THE IMPACT OF AUTOMATION UPON WARSHIP DESIGN

THE 'TOTAL SYSTEM' CONCEPT

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Summary

The purpose of this article is to discuss the possible effects of future trends in control and surveillance technology upon warship design. During the past ten years the commercial marine has seen a substantial increase in the level of automation of ship control and allied functions, and the reasons for this are examined in the warship context with particular reference to the important factor of crew size. Although the article is written primarily from the point of view of machinery control and surveillance, it nevertheless identifies the need for the whole ship to be considered as a 'total system' as a conceptual approach to the problem of control and surveillance design. The article concludes that the development of warship design now stands at a critically

important crossroads, and that it is necessary to make a fundamental re-appraisal of the role of the warship and the part to be played by the crew in order to determine which technological path to follow. Either way, decisions taken during the next few years could have a far-reaching effect, not only upon warship design but also upon the very nature of naval service.

It is emphasized that this article represents the personal views of the authors, and does not necessarily reflect either the opinion or the policy of the Ministry of Defence (United Kingdom) or the Ship Department.

Introduction

During the past decade, the automation of ship control and machinery surveillance functions has become a generally accepted practice in the commercial marine industry, and has been recognized by both ship owners and classification societies as being the cost-effective way to operate merchant shipping. The influences which have brought about this change have been economic: as the costs of sea-borne man-power have risen and as difficulties of recruitment have increased, methods have been devised of achieving compensating reductions in crew numbers. Not surprisingly, therefore, the introduction of automation in the commercial marine field has concentrated initially in providing remote control and surveillance of ship's machinery at the one position which, under present maritime law, always has to be manned —the Bridge. Thus Bridge Control was an essential feature of the technology which made the Unattended Machinery Space (UMS) concept feasible, and this has resulted not only in a significant reduction in crew size but also in the release of men, who would otherwise be watchkeeping, to the more 'productive' tasks of maintenance and ship husbandry.

The elimination of direct supervision of machinery as a major task in automated merchant ships has probably been carried to its practical limit in modern control and surveillance system designs. It would seem that the only prospects of achieving further reductions in manpower lie either in improving reliability and thus reducing the need for maintenance on passage, or by attacking such fundamental concepts as the need for bridge watchkeeping. The Partially Unmanned Bridge (or PUB) concept is a move in the latter direction which is gaining some support. In summary, the commercial marine scene is one in which great conceptual changes have been made during the past ten years. The technological and commercial viability of automated ships has been established, but the long-term effects—particularly in terms of the effects of automation upon the social attitudes, motivation, and sense of responsibility among crew members—are only just beginning to emerge.

In contrast, and because of the lack of commercial pressures, the introduction of automation into the ship control and machinery supervision areas of warship design has been more hesitant. Some moves have been made in the direction of Bridge Control, following commercial marine practice, but without any detailed assessment of the objectives, and some forms of remote operation and surveillance of machinery have been introduced to meet specific NBCD requirements for operation under closed-down conditions. However, no clear policy has emerged, though the pressure from industry to adopt increasingly sophisticated automated systems is becoming greater every year as controls technology advances. The aim of this article therefore is to consider the impact of further automation of ship control and machinery management functions as it is likely to be reflected in the ability of a warship to meet its operational requirements, and in its probable effects upon the size, motivation, and training needs of the crew. In pursuing this aim it is necessary first, to examine some of the possible benefits which may accrue from automation, and to consider their relevance to the warship case.

The Need for Automation

The function of a merchant ship is to arrive at the port of destination safely, after an uneventful and economic voyage. At sea, the objective is to settle down to a stress-free, steady-state condition as soon as possible after leaving harbour, and to maintain that condition for as long periods as navigational conditions will permit. The function of the warship on the other hand is to go to sea and stay at sea for the duration of a specified mission, under conditions which may be anything but uneventful. Once at sea, the objective is usually to avoid steady-state conditions as far as possible, except on passage—and even then the opportunity is usually taken to impose a measure of operational stress on both crew and machinery by the exercise of manoeuvres, drills and emergencies in order to perfect the ship's response to any situation that may develop. In view of this fundamental difference in function, it cannot be surprising that the designs, methods, and attitudes of engineers working in the naval and commercial marine fields have traditionally been reflected in two quite distinct philosophies. Thus although the motivation to design and implement automated ship control and machinery surveillance systems in merchant ships sprang from the economic need to reduce sea-going manpower, it cannot be assumed that by following the same practices in the warship application it will be possible to achieve similar savings.

During recent years, however, the essential difference between what is acceptable for a warship and what is acceptable for a merchant ship has been obscured by economic pressures to adopt a commonality of concepts, designs and standards. Thus automation of warship machinery control and surveillance systems is already following the trends set in the merchant marine, but without any in-depth studies of the full implications of such trends in terms of manpower, effectiveness and support. In the authors' opinion there is an urgent need to return to first principles, and to design a technical strategy for the future development and implementation of automated systems in the warship application, based equally upon trends in control and surveillance technology and upon the operational requirements of the warships themselves.

The automation of a given function is usually justified under a combination of five headings:

(*a*) That a hazardous operating environment, limitations of space or other physical constraints exclude the possibility that the task could be performed by a man.

(*b*) That, owing to the nature of the task, it can be performed more effectively by automation.

(*c*) That the use of automation offers an overall economic benefit.

(*d*) That the use of automation releases manpower for more important or more rewarding tasks.

(*e*) That the use of automation reduces the technical demands upon the operator, and lowers his responsibility to the point where a less-qualified grade of labour may be used.

It is necessary to examine each of these factors in the light of warship operating experience.

Environmental and Physical Constraints

The possibility of contamination of ships' machinery spaces under nuclear fallout conditions or under chemical warfare attack led to the requirement for occasional unmanned remote-control of these areas and the implementation of this requirement has necessitated a measure of automation of some control and surveillance functions. This requirement is evidently a continuing one but it seems likely that any new constraints of this type in the future will be in the 'desirable' rather than 'essential' category and will be related to the working environment—noise, temperature, humidity, etc. Thus in gas-turbine and high-speed diesel ships there is an added incentive towards remote operation and control.

One manpower-intensive task which often has to be performed in the face of a severe environmental hazard is that of fire-fighting. On this argument alone there would seem to be a strong case for a greatly increased level of automation of fire detection and fire-fighting facilities in a warship, and it will be seen later that this case becomes even more important if a serious attempt to reduce manpower levels is to be made.

Improved Effectiveness

This is, of course, the major argument which has led in recent years to the extensive automation of warship weapon systems. Here, the urgent need to reduce reaction times as a counter to high-performance aircraft and missiles, coupled with the ever-increasing complexity of the tactical picture, has led to the development of advanced-technology data-handling and fire-control systems in which the human operator is reduced to a monitor/veto function. In the machinery controls field, the case for automation judged against this criterion is much less marked. There is very little evidence that human operators have any serious shortcomings when controlling ships' machinery systems, and the time-constants involved even in emergency manoeuvres, or in changing from one machinery state to another, are long enough—even in gas-turbine ships—to present no difficulty to trained naval personnel.

Although there are no new factors in the operation of ships' machinery systems therefore which *necessitate* a general increase in the level of automation, there are none the less a number of areas where greater automation might be expected to result in improved effectiveness, and these must be included in the overall strategy. They include:

(*a*) *Surveillance:* The human operator is notoriously ineffective at monitoring the steady-state performance of machinery because his attention wanders unless his interest is held by a changing sequence of events. Automatic alarm and warning systems, designed to alert the operator if potentially hazardous thresholds are exceeded, are therefore likely to be highly effective.

(*b*) *Protection:* Human operators are subject to errors of judgment and drill, and the risk of these errors increases as the transient response of machinery becomes faster as the inevitable concomitant of high performance specifications and high power/weight ratios. A well-engineered automatic control system on the other hand is vulnerable only to component failure, and externally-inflicted damage: it therefore offers a potentially superior performance in the protection of machinery systems against specified and predictable events, but with the penalty of lacking any versatility to deal with the unexpected.

(*c*) *Economic Management:* Automated control systems can be optimized to take account of complex parametric interactions and drifts which lie well beyond the scope of even a well-trained operator. Warships are not noted for their economy in operation, and some potential may be assumed to exist for computer-aided systems to manage the consumption of energy and other resources to economic advantage—possibly to the extent of allowing an increase in mission time.

(*d*) *Health Monitoring:* Most maintenance systems in use in warships today invoke an 'Upkeep-by-Exchange' policy or a variant of it. In such systems the replacement of major machinery is nearly always decided on a time-related basis—the periodicity being determined by service experience with similar equipments, or by theoretical failure-rate predictions modified by a suitable safety factor. It is evident that any system which enables the necessity for replacement to be determined by failure predictions based upon *measured* wear and parametric trends will achieve significant economies both in monetary terms and in the critical operational factor of ship availability.

Health-monitoring and trend-analysis systems are already available for specialized applications, and a significant growth in their warship application can be expected during the next decade.

The Economic Case

It has already been established that the strongest motivating influence in the automation of ship control and machinery surveillance in the mercantile marine has been the need to economize in sea-going manpower. In the naval context the case for reducing ship complements is—superficially at least—even more compelling: not only is there a potential saving in direct costs but also a saving in weight and space which can then be used to improve the weapon fit or enhance some other operational feature of the design. In monetary terms, the true cost of the serviceman afloat is difficult to assess realistically because it is a function of a number of complex and interacting factors. These include:

(*a*) *Prime Costs:* Shipbuilding costs of accommodation, domestic and recreational facilities, plus a proportional cost of the increased size of the ship necessary to make these facilities available.

(*b*) *Career Costs:* Total pay and pension attributable to naval service, divided by total sea-time.

(*c*) *Afloat Support:* Proportional cost of food, cooking, fresh water, heating, cooling, ventilation. Proportional cost of administration and medical services.

(*d*) *Ashore Support:* Proportional costs of training, welfare, administration, etc.

A very rough estimate suggests that prime costs (*a*) for a junior rating in the Royal Navy is about £10–15k per man per ship, and that career costs (*b*) exceed £10k per man per year. Taking into account these, other potential savings under (*c*) and (*d*), and the general saving in weight and space, it is clear that a reduction in complement of one man at the design stage integrates into a substantial economic benefit when taken over the whole life of the ship. The conclusion must be that automation, *where it genuinely replaces a man in the ship's complement at the design stage*, will be a highly cost-effective investment.

More Effective Use of Manpower

The use of automated data-handling systems for track-sorting, target identification, and the routine processes involved in compiling the tactical picture has achieved significant reduction in the number of men required in the Operations Room (CIC), and at the same time has freed the Command Team for the more important, stimulating and anthropomorphic tasks of threat evaluation, tactical decision-making and combat control. In the machinery control field on the other hand, there is a serious danger that automation of machinery management will remove the primary source of interest and motivation from the sphere of responsibility of the more qualified and experienced engineers. In this sense machinery automation may prove counter-productive in that it frees manpower only for the more humdrum chores of routine maintenance and ship husbandry. It will require a serious fault to add the spice of professional interest to an otherwise insipid existence.

Experience in automated merchant ships suggests that this may already be a problem. There is some evidence that a lack of specific responsibilities—such as watchkeeping—coupled with an increase in leisure time and spending money has contributed in recent years to a significant increase at sea of drunkenness and other social problems.

Use of Less-Qualified Labour

Advanced technology control and surveillance equipment is designed to make very few demands upon the technical qualities of the operator and maintainer when it is functioning correctly but, paradoxically, it often imposes a much greater strain upon technical knowledge and diagnostic capability when it does develop a fault—especially if that fault is outside the scope of the built-in diagnostic aids. The dilemma is especially acute in the case of a warship which has to be self-supporting and which has to respond swiftly to system failure or even action damage under combat conditions.

The implication is, therefore, that if the ship is to be capable of some measure of self-support—particularly in recovery from the effects of shock and minor action damage—then it is necessary to retain onboard the highest level of technical expertise available. This is certainly borne out by experience in the weapon system field where a high degree of automation is often accompanied by extreme difficulty in finding suitable employment for junior maintenance ratings. Thus, in the warship application, automation may *increase* rather than reduce the need for highly-skilled personnel. It therefore follows that less-qualified labour can only be used as a substitute if:

(*a*) the requirement for self-support is reduced, or

(*b*) greater dependence is placed on automatic reversionary modes (i.e. system redundancy).

The implications of these two conclusions are discussed later in the article.

In summary, although there are a number of areas where the automation of machinery control and surveillance functions offers potential advantages to the warship designer in terms of operational effectiveness, none of these can be placed in the 'essential' category, and some at least could have downstream effects upon manpower utilization which may be less than desirable. The authors believe that although a further and significant increase in the complexity of machinery control and surveillance systems may seem technologically appropriate and superficially attractive to subjective judgement, it is unlikely to be cost-effective in ship terms unless it is accompanied by a compensating reduction in crew size. The article now considers, in some detail, the factors influencing warship complements.

Warship Manning Constraints

The manpower requirement for an operational warship is determined by two task components:

(*a*) *Scheduled Tasks:* These are the 'routine' or predictable tasks associated with the operational control of the ship, its weapons, its machinery and its men. Typical examples of tasks in this category are:

Command
Ship control (OOW) and safety
Weapon control
Machinery control
Rounds and patrols
Routine maintenance

Routine administration
Food preparation, etc.

(*b*) *Unscheduled Tasks:* These are the intermittent and unpredictable tasks that are a function of the operational use and abuse to which the ship has been subjected. The frequency with which they occur is often a measure of the cumulation stress on machinery and men. These include:

Provision of landing and boarding parties
Fire-fighting
Repair of damage
Fault diagnosis and rectification
Operation of manually-controlled reversionary modes
Use of sea-boats
Replenishment
Accidents, personnel emergencies, etc.

In general it may be said that it is the performance of scheduled tasks that determines a warship's operational effectiveness, whereas it is the performance of unscheduled tasks that determines the ship's ability to sustain that level of effectiveness throughout the mission. It may also be observed that whereas the scheduled tasks provide the main motivation for the crew, they are also the tasks which are the more easily automated since the tasks themselves, and the circumstances relating to them, can be more easily defined. In the past, the scheduled tasks have always proved to be the dominant factor in warship complementing, and this has provided a pool of reserve manpower in the ship (watchkeepers off watch, maintenance daymen, cooks and stewards, etc.) who could always be available to meet any emergency or unscheduled activity. Unfortunately this comfortable position has been steadily eroded during the past ten years, at first by the progressive automation of weapon system functions, and more recently by the introduction of low-manpower propulsion systems (gas turbine and diesel) following the general retreat from steam.

The point has now been reached, however, where the *unscheduled* task load has become the dominating factor in determining a warship's complement. An illustration of this has recently been provided by the issue of an instruction —following an incident in a Royal Navy ship—setting the *minimum* number of men required to be on board a conventional frigate at any time for fire-fighting duties as between 30 and 40. If this is to be the minimum manpower force to be available at all times under either operational conditions at sea or whilst giving shore leave in harbour then, in practical terms, it sets the minimum total complement for a 2000–3000-tonne frigate at about 150 men. Similar arguments can be advanced for other unscheduled tasks such as damage control, landing parties, major cleaning and painting exercises, etc. Support for the figure of about 150 men as a representative minimum for a modern frigate built to a conventional Operational Requirement, and incorporating state-of-the-art control and surveillance technology, has also been provided by recent operating experience with H.M.S. *Amazon* (2500 tonnes; 160 men). This experience has clearly demonstrated that, whereas the scheduled tasks of day-to-day operational deployment present little difficulty for the crew, the ship is nevertheless manned very close to the minimum limit in her ability to meet the unscheduled task load, and that very little margin exists to absorb the effects of illness, promotion, and other personnel contingencies.

The conclusion at this stage is that, although the technology now exists (or, if it does not exist already, it will certainly be developed in the near future) that will enable a large proportion of scheduled tasks to be automated, it would be quite wrong to assume that such an increase in automation would, by itself, bring about a compensating reduction in ships' complements. Moreover, there is a danger that the widespread and exclusive automation of scheduled tasks will upset the delicate balance between interesting and rewarding work for the ship's company and tedious but necessary 'chores'. The upsetting of this balance could lead to a lowering of motivation and morale. Thus it is clear that in future warship designs the automation of any task must be considered in relation to the manning policy for the ship as a whole in order to achieve the right balance between effectiveness, economy and job satisfaction.

The corollary of this argument is that, if it is required to seek the reduction of warship complement as a desirable objective for economic or other reasons, then the approach should be to 'prepare the ground' for further automation by first reducing the *unscheduled* task component. The following list indicates a number of the more obvious ways by which this could be achieved:

(*a*) Modifications to ship operational requirements and operating characteristics, including:
- (*i*) Acceptance of shorter mission times.
- (*ii*) Acceptance of lower availability.
- (*iii*) Reduced flexibility in operational role.
- (*iv*) Less emphasis on ship survival following action damage.
- (*v*) Greater reliance on shore support.

(*b*) Measures to eliminate manpower-intensive unscheduled tasks:
- (*i*) Automation of fire-detection and fire-fighting functions.
- (*ii*) Elimination of manual reversionary modes of operation by implementation of greater redundancy in system design.

(*c*) Measures to reduce the need for high-grade technical support afloat:
- (*i*) Increased reliance on system redundancy in design.
- (*ii*) More accurate prediction of system/equipment failure.
- (*iii*) Acceptance of a higher mission abort rate.

(*d*) General factors:
- (*i*) Design for cleanliness.
- (*ii*) Mobile support—rapid replacement of personnel in an emergency, etc.

All the foregoing possibilities have profound implications for the warship designer, and it is not the purpose of this article to advocate their adoption without a detailed study of the consequences. It is self-evident, for example, that the acceptance of a significantly reduced ship availability, (*a*)(*ii*), is unlikely to be a cost-effective measure if it necessitates an increase in the number of ships required to meet an operational commitment. Nevertheless, it is the authors' belief that these and other possibilities for reducing the unscheduled task component of future warships must be evaluated if the prospects for automation are to be seen in a true perspective. The main theme of this article is that the point is being approached rapidly when a fundamental choice has to be made: either to oppose further automation (except in carefully-selected areas) as a deliberate policy decision in order to maintain the traditional qualities of flexibility and self-sufficiency that are embodied in the manpower-intensive nature of contemporary warship design, or to yield to the forces of technological momentum and to modify naval strategic thinking and long-term planning in the light of the conceptual changes in ship design that could result from a substantial increase in the implementation of automated control and surveillance systems. The path along which selection of the second option could lead us is now explained.

The 'Total System' Concept

The traditional approach to the design of machinery control and surveillance systems has, in the past, been equipment or machinery orientated. In practical terms this has meant that selection of control and surveillance hardware has been made, in the first instance, on the basis of the technical requirements of the machinery fitted, and that important decisions relating to the numbers, abilities, training, and specific tasks of the operators themselves have been relegated to a later stage in the process of ship design. Not surprisingly, the result of such a piecemeal approach has been an inadequate man-machine match exemplified by a profusion of different display concepts and instrumentation standards in most warship designs.

The need to consider the balance between manpower and automation in relation to the ship as a whole has been emphasized in previous paragraphs, and it is clear that as the number of men in a given ship's complement reduces even greater emphasis must be given to matching the machinery control and surveillance system to the operators who remain: in other words, the traditional process of ship design outlined above must be reversed, and the system as a whole must be tailored to the requirements of the crew as a *first* priority. It is also self-evident that as ships' complements reduce, and the level of automation increases, each man effectively becomes responsible for a greater proportion of the ship, and the long-established demarcations between engineering disciplines, and between operator and maintainer must be set aside. In retrospect, one can see that this process of rationalization has, in fact, been going on for some time: what is not so obvious is that a further increase in warship automation could accelerate the process to the point where the whole career structure for naval technical personnel might have to be revised.

Returning to the concept of control and surveillance system design, the foregoing has shown that future, highly-automated systems must enclose two fundamental principles:

(*a*) That they should be designed to meet the needs of the operator, and must therefore be based upon a detailed analysis of the operators' tasks.

(*b*) That they should encompass as a single design concept all aspects of control and surveillance related to the specified task.

Against these two principles, the control and surveillance system can be seen in its proper perspective as the total interface between the ship and its machinery on the one hand, and the men who operate and service it on the other. The interface may thus contain elements of different technologies (electronic, mechanical, hydraulic, etc.) appropriate to the specified task, and will also include within its boundary any internal communication requirements or other forms of human contact associated with the implementation of that task.

This interpretation of the control and surveillance function has been termed the Total System Concept. Its analogy to recent conceptual thinking in the weapons field is obvious: the interdependence of the underwater, surface and above-water roles of the modern warship has reached the point where weapon systems can no longer be considered separately, but must be integrated to form a 'total weapon system' package, both in terms of its ability to meet the threat and in the way it interfaces with the operators in the Operations Room (CIC). It is the authors' belief that this conceptual approach must eventually be applied to the ship as a whole.

Task Identification

The scene has now been set for an examination of possible trends in warship design in the context of the Total System Concept and on the assumption of

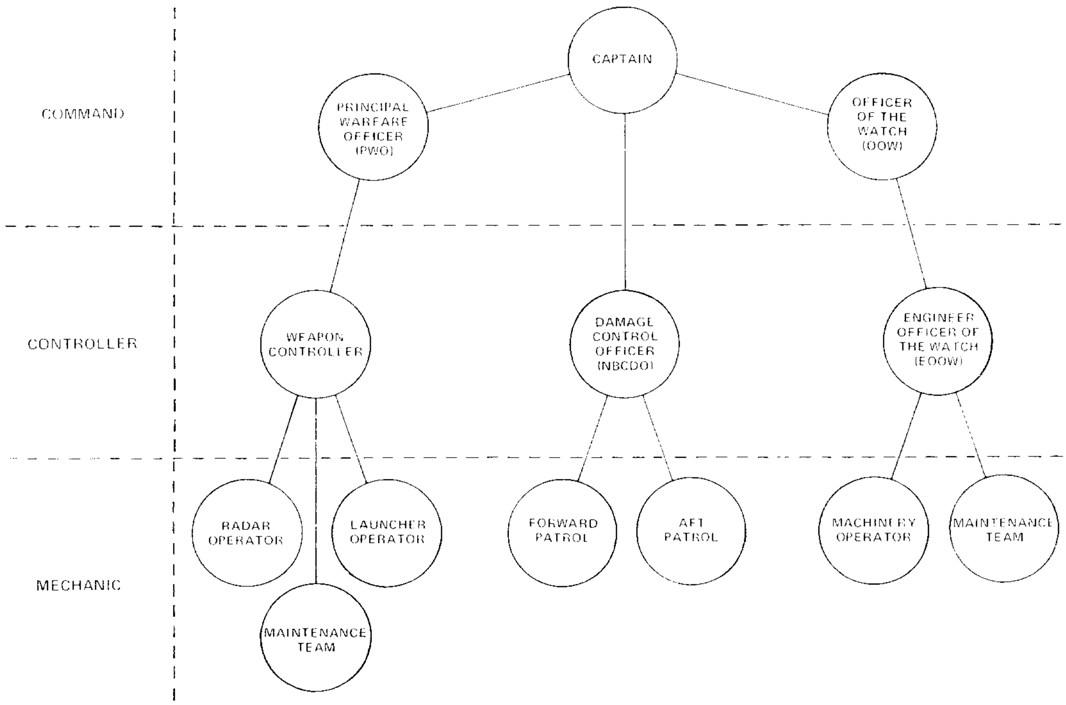

FIG. 1—OPERATOR TASK LEVELS

a significant increase in the degree of automation employed. Superficially it would appear that any attempt at a detailed analysis of operator tasks on a ship basis would be a mammoth undertaking complicated by differences in ship requirements, operating characteristics and fitted machinery—to say nothing of differences in naval customs, organization and usage, if the attempt is made on a supra-national basis. This article, however, is pitched at the conceptual rather than the system-design level and for this purpose a more generalized definition of operator tasks will serve.

Warships are normally organized on the basis of a hierarchical structure on the lines of that shown in FIG. 1. The three levels of operator defined in this hierarchy are of course generalized but, in terms of hardware management, it may be said that the Command is concerned with ship-level, the Controller is concerned with system-level, and the Mechanic is concerned with equipment-level tasks.

The responsibilities assigned to the three levels of operator are described in TABLE I in terms of a 'broad definition'. For system design purposes, of course, it would be necessary to break these definitions down into equipment, system, or ship-specific activities as appropriate. In carrying out such an analysis it is important to draw a distinction between *tasks* in which the operator is called upon to exercise some peculiarly human attribute such as judgement, experience, pattern-recognition, etc. and *functions* in which the operator is required to perform as a machine, reacting in a specific manner to a specific input. Thus, in the fragment of the Total System which is concerned with the transmission of steering orders, the officer-of-the-watch (OOW) giving the orders to guide the ship is performing a *task* whereas the helmsman translating those orders into wheel movement is carrying out a *function*.

To carry this illustration a stage further, it is not difficult to imagine circumstances in which the presence of a human operator at the wheel might become essential (failure of automatic steering, holding the ship steady against heavy seas, etc.). In such circumstances the helmsman would be using his experience and judgement in the performance of a definable *task*. Obviously the distinction between what constitutes a *task* and what constitutes a *function* is not always as clear-cut as in this example because the borderline between the relative capabilities of man and machine is always shifting under the pressure of technological innovation. The distinction is, however, an important factor in assessing the possible impact of automation on ship manning strategy: all functions may (by definition) be automated if it can be shown to be cost-effective to do so; no task may be automated (also by definition)—at least within the limits of known technological trends. It therefore follows that if a manpower requirement is determined by a set of tasks, then the only way in which this manpower commitment can be reduced is by the elimination of the task itself, and the acceptance of the consequences of eliminating that task.

TABLE I—*Levels of work*

Operator		*Broad Definition of Responsibilities*
Command	T1	To decide the tactical disposition, priorities and methods for the ship in meeting its assigned operational tasks.
	T2	To decide the technical and material priorities for the ship in order to meet T1, in the light of any material or environmental constraints.
	T3	To decide personnel priorities in order to meet T1.
	T4	To manoeuvre the ship under hazardous navigational circumstances.
Controller	T5	To deploy the system(s) under his authority to meet the requirements of the Command.
	T6	To advise the Command on technical/material priorities and options in the area in which he has responsibility to meet T2.
	T7	To direct the activities and monitor the performance of the men in his charge in order to meet T5.
Mechanic	T8	To operate systems and equipment as directed by the appropriate Controller.
	T9	To carry out maintenance and repair work as directed by the Controller.
	T10	To operate equipment under hand control in reversionary modes.
	T11	To monitor a specified section of hull/equipment for NBCD purposes.
	T12	To take independent action in the event of an emergency to safeguard the ship (NBCD).

Even a cursory inspection of the broad definitions given in TABLE I is enough to convince that the activities listed against the Command and Controller level operators should be categorized as *tasks*, and that there is very little prospect that the requirement for any of these tasks could be eliminated. At the Mechanic-level, however, it could reasonably be anticipated that more detailed analysis would reveal a high percentage of *functions* (implementing changes in machinery state, data-logging, some NBCD activities, etc.) which could be automated, and a number of *tasks* (local/hand control of machinery, provision of landing parties, etc.) the requirement for which could be eliminated with the acceptance of some reduction in capability and self-sufficiency. Thus, via a different approach, the same conclusion is reached as previously: namely that so long as certain prerequisites are met in 'preparing the ground' the way does lie open for a significant reduction in the size of future ship complements.

Set against the background of reducing the Mechanic-level tasks and thereby reducing ship complements, the Controller-level responsibilities in TABLE I assume a different emphasis. In particular, the supervisory aspects of the Controller's work in directing his juniors' activities and in monitoring their performance diminish, and the consultative aspects of his work in advising the Command increase. An interesting illustration of this has been provided by recent experience in H.M.S. *Sheffield* and Hr. Ms.: *Tromp*—both highly-automated ships fitted with Bridge Control over a COGOG propulsion system. In both these ships it is understood that the Marine Engineer Officer (MEO) stations himself on the bridge when operating under bridge control in hazardous navigational conditions: this in spite of the fact that in both of these ships markedly superior facilities for assessing the performance of the machinery plant as a whole are provided in the ship control centre (SCC). It seems likely that intuitive reaction of the MEO to his new environment in these ships is that his need to monitor the performance of his SCC team has been overtaken, when in bridge control, by his need to be able to advise the Command directly in the event of an emergency. No doubt the fact that the view from the bridge—especially when entering harbour—is likely to be somewhat more entertaining than the SCC console also has something to do with the MEO's decision.

The implication is that once the main constraint of his supervisory role (T7) has been removed, the MEO would prefer, under all potentially hazardous situations including combat, to be in the operations room in personal contact with the Command in order to be able to advise him at first hand about the state of the ship, its machinery, and its personnel. This process of contraction at Controller-level has already taken place in the weapons field where the various weapon system Controllers are situated in the operations room as a small nucleus of operational authority known as the Command Team. Thus it is easy to envisage, within the Total System Concept, the tasks appropriate to a 'Machinery Controller' (i.e. a combination of MEO and NBCDO responsibilities) being included in the design of the operations-room complex. In the Royal Navy, at least, the lack of such an input to the Command Team has been felt for some years and, under operational conditions, has inhibited the Command in carrying out his tasks T2 and T3.

The main reason why the idea of Machinery Controller has never, in the past, progressed beyond the conceptual stage was that no possibility could be

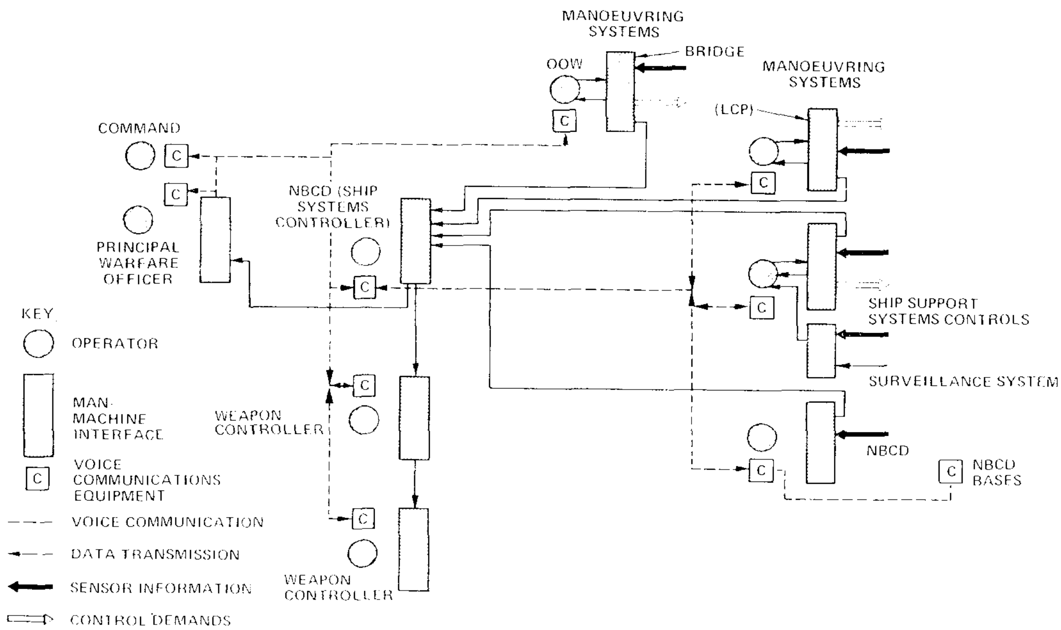

FIG. 2—CONNECTIONS BETWEEN MACHINERY MAN-MACHINE INTERFACES AND SHIP COMMAND/WEAPON CONTROL

seen of including all the facilities he would require into an already seriously overcrowded operations room. Since such facilities and better already existed in the SCC or its equivalent, there seemed to be little point in duplicating them elsewhere. For the future, however, the requirement for a permanently-manned SCC could be eliminated along with the associated Mechanic-level tasks and functions; and the technology already exists, by the use of data-processing systems and interactive displays, to compress such control and surveillance facilities as the Machinery Controller might require into a console suitable for operations room fitting. It is certainly difficult to argue that, using modern technology, the Machinery Contıoller would require any more space than that taken up by the facilities provided for an average Weapon Controller. An illustration of the total system concept, showing the relationship between machinery control and weapon system elements in the operations room, is given in Fig. 2.

Implementation

A picture is beginning to emerge of a highly-automated and low-manpower warship being operated somewhat on the lines of a modern aircraft, with all tactical and technical decisions and all effective control being vested in the Command Team in the operations room (the analogue of the flight-deck crew). Apart from the bridge (for navigation and ship safety), very few—if any—'scheduled tasks' would be performed outside the operations-room complex, and the manning requirement for these spaces would thus determine the minimum crew size if the unscheduled task component were to be ignored.

Whilst all its automated machinery is functioning correctly, such a warship would undoubtedly be as effective as its traditional counterpart but it must also be judged against the aspects of availability and reliability, vulnerability and increased dependence on shore support.

Reliability and Availability

A highly-automated warship is certain to be considerably more complex than its conventional equivalent and thus, on a component count alone and ignoring such factors as operator- and maintainer-induced failures, some increase in the overall component failure rate is to be expected. Whether or not this increased rate of component failure is reflected in a similar increase in system failure and thus a reduction in ship operational availability is a matter for system engineering design. In this context the recent development of high-integrity multiplexed systems for aircraft control is particularly relevant —especially for the so-called 'fly-by-wire' application in which no manually-controlled reversionary mode is possible. In such systems, although component failure follows the conventional pattern, system duplication and fault tolerance is such that the incidence of overall systems failures has to be measured in tens or even hundreds of years.

The previous paragraph applies particularly to electronic systems, but rather less to the larger mechanical components of a system that are often difficult if not impossible to provide in duplicate. However, the failure of such components is usually a serious matter requiring remedial action in harbour notwithstanding the technical competence of the maintenance team. As such, the consequences of major mechanical failure are unlikely to contribute significantly to any difference between the operational availabilities of automated and conventional warships.

Vulnerability

The case of accidental or enemy-inflicted damage is, of course, very different. The ability of a warship to be able to survive a first strike and then to retaliate is an important operational, strategic, and even political requirement. The performance of a modern warship in its ability to withstand damage and to continue fighting is not encouraging: weight considerations usually preclude the use of armour, and the weapon and machinery systems are so dependent upon 'general services' that the 'volume of vulnerability' associated with a particular function often encompasses a large proportion of the ship. Thus the crippling of a chilled-water plant could result in the loss of radar.

Without wishing to imply that control and surveillance automation can overcome this difficult problem, it is noteworthy that technological trends in the use of dedicated micro-processors and digital-data highways tend to reduce these 'volumes of vulnerability' by localizing control at the plant itself, and by providing alternative data routes in the event that one should be destroyed. By reducing the volume of vulnerability to a limited number of small zones, the use of localized armour might even become a feasible proposition.

Other aspects of vulnerability are concerned less with the technology of the automated ship and more with the absence of a manpower reserve to deal with repair of damage, fire-fighting, and the control of flooding and ventilation. Excepting the repair of physical damage, there seems little reason why the other functions should not be automated—or at least activated by remote control. Closed-circuit television could be used for the remote surveillance of important spaces, and could obviate the need for patrolmen. With regard to the effects of damage and watertight integrity, the elimination of the need for regular human access to compartments could be used to advantage in increasing water-tight integrity.

Dependence on Shore Support

The removal of skilled maintenance personnel from the automated ship would inevitably increase the dependence upon shore support. It could, however, be argued with some justification that their abilities would be more effectively employed serving a fleet rather than a single ship. In technological terms, the upkeep of the automated warship would necessitate the development of sophisticated data-logging, health-monitoring, and trend-analysis techniques: in this area there would be much to learn from the commercial marine industry.

Conclusion

The warship to emerge from the conceptual picture so far outlined would be expensive, complex, and revolutionary. If the weight saving resulting from the reduction in manpower were used to supplement the weapons fit, it could also be highly effective in meeting its major operational tasks, although it would lose some flexibility in meeting the secondary requirements. The ship could also be designed from the outset as a 'hard target' if this were identified as an important attribute. The overall cost-effectiveness of such a ship could only be established by an in-depth study of all the implications, but would depend in the main upon the extent to which the complement could be reduced: a figure of 50–80 men for a 2500-tonne frigate might be a realistic target figure for such a study.

The case for the automated, advanced-technology, high-integrity warship has been made to stimulate thought on a vital issue: whither automation in the warship context? The authors concede that the issues involved are unlikely to be as clear-cut as would appear from the necessarily superficial treatment given to the subject in this article: more detailed analysis of the argument would almost certainly lead towards compromise. Nevertheless, they firmly believe that the basic principles embodied in the Total-System approach to control and surveillance system design are essential if a reasoned approach to the balance between automation and manpower in warship design is to be achieved. In the wider sense we believe that we are approaching a crucial decision point in naval technical history, and are facing a choice between a deliberate policy to maintain the *status quo* on the one hand, and taking the full advantage of what modern control and surveillance technology has to offer in a fundamental rethinking of our warship design policy on the other. The latter course will have a major impact on nearly every aspect of naval thinking, from the creation of new ship requirements to the manning, training and composition of the Navy—even to the pattern of naval life as we now know it. It is not an easy choice, but it is certainly an exhilarating and stimulating challenge.