of Pitch and Heave Control on Forward Speed.

6. MODEL TESTS

Prior to full-scale sea trials, the guidance system was tested on a free-sailing 3.4 m long car ferry model (the same vessel that was used to evaluate hydrodynamic coefficients).

The vessel was fitted with a computer which had the optimal control and filter software installed. An inertial navigation system consisting of 3 accelerometers, 3 rate-gyros and one heading gyro was employed to measure state variables. Main engines and rudder were driven by servo-systems that could be either under computer or radio control. Figure 6 shows a typical set of raw measurements taken from the instruments.

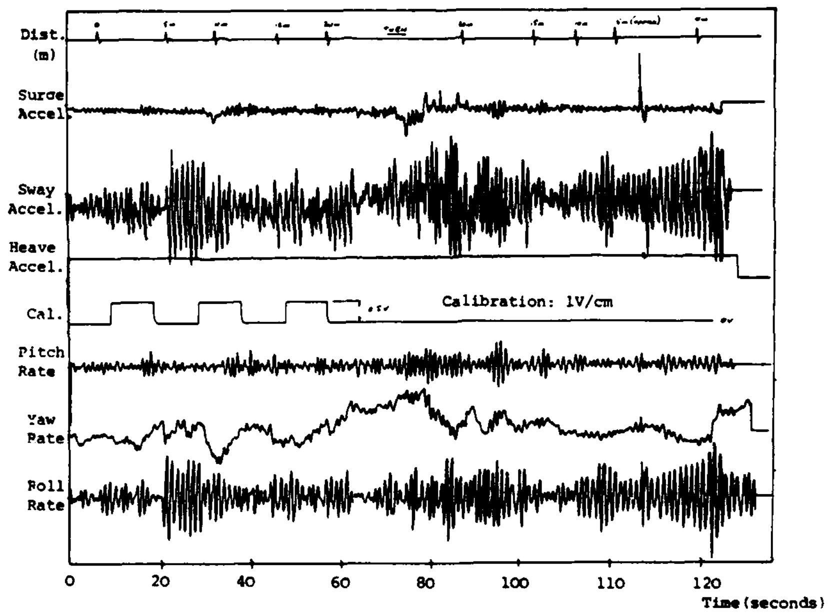

Figure 6. Raw Data taken from Inertial Instruments on Model Car Ferry.

In Figure 7 the model is placed initially 5 m off-track and is required (a) to lock onto the present track and (b) to lock onto a 90 degree track. Both filtered measurements and simulation results are displayed and it can be seen that the system anticipates the way-point to prevent transient overshoot. Figure 8 shows unfiltered, filtered and

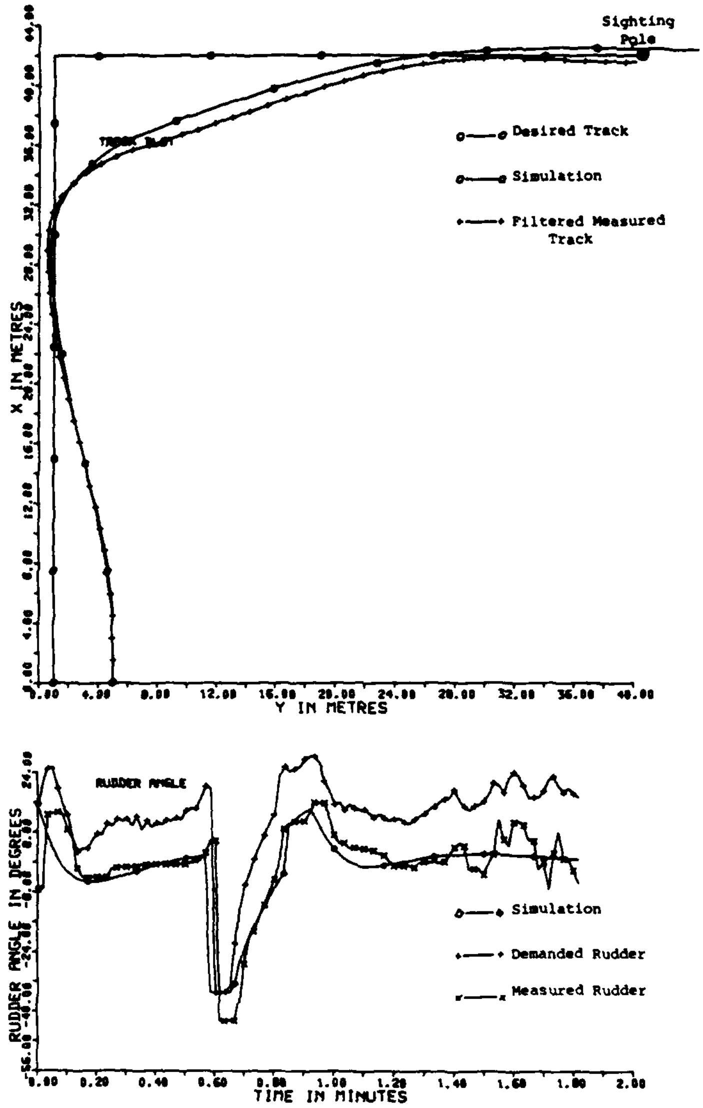

Figure 7. Simulated and Filtered Measured Track: Free-Sailing Tests on Model Car Ferry.

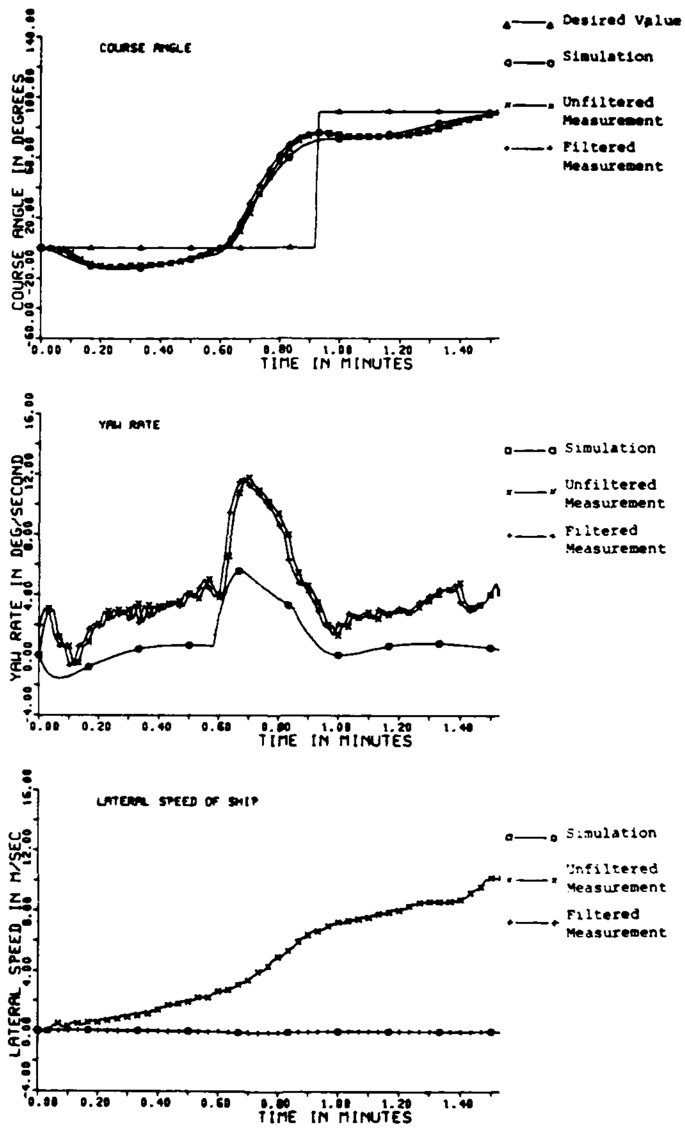

Figure 8. Simulated, Unfiltered and Filtered Measurements: Free-Sailing Tests of Model Car Ferry.

simulated measurements of course angle, yaw-rate and lateral speed. In the latter case, the integration drift of the unfiltered measurement can be seen.

7. SEA TRIALS

The guidance system was fitted on to an 11 m long twin-hulled vessel and tested in the approaches to the Port of Plymouth. The mathematical model of the vessel was obtained from a series of manoeuvring trials.

The navigation instruments consisted of Decca for position fixing, log and flux-gate compass. Overall positional accuracy was monitored by Trisponder, installed on the vessel for hydrographic surveying purposes. All measurement signals were sent to a dedicated microprocessor, which relayed the information to the main guidance computer. Measurements were taken every 1.5 seconds, during which period the optimal filter and control calculations took place, resulting in demanded rudder and engine speed data being conveyed to the electro-hydraulic steering gear and also to a linear positional servo attached to the engine control mechanism.

Figure 9 shows a section of the cross-track error as the ship is guided into Plymouth. Initially the vessel is 20 m off track, but quickly locks on, to lie generally within 5 m of the desired position.

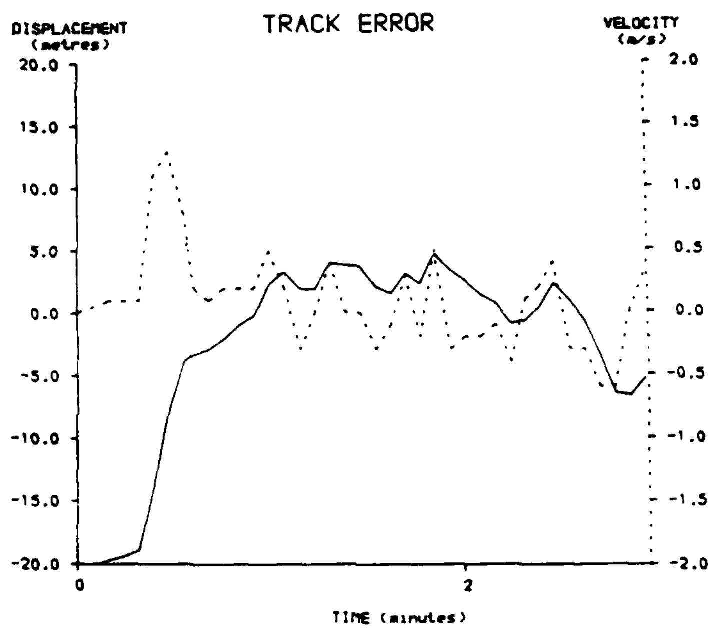

Figure 9. Cross-Track Error: Full-Scale Sea Trials.

8. CONCLUSIONS

In designing a ship guidance system, the overriding aim is to improve safety at sea. As increased reliance is placed upon automatic systems it is essential that they maintain high integrity at all times. It is also important to keep the ship's master informed as to what events are taking place so that he is always in a position to override the automatic system in the case of failure, or when he deems it necessary to do so.

The developments described in this paper form part of the overall general trend to increase automation at sea. There is a move to implement Vessel Traffic Systems in all major ports. Such systems will rely on advanced surveillance and communication techniques, which together with shipborne automatic guidance systems will increase efficiency of port operation and at the same time improve safety levels.

NOMENCLATURE

Matrices and Vectors

A	Discrete state transition matrix.
B	Discrete control matrix.
C	Discrete disturbance matrix.
F	Continuous time system matrix.
G_C, G_D	Continuous time forcing matrices.
Q	State error weighting matrix.
R	Control weighting matrix.
r	Desired state vector.
S	Feedback gain matrix.
u	Control vector.
u_{opt}	Optimal control vector.
v	Noise vector.
W	Riccati matrix.
w	Disturbance vector.
x	Ship related state vector.
x	Best estimate of ship related state vector.

Scalar Symbols

I_y	Ship moment of inertia about y axis
I_z	Ship moment of inertia about z axis.
K	Integer counter.
m	Ship mass.
n_A, n_D	Actual and demanded engine speeds.
q	Pitch-rate.
$q_{11} \cdots q_{12\ 12}$	Elements of state error weighting matrix.
r	Yaw rate.
r_{11}, r_{12}, r_{13}	Elements of control weighting matrix.
t	Continuous time.
T	Sampling time interval.
T_n, T_R	Time constants for main engines and rudder.
u, u_c, u_a	Forward velocity of ship, current and air.
v, v_c, v_a	Lateral velocity of ship, current and air.
x,y,z	Ship related cartesian coordinate system.
w	Z-direction velocity.
X,Y,Z,M,N	Hydrodynamic coefficients.
δ_A, δ_D	Actual and demanded rudder angles.
ζ_a	Significant wave height.
ψ	Heading of ship.
θ	Pitch angle.
β	Fin angle.

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