CONTROL OF WARSHIP MACHINERY

BY

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Introduction

After oars and sails, the next means of propulsion for warships was steam machinery, first in the form of reciprocating engines and later steam turbines. More recently we have seen gas turbines, diesel engines, and nuclear propulsion. In addition, the high cost of skilled manpower and of accommodation on board has prompted designers to strive towards a reduction in the size of the engineering complement of warships. These factors, taken together with the very rapid technological advances in the last few years, have resulted in significant changes in the methods of controlling warship machinery. One cannot hope to review all of these factors in an orderly fashion in a single paper and I hope that the various aspects on which I have elected to focus will be of interest and will provide at least a reasonably balanced picture, concentrating on the more recent past and present.

By virtue of their role, the machinery control requirements of warships differ from those of merchant ships. In warships the systems must allow for rapid load changes in the propulsion machinery, must be capable of operation after equipment malfunctions, and must allow continued operation following action damage. For example, TABLE I shows the several layers of control positions currently provided in a typical warship.

TABLE I—*Machinery Control Positions*

Position	*Extent of control*
Bridge	Control of propulsion power with limited surveillance
Ship control centre	The main control position with extensive surveillance
System control unit in machinery spaces	Centralized control of one shaft set with limited surveillance
Individual plant controls in machinery spaces	Local manual control of individual equipments with associated instrumentation

Machinery control systems tend to be 'tailor made' for a given warship design. They require to control complex plant while retaining flexibility to cope with changing operational scenarios. They are expected to have a life of twenty-five years or more, and this has a major impact on their maintenance philosophy. They must withstand shock, vibration, and relatively high temperatures. They must be highly reliable and to an extent 'sailor-proof'. All this costs a lot of money. Furthermore, numbers off are relatively small, and budgets for development of control systems are also quite small (by comparison, for example, with development of electronic systems for space application). The control manufacturer must, therefore, develop systems which he feels will be acceptable to the defence industry but whose research and development costs cost be amortized over more than one project. This means that there is usually going to be a technological push by industry in addition to any technical pull by the individual navy project. In these circumstances it comes almost as a surprise to realize that, on reflection, the rate of application of 'new technology' to warship machinery control has been quite good. Some may still crave for rod-gearing in place of existing analogue electronic systems and look in awe at the rush towards digital technology.

Early Development of Remote and Automatic Controls

The development of steam machinery proceeded on the basis of engine rooms and boiler rooms which were manned at all times, and in which the various necessary control functions were exercised locally by the engine room and boiler room staff applying directly whatever force and torque was required to move valves, etc. The quest for increased efficiency and higher power density of the machinery, supported by continual technical developments and discoveries, resulted in machinery of ever-increasing sophistication and less tolerance to various degrees of maloperation. These developments forced the invention and application of various automatic control systems and provided the starting point for the evolution of modern controls schemes as applied to warships. The control problem in these ships is made particularly difficult because of the need to be able to change power very rapidly, which in steam ships imposes corresponding changes on the required output from the boilers and on the boiler firing rate; this, for example, is quickly reflected in an initial high demand for feed water when power is reduced and the steam bubbles in the water tubes of the highly rated boiler collapse. Following on this immediate effect, a reduction in firing rate and a reducing feed flow in due course bring the boiler into equilibrium again at the lower power.

As might perhaps be expected, automatic control was applied first where the response times were short, and where very frequent adjustments were needed. The closed feed system of the steam plant was an early candidate, and was provided at its two extremities with automatic controllers: at one end to control the water level in the main condenser; at the other end the water level in the boiler. The boiler water level must be maintained high enough to ensure that tubes are not starved of water, but low enough to avoid risk of carry-over of water into the turbines.

In the steam plant, flows of feed water and of steam were large and at considerable pressures; there were valves to be controlled, dampers to be moved. Initially the quite considerable effort required was applied by the (human) operators directly to the valve handwheels, etc. When automatic control began to be applied, the first thought was to use for motive power the pressurized fluid that was being handled. Remote control normally relied on mechanical extension of the valve spindles and still used human effort at the remote handwheel. Later developments included the use of pneumatics and hydraulics to provide the necessary power to move the valves needed for plant control. By contrast, in the current naval machinery schemes using gas turbines and diesel engines, the prime movers do not employ a working fluid in a closed cycle and in general have no need for the application of considerable effort to large control valves.

Remote controls were originally developed to permit co-location of instrumentation and some controls on a manoeuvring platform in the engine room, to facilitate control of the increasingly complex machinery. Self-contained control rooms or manoeuvring rooms were fitted adjacent to the machinery spaces in a number of British aircraft carriers of pre World War II design.

However, these were in fact monitoring rooms (or surveillance rooms to use modern parlance), in which was displayed the main information from the various engine rooms and boiler rooms relating to main engines, boilers, turbo-generating sets, and main propulsion auxiliaries. Whatever control was exercised from these manoeuvring rooms was largely by telephone, by telegraph, or by broadcast instructions to the individual machinery spaces, rather than by any more direct means.

Various incidents have led to the gradual evolution of rules for the application of remote control, Consider for example the fire in the boiler room of H.M.S. *Renown*, which occurred in 1927, and was caused by a mistake during fuel transfer to double bottom tanks in one of the boiler rooms. In those days the filling arrangements were a standpipe with an open-ended funnel and a filling valve above. The stoker who was effecting the transfer kept sounding the wrong tank, so that the first indication of problems was when the standpipe completely filled and oil overflowed into the boiler room, some of it striking the hot boiler front and catching fire. Due to a somewhat complicated sequence of events, oil continued flowing in the boiler for quite a while, feeding the fire and with the fans supplying air to the closed stokehold providing the necessary oxygen. After analysis of these events, it was decided in future to specify remote controls situated outside the machinery spaces, to act on master shut-off valves for fans and fuel pumps. A point to note is that, while the sounding of tanks by the use of a dip-stick is unlikely to give a wrong indication due to any failure of instrumentation, it provides precious little protection against human error! I shall discuss later the importance of presenting information to the operator in a manner which will minimize the chances of error.

It is interesting to remember that, between the first and second World Wars, naval engineers were brought up to believe that steam machinery had to be treated very tenderly. It was commonly accepted that it took a whole hour to work up from cruising to full power, and indeed another hour to work down again. Of course the necessities of war disabused everyone in this respect, and in 1950–53 the Admiralty carried out a series of engine and propeller trials in the destroyer H.M.S. *Savage*. These established the feasibility of changes in steam propulsion power from zero to full power in very short times, about 10 to 15 seconds, and provided valuable measurements of the transient overloads of torque and thrust which occurred.

A significant event which affected the requirements for automatic and remote controls was the advent of nuclear warfare. To give the ship the best chance to survive, it was proposed to close all vents from the atmosphere to the machinery spaces when danger threatened, to provide enough cooling to prevent damage to machinery, and to arrange for the engineering complement to retreat to an air-conditioned 'machinery control room' from which surveillance and control of the machinery could be exercised, and which would act as NBCD (nuclear, bacteriological and chemical defence) headquarters. Quite apart from the nuclear aspect, World War II experience in the tropics showed the desirability of an air-conditioned control room where personnel could exercise cool judgement, and not be overcome by heat exhaustion.

Thus an operational need for remote control of machinery was established and a development programme was initiated in Britain for its introduction into the fleet. For boiler control, effort initially centred around remote control of forced draught blower speed, fuel supply pressure, and boiler damper positions; in short transferring to the machinery control room the manual functions previously carried out in the boiler room. However, ongoing development work suggested that this 'half-way house' was unlikely to be satisfactory and the emphasis changed to the development of automatic boiler control rather than remote control. The first fully automatic boilers used at sea by the Royal Navy were in H.M.S. *Tiger*. The developments following from the initial trials in H.M.S. *Tiger* produced an extremely flexible boiler plant with the possibility to increase the boiler output from low to full load in a few seconds without hazard to the boiler and with the boiler room unattended. A major milestone was the design of an automatic fuel spill control system which has come to be known as the TBS system.[3] The fuel supply to the boiler is delivered from a steam turbo-driven fuel oil service pump and is controlled such that the required quantity of fuel is sprayed into the boiler and the remainder of the pump output is passed, or spilled, back to the system upstream of the service pump. Before the development of the TBS system three methods of spill control were common:

(*a*) constant speed pumps.
(*b*) constant supply pressure.
(*c*) constant differential of supply-spill.

For warships application of the latter two were impractical. Constant differential could not give the required turn down within an acceptable pressure range, and constant supply pressure meant huge pumps. Constant speed had also proved unsatisfactory in H.M.S. *Tiger* and so the new system was developed.

The system was designed to link supply pressure and spill pressure with a known linear relationship and is shown diagrammatically in FIG. 1. The control mechanisms were fuel pump throttle valve position and spill valve position. Two independent pressure control loops were used for this purpose. The demands to the control loops could either be manual input or be automatic to produce the desired supply-spill pressure relationship. The system as shown in FIG. 1 extended to the boiler air supply and therefore covered the entire combustion control.

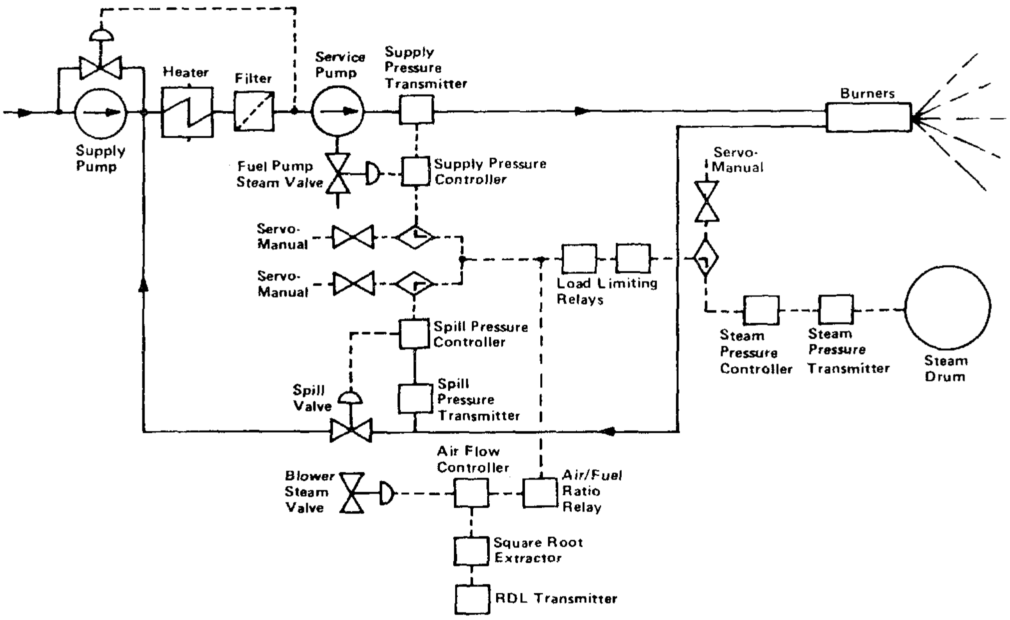

FIG. 1—TBS SYSTEM FOR BOILER AUTOMATIC FUEL CONTROL

Pneumatics were used as the sensing, control and actuating media for the TBS system. The overall ship pneumatic system also included fuel temperature control, boiler water level control, surveillance information to be fed back to the machinery control room, and of course remote operation of the main turbine throttle valves and boiler dampers. The key to success for the overall system was, however, the development of the fuel supply and spill pressure control arrangements.

The DEVONSHIRE Class guided missile destroyers and the ASHANTI Class frigates of the 1960s had fully automatic boiler control, and were fitted with centralized control from machinery control rooms as shown in FIG. 2.

It is now usually accepted that the schemes of control and surveillance must be considered in the early design stages of the equipments, subsystems, and whole ship machinery schemes. Later, it is sometimes possible to compensate for machinery design deficiencies or restrictions by modifying the control system design; however, even if effective, such a procedure imposes an applied control on a machinery system which, by appropriate design, could have managed well without this complication. Sometimes, of course, no amount of applied control can help. A friend of mine tells this story from his wartime service in H.M.S. *Implacable*: 'The ship was cruelly short of feed water, principally because the make-up feed requirements of the system were incompatible with the capacity of the fresh water distilling plant, and water rationing imposed on the ship's complement could not do enough to ease the problem. The situation was exacerbated by an increased wartime complement, operation in the tropics, and reduced opportunities for maintenance'. The story relates that on one occasion the ship might not have been able to reduce power without risk of damage because to do so would trigger off a demand for extra feed water (to make up for the loss of ebullition in the boilers) which the system just could not meet, and the spectre of the unfortunate ship being condemned to steam at high powers for ever may give rise to some amusement. Redesign of boilers, tightening up of steam system design, bigger or more available distillers—yes, any one of these might have solved the problem, but although the primary reason was unacceptable reduction in water level in the boiler, no amount of imposed control would have been of any help.

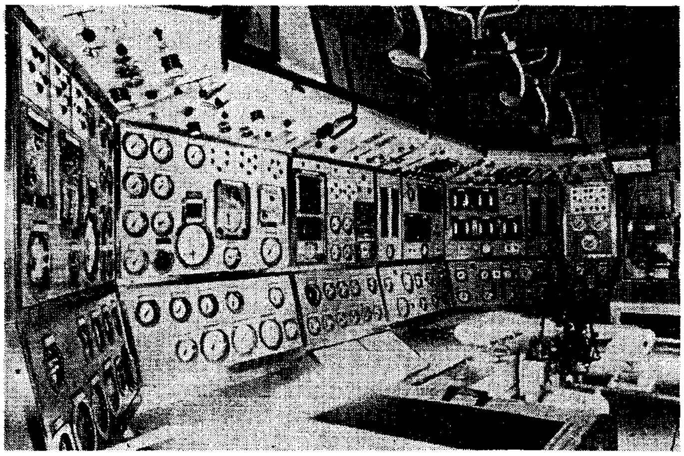

FIG. 2—GUIDED MISSILE DESTROYER MACHINERY CONTROL ROOM

Lest we get too blasé about modern advances in automation and reductions in manning, it is sobering to recall the achievement by the Royal Navy in the 1930s, yes, fifty years ago. The Navy wanted to arrange for some gunnery practice, and the solution was to delegate two battleships to act as targets. One of these was H.M.S. *Centurion* as shown in FIG. 3. It would have been perhaps a little dangerous to have the targets manned in the normal way, and so they were arranged to be capable of steaming without any people on board.

The remote control system was operated by a dialling system rather similar to an old fashioned Post Office dialling system. Up to one hundred instructions could be radioed to the ship which transmitted back that the instructions had been received—a digital control system! The commands which could be given to the unmanned ships included:

(*a*) Ahead manoeuvring valve position operated by a geared electric motor, to open or close a given fraction of a turn at a time.

(*b*) Fuel bypass to suction increased or decreased in given pressure increments.

(*c*) Steering gear instructed to steer a given course in 10° steps.

The ship could transmit information such as shaft speed and boiler steam pressure back to its escorting destroyer. For more information, refer to Commander Goodwin's article.[8]

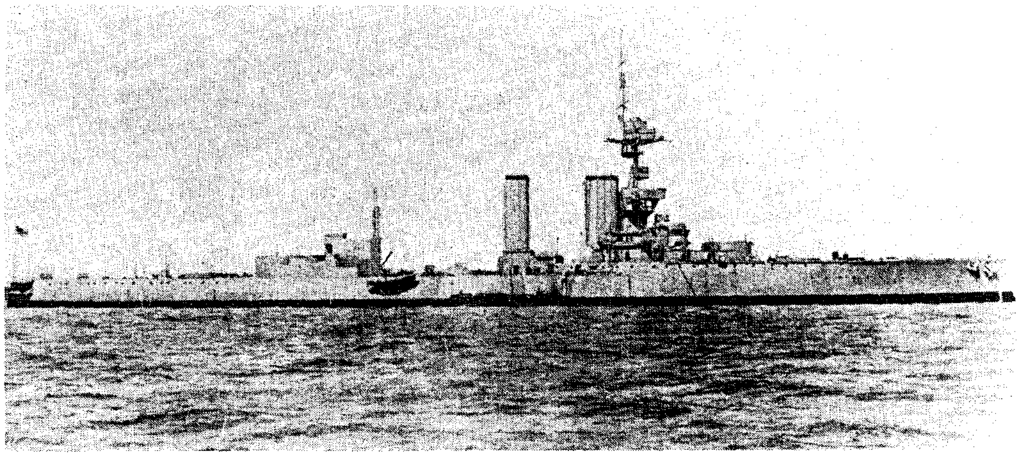

FIG. 3—H.M.S. 'CENTURION' ABOUT 1930

Existing Schemes with Internal Combustion Engines, Controllable Pitch Propellers and Electronic Controls

A major milestone to influence machinery control systems was the introduction of aero-derivative gas turbines into the fleet for main propulsion. Instead of developing a new engine for each new class of ship, as was the case with steam plant, gas turbines and diesel engines are developed as 'standard' machines, to be used singly or in various combinations and quite often without any special development for each class of ship. In consequence the engines are supplied with a reasonable amount of their own integral control which must be matched to the overall ship control scheme. Furthermore, because these engines tend to be uni-directional, there is a need to control combinations of clutches and couplings within reversing gearboxes; or to control the pitch in controllable pitch propellers to obtain acceptable manoeuvring performance; or to fit some form of electric transmission.

In addition to these aspects the change to gas turbine propulsion in U.K. warships coincided with a period of rapid development in control system design.

The first application of aero-derivative engines for major warship main propulsion was the conversion in 1966 of H.M.S. *Exmouth*.[6] The machinery fit consisted of one Olympus gas turbine in a new forward engine room and two Proteus gas turbines in the after engine room. The engines drove into a single gearbox which in turn powered a KaMeWa controllable pitch propellor supplied by Stone Manganese Marine. An air-conditioned combined switchboard and machinery control room was built into the starboard side of the ship. A pneumatic control system with comprehensive instrumentation was supplied by Bailey Meters. The control system allowed remote start/stop of the engines, and controlled engine power and propeller pitch from a single lever. Pneumatic controls had been selected for H.M.S. *Exmouth* because at the time that was the only type of system available for immediate warship application. Pneumatic control is particularly suitable to control systems with large numbers of control devices requiring significant power actuation, since standby power for such systems is comparatively easily made available using high-pressure air reservoirs. For gas turbine application no major power actuators were necessary other than for propeller pitch movement and SSS (synchro self-shifting) clutch sleeve movement. Both of these, it so happens, were undertaken by hydraulics.

In 1967 the Ministry of Defence commissioned a study to examine and compare in detail various possible control system designs that could be applied to main propulsion machinery of an all gas turbine warship. The study was to include pneumatic, fluidic, and electronic systems, and several firms were approached. The main aim was to provide a basis on which to select the control technology and surveillance philosophy that could be applied to the Type 42 destroyers which were on the drawing board at that time. The conclusion of the study was that electronics could and should be used in the Type 42 destroyers, the change from existing pneumatic controls being made on the grounds of cost, maintainability, reliability, space saving, compatibility with surveillance systems, flexibility of control units, reduction in spares, and accuracy of control functions.

Hawker Siddeley Dynamics Engineering (HSDE) were subsequently awarded a contract for the supply of the Type 42 control system. And so the first Royal Navy ships to use solid state analogue electronic control of the propulsion machinery were the Type 42 destroyers and Type 21 frigates. The machinery fit for these ships was the twin-screw COGOG arrangement with one Rolls-Royce Olympus and one Tyne gas turbine per shaft driving a controllable pitch propeller, of Stone Manganese Marine manufacture, through a double reduction gearbox.

At this point it may be useful to define some of the gas turbine power plant schemes:

COGOG:	COmbined Gas Or Gas, with one high power and one lower power gas turbine geared to each shaft. The two engines never drive together; always one or the other.
COGAG:	COmbined Gas And Gas, with two gas turbines geared to each shaft. The engines may be used either singly or both together.
CODOG and CODAG:	As above, but with the lower power engine being diesel.

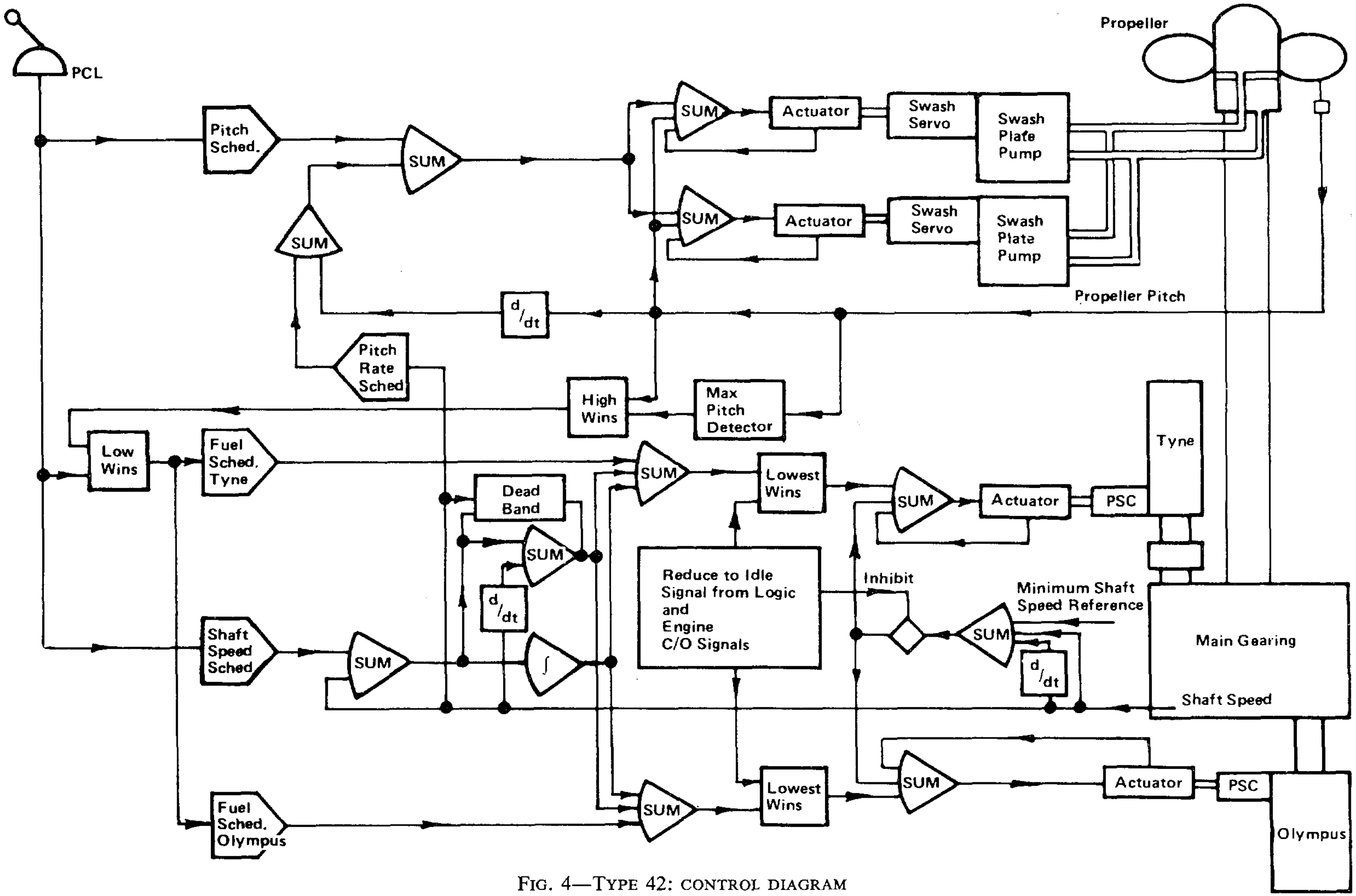

FIG. 4—TYPE 42: CONTROL DIAGRAM

The original Type 42 control system is shown in simplified block diagram form in FIG. 4. A single control lever (PCL) controls both engine power and propeller pitch. The throttle and pitch demands are derived from function generators (schedules) to program pitch and throttle demands from a single demand. Corrections are applied to these programmed demands by the shaft speed controller which has proportional, derivative, and integral terms. The authority of the shaft speed controller is limited to 40 per cent. throttle correction for the proportional and derivative terms and to 10 per cent. correction for the integral term.

The proportional and derivative terms have a deadband of 10 per cent. of instantaneous shaft speed to prevent oscillation of the throttles due to wave motion. The integral term operates on a long time constant without deadband, providing an automatic trim facility to allow for changes in engine power due to ambient temperature and fouling effects.

During violent manoeuvres the propellers generate high reverse thrusts when the pitch approaches zero at high ship speeds. In these ships, to reduce the reverse thrust peak during a high-power stop, the pitch rate was reduced to a level which was considered unacceptable for low-power manoeuvring; consequently a variable pitch rate system, controlled as a function of shaft speed, was used. In current Type 42 ships the actual method of achieving this differs slightly from FIG. 4. An additional 'low shaft speed controller' having proportional plus derivative terms adds to the throttle demand when the shaft speed falls below the self-sustaining speed for various gear-driven auxiliaries. The control hardware supplied by HSDE included several modules each containing analogue control circuits; a typical example is shown in FIG. 5.

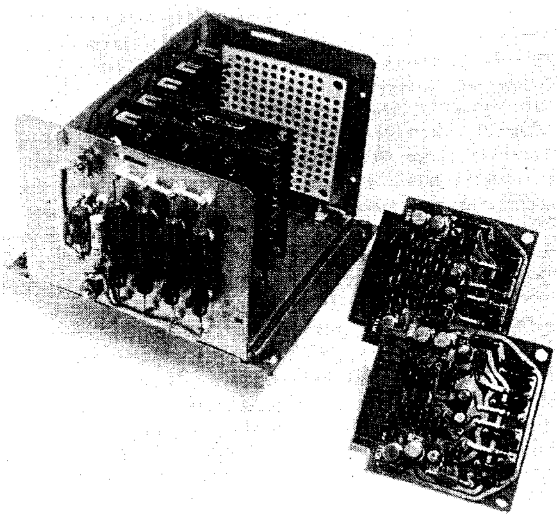

FIG. 5—HSDE ANALOGUE CONTROL MODULE

Many lessons were learned when the above ships went to sea. The engines behaved a little differently from what had been expected from test bed runs, with the result that the throttle rates were reduced to prevent gas generator stall.

It is evident that the automatic control system described above is relatively complex and it includes relatively high gain closed loop controls. During manoeuvring, a closed loop on shaft speed determines the instantaneous power demand. The reduction in gas turbine throttle rates has meant that the closed loop controls have less effect than was the design intent and in more recent designs it has been possible to demonstrate that a simpler 'open loop' system can work just as well. The open loop system does not have the proportional and derivative terms and simply sets a demand power according to PCL position—subject to one or two limits. Several ships are now at sea and operating effectively with such open loop systems. Ship performance is not impaired in comparison with closed loop designs and the system is simpler and hence should be more reliable and easier to maintain.

The development of the propulsion control system for H.M.S *Invincible* is worthy of a mention. This ship has a twin-screw COGAG machinery arrangement with two Olympus gas turbines per shaft driving a fixed pitch propeller through reverse reduction gears, the reversing mechanism being large fluid couplings. There is no need for any additional control functions simply because it is COGAG. We had thought of a load sharing control—such as one would find in a diesel engine CODAD arrangement—but this proved to be unnecessary for several reasons. In particular the gas turbines are not under the control of a high gain speed governor of the type associated with diesel engines and so their power output is not nearly so sensitive to tolerance differences; further, the gas generators are connected aerodynamically rather than by the mechanical connection of diesel plant and therefore they can develop their demanded power virtually irrespective of power turbine speed; and the torque imbalances in the input pinions result in torque loadings no higher than would be the case in single engine per shaft operation.

However, the control of drive mode changeovers and the manoeuvring control in fluid coupling drive was quite complex. For this ship a comprehensive simulation study was undertaken to develop the control algorithms and an unusual shore test facility with 'power injection' was developed, both of which will be referred to later.

The introduction of CODOG schemes gave rise to interesting control requirements in the diesel engine drive mode. The controllable pitch propeller in CODOG plant must obviously be sized to absorb the power of the gas turbine. When in diesel engine drive, small changes in propeller pitch result in high load changes to the lower powered diesel engine. The governors for these engines have quite high gains with droop settings of 3 or 4 per cent at full speed. This causes large fuel rack movements as the diesel speed reduces due to these load changes. These engines are usually turbo-charged and their rate of loading must be carefully controlled to prevent turbocharger surge. Thus there is a requirement for a carefully tuned diesel load control system. FIG. 6 shows a comparison of relevant parameters during a ship acceleration manoeuvre: the dotted lines relate to an early load control scheme with propeller pitch controlled as a function of engine speed error; the full lines show behaviour with a more recent control scheme with propeller pitch

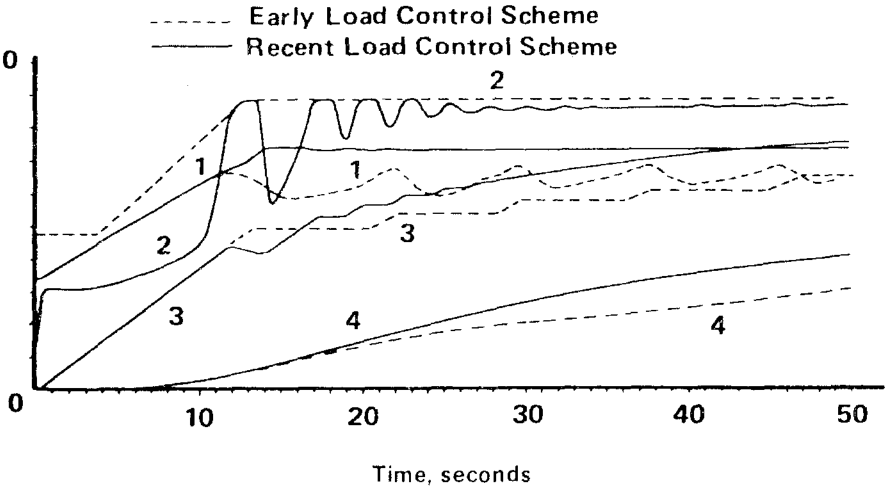

FIG. 6—SHIP ACCELERATION

1: engine speed
2: fuel rack
3: propeller pitch
4: ship speed

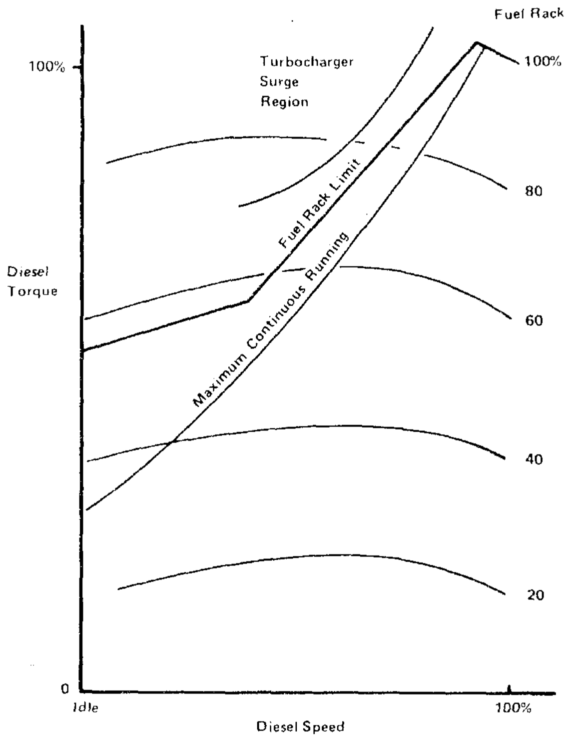

FIG. 7—DIESEL ENGINE PERFORMANCE MAP

controlled as a function of both engine speed and fuel rack position. The more effective load control system requires continuous measurement of diesel engine fuel rack position and this required a reliable fuel rack position sensor to be developed by the engine manufacturers.

The diesel engine load control mentioned above calls for further explanation. Consider the diesel engine performance map shown in FIG. 7. It is usual for a mechanical limit to be included within the governor to prevent the fuel rack from supplying enough fuel to give rise to turbocharger surge. The fuel rack limit in fact restricts maximum available torque at medium- to high-speed to only a little more than the torque required for maximum continuous operation.

The high gain of the governor means that relatively small changes in diesel engine speed result in large fuel rack movements. To obtain the best transient performance it is necessary to have a load control system which will prevent the fuel rack impinging upon the fuel rack limit. A typical scheme which will allow this to be effected is to make propeller pitch rate (i.e. diesel engine loading rate) a function of the difference between the instantaneous rack position and the maximum continuous running line—or some other load limiting line agreed with the engine builder. The resultant load control scheme would be typically as FIG. 8. It can be seen from this

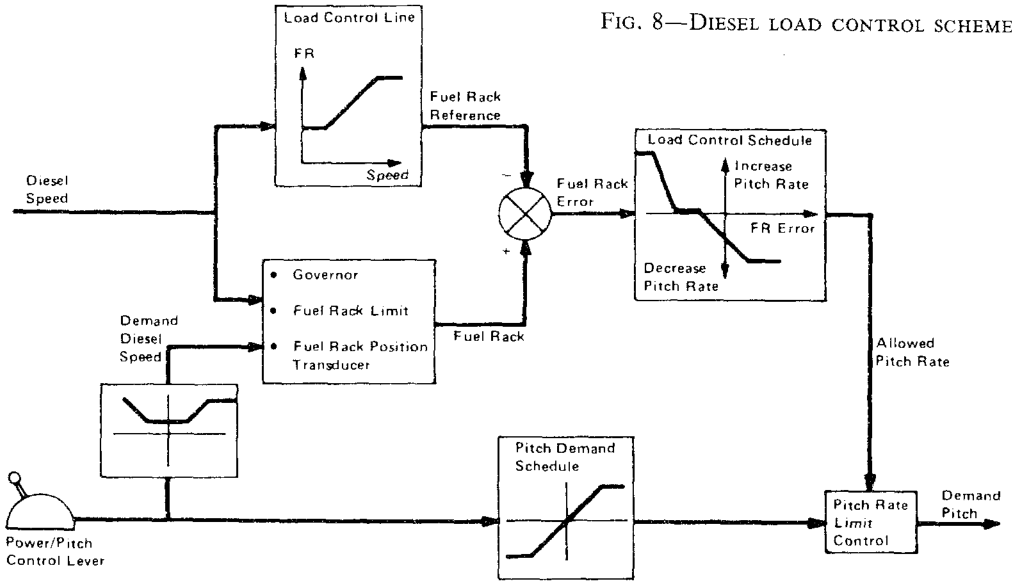

FIG. 8—DIESEL LOAD CONTROL SCHEME

figure that the pitch rate is controlled by a load control scheme as a function of a fuel rack margin signal. The fuel rack margin signal is derived by comparing a reference value with actual rack position. The reference value is itself derived from a load control line as a function of engine speed. This load control line can be the engine manufacturer's maximum continuous rating curve but it is usually tuned for a given ship application.

The analogue control hardware has been updated from the earlier module-based systems and an example of a more up-to-date design is the D1000 system supplied by HSDE to the Royal Danish Navy for the CODOG machinery for the NIELS JUEL Class corvette. A printed circuit card from this system is shown in FIG. 9.

A machinery scheme now receiving interest for warships around 2000 tonnes displacement is CODAG where the combination of diesel and gas turbine power is used for full ship speed. This arrangement usually requires a two-speed gearbox for diesel drive to ensure that this engine can operate at its rated speed both at ship cruising conditions and also at ship's full power. In consequence there is a need for additional control functions to operate the clutches. Such schemes have been examined for several applications: the conclusion is that, while the control is a little more complex than for the more conventional CODOG systems, it will be possible to design a satisfactory system to achieve acceptable ship and machinery performance.

At the time of writing, the design of a new Royal Navy warship (the Type 23) is well under way. This frigate is scheduled to be the first ship of the Royal Navy to have a digital electronic control of the propulsion machinery, the nominated main machinery controls contractor being Vosper Thornycroft Controls, who are supplying their D86 system, some cards from which are illustrated in FIG. 10.

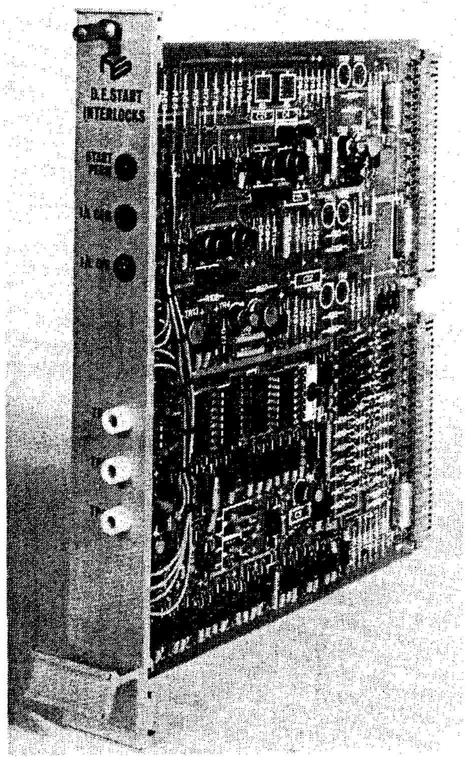

FIG. 9—HSDE PRINTED CIRCUIT CARD FOR CODOG CORVETTE

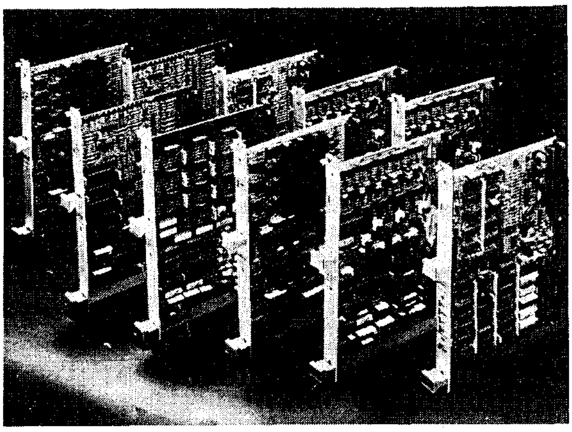

FIG. 10—VOSPER THORNYCROFT (U.K.) D86 SYSTEM CARDS

In the mid 1970s the Ministry of Defence initiated a comprehensive machinery control and surveillance research programme to gain an appreciation of the impact of automation on the whole ship. The aim of the programme was to determine the optimum balance between man and hardware and then to define the hardware necessary to match the balance. The research programme also identified that software costs would rise substantially by comparison with hardware costs and that the software which embraces the function of control and surveillance should have a life requirement related to the machinery as distinct from the electronics which host it. A need was, therefore, identified for longlife software designs capable of support throughout the life of individual ship classes.

Arising from this work a 'demonstrator project' was ordered and resulted in the build of a distributed digital system for propulsion control, to be tested and evaluated at the Royal Navy research establishment at West Drayton, which is now an outpost of the Royal Aircraft Establishment. This system was organized so as to allow the control functions to be distributed whenever possible, thus preventing all the eggs being in one basket and hence minimizing the effects of action damage and increasing the capability of the local control stations. The demonstrator was based upon a 'reference' ship since no new ship design was on the table at that time. The reference ship was a frigate having twin-screw COGAG machinery utilizing the Rolls-Royce Spey gas turbines and driving controllable pitch propellers. The electronics were required to be 'nuclear hard', and at the time the only microprocessor which met these requirements was the Ferranti F100L. The system is shown diagrammatically in FIG. 11.

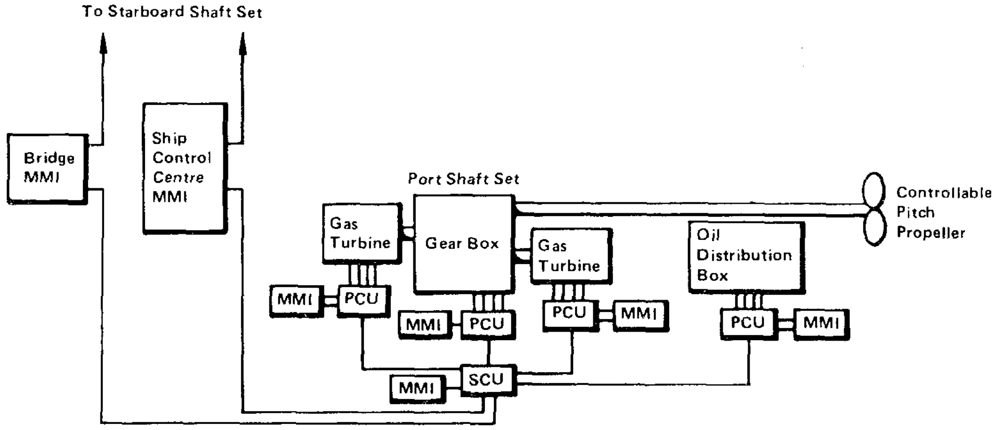

FIG. 11—COGAG DEMONSTRATOR SYSTEM

SCU: system control unit
PCU: plant control unit
MMI: man/machine interface

The plant control units (PCU) communicate to a central system control unit (SCU) along duplicated serial digital links (in this case the links were the 3 Mb/s Ferranti S^3 system). Facility was provided for the SCU to communicate with the ship control centre (SCC), the bridge and, in bigger ships, a control panel in the machinery spaces adjacent to the SCU. The system has just completed evaluation at West Drayton, and many lessons have been learned for future ship application.

Design Tools

Mathematical Modelling

The control system designer has, in addition to the application of control theory, several other tools at his disposal.

A major item in his armoury is mathematical modelling of the ship and propulsion machinery to provide a simulation of the transient performance of both. This has become a near-essential requirement if one is to achieve an optimum design with minimum setting-to-work problems and all of the ships, post-1970, mentioned in this paper have had their control systems designed using such facilities. The mathematical modelling, or simulation, is used to assess the transient speeds and loadings during normal operation. It is also capable of predicting the effects of system failures which would be too hazardous to prove on test beds or at sea.

If the simulation is implemented to run in real time, additional benefits accrue. It is then possible to connect the actual control hardware to the simulation computer and to test the control system through its full operating range prior to installation in the ship. This has been done on several occasions and has become normal for all new designs to be implemented in Royal Navy ships.

For the *Invincible* design a comprehensive shore test facility was built at Rolls-Royce's works at Ansty to conduct trials on one shaft set of machinery. It is always a nice point of judgement to decide whether the cost of such test facilities would be justified for each ship class. When not provided, the real-time simulation for control system evaluation becomes even more important. In the shore tests of the *Invincible* machinery, one aim was to evaluate the performance of the large fluid couplings during manoeuvring. This was a practicable aim because in this case two Olympus engines drive into a single gearbox, and so it was possible in effect to allot one of these engines to act as an injector of the transient torques which at sea arise from the propeller during ahead/astern manoeuvres. To this end a 'power injection' control was developed and implemented on a PDP8 digital computer[5].

This control was effectively an on-line real-time simulation which controlled the combination of one Olympus gas turbine and the water brake to produce the same load torque transients as would be experienced on board the ship during acceleration and crash stop manoeuvres. Thus on the test bed at Ansty, one engine was operated under normal ship control, and was loaded by the other engine and dynamometer which were under computer control. The control algorithms incorporated into the PDP8 were themselves designed by using a mathematical model of the shore test facility and, when implanted in the PDP8, were then debugged by connecting it to the real-time simulation on a hybrid computer.

Mock-ups

The use of control and surveillance system mock-ups plays a vital part in control and surveillance system design. Mock-ups can be either passive or active. Passive mock-ups, for example as shown in FIG. 12, are used by system designers as part of the operational assessment of the design and by the shipbuilder prior to build, to examine access, cable runs, pipe runs, etc. Active mock-ups are, effectively, embryo simulators and can be used with good effect to test a control room design under simulated intense operational conditions. This is done for control rooms for the propulsion plant for nuclear powered submarines.

Hazard Studies

It would be most imprudent to design any control system without taking account of the effect of system failures. This is particularly so in the case of

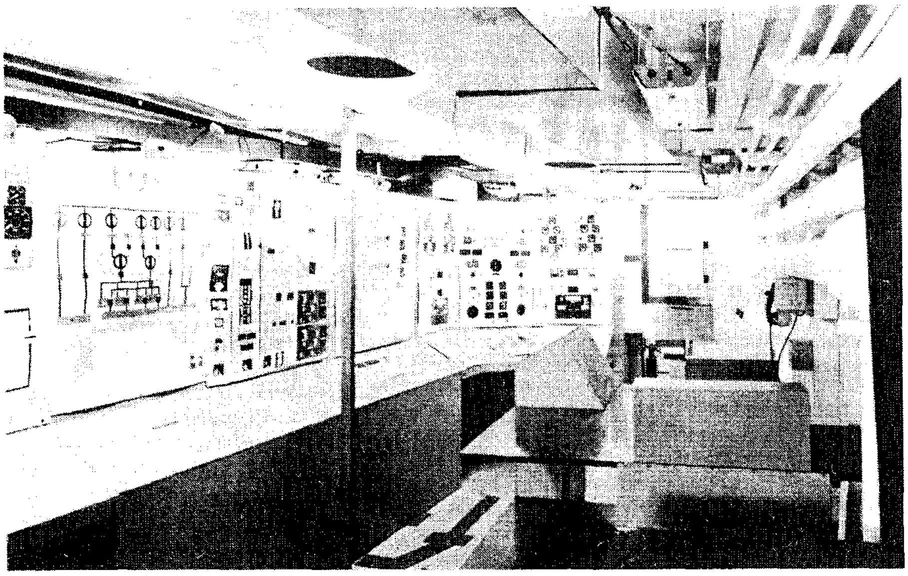

FIG. 12—TYPE 22 SHIP CONTROL CENTRE MOCK-UP

a warship, where the aim must be to minimize the effect of system failures. For most warship controls, applications of failure mode and effect analysis (FMEA) and fault tree analysis (FTA) studies are undertaken. FMEAs are used to judge the effect of system failures and FTAs are used by the reliability assurance engineer to check that the overall system design can meet the reliability and availability targets set by the Naval Staff.

An example of the combination of FMEAs with simulation is that undertaken for the Type 22 frigate where all the significant failure modes, identified from the FMEA, were simulated on a hybrid computer to quantify their effect. A sample trace from this simulation work (FIG. 13) illustrates the reverse rotation of the starboard shaft which occurs as the result of starboard engine trip five seconds after the start of a crash stop manoeuvre.

Submarine Controls

The control techniques used for the propulsion machinery in nuclear and conventional submarines do not differ greatly from those employed in surface vessels. However, the requirements for performance and reliability are significantly more stringent. In common with the shark, a submerged submarine needs propulsion power to stay alive and effective. Nuclear safety, of course, adds its own strict standards and immediately a conflict of interest becomes apparent: nuclear safety aims to shut down the power source, while submarine safety aims to maintain the power source.

Space and manpower are even more strictly rationed in submarines and the grace time in which one must react to an incident is generally shorter than in surface ships. The need is clearly identified for a comprehensive centralized control and surveillance scheme with the thorough application of operational experience, human factors, and ergonomics.

Nuclear incidents require careful and considered action by the operating staff and the first step towards this is the presentation of the state of the plant in clear unambiguous terms. Had the operators at the Three Mile Island been properly informed as to what was happening in the plant, the end results would have been very different.

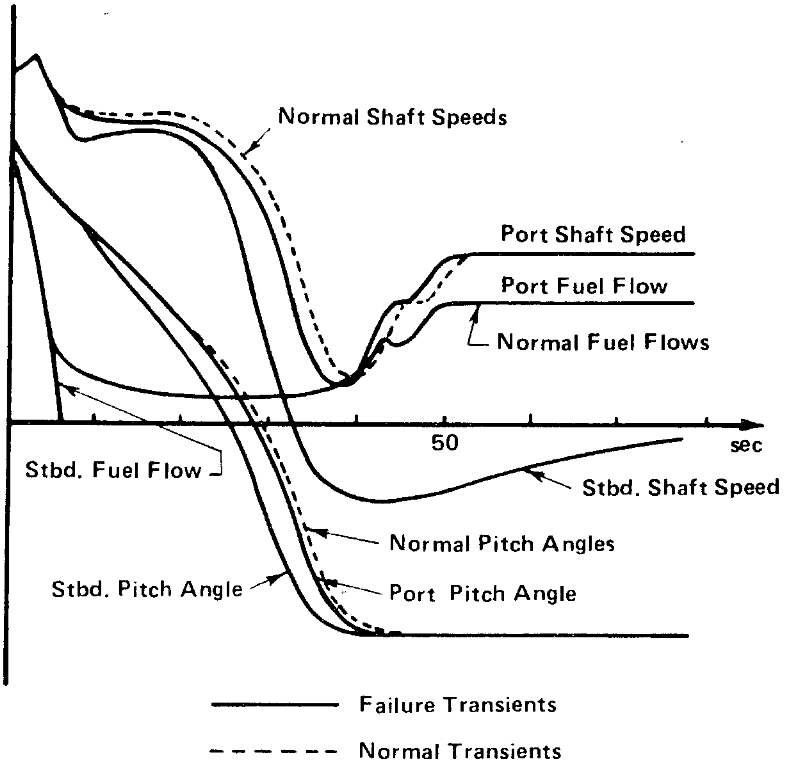

FIG. 13—TYPE 22: ENGINE TRIP DURING CRASH STOP, SHOWING STARBOARD ENGINE TRIP 5 SECONDS AFTER START OF MANOEUVRE. EFFECT ON SHAFT SPEED, FUEL FLOW, AND PITCH ANGLE TRANSIENTS

Surveillance Systems

In the early days of machinery control and surveillance system design, and indeed until sometime in the 1960s, it was relatively easy to separate control systems from surveillance systems. Control could be manual, pneumatic or analogue electronic while surveillance was likely to be analogue or digital electronic. Today with digital control the systems tend to be integrated much more.

The transmission of data to the ship control room was identified as a major item in the definition of surveillance requirements for warships. In the 1967 study of control systems for the new all gas turbine ships being designed, a parallel alarm system was compared with a scanning system—the parallel system being individual wiring of all channels to the control room—and it was concluded that the commercial Decca ISIS scanning system most closely matched the Royal Navy's requirements for surface ships and submarines. A naval version of this system was subsequently fitted to Royal Navy ships including the Type 22 frigates and the INVINCIBLE Class.

The configuration of the ISIS system is shown in FIG. 14. The system can scan at 400 channels/second and each channel receives information from standard types of transducer which are wired to local scanners located within the machinery space, each scanner accepting up to forty channels. The signals are amplified within the scanner units and are transmitted sequentially to the central processor. Each processor can be connected to six local scanners. The control panel for the system is mounted within the machinery room control console and has the capability to present the channel value, high and low alarm limits and test values. A logging facility is fitted to provide alarm history recording and logging.

In the Type 42, 21, and 22 classes of Royal Navy frigates and destroyers another useful surveillance facility was included which has proved to be of value to the maintainer. The system, supplied as an integral part of the control console, is known as the dynamic data recording (DDR) system and has all major control parameters connected to a patch panel which then allows these to be patched in groups to an ultra-violet (UV) recorder. In the Type 22 frigates this was extended by interfacing it to a continuous loop tape recorder with multiplexing to allow recording of up to ninety channels. The system is akin to the aircraft 'black box' and is good value in identifying the cause of system failures particularly associated with control logic or to help sort out those chicken and egg situations which can occur with highly interactive systems.

More recently a development programme was initiated by MOD to examine the potential of distributed digital technology to provide additional surveillance facilities to the operator. The resulting system is known as PASS (propulsion and auxiliaries secondary surveillance system). This also was set up for evaluation at the MOD research establishment at West Drayton. An

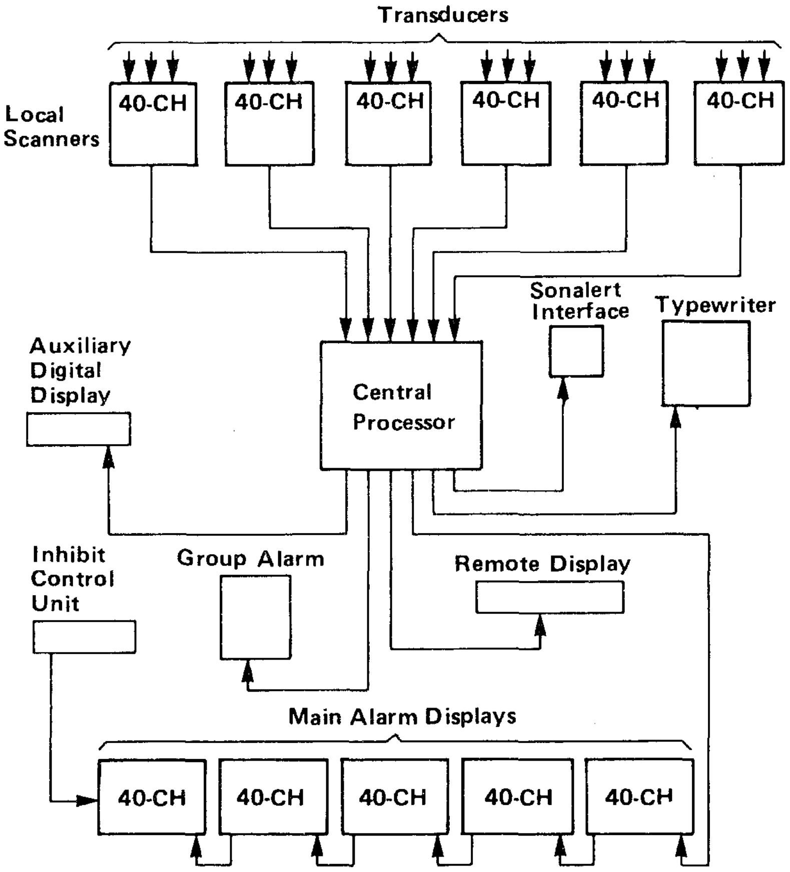

FIG. 14—DECCA ISIS
CH: channel

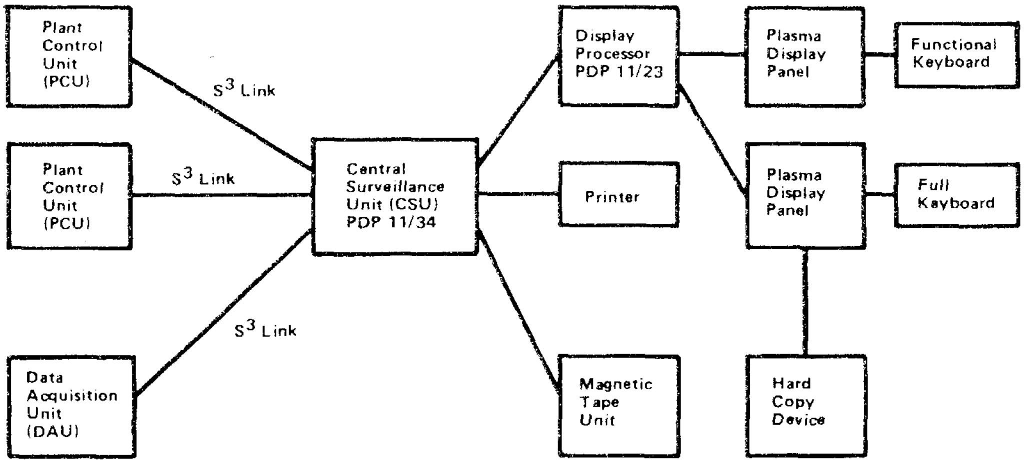

FIG. 15—PROPULSION AND AUXILIARIES SECONDARY SURVEILLANCE SYSTEM (PASS)

outline of the system, which was built using commercially available hardware, is shown in FIG. 15. The system collects data from data acquisition units for auxiliary ship systems and also interfaces with the plant control units of the 'demonstrator' described above to obtain propulsion data. The key features of the prototype system are:

(*a*) Parameter pages displaying information on each plant system via visual display units (VDUs) e.g. pressures, temperatures, etc.

(*b*) History pages on the VDU giving individual parameter information over a specified period.

(*c*) Logging facility, operating both automatically and on demand, outputting via the printer, the VDU, or the portable data storage.

(*d*) Maintainer assist pages providing any calculated data, including running hours, number of starts, trend graphs, and performance calculations displayed on a VDU.

Lord Kelvin once wrote:

> I often say that when you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you are scarcely in your thoughts advanced to the state of science, whatever the matter may be.

Well, perhaps we can satisfy Lord Kelvin that we are now in a position to measure many things. His statements would, though, seem to be particularly appropriate to the current state of condition monitoring on board ships. The data that the surveillance systems collect are used by the operator to protect the machinery and by the maintainer to try to identify faults before serious failure occurs. However, we still appear to be a long way from having fully acceptable prognostic algorithms for inclusion in condition monitoring systems and this is an area which should see substantial growth in the next few years.

An operator's capacity to analyse a mass of information is limited, and indeed when swamped with information he may be unable to react logically. With recent trends to reduce manning it is, therefore, especially important to present information to the operator in an easily assimilable manner. FIG. 16 illustrates the trend in reducing engineering complement on board, in Royal Navy frigates and destroyers, since the turn of the century. It is unlikely that this trend will continue because one must provide the necessary manpower for damage control parties and ship husbandry work. Nevertheless manning has been substantially reduced.

The developments in man/machine interface design have been quite striking. From the early manoeuvring platforms, we now see quite sophisticated systems with application of intelligent displays integrated into the console in virtually all current naval ship deisgns. For surface ship application the current thinking is towards the 'integrated ship control centre' which integrates the control and surveillance of ship's machinery with damage control. As may be imagined, the progress of this work has been given a new impetus as a result of feedback from the recent operations in the South Atlantic.

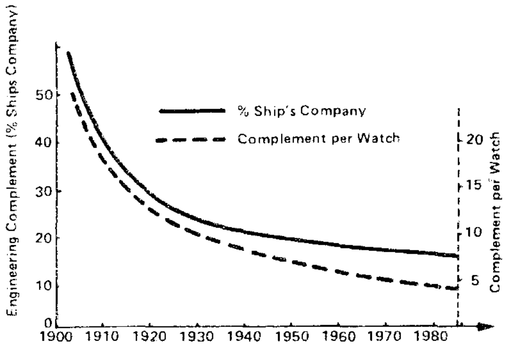

FIG. 16—MARINE ENGINEERING COMPLEMENT IN FRIGATES AND DESTROYERS

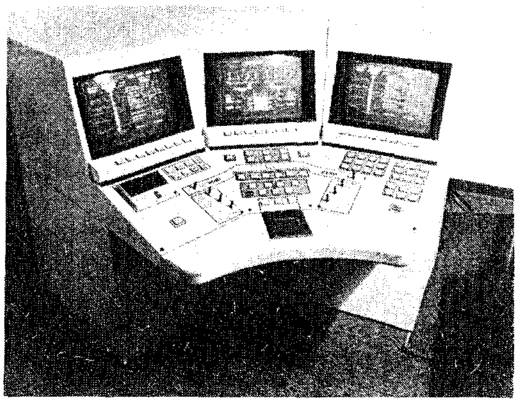

FIG. 17—SHIPBOARD INTEGRATED MACHINERY CONTROL SYSTEM (SHINMACS) CONSOLE

It is thought that the trend to increase the use of VDU presentation and to reduce the amount of conventional panel type displays will continue as the reliability of digital systems increases. In the merchant ship area one can see this in the projected designs for the so-called 'VDU bridge' concepts which begin to look like sophisticated aircraft cockpits. An example of such developments in the naval scene is the machinery control console design proposed by the Canadian Department of defence[9] for SHINMACS (shipboard integrated machinery control system), shown in FIG. 17.

Canada and the U.S.A.

In Canada a development programme has been underway to develop a system known as SHINPADS (shipboard integration processing and display system) which is a shipwide data communication system for combat ships[4]. For machinery control the SHINMACS[1] system now under development utilizes some of the SHINPADS hardware. The system places strong emphasis on the man/machine interface requirement and is based on the concept that the modularity, flexibility and standardization within SHINMACS will cater for changing operational and manning requirements.

In the U.S.A. in the past, research and development for control and surveillance systems has tended to be done during shipbuilding programmes, thus imposing associated time constraints. However, a shipboard data multiplex system (SDMS) has been developed, which is a general purpose information transfer system for internal data communication requirements. It is intended for use in warships in the 1980–90 period. The system is shown diagrammatically in FIG. 18. The system is intended to replace the miles of unique signalling cabling installed in each ship, in order to reduce weight and cable costs. Current developments with this system appear to be aimed at utilizing fibre optics for the data bus rather than wires, and many Western navies including the U.S. Navy are actively investigating the practicability of this.

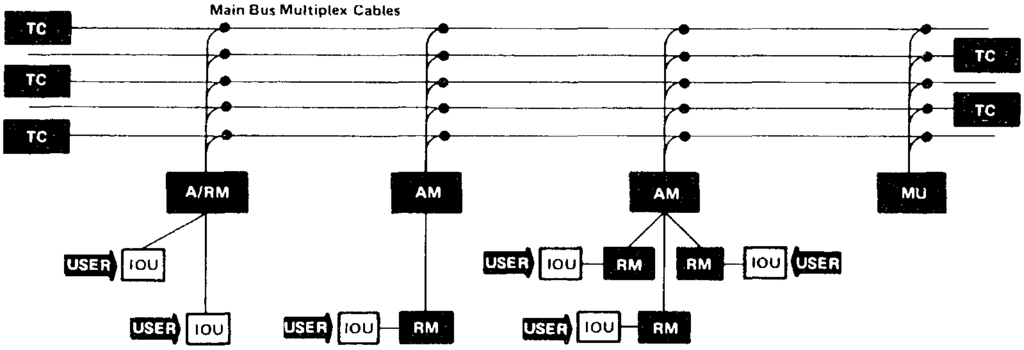

FIG. 18—SHIPBOARD DATA MULTIPLEX SYSTEM (SDMS)

TC: traffic controllers
AM: area multiplexers
RM: remote multiplexers
A/RM: area/remote multiplexers
IOU: input/output units
MU: maintenance unit

Training

Because the conditions in various navies are different, it is to be expected that the approach to training of the control system operators and maintainers will not always be the same. The variables include the availability of suitable manpower, the career structure, the degree of integration of the various disciplines, and the nature of the training establishments.

In the Royal Navy a most helpful development was the decision some time ago that the marine egineering branch will be responsible both for mechanical and electrical systems aboard ship. The imminent arrival of digital technology into the machinery control system has already caused the Royal Navy to consider these aspects as a basic part of the naval marine engineering training, rather than a special 'add-on' course to be taken as and when required.

Another example is offered from Canada[17], where there is a significant shortage of skilled manpower. Here the Canadian Forces are moving towards the establishment of a new controls and instrumentation trade. The training is intended to be structured around the recent marine engineering technician training programme which incorporates civilian community colleges and instructors. The curriculum stresses control systems technologies, including digital techniques, microprocessors, signal conditioning, etc. The course is approximately three years long and I am advised that to date the graduates have exceeded all expectations.

There is some movement worldwide towards integrating the trades which look after control systems for machinery and for weapon systems. However, with the large amount of built-in test equipment, and the reliance on a lot of 'repair by replacement', perhaps the case for this is not as strong as may appear at first sight.

In the naval context, operator training now almost always includes the use of computer-based training simulators. Using these simulators the operator can get first-hand experience of the time response of the system and build up a good understanding of the interaction of the various plant items. An important aspect is the need to carry out certain tasks within prescribed times, highlighting the need for teamwork and good communication between all members of the driving team in the ship control centre.

Simulator training is being taken a stage further in some current naval designs with consideration being given to 'on-board' training simulators. There is no doubt that the technology is available for such simulators, the idea being that under cruise or harbour conditions the machinery console in the ship control centre communicates with a simulation computer rather than with the actual machinery. This is made possible by the nature of distributed digital control and surveillance systems with each data collection unit or control console communicating on data links. Thus the console would be connected to the data bus as would the simulation computer. Software switching could then be used to transfer from real control to training mode. If the ship is cruising, the machinery would be taken into local control or perhaps into bridge control.

On-board training has certain potential advantages:

(*a*) The operators can be trained in breakdown situations, thus maintaining their operational/diagnostic skills at a higher level than would be the case with more infrequent access to shore-based trainers.

(*b*) Seldom are two ship control consoles or ship systems identical, even within a class, and the operator is being trained on the actual console which he will be required to operate.

However, further work needs to be done before such a scheme is developed to the state where it may be built into a warship control system, with adequate assurance of operational practicability and safety.

Observations and a Look into the Future

Development and application of machinery control and surveillance over the last twenty years has matched and complemented the development of the machinery schemes. One would pick out four important but largely unconnected influences:

(*a*) The requirement for ability to control machinery from a central air-conditioned location.

(*b*) The change in surface ship propulsion from steam to internal combustion engine.

(*c*) Increasing costs, leading to a strong desire for reduction in crew numbers.

(*d*) Development in solid state electronics and computer technology.

In the early days, the first flush of enthusiasm resulted in a tendency to over-design or unnecessarily complicate control and surveillance systems, partly as an over-reaction to the desire to reduce manning, partly arising from the fear of the unknown, and partly perhaps just because the technology was there. It would appear that the enthusiastic development of automatic control systems has not been matched to the same extent by the development of transducers and in many cases these have proved to be the weak link in terms of accuracy, reliability, etc. However, it is fair to say that a more deliberate and systematic approach to advancing technology is now in evidence.

There would now appear to be a concensus among Western navies that manning reduction in the marine engineering departments of surface warships has gone as far as is practical, particularly when bearing in mind the constant need for routine maintenance, and the occasional need for damage control and emergency repair.

It is important that the control and surveillance system as a whole, and each part of it, should be shown to justify its inclusion. Furthermore, it is imperative that these systems should achieve adequate reliability and that recovery from any malfunctioning, if it does occur, should be operationally acceptable. It is certainly to be hoped that there will be no repeat of those instances in certain navies (though I hasten to add not the Royal Navy), where the increase in manpower to maintain complex control systems with poor reliability has outweighed the manning reductions originally used to justify their fitting!

The fear of the unknown is well exemplified by the precautions taken in the Yarrow frigate *Rahmat* which has a combining gearbox driving two controllable pitch propellers from a single engine. The fear was that during a tight turn at full power, the shaft on the inside of the turn would suffer severe over-torque; the precaution was to arrange for an automatic reduction in the gas turbine power if a helm angle greater than some predetermined value was requested. In the event, trials proved that this refinement was unnecessary. Nowadays, if enough basic information is available, the need or otherwise for some such safety feature can be investigated well in advance by the use of mathematical modelling.

These computer simulation techniques are very suitable for the evaluation of alternatives for optimum machinery control and ship's performance. Simulations of various options for control can prove to be invaluable during sea trials for final tuning of the system. Conversely, the results from sea trials provide the essential validation of the models and add confidence in their application on future occasions.

The increasing use of software-based systems relies on the ability to maintain the software. Rapid developments in technology are causing hardware costs to fall. The same is not true of software costs: these, particularly because of the small production runs of naval ships, may well become the dominant factor. Therefore it may be worthwhile designing the software to live through one or more changes in hardware in the life of the class of ships to which it is applied. Hence its structure, design, test procedures, etc. must be rigorous and fully documented to ensure that it can be maintained for up to forty years. (Ships with the Y.100 machinery first went to sea in the 1950s, and will certainly continue in use for another ten years and perhaps longer).

The dividing lines that used to exist in some navies between the shipwrights and the electrical and mechanical disciplines have been gradually disappearing, and there is an easily discernible trend towards a common approach by everyone concerned with machinery aboard ship, whether it be for propulsion, hotel services, surveillance, gunnery, missiles, or whatever. The responsibilities on board may be divided between the functions of float, move and fight, but the technology to support these functions shows an increasing kinship in the way that the systems will be maintained.

Although maintainer training for the developing control system technologies has been recognized as an important issue by the various navies, it is important that the system is designed to ease the maintenance task on board. In some navies the marine engineers responsible for digital controls may well receive similar instruction to that previously associated with weaponeers while other navies may decide to create a new trade altogether. It is hoped that the new systems being conceived now will have adequate built-in-test and imbedded training facilities to keep the fault diagnosis task within manageable proportions.

The benefits and the feasibility of providing on-board training facilities may well see such arrangements fitted on board during the next decade. The enhanced operator familiarity that these systems will offer should further improve maintenance capabilities.

Engineers are not noted for accurate predictions of the future, but I feel it necessary to put forward a few thoughts. In recent years there has been a major shift from 'hard wired' to software-based control systems and there is every indication that these new systems will be successful. If this is so, then it seems certain that their further development will be rapid and will greatly benefit from the current explosion of interest in information technology and from the effects of the associated funding. In the U.K. the recently set up Alvey Directorate is scheduled to progress four main technologies, and three of these (software engineering, intelligent knowledge based systems (IKBS) and man/machine interface) must be directly relevant to naval machinery control and surveillance.

Particularly advances can be expected, I believe, in the area of fault diagnosis and option selection, which will rest on the work currently in progress on expert systems and IKBS. Naval ships must be capable of withstanding maloperation, malfunction, breakdown, and action damage. The permutations of these have been so formidable that in the past full reliance has always been placed on the 'man' to assess the situation, use his experience, and take appropriate actions. In future, I believe, very much more advantage will be taken of the developing technology of expert systems and IKBS to help in these cirumstances.

Presentation of decision-making and control functions to the (human) operator in a control room has seen gradual steamlining over the years, but there is much scope for further development in the man/machine interface which would lead to safer and more error-free operation. There is also much scope for cross-fertilization with work in the weapon and action information organization areas. The technology is available and advancing rapidly. The challenge is to select the useful from the possible, and to identify the best way to profit from the developments.

Acknowledgements

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