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EVALUATING THE COST-EFFECTIVENESS OF MACHINERY CONTROL AND SURVEILLANCE OPTIONS

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Abstract

Early studies on the cost-effectiveness of automating the operation of ships and machinery indicated that significant benefits would arise from reducing the level of manning. Future benefits will be subject to a law of diminishing returns as crew complements shrink.

The range of possible machinery system options continues to expand in the continuing search for optimum ship performance, and current developments in electronic technology have reached the point where the number of machinery control and surveillance options and applications is considerable. Commercial and naval experience with first-generation systems has shown that selecting the optimum system is difficult.

In this situation of high potential risk, high potential benefits and many options, the need for a systematic method of evolving the design of a machinery control and surveillance system is obvious. This article describes a systematic basis for analysing machinery control and surveillance options to establish manning, system integrity, life-cycle costs and performance penalties.

The results of a pilot study on a hypothetical small warship are presented and the general conclusions are discussed.

The cost data presented in this article are mainly historical and although every effort has been made to render costs to a common standard, the £ unit of account must be regarded as notional, its use being for comparative purposes only. On no account should it be regarded as a realistic price indicator for current or past equipments or systems.

(This is a companion article to that presented by Capt. G. W. Marsh, RN, and Cdr. A. J. Stafford, RN: "The Control and Surveillance of Ships' Machinery — the 'Total System' Concept" on the range of possible Machinery Control and Surveillance options, and the factors to be considered from the operators' viewpoint in selecting the options).

Background

The machinery control and surveillance systems currently in use have been produced in response to a drive to cut operating costs by reducing the level of manning. In the RN this drive has been in two phases:

- the first introduced automatic control at plant level and provided a remote centralised position for control and surveillance of the main machinery. This approach was applied to steam-propulsion ships, where the associated machinery space environmental conditions and poor plant controllability were further factors in the introduction of plant control automation using pneumatics.
- the second extended the scope of the remote control centre to cover all machinery, and provided a greater degree of automation at system level (see the chapter entitled System Concepts in Machinery Control and Surveillance) in particular, the provision of bridge control. This approach was implemented with the introduction of gas-turbine-propulsion ships, the control medium being electrics.

In the commercial marine field a further phase — to reduce manning to a minimum level by introducing systems which employ digital electronic technology — is just beginning. Before embarking on a similar phase of automation in RN ships, it was decided that a thorough examination of the potential benefits and problems should be conducted.

Initially, this examination was focused on the application of digital systems based on microprocessors which, judged on their technical capabilities, were found to be both feasible and attractive. However, experience in introducing both the second phase of machinery automation and computer-based weapon action information systems has highlighted the problems of imposing centralised control on systems whose characteristics were not sufficiently well understood, and it was therefore decided to commission a pilot study to examine the broader picture by clearly defining the requirements and assessing whether, in fact, automation offers the most cost-effective ways of meeting them.

On reflection, it seems remarkable that the question of cost-effectiveness was only briefly considered before, but examination of the proceedings of earlier Ship Control Symposia reveals only two papers relating to the topic. The key reason for this seems to be that the marine industry was conditioned into the beliefs that not only was it technically feasible to replace men by automation, but also that the benefits were so great as to outweigh the cost of the systems replacing the men. While the first of these beliefs has some validity, the second is questionable — particularly in the current situation, where automation becomes more complex, in order to replace fewer men.

It therefore follows that the requirements of the ship and machinery systems must be established by reasoned argument based on fact, and the merits of man as a means of control must be objectively assessed alongside those of available hardware technologies. This article presents basic system concepts on which future system requirements can be based, and includes a cost-effectiveness analysis of several manpower/automation configurations based on data derived from current systems. The implications for future system configurations, the role of men and the use of new technologies are discussed.

System Concepts in Machinery Control and Surveillance

The Interface Concept

The machinery control and surveillance system of a ship is part of its overall command and control structure. In conjunction with the ship's operators and maintainers, it acts as an interface between the command and the machinery systems, and its function is to ensure that these systems fulfil the role desired by the command. The interface concept therefore implies that extensive automation cannot be effective unless the machinery system aspects are considered from the command level in the context of the ship's role.

From the command level, the machinery systems of any ship can be considered as comprising a number of basic functional groups — those to meet the prime task, those for manoeuvring, and those which support the machinery and operators — as shown in Fig. 1. Within each group there may be several interconnected systems, each containing several items of machinery plant, possibly of differing types. As seen from the command level, therefore, the control of the machinery consists of a hierarchy of functions: At the lowest level the function of the hierarchy is concerned solely with the control of single plants; at the next level, it is concerned with the co-ordination of plants within systems, and at the highest level its function is one of co-ordinating systems within a group. At present, automation is at the system and plant levels and, since any major extension of automation must involve the group level, extension must be considered in the context of the ship's role.

While, from the command viewpoint, the formation of a machinery systems concept is sufficient to provide a rational basis for future automation, the type of ship and its operating role will impose various constraints on the way in which the command operates — and this, in turn, will dictate a basic command/operator structure, which automation will rarely be able to overcome. Examination of the characteristics of the machinery systems in each functional machinery group shows that control requirements are similar within each group, and that the only systems which need to be manned continuously are those concerned with the prime task and those concerned with manoeuvring. Since the first depends upon the ship's role and the second upon the type of ship, it will be in those systems that the ultimate constraints on manning will lie.

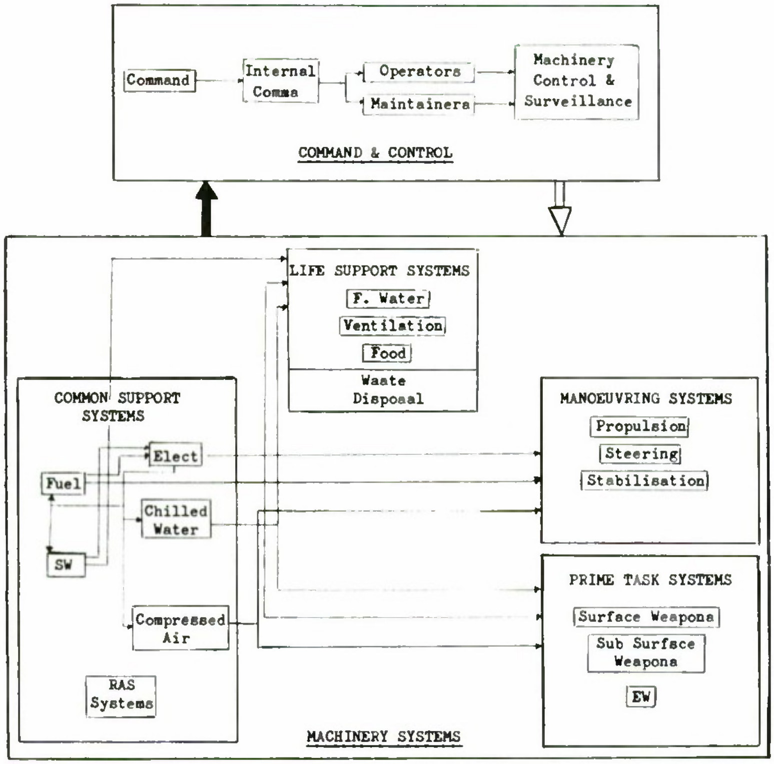


FIG. 1.

The 'Man-Automation Balance' Concept

The interface concept implies that the highest level of operational function, adjacent to the command level, will remain a human task. Since, at plant and system level, automation is well advanced, there is clearly some intermediate level at which men and automation must balance. Since the prime motivation for automation was the reduction in manpower, the major benefits were achieved by automation at the plant and system level. Clearly the next stage of automation involves more complexity for much less reward in terms of manpower reduction and hence the point of man-automation balance is sufficiently close to warrant its consideration in any further development.

It would be wrong however to expect a universal solution. From the foregoing discussion on the interface concept the influence of ship role and type will effect the optimum balance and it is readily apparent that the balance for a warship will always be at a lower functional level than the balance for a commercial products carrier with its simple machinery fit and mission profile. Whatever the ultimate level of automation adopted in the naval or commercial field, the emphasis will universally change to improving the efficiency of the man and reducing his dedication to low-productivity tasks. In this situation the role of automation will be to assist man rather than to replace him and, in equipment terms, this will result in more extensive use of sophisticated surveillance systems — collision avoidance and machinery health monitoring being cases in point.

The Configuration Concept

In addition to the main issue — the choice between man on the one hand and machine automation on the other there is a second issue to be considered, namely the location of man/machine interfaces and control equipments. The need to improve efficiency, and to increase man's flexibility by reducing his dedicated-task load, also requires some flexibility in the location of equipment.

In the present generation of systems, the usual solution is to centralise control positions and control equipment in a single compartment. Such a solution is inflexible and possibly impractical for higher levels of automation. However, the technical feasibility of distributing the controls equipment is no longer in doubt, and therefore the merits of distribution must be considered. As the basis of this study, five configuration options with varying degrees of man-automation balance and control location have been established to provide a basis on which to assess the case for distributing man/machine interfaces and system and plant controls.

The Scope of the Study

Configuration Options

The five configuration options selected for study are defined in the following paragraphs:

Option 1 is the "basic" option which consists of automatic plant protection functions and manual start-stop functions of plant control. System control functions for propulsion and electrical distribution are manual, and are located at centralised control positions. This option requires manned machinery spaces, although manning requirements have been kept to a minimum for this condition.

Option 2 is essentially the same as Option 1, but with propulsion controlled manually from a centralised control position on the bridge. In this typieal "tugboat" configuration, the machinery space manning requirement is reduced to wandering watchkeepers only.

Option 3 is the "basic UMS" configuration, in which centralised remote surveillance is provided for all machinery, in addition to the features described for Options 1 and 2. The need for wandering watchkeepers is minimised, although plant in the machinery space must still be started and stopped manually.

Option 4 In this configuration the addition of centralised remote control of all plant, including the automation of plant start/stop functions, provides unmanned maehinery-space operation for all but emergeney conditions such as fire and flood. This option is a simplified version of the configuration adopted for the Type 22 frigates.

Option 5 is the most complex configuration, analogous to that of a modern airliner. It has fully-automated system functions for all machinery, together with a sophisticated secondary surveillance capability. The remote control positions are dispersed — manoeuvring controls on the bridge, ship support controls in the operations room, etc. — and eaeh group is operated by its user, from a compact man/machinery interfaee. The secondary surveillance system is operated from a technical office as a maintenance aid.

Machinery Systems

The support system machinery fit of the small hypothetical ship used as a basis for comparison consisted of three generators plus chilled and fresh water plants and LP air. There were two propulsion options, namely a three-engine/twin CPP CODOG arrangement and a twin-engine/twin FPP COGAG arrangement with reversing gearboxes.

Control and Surveillance System Technology

The estimates of cost and other data for the control and surveillance system options, had to be based on the variety of technologies in use in the most recent designs of RN ships. At "plant" level, the control technology is predominantly hydromeehanical with high-power electromechanical interfacing, although some plant controls do use electronics; this is largely the same technology (*i.e.* analogue signals, discrete components on small printed circuit boards with module packaging) as that used for the remote system functions.

Most of the surveillance systems in current use are direct hardwired to meters or to solid-state-logic alarm systems; some have time-division-multiplexed analogue warning systems incorporated. The man/machine interfaces are mimic displays with conventional alarm indicators, meters, switches and levers.

Study Method

The most common method of selecting one design option from several is, firstly, to establish certain characteristics of each option (*e.g.* space, weight, and reliability) and, secondly, to eliminate options on a comparative basis. Such a method is quite adequate for options which are simple and similar, but it has a number of disadvantages when applied to widely differing options with a large number of characteristics, especially if the relative importance of each characteristic is not fully understood.

In the first place the degree of optimisation achieved depends on the initial options selected for study; if these differ significantly, an intermediate solution could exist. Further if the relative importance of the characteristics is not understood then it is difficult to apply good selection criteria, without which it is impossible to arrive at an optimum solution. With the common method, the study usually results in a mass of data and a set of ranking factors designed to produce the analyst's preferred option.

In this study, all five options were quite different and the characteristics to be considered — life-cycle, costs, space, weight, reliability, vulnerability, operator and maintainer manpower, support and installation requirements — were many and varied. A new approach was essential.

Characteristics, Criteria and Method of Selection

The concept of cost-effectiveness was introduced as the basic criterion for evolving an optimum design. Each of the characteristics outlined above contributes either to cost, or to effectiveness, or to some physical constraint or even to a combination of all three. By studying the relationships between characteristics under these three headings, the selection process was reduced to a reasonable task.

The next step was then to decide whether cost or effectiveness was to be the prime consideration of the study. In this study, cost was chosen as the variable of prime interest. The next stage was then to conduct a tradeoff study, examining those characteristics which contribute to effectiveness and physical constraints, to establish cost benefits and penalties. In this way the possibility of intermediate options can be identified and, most importantly, low-cost options are not prematurely eliminated by arbitrary external criteria — in fact, the ease with which effective but inexpensive solutions can be identified is an additional aid to improving effectiveness within a fixed cost budget.

Basis of Costing Study

A principal objective of the study was to identify the areas which contribute most to the high initial cost of a modern sophisticated warship. To this end, the initial cost of each configuration option was estimated for both machinery fits in the hypothetical warship. Since, basically, automation was introduced into the RN to reduce life cycle costs then this aspect, too, was included in the study. Both costing aspects were applied to a single ship, rather than to a class of ships or to a new construction programme of several ships. The merits of extending the scope to cover these aspects are included in the discussions.

The costs of men and equipment contribute to ship initial and life cycle costs in both direct and indirect components. The indirect components result from use of ship services, installation space, and repair facilities, and are related to the system characteristics of reliability, space, weight, operator manpower etc. It becomes necessary to consider these indirect components when the direct components of cost are similar.

The work described in this article is based on direct components of cost. It was not possible to put precise figures on the indirect factors which influence initial costing, but their upper limits were estimated to be:

Equipment weight	£4K per ton
Accommodation space and equipment	£3K per man
Life support service machinery	£10K per man

Associated maintenance and support costs add about 300% to the costs of each of the above factors. Work on the quantification of indirect factors is continuing.

The initial cost data for the machinery control and surveillance system were drawn from a wide variety of sources, and were categorised under the following headings:

- On-Plant Control Equipment
- System Control Equipment
- Consoles and Surveillance
- Transducers

Hardware and installation costs were estimated for each category.

Depending upon the degree of plant complexity, the costs of plant control units varied between £5K and £10K per plant. System control unit costs, which were also dependent of complexity, were up to £20K/system. Many types of consoles were analysed and it was found possible to cost consoles on the number of input/output functions with a surprising degree of accuracy, a typical figure being £100 per function.

Alarm logic, signal conditioning and transducers similarly showed consistent total costs of £350/channel, whether for a hardwired system or for the multiplexed system considered in this study. Installation costs of £7/metre for 12-core control and instrumentation cable, and £0·7 per termination were taken from current MOD data. All data were checked against ship systems not included in the data base; the overall difference between predicted and quoted costs was about 15%.

The life cycle costs study was based on the same data for initial costs and essential spares support costs. A figure of £10K per man was used for both operators and maintainers. For all five options, it was assumed that no refits would be undertaken during the twenty-year life of the ship — although additionally, the effect of a three-year refit of electronic modules, with half-life replacement of the system, was analysed for Option 4. The sensitivity of the costing to discounted cash flow factors of 5% and 10% was also established. For the purposes of this analysis the initial acquisition costs were assumed to be spread over three years in blocks of 25%, 25% and 50%.

Basis of System Effectiveness Study

The effectiveness of any control and surveillance system is the extent to which it permits the potential of the machinery systems to be realised by the command. Reductions can arise in two ways, it may arise from bad design of the method of interfacing with the command and machinery, or it may arise from the interface failing to react in the desired manner. Whilst the first may be overcome by better design the second will always impose the ultimate limiting factor on effectiveness. For this reason study of the effectiveness aspects has been confined to factors concerning failure modes and effects, in particular the frequency of failure and the proportion of failures leading to undesirable effects of varying degrees.

The study method was then used to assess the failure rates and repair times for current systems against the basic requirements of the hypothetical warship, and then to assess the cost benefits or penalties resulting from postulated changes in technology or configuration.

The costing study identified the areas of high cost as being plant control and surveillance, and consequently the effectiveness study was concentrated on these areas in order to obtain the highest possible cost benefit. Failure rates for plant control equipment were obtained from conventional reliability prediction techniques, and failure rates for the machinery plant being controlled were found from test house and operational data. System control unit reliabilities were established for propulsion and steering systems by similar techniques. The validity of the data where possible was checked against operating data from H.M.S. *Amazon*, and reasonable agreement was obtained. The merits of advanced technologies in improving integrity, either by increasing equipment reliability or by allowing built-in integrity, were assessed from a number of studies of the use of hybrid microcircuits and digital systems.

It will be appreciated that the data described in the preceding paragraph relate only to the "machine" part of the man-machine interface, and that it is necessary to consider also the failure rate of the man. Data from which human error rates can be assessed are available in the form of RN statistics on groundings, collisions and berthing incidents; these data were analysed to provide a comparative basis.

For the surveillance, equipments the failure rates were obtained from in-service data where available, or by estimation and comparison with the known data. A total of five surveillance systems was analysed, including hardwired, analogue and digital time-division-multiplexed transmission and central processors — all with varying degrees of capability.

- A: Parallel hardwired channels providing gauge, state and alarm indication.
- B: Scanned system utilising hardwired CPU providing alarm and data logging facilities.
- C: Parallel hardwired system providing alarm indication and data readout facility.
- D: Scanned system incorporating software-based CPU and providing all required indication by means of a VDU.
- E: Parallel hardwired system, incorporating software-based CPU providing alarm and state indications and data-logging facilities.

The acceptability of each system was assessed by calculating the probability of failure occurrence, within a pre-defined mission length, for the following types of failure:

(a) Loss of channels associated with a single machinery plant

(b) Loss of the complete system

and by comparing these with typical rates of machinery failures and for certain common-mode failures (such as the power supply failure rate). Costs for systems currently available and similar to those defined above were used in an effort to obtain realistic comparisons, and estimates of installation cost were based on MOD(PE) data. The trade-offs between cost and integrity were then identified, and where possible the relative influences of configuration and technology were determined. It was assumed that improvements in the integrity of each system would be brought about only by the duplication of complete functional units and not by redesign; this allowed the changes in configuration to be costed from the available data.

Basis of Physical Constraint Study

The objective of the physical constraint study was to determine whether for any option the space and weight of any part of the system exceeded any constraints imposed by compartment size and layout, ship displacement or stability.

For a range of current naval control and surveillance systems, space and weight data were assembled and analysed to establish some general rules. In general it was found possible to relate equipment size and weight to the input/output channel count for the equipment. A linear relationship was identified for consoles, with the slope of the characteristic falling the newer the technology employed. The smaller equipments, such as plant controls, exhibited a highly non-linear relationship tending to a constant level for complex equipments.

Equipment space envelopes were then estimated for each configuration option and layouts were developed for machinery spaces and control positions. Constraints imposed by other equipment and compartment boundaries, pipe and cable runs, access and removal routes were identified and wherever possible, means of overcoming them were investigated.

The weights of the equipments and of the interconnecting and installation hardware were also estimated, for each configuration option, and the effects on displacement and stability were established. Weight distribution was assessed for each option.

Commercial Standard Study

The main body of the study was based on data derived from existing naval control and surveillance systems and it was considered that some comparison with commercial systems was essential. A study was therefore commissioned to produce and cost the outline designs for an Option 4 system to commercial standards, to identify the principal differences between commercial and naval designs and to assess the relevance of classification society and naval specifications. The results of this study were compared with those of the main study and the conclusions were checked where possible against those from similar exercises in hand on the production of a low-cost frigate.

Results

General

The results described are those for the CODOG machinery fit, incorporating two propulsion diesels and a single gas turbine; these results do not take account of NBCD requirements. Due to lack of space, only these results relevant to the main conclusions of this article are included.

Costs

Tables 1 and 2 show estimated hardware and installation costs for each of the five options. The costs are shown in four sections, *i.e.* on-plant controls, system controls, consoles and transducers, with the console costs subdivided into hardwired surveillance, auto surveillance, and controls. The cost of electric conversion equipment has been included in the installation cost of on-plant controls—in fact it is about 50% of this figure.

The costs shown in Tables 1 and 2 are shown graphically in Figs. 2 and 3, Fig. 2 shows the cost buildup for each option above the common base of on-plant controls (it should be noted that Options 1 and 2 do not incorporate auto-surveillance). The cost shown for each section is the total of hardware and installation. For each option, Fig. 3 shows the

TABLE 1.

Option	Hardware £000	Installation £000	Total £000
1	123·1	28·3	151·4
2	143·0	31·0	174·0
3	258·9	79·4	338·3
4	309·5	94·7	404·2
5	338·8	101·6	440·4

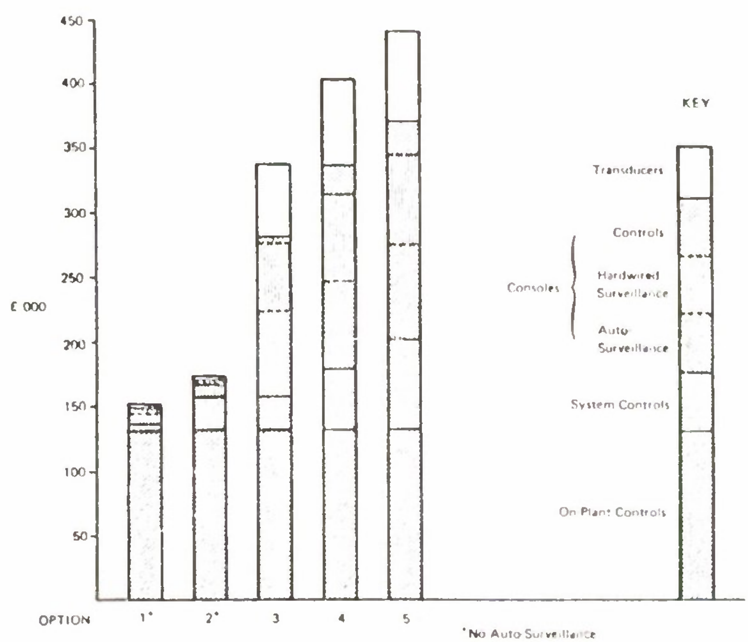
various constituent costs as percentages of the total system cost, to demonstrate the trends from option to option. The curves for consoles and transducers are shown dotted between Options 2 and 3 as, in practice, both curves would show a step increase in cost because of the introduction of auto-surveillance.

The above results have been selected for general interest and discussion from which the following points are noted:

TABLE 2.

Option	Item	On-Plant Controls £000	System Controls £000	Consoles: Surveillance Auto £000	Consoles: Surveillance Hardwired £000	Consoles: Control £000	Transducers £000
1	Hardware	107·9	5·8	–	5·3	2·4	1·7
	Installation	22·9	0·6	–	3·0	1·6	0·2
2	Hardware	107·9	23·6	–	6·1	3·1	2·3
	Installation	22·9	2·4	–	3·4	2·0	0·3
3	Hardware	107·9	23·6	41·7	31·0	3·1	51·6
	Installation	22·9	2·4	24·2	21·7	2·0	6·2
4	Hardware	107·9	44·0	43·1	40·4	13·6	60·5
	Installation	22·9	3·1	24·8	27·0	9·6	7·3
5	Hardware	107·9	64·2	47·6	42·0	14·3	62·8
	Installation	22·9	5·1	26·7	27·5	11·8	7·6

FIG. 2.



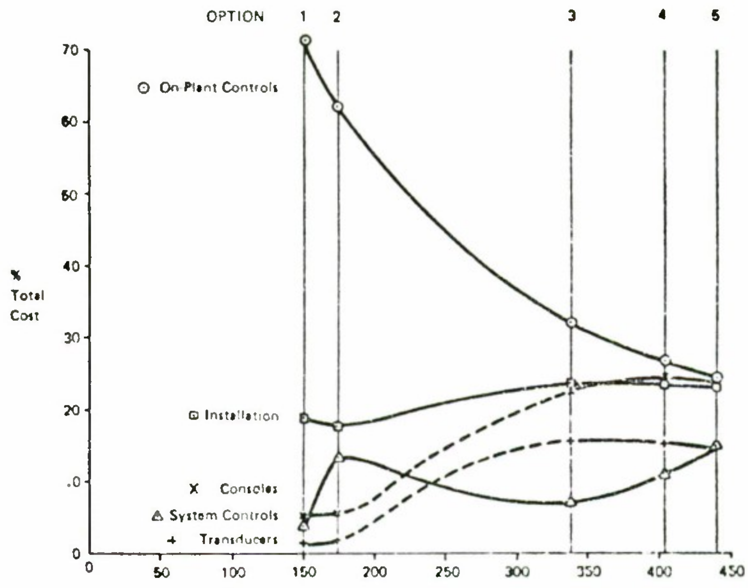


FIG. 3.

(a) The dominating effect on on-plant control hardware costs. These are shown to be at least 25% of total costs, even in the most complex option in the basic option they account for no less than 70% of total cost.

(b) The percentage of costs attributable to the provision of remote control facilities never exceeds 15%.

(c) Installation costs are around 20% of total costs, regardless of the sophistication of the system.

(d) In the more complex options, console costs account for almost 25% of the total cost.

Considering Option 4, the total cost of the system was approximately double that obtained from the commercial study. Areas of greatest difference were the propulsion system control (where the ratio of commercial costs to naval costs was approximately 1 : 4) and the SSC console (approximately 1 : 2.5). Commercial costs for the auto-surveillance system were about 30% lower, while there was little difference between the commercial and naval costs of the smaller bridge and CCP consoles.

On reflection, the costs shown for Option 5 are thought to be low; the amounts allowed for health and trend monitoring equipment may have been insufficient.

Life Cycle Costs

The factors, considered in this study were: initial acquisition costs, maintenance, and manpower costs. On manpower, it was estimated that the number of operators per watch (on a three-watch system) would be seven for Options 1 and 2, and five for Options 3 and 4; Option 5 would have three operators per watch, supported by one 'dayman' operator whose duties would be mainly supervisory. An allowance was made for one maintainer, who would not be a watchkeeper.

Table 3 shows the summary of total annual costs. A summary of total Life Cycle Costs at undiscounted and discounted rates is shown in Table 4 which also shows initial acquisition costs as such and as percentages of the total. This information is presented graphically in Fig. 4.

The undiscounted life cycle costs (Fig. 4) show an 18% reduction between Options 1 and 2 and Options 3 and 4. This is because the manpower costs, which dominate all other costs — including those of initial acquisition — are lower in Options 3 and 4.

Each increase in discount rate tends to flatten the curve into an almost horizontal line, showing that there is no significant economic advantage in choosing any one of the first four options.

Option 5 however, because of its inherent low manning level is 39% lower than Options 1 and 2 in terms of undiscounted life cycle costs. When discounted to 10% the cost of this option is still 29% lower than that of Option 1 or Option 2. For this relationship to be significantly affected, the initial acquisition costs would have to be dramatically increased. The underestimates of initial cost previously mentioned would not significantly alter this situation.

TABLE 3.

	Total Annual Cost (£)				
Option	*1*	*2*	*3*	*4*	*5*
Operator manpower	220,000	220,000	160,000	160,000	110,000
Propulsion system maintenance	–	2,400	3,600	5,100	5,100
Surveillance maintenance	–	–	1,200	1,200	1,200
Transducers maintenance	100	100	1,700	2,000	2,000
Totals	220,100	222,500	166,500	168,300	118,300

TABLE 4.

	Option				
	1	*2*	*3*	*4*	*5*
Initial Acquisition Cost(£k)	151·4	174·0	338·3	404·2	440·4
Life Cycle Costs—Undiscounted					
Total LCC	4553	4624	3668	3770 *4301	2806
Initial Acqn Cost as % of Total	3·3	3·8	9·2	10·7 *9·4	15·7
Life Cycle Costs—5% Discounted					
Total LCC	2629	2677	2223	2278 *2521	1751
Initial Acqn Cost as % of Total	5·4	6·1	14·3	16·7 *15·1	25·1
Life Cycle Costs—10% Discontinued					
Total LCC	1684	1721	1473	1543 *1800	1224
Initial Acqn Cost as % of Total	8·0	9·0	20·5	23·3 *20·0	36·0

* With refit (see Section Characteristics, criteria and method of selection)

Space and Weight

The study established whether major constraints existed in space and weight for Options 1 to 4; Option 5 was not considered in this part of the study. As the study was intended to apply to small warships in general; no attempt was made to produce detailed designs. The results of the study were derived from information on equipment used in present-day ships, modified to reflect the specific requirements of each option.

Table 5 details results obtained for consoles together with the estimated floor area required for control and surveillance equipment and personnel. Table 6 details the total weight and volume of control and surveillance equipment in the machinery spaces, together with cable weights.

TABLE 5.

Function		*Option 1*			*Option 2*			*Option 3*			*Option 4*		
		BR	*SSC**	*CCP*	*BR*	*SSC**	*CCP*	*BR*	*SSC*	*CCP*	*BR*	*SSC*	*CCP*
Panel Area	(m^2)	0·23	0·30	0·5	0·36	0·30	0·64	0·28	1·8	0·64	0·41	4·5	0·34
Required Console Vol	(m^3)	0·18	0·25	0·4	0·28	0·25	0·5	0·30	2·2	0·5	0·32	5·6	0·26
Console Weight	(kg)	180	100	175	227	100	250	235	900†	250	245	1800†	120
Estimated Floor Area	(m^2)	3·2	0·98	3·3	4·2	0·98	5·9	4·3	7·9	5·9	4·6	7·8	5·0

* For Electrical Distribution only.
† includes autosurveillance equipment.

The total weight of all control and surveillance equipment, including cable, increases through the options from approximately 5260 kg to 8710 kg, cable contributing from 20% to 27% respectively. In comparison with plant weight, that of the control and surveillance equipment cannot be considered as a major constraint; it is approximately equal to the weight of one air-conditioning plant, or 30% of the weight of a diesel generator.

Calculations of the weight distribution of the machinery control and surveillance equipment showed that, in general, the position of the ship's centre of gravity would not be significantly affected, and that the weight of the equipment is less than 0·5% of the total weight of the ship. It is therefore considered that any effects on stability and displacement would be insignificant.

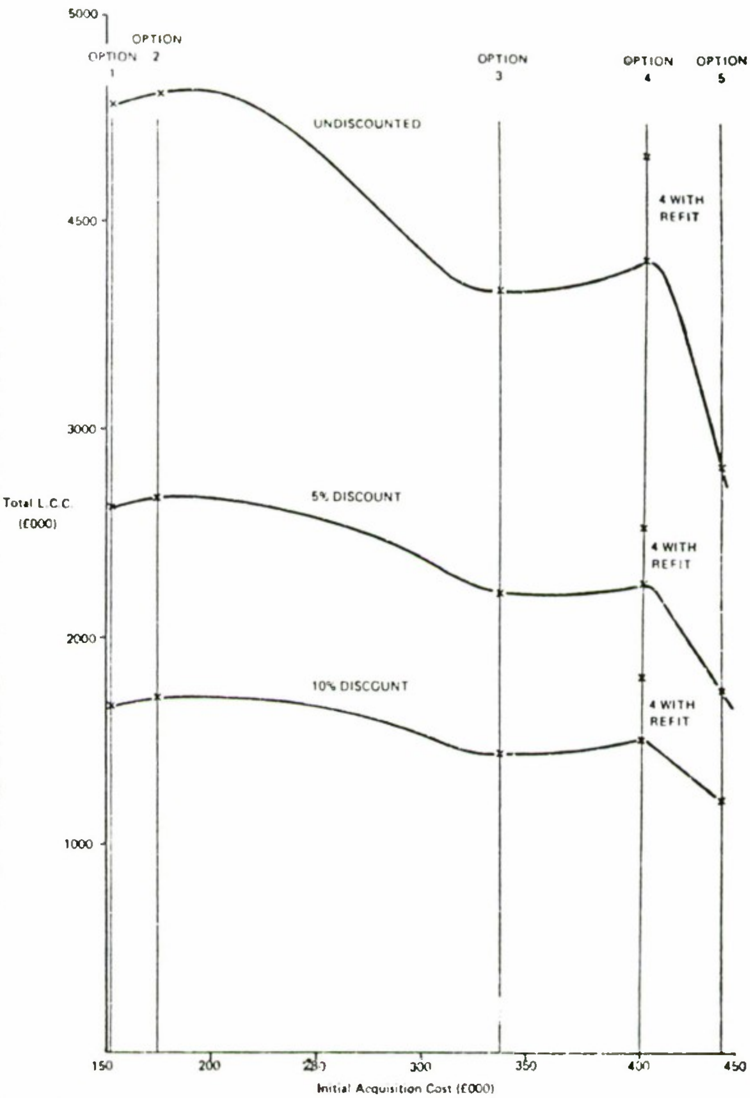


FIG. 4.

Panel areas and console volumes are generally greater than in comparable commercial systems. This is probably because modular packaging, which is relatively inefficient in terms of volume and weight per function, is extensively used in the naval equipments considered in the study.

TABLE 6.

Option	*Equipment in Machinery Spaces*		*Cable*
	Weight (kg)	*Vol (m³)*	*Weight (kg)*
1	3713	5·21	1072
2	3713	5·21	1072
3	4070	6·68	1788
4	4070	6·68	2324

System Effectiveness: Controls

Table 7 shows the basic failure rate and repair data for plant and its control systems. Plant failures are divided into non-repairable at sea (NRS) and repairable at sea (RS) categories. The repair time (MTTR) for plant control was assumed to be one hour in all cases. This table also contains some basic data on the Propulsion and Steering System Controls.

The data on groundings, collisions and berthing incidents showed that, on average 30% of all ships at sea are involved in an 'incident' during a year, and that 80% of incidents are attributable to human error. Control failure and machinery failure are responsible for 3% and 9% of all incidents respectively.

Increasing the complexity of plant or of control systems will reduce reliability. From Table 7 the comparison between repairable at sea (RS) plant failures and control failures shows that controls appear to be two to ten times more reliable than plant, the one exception being the gearbox. The reason for this anomaly was that the particular gearbox from which the data were obtained had a control system which was complex in comparison to the plant.

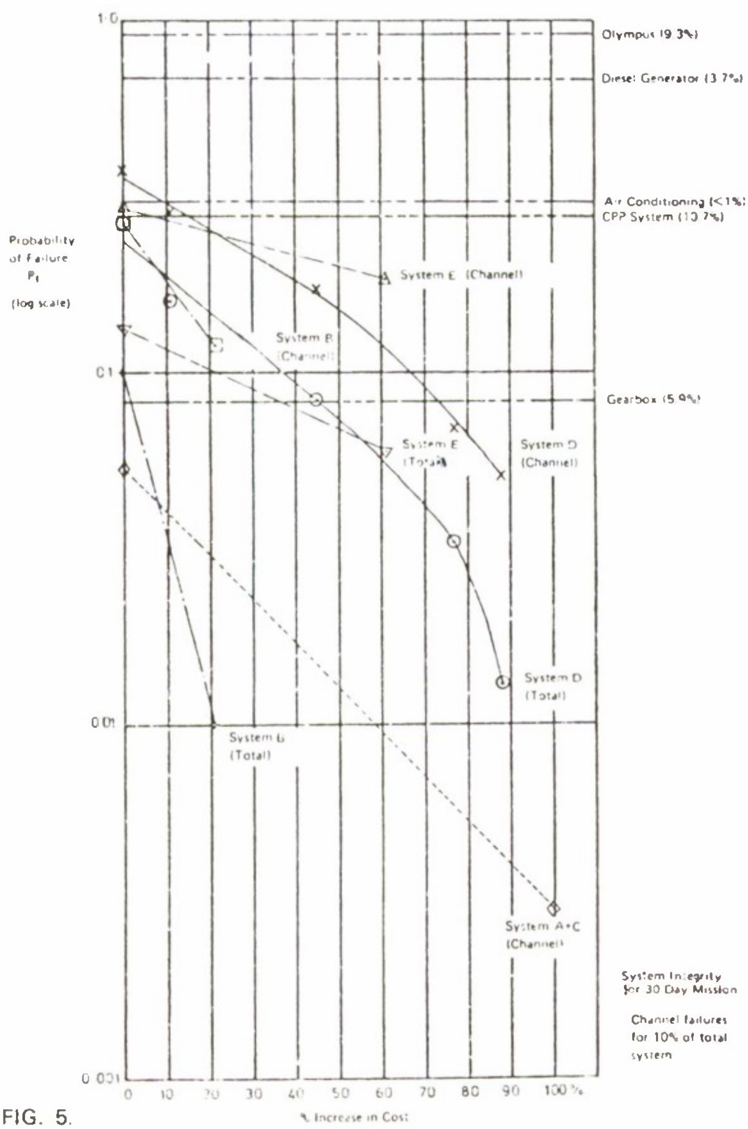


FIG. 5.

TABLE 7.

Plant or System	*Machinery* λNRS %/1000 hrs	λRS %/1000 hrs	MTTR hrs	*Control* λ %/1000 hrs	*Remarks*
Diesel Generator	20	150	5	27·6	Electronic Control
CPP System	2·4	44·5	4·4	27·4	
Air Conditioning	31·9	18·4	6·1	10·3	
Gas Turbine	25	250	3	16·3	Electronic Control
Gearbox	5·7	4·2	6·3	31·4	Reversing Type
Steering Control System:					
Analogue	–	–	–	37·5	Single Channel
Digital	–	–	–	6·3	Single Channel
Propulsion Control System	–	–	–	22·5	Power/Pitch System

Failure rates quoted are approximate

If the proportion of failures resulting in unacceptable machinery modes is taken as a criterion for assessing control integrity requirements, then system design becomes a major factor. Investigations have shown that, in some cases, as many as 50% of failures would result in unacceptable machinery modes — whilst in others, where the system would incorporate fewer interdependencies, a proportion as low as 5% has been predicted.

The reliability of system controls can be assessed by comparing the proportion of ship accidents caused by failures of system controls with the proportion attributed to human error. It is obvious from the results that even significant improvement in the integrity of system controls would improve ship accident rates only marginally.

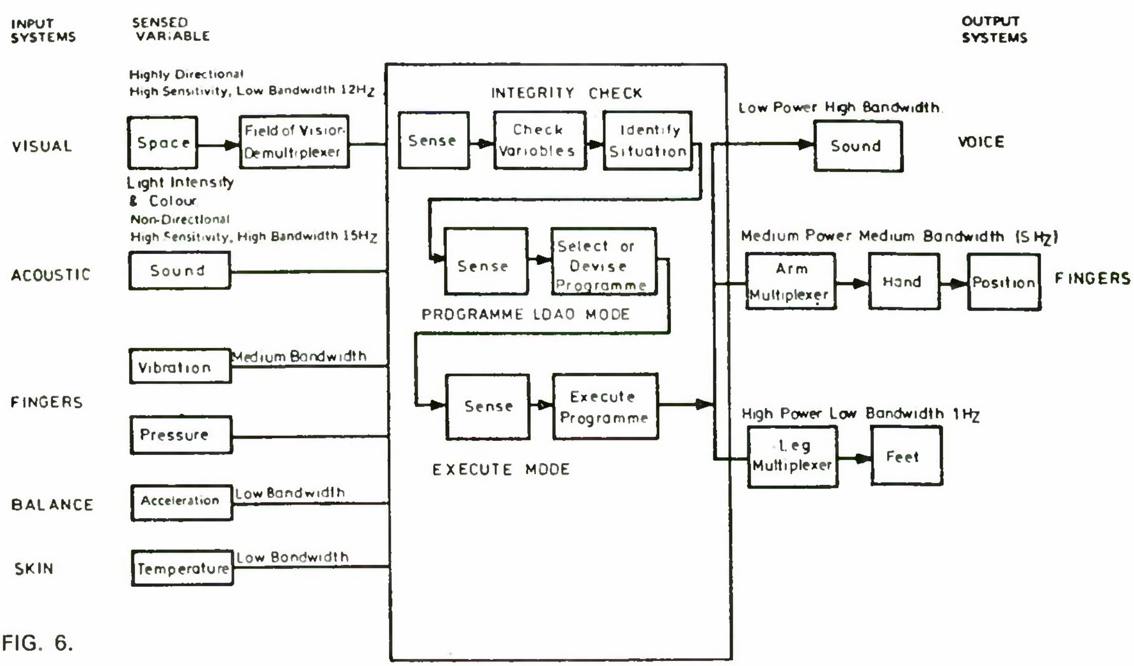


FIG. 6.

System Effectiveness: Surveillance

The results showed that, for a 360-channel installation, the costs of Systems A and B are similar and are approximately double those of the other three systems. However, Systems D and E have the particular advantage of low additional costs associated with system expansion. Systems A, C and E are basically similar (they are all parallel-wired to some central point); the installation costs of each are assessed as £28,000. The installation cost of System B is approximately 70% of that of Systems A, C and E, this being due to a reduction in cabling brought about by the incorporation of local multiplexing units. The installation cost of System D is approximately 50% of that of Systems A, C and E, largely because of the incorporation of local multiplexing units with a smaller parameter-handling capability. The results in general show that the hardware and installation costs are of the same order, and hence any saving in either of the two areas are equally significant.

The equipment costs for the more complex software-based systems are lower than those of the simpler hardwired systems, and the former also offer greater flexibility and capability of expansion. However the costs associated with the development of the software to run them must also be considered to see whether the 'standard packages' usually supplied by equipment manufacturers are adequate to perform the functions required.

It is apparent that installation costs can be significantly reduced by employing a system which utilises local multiplexing units. The savings depend upon the number of multiplexing units used, and there is an optimum situation which largely depends upon the machinery layout and surveillance requirements.

To enable system integrity to be considered, calculations were made for different mission lengths and channel failures within different proportions of the system capability. Also the sensitivity of the results to the estimations and assumptions made was investigated. However it is possible to reproduce only a sample of these results here. Fig. 5 shows the cost penalties incurred in improving system integrity. The particular case shown is that of a 30-day mission and channel failure within a group of channels equivalent to 10% of the surveillance system capacity. Some systems lent themselves to unit duplication more readily than others — hence the difference in the number of data points shown. Also shown is the probability of plant failure within the mission time and the typical percentage of surveillance capability dedicated to each plant or system.

In general, the surveillance system integrity requires improvement. However, to assess the integrity requirement realistically, one has to consider individual plant and parameter requirements — which can only be done by considering the effects of a plant failure on the overall ship operation. The integrity of the complex surveillance systems considered in the study is not easily improved within areas associated with particular plant and it is necessary that overall system integrity be improved as a first step; this however, increases costs. The integrity of the simpler systems, however, can be increased simply, by channel duplication.

The results of this analysis were found to be largely insensitive to possible inaccuracies in the estimations made.

Discussion

Projection to Other Ships

For a small ship, the life cycle costs would show little or no change regardless of the level of automation chosen and therefore, from the standpoint of cost-effectiveness. Option 2 is clearly the optimum choice because for low initial cost, it provides maximum manpower flexibility. The immediate question is: to what extent is it the optimum for other types of ship, either naval or commercial? For larger naval ships, estimates of the major cost components (operator consoles, installation and plant controls) can be made, adjusting for increases in machinery plant items and in ship length. On this basis the initial cost of Option 4 is £0·9M for a guided missile destroyer, rising to £1·2M for a small aircraft carrier. Since the watchkeeping manpower level for Option 4 does not rise in direct proportion to the two variables which heavily influence initial cost, and since no additional maintenance effort is required, then an efficient centralised manning scheme for Option 4 becomes increasingly attractive. However, for large ships the initial equipment cost is considerable — in fact it is more in balance with manpower costs. The optimum choice for large or complex ships therefore, is Option 5, which would have the watchkeeping team of a conventional frigate.

From the effectiveness point of view, no strong case appears to exist for any one configuration option for small ships. For large ships, however, the need to decrease vulnerability and keep machinery available under action damage increases the bias towards Option 5, the ultimate case in point being a nuclear submarine with its complex and interactive machinery fit operating in a highly hazardous environment.

For commercial ships, automation would seem in principle to be much more cost-effective, since the machinery fits are usually very simple and the basic equipment cost is less than half of its naval counterpart. The penalties for overmanning are therefore much more severe. The cost components for a commercial ship system are dominated by those of installation and remote operator facilities, and hence the optimum configuration for commercial ships is clearly Option 3.

Integrity, Costs and Redesign

The integrity of control and surveillance systems may be improved by increasing their reliability (*i.e.* by having fewer failures) or by increasing their complexity in order to counter failures by reversion to an alternative mode. Increase of reliability implies either the use of components with higher intrinsic reliability, or use of new technology to reduce the component count whilst keeping the function identical. (Simplification of the control algorithm would also result in increased reliability, but further simplification is not considered possible). Neither of these approaches offers much by way of cost benefits — in fact the use of high-reliability components would result in significant cost increases. Also the sensitivity of increases in integrity to overall increases in reliability is one to one at best, and a worthwhile improvement in reliability would be difficult to achieve. For these reasons, increased reliability can be discounted as a means of improving integrity.

Increased complexity could certainly improve integrity — but at the expense of reliability, unless countered by the use of new technologies in design. The necessary increase in complexity may be only small, and so the need to maintain reliability levels would not be paramount; this depends very much on detail design, however, and the subject is difficult to quantify. It must be noted that, while redesign may well improve integrity, it would also affect costs. In some cases, cost could be reduced by using integrated circuits rather than discrete components and/or by more efficient packaging methods. Redesign at component level can reduce component count in certain areas by a factor of 10. It can also increase reliability by as much as four times and reduce costs by up to 40%.

Software-based systems can reduce cost by allowing a small number of components to be shared across a number of functions, as is the case in some of the surveillance systems considered. For a given expenditure — and discounting systems with small channel requirements — then the more complex software-based surveillance systems are most cost-effective; this becomes more evident as the channel requirement increases. Moreover, if the present upward trends in manpower costs against material costs continue, installation costs will become increasingly significant, further reinforcing this point.

The principal difference between commercial and naval designs was considered to be the naval requirements relating to shock damage; certainly some of the apparent cost advantages of commercial equipments stem from the fact that it is not required to meet naval shock specifications. Also it may be that too high a price is being paid for approved components in naval systems, with not particularly high returns in terms of the overall integrity of the equipment.

In general, commercial equipments incorporate more advanced technology. This can be seen in the surveillance system where, because of the introduction of software, the system has a potentially higher capability with increased versatility — at lower cost.

Areas in Which to Improve Cost-Effectiveness

The results clearly demonstrate that much of the cost benefit envisaged from the implementation of the second phase of automation in Royal Navy ships has failed to materialise. The principal cost factors reducing benefits are:

(a) the inefficiency of current manning schemes

(b) the high cost of operator display facilities and of system installation.

The principal factor affecting costs is the watchkeeping requirement. In non-automated options it dominates the life cycle cost, and in automated options it dominates the initial cost. For small ships with small reliable machinery fits, watchkeeping is not cost-effective, whether implemented manually or automatically.

Man is a highly sophisticated control device, analogues in many ways to a digital processor system, but more versatile as illustrated in Fig. 6. The number of man's sensor types, and the wide variety of his bandwidth capabilities, together with the multiple capabilities associated with his sensor and output systems gives him an enormously powerful input-output system. His central processor system runs in at least three modes, its most powerful facility being the ability to construct a programme for executive action from memory. Unfortunately the weakest link in the system is the logical thinking mode which is essential for integrity checking; generally, man is a poor logical thinker — and he is very slow in this mode.

The many similarities between man and digital systems, however, should result in easier methods of interfacing man and automated systems. Indeed the disadvantages of present generations of analogue systems arise from the use of parallel transmission and display of information, instead of using multiplexed data from the plant level in the system. The use of digital systems to provide multiplexed data transmission and display will reduce cost and will also provide the means of overcoming man's inherent weaknesses in logical checking at speed. Hence it will contribute to an increase in basic overall system integrity.

Clearly, system cost effectiveness can be improved in areas related to the use of man and the methods of interfacing him with the systems for the acquisition and display of data.

Other important factors contributing to the low cost-effectiveness of present systems are the substantial penalties in installation cost resulting from the location of control and surveillance electronic hardware in positions remote from the machinery spaces and the severe integrity requirement imposed on a centralised surveillance system by the need to monitor a relatively reliable plant (such as a gearbox) when the bulk of its task is concerneed with monitoring plants of significantly lower reliability.

How to Improve Cost-Effectiveness

The predominance of manpower costs dictate that more efficient methods of manning should be devised. It should be possible to reduce manning levels to some extent without increasing the present level of automation at all. The companion paper argues that automation will probably be necessary to reduce the present manning level in areas other than conventional machinery control and surveillance.

The high reliability and small size of digital systems permit the implementation of plant control and surveillance functions on the machinery items which they control. Significant cost benefits for the overall system may therefore result from reductions in the number of equipments and in the amount of ship cabling.

The local implementation of certain functions may permit the overall system integrity to be tailored to the needs of individual plants, and this, together with the lower cost of distributed systems, may improve the cost-effectiveness of surveillance systems. Ultimately it should be recognised that it may be more cost-effective to consider separate surveillance arrangements (or even no surveillance at all) for reliable plants whose function is not critical.

Conclusions

The conclusions of this study for a small warship can be summarised as follows:

The system concepts discussed have been extremely useful as a basis for the study in providing a powerful and flexible method of evolving configurations (observing that automation is not universally beneficial) and of identifying hardware solution that will improve cost-effectiveness.

The use of life cycle costing techniques involving discounted cash flow shows, that, for a small warship with present technologies, automation produces few significant economic advantages. If more sophisticated automation, solutions were to be adopted, no major space, weight or maintenance constraints should arise, provided that space requirements are recognised early in the ship design.

Manpower costs dominate all other costs, even with present levels of automation, and hence greater efforts should be made to produce efficient manning sehemes, achieving an optimum balance between men and automation within the constraints of operational efficiency. The temptation to reduce manning by adding automation should be resisted until this is achieved. A general limitation on the development of efficient manning schemes is the baekward state of the art in understanding the control characteristics of man.

Savings can be made by adopting commercial marine standards, partly because of the more advanced technology used in commercial equipment. The main area of difficulty will be in meeting the naval shock standards.

It is considered that the integrity of surveillance systems using centralised processors requires to be improved. The cost-effective solution for surveillance systems is to use software based systems with local multiplexing units.

The present reliability of control equipment is acceptable but integrity must be increased, and this should be done by increasing functional complexity. New technology and redesign should be used where practicable to maintain the present level of reliability.

The dominance of manpower cost is likely to maintain the emphasis on reducing the numbers of men at sea, although the role of automation in the future will be to assist man rather than replace him. Systems based on digital technology will be eminent in this role. A key stage will be reached when digital hardware costs have reduced system costs to the point at which the costs of display and plant control are dominated by those of installing the cabling. At this point, a major switch to digital technology must occur. It may be expected to affect all types of ship, both commercial and naval.

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THE IMPACT OF AUTOMATION UPON WARSHIP DESIGN—THE "TOTAL SYSTEM" CONCEPT

Captain G. G. W. Marsh, O.B.E., M.A., R.N., and
Commander A. J. Stafford, M.I.E.E., M.I.Mech.E., R.N.

Abstract

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 field 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 emphasised 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 recognised 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 manpower 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 watch-keeping. 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 nonetheless 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 judgement 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 optimised 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 war-ships 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 specialised 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 economise 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 costs 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 above) 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 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, and/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, this discussion has demonstrated that 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 may have downstream effects upon manpower utilisation 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. It is now necessary to consider 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 (OOW)
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 cumulative 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 warships operational effectiveness, whereas it is the performance of unscheduled tasks that determines the ships' 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 warships 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 firefighting 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 2,000 - 3,000 tonne frigate at around 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* (2,500 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) which 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. However, 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 above 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. It is now necessary to explain the path along which selection of the second option could lead us.

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 emphasised in previous paragraphs, and it is clear that as the number of men in a given ships 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 rationalisation 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, we have 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 warships 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 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, organisation 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 generalised definition of operator tasks will serve.

Warships are normally organised on the basis of a hierarchical structure on the lines of that shown in Fig. I.

The three levels of operator defined in this hierarchy are of course generalised, but in terms of hardware management it may be said that the Command is concerned with ship-

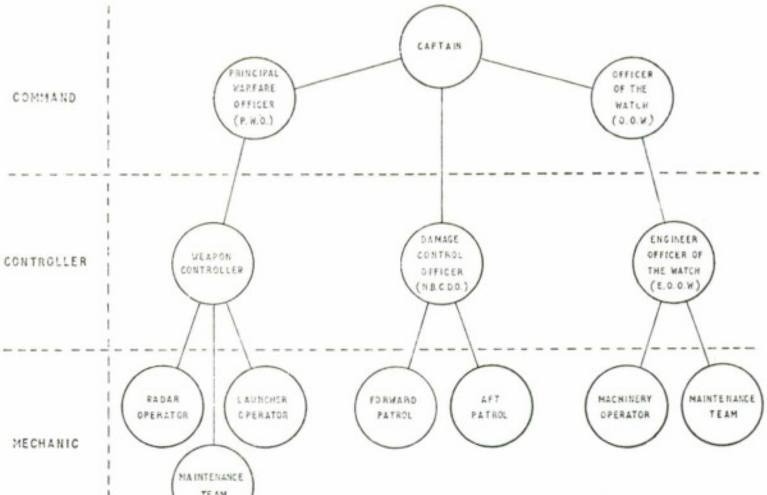


FIG. I — OPERATOR TASK LEVELS

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 Fig. 2 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.

Even a cursory inspection of the broad definitions given in Fig. 2 is enough to convince that the activities listed against the Command and Controller level operators should be categorised 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 pre-requisites 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 Fig. 2 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 H.N.L.M.S. *Tromp* — both highly automated ships fitted with Bridge Control over a COGOG propulsion system. In both these ships it is understood that the Marine Engineering 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 reactions 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.

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 above, in the light of any material or environmental constraints.
	T3 To decide personnel priorities in order to meet T1 above.
	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).

FIG. 2

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, and 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 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 that 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 Controller 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. 3.

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.

Such a warship would undoubtedly be as effective as its traditional counterpart whilst all its automated machinery is functioning correctly, 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 system 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 which 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

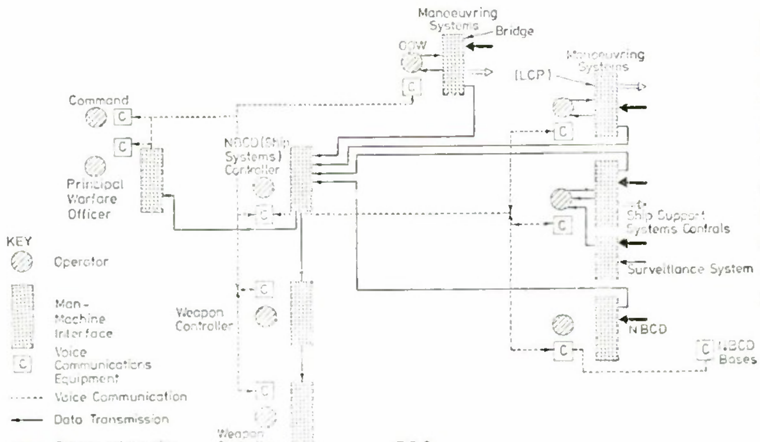


FIG 3

CONNECTIONS BETWEEN MACHINERY MAN-MACHINE INTERFACES AND SHIP COMMAND/WEAPON CONTROL 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 high ways tend to reduce these "volumes of vulnerability" by localising 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 localised 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 upon 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 outlined above 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 2,500 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 discussion 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, we 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, or to take 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.

ADVANCING UNDERWATER TECHNOLOGY

L. D. Wyld, Ph.D.

Naval Underwater Systems Center

The mission of a United States Navy laboratory is defined by the Department of the Navy. That of the Naval Underwater Systems Center (NUSC) is to be the principal research, development, test and evaluation center for submarine warfare and submarine weapon systems.

"Essentially," said NUSC's Commanding Officer, Captain William L. Bohannan, "that means sensors, launchers, fire control, weapons, and communications for underwater surveillance and antisubmarine warfare: their development, their integration into a total combat system, their military application, and their maintenance and readiness during their life cycle in fleet use."

"If you were to gauge the contribution and responsibility of this Center," observed Captain Bohannan, "you have only to note that most of the principal sensors and weapons of our submarine and surface antisubmarine forces have been and are the products of this Center's efforts."

With a current staff of over three thousand persons, including some 170 resident military program personnel intimately involved with the technical effort, NUSC operates two principal R & D laboratory complexes in Rhode Island (Fig. 1) and Connecticut, with a major undersea test and evaluation center at Andros Island in the Bahamas, and other facilities and field stations in Bermuda, Florida, New York, and New England. Through an exchange scientist program NUSC is represented at the Admiralty Underwater Weapons Establishment, England; New Zealand Defence Scientific Establishment; Royal Australian Navy Research Laboratory; SACLANT ASW Weapons Research Center, Italy; and other related installations.

History of the Center

NUSC officially dates from the 1970 merger of the Navy Underwater Sound Laboratory at New London, Connecticut, with over three decades of distinguished pioneer work in sonar, acoustics, and electromagnetics research; and the Naval Underwater Weapons Research and Engineering Station at Newport, Rhode Island, whose history in underwater ordnance technology extends back to the 1860s.

The Underwater Sound Laboratory was the lineal descendant of two World War II laboratories operated by the U.S. National Defense Committee in close cooperation with the Navy, the Columbia University Division of War Research and Harvard University's Underwater Sound Laboratory. The Columbia laboratory at New London focused chiefly upon the development of passive sonar detection devices; at Cambridge, Massachusetts, the Harvard laboratory gave primary attention to sonar of the echo-ranging type and originated the early scanning sonar techniques. In July 1945 the sonar portion of Harvard's effort was transferred to New London and merged with the work undertaken by Columbia, creating the Underwater Sound Laboratory within the U.S. Navy's laboratory system. In the ordnance area, NUSC derives from the Naval Torpedo Station established in Newport in 1869, through its successors which included the Central Torpedo Office (1947), the Naval Underwater Ordnance Station (1951), and the Naval Underwater Weapons Research and Engineering Station (1966).

The Center and its predecessor establishments have made wide-ranging contributions to the solutions of problems of undersea warfare and to the fields of oceanography and

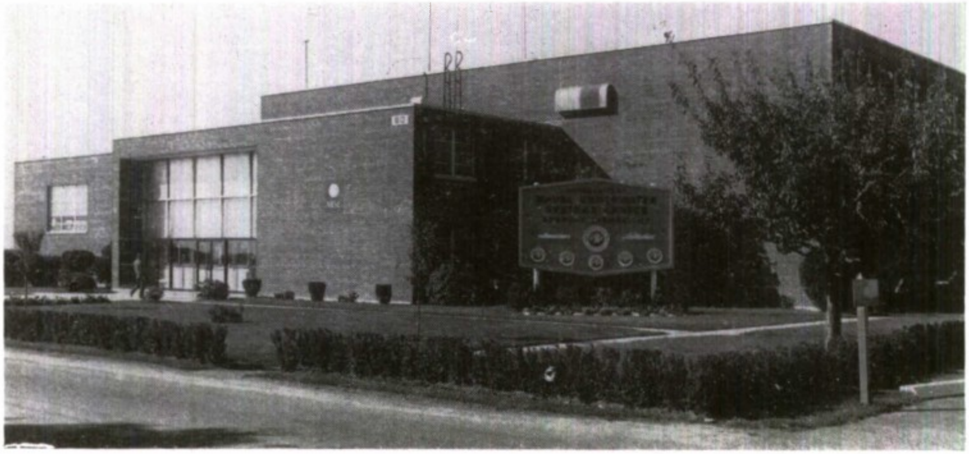


FIG. 1. Entrance building for visitors to Center headquarters and the Newport Laboratory. Capt. W. L. Bohannan is the Commanding Officer; the Technical Director is Dr. C. N. Pryor, Jr. The Naval Underwater Systems Center is one of eight laboratory centers operated by the Naval Material Command under the Director of Navy Laboratories.

ocean engineering. NUSC has been a pioneer in sonar system development, the invention of the underwater telephone for submarine-to-submarine and submarine-to-surface communication, several deep-ocean engineering "firsts," and the development of underwater ranges, mobile acoustic targets, new torpedoes, and torpedo-launch systems.

Underwater Combat Systems Integration

High performance submarines need sensors, computers, controls, displays, launchers, and weapons working together as an integrated combat system. This integration is performed by combat system control, a key element in total weapon system effectiveness. NUSC engineers and scientists are specialists in this field, which involves the complex electronic equipment that translates sensor data about the target into position and velocity data from which weapon orders are generated, weapon settings made and attack carried out. In this area, the Center is involved in the development of advanced combat control systems for new submarines and at the same time has design cognizance and in-service engineering responsibilities for existing torpedo and ASW missile systems.

In the Center's unique fire control development laboratory new and operational systems are dynamically exercised during development and after their fleet introduction to verify their performance. Follow-on developments for fire control systems are tested in this facility

FIG. 2. The system certification and integration facility is a central computer complex for evaluating combat systems and components for new-construction submarines. The SCIF provides realistic at-sea simulations, such as sonar and periscope inputs.

using simulation for the environmental and tactical situations.

Three current installations in particular reflect NUSC's participation in major system developments: a system certification and integration facility (SCIF) for the SSN 688 class and class-improvement combat systems, a land based evaluation facility (LBEF) for the Trident class command and control system (CCS), and a submarine integrated attack center (SIAC) laboratory.

In the SCIF and LBEF facilities (Fig. 2) a combination of stored sea test data and simulators permit system testing for integration, certification and early warning of possible shipboard installation and operational problems. In the SIAC an integrated network of computers, displays, portions of operational systems and laboratory instrumentation is operational for developing advanced system concepts and investigating the interrelationships between operational tactics and submarine combat system design.

Fleet Readiness

Combat readiness is the essential element in the defensive posture of the fleet. Design cognizance and in-service engineering for underwater combat systems in production or in service are important parts of the Center's mission. From surface and submarine platforms, through sensors and communications, fire control, launchers, and weapons, NUSC fleet readiness programs assist with the introduction of new systems, maintain systems at a high level of readiness, increase system effectiveness, and respond to pressing fleet needs through on-site assistance. This fleet experience is a tremendous benefit to the research and development phases of Center programs.

For fleet introduction of new systems, early in the development phase NUSC takes a hard look at what is presently in the Fleet to determine what is needed to accommodate the new system. These studies form the basis for a fleet introduction plan. The plan outlines policy and guidance, and provides other concerned agencies, Government and private industry, with an overview of the total effort required to make the system fleet operational. From this point, NUSC involvement mushrooms to responsibilities in production, support facility activations, training, and ship certifications. For several years the Center has been deeply involved in Fleet introduction of the Torpedo Mk. 48 weapon system.

Other important elements in the Center's fleet readiness effort are programs devoted to accuracy and effectiveness. During shipbuilding and overhaul NUSC resident and special-team personnel provide technical assistance for the installation and testing of system hardware. Subsequently, prior to final acceptance, consolidated operability tests (COT) are conducted on submarines completing construction, major conversion, or regular overhauls. Further help is provided with weapon and sensor systems during surface ship/submarine post-construction or overhaul trials conducted by the Board of Inspection and Survey (INSURV), through weapon system accuracy trials (WSAT) to evaluate the capabilities of entire underwater systems (see Fig. 3 A/B), shipboard sonar certifications and groomings, system monitoring and evaluation, tactical exercise assistance, and through weapon performance analysis.

Ashore, NUSC augments its extensive at-sea fleet readiness programs with strong service engineering programs. For production, the Center assists with the preparation, maintenance, and compilation of design disclosure and quality assurance documentation, and develops and monitors production and quality assurance processes. For logistic support, NUSC determines supply procedures and requirements and provides assistance with procurement and repair of spare parts and subassemblies. The Center has been consistently recognized for reducing procurement costs and developing innovative underwater system modular replacement and repair concepts.

NUSC service engineering also plays an important role in system modification, training, and maintenance. Since during their service life, underwater systems usually require modification to optimize performance and reliability, NUSC provides technical assistance to correct deficiencies, and to alter fleet equipment for increased capability and for compatibility with new developments. Service engineering also provides the knowledge, and maintenance methods and facilities needed to sustain optimum system fleet readiness. Center technical services include curricula specification and preparation, technical review of training manuals, and coordination of the installation and alteration of equipment used for training purposes. In addition, NUSC personnel provide special training as needed aboard ships,

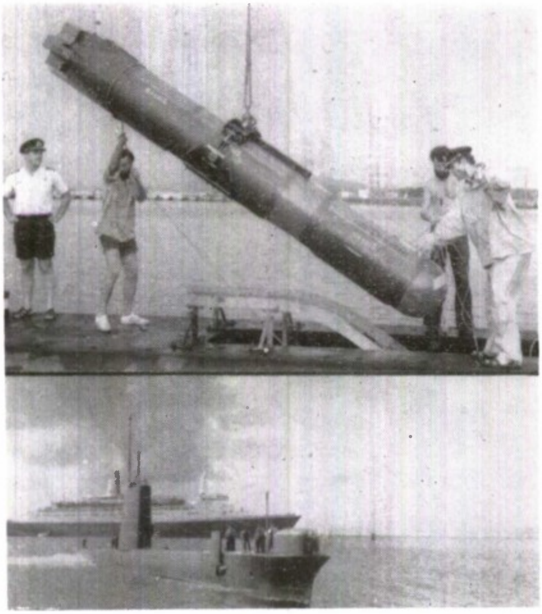


FIG. 3a. A torpedo is loaded aboard the Canadian submarine H.M.C.S. *Onondaga* during preparations for a weapons systems accuracy trial (WSAT) at Roosevelt Roads. The WSAT was conducted in January 1973 by personnel from the U.S. Naval Underwater Systems Center. 3b. Arriving at Fredericksted, St. Croix, during a weapons systems accuracy trial (WSAT), the Canadian submarine H.M.C.S. *Onondaga* passes the British commercial liner *Queen Elizabeth II*.

at shore establishments, and within the extensive laboratory facilities of the Center. To ensure adequate system maintenance, the Center participates in the preparation, maintenance, and modification, as required by fleet feedback and technical experience, of all elements of the Navy Planned Maintenance System including the Maintenance Requirement Card and Maintenance Data Collection System Programs. NUSC also has responsibilities for the design and establishment of shipboard and shore-based workshops used by the fleet.

NUSC resident representatives are assigned to major fleet ASW commands in Naples, Italy; San Diego, California; Pearl Harbor, Hawaii; Yokosuka, Japan; Norfolk, Virginia; and New London, Connecticut. In addition, the Center has a number of skilled technical persons in the field full time, dispersed throughout the world where the fleet operates, engaged in experimental and scientific work on new systems or providing engineering support for in-service equipment.

Sonar Programs

Most new sonar systems in today's Fleet were conceived and developed in the Center's New London laboratory, including the most advanced surface ship sonar, the SQS-26. NUSC is currently engaged in a major program for upgrading the SQS-26 and integrating it with variable depth sonar and LAMPS (light airborne multipurpose [ASW] system); and NUSC serves as technical program manager for the BQQ-5 submarine sonar series, designed for the SSN 688 fast attack class of submarine. The BQQ-5 is the base-line for the BQQ-6 Trident class sonar system currently under development.

Center-developed ceramic and magnetostrictive transducers have been prototypes for most of the sonar system transducers in Fleet use today. In the holography laboratory sensitive transducers which produce the sonar pulses undergo intensive study. Holographic patterns provide contour maps of the deflections of the vibrating diaphragms; variations in the holography pattern give clues to the dynamic characteristics of the transducer diaphragm — clues which can lead to improved sonar systems.

NUSC has been responsible for major advancements in surface ship sonar, involving highly directive and powerful transducers in bow domes where sonar is less susceptible to adverse seas. An important development has been the variable depth sonar, a system mounted over the stern of a ship to provide detection of close-in, below the layer, and aft targets. In support of some of the Navy's major surveillance programs, Center staff have developed a broad range of deep-sea instrumentation and ocean-engineering techniques. Typical was the emplantment of the 15-ton Eleuthera source — one of the largest transducers ever positioned in the deep ocean (Fig. 4).

Weapons

To fulfill its mission, Center engineers contribute to the development of underwater weapons for U.S. forces at sea, drawing upon extensive experience and tradition at the Newport laboratory dating back to the torpedo station of the 1860s. Most recent Center efforts to provide fully tested weapons of high performance have centered on the Torpedo Mk. 48 weapon system, the primary tactical weapon of the U.S. submarine forces. Working closely with other Navy laboratories, introducing new systems to the Fleet, and certifying system performance have been major Center responsibilities.

In its continuing program to improve torpedo performance, the Center engages in weapons research in several areas. It is a leader in multiplatform torpedo technology — a smaller, lighter torpedo that could be launched by air, surface, or submarine platforms and still carry an effective payload against the targets expected in the next decade. A quiet torpedo technology program involves research for torpedoes which can get close to a target before detection.

Mathematical modeling allows for computer analysis of preliminary concepts and designs for new weapons. Thousands of simulated torpedo attacks can be made in a single day using various system parameters and tactical scenarios. If the data prove out the validity of a system, the next step is the fabrication of initial hardware. In the NUSC electronics assembly shop, for example, prototype electronic systems are assembled and tested; and in the environmental simulation laboratory, prospective components are subjected to a variety of environmental conditions to test their ability to withstand extremes.

To provide essential support for weapon advances, propulsion systems must also be continuously investigated and developed. Recent achievements in electric torpedo propulsion include a substantial increase in energy-density through pile-type battery design, and new, high power electric motors fully competitive with thermal systems. Advanced thermal propulsion concepts, such as trochoidal rotary piston engine (Wankel) applications, are also being pursued. The propulsion laboratory complex at the Center includes a deep-depth torpedo test facility and a component test facility; and both basic and applied research in fuels, chemistry, noise reduction, and materials is conducted.

FIG. 4. The largest transducer element yet built, this 15-ton sound source was part of a facility at Eleuthera. Recovered under NUSC direction in July 1972, it was found to be still operable after six years on the ocean floor. Recording and analysis of data from the Bendix-built equipment were conducted at NUSC's Bermuda and New London laboratories.

Launcher Technology

Since weapon effectiveness is null without an effective launching system, Center engineers constantly seek to improve existing launchers for in-service torpedoes and missiles, and to develop new torpedo ejection systems.

NUSC has design cognizance and technical direction responsibility for all in-service torpedo tubes — both submarine and surface ship — and for antisubmarine rocket (ASROC) launchers. Important accomplishments have been the development of a flexible hose for wire-guided torpedoes that permits torpedo launch and wire guidance at higher speeds with greater submarine maneuverability, and the development of a turbine pump ejection system for the Trident class. The latter will serve as a smaller, quieter, and easier-to-maintain replacement for the reciprocating or ram pump system. Center engineers are also studying design requirements for high speed, damage free weapon launch along with improved weapon handling techniques.

A new wire guidance dispenser, mounted directly on the torpedo (Fig. 5) helps shorten torpedo load and reload time. The Center's launcher group has also developed a fast and safe system for recovering exercise torpedoes (Fig. 6) — one which can pluck a torpedo out of the water in high sea states in minutes and return it to shore for further use.

Oceanographic Activities

To carry out the Center's mission as the United States Navy's principal RDT&E Center for submarine systems, and to assure the successful operability of those systems in the real world, continuing attention is given to the ocean sciences and ocean engineering. Center scientists make worldwide scientific cruises to explore the energetics of wind wave motion, temperature variations in space and time, the effects of oceanographic parameters on sound propagation, seasonal variations in tidal currents, topography and sedimentology, and the physical chemistry of sea water.

These scientists have participated in joint efforts with New Zealand in KIWI ONE, investigating propagation loss in deep-ocean areas, and with the Lamont-Doherty Geophysical Laboratory in MAINLOBE (major investigation for low-frequency ocean bottom loss experiments). They have cooperated with such organizations as the Smithsonian Institution in Project OCEAN ACRE, a detailed study of the acoustic and biological characteristics of the deep-scattering layer in a one-degree-square ocean area southeast of Bermuda; and NUSC oceanographers have made studies of oceanographic variability and air/sea interaction in the western Mediterranean in cooperation with the SACLANT Center at La Spezia and several NATO countries including France, Italy, Norway and the United Kingdom. The observations, part of operation COBLAMED, were designed to examine the dynamics of the upper layer of the western Mediterranean near the Gulf of Lyons, and the response of this area to the strong Mistral winds blowing down the Rhone Valley in France. These experiments were made in 1969 and 1973.

Measurements are made using an array of moored buoy systems containing thermistor chains and recording current meters which extend from the surface to 60 m, through the shallow thermocline of the Mediterranean. The buoys are placed in a triangular array around the French Bouée Laboratoire (Fig. 7). Continuous records of current, temperature structure and meteorological conditions recorded on the Bouée Laboratoire provide a fundamental picture of the oceans' response in terms of mixing and heat flux, to variable wind and sea conditions at the sea surface. The configuration of the various sensors permits spatial and temporal correlations to be made which can provide better understanding of the

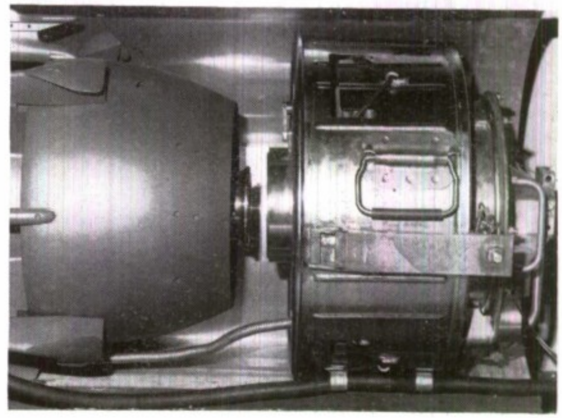


FIG. 5. This torpedo-mounted guidance wire dispenser was developed by NUSC to eliminate the problems associated with torpedo stowage, handling and guidance wire splicing onboard submarines.

FIG. 6. Seconds after retrieval of exercise torpedo from the water, the weapon recovery cage and its cargo are enroute to the land station. The retrieval operation with this diverless system averages under one minute.

mechanisms of heat and energy transfer and, hence, prediction of ASW/sonar conditions.

Another observational period is being planned for the fall of 1976 when France will have their new BOHRA II Laboratory moored off the coast of Marseilles. This project is jointly sponsored by the NATO Science Committee for Oceanography and government and university laboratories from the participating countries.

NUSC oceanographic work has resulted in a new model for the acoustic detection of objects buried in bottom sediments, validation of mathematical simulation techniques for cable-moored oceanic buoy system design, and significant progress in armored cable design and engineering.

Based upon postulations made by an exchange scientist, Mr. Paul Scully-Power of the Royal Australian Navy Research Laboratory, a cooperative investigation proposed by NUSC and Scripps Institution of Oceanography led to discovery by SKYLAB 3 of large scale eddies (about 60 miles across) off Mexico's Yucatan Penninsula and off the east coast of Australia. Oceanographic measurements were obtained of the depth and horizontal dimensions of the eddies by air-dropped expendable bathythermographs in the Yucatan area in order to quantify the SKYLAB data.

In a more recent Australian, New Zealand, and U.S. experiment, NUSC scientists participated in a joint international acoustic and oceanographic program — designated ANZUS Eddy — to measure the acoustic transmission properties of steep thermal gradients. This experiment was conducted by the New Zealand research ship TUI staffed by members of the Defence Scientific Establishment, and the Royal Australian Navy ship KIMBLA with members of the Royal Australian Navy Research Laboratory and of the Naval Underwater Systems Center aboard. The U.S. National Aeronautics and Space Administration (NASA) provided additional support to the project in the analysis of cloud cover pictures of the Tasman Sea, taken by weather satellite, which indicated the presence and locations of the eddies to be investigated.

In addition, NUSC oceanographers conduct environmental studies related to the impact of dredging, spoil disposal, and water pollution.

Range Technology and Development

Since systems must be tested at sea, NUSC has also been in the forefront in the field of underwater range technology. International recognition has come through its work in the research and development of underwater tracking ranges. The Center conceived and played a major role in developing the Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahama Islands (Fig. 8). NUSC has responsibility for the development of improved instrumentation and has full management control of the facility, the world's largest deep water range for undersea ordnance and acoustic systems evaluation. Construction of the facility was made possible by agreement between the United States, United Kingdom and Bahamian governments.

FIG. 7. Oceanographic Research. As part of studies to understand and predict variability in the upper ocean, NUSC scientists have participated since 1969 in COBLAMED, a project conducted jointly by laboratories from five NATO nations. In this effort a series of synoptic oceanographic observations are made from ships and buoys around the French-manned Bouée Laboratoire shown here.

Center expertise in range technology was applied in developing instrumentation for the Barking Sands Underwater Range, Hawaii, for which NUSC maintains an advisory role. The Center also maintains shallow water ranges, where experimental torpedoes can be operated to explore the influence of shallow water environments. NUSC has also been in the forefront of mobile range development, with the objective of providing expendable or deployable underwater tracking systems which will permit exercises and evaluations to be carried out in deep water without the necessary shore-based instrumentation.

NUSC-United Kingdom Cooperation

Data exchange agreements have been made between NUSC and the U.K. on virtually every aspect of undersea warfare research. In the past year, two unique U.K. facilities have been used to conduct research on the nature of torpedo self-noise. In one case, the effect of boundary layer transition noise on transducer output has been studied at the AUWE, Portland facility. Also, in conjunction with the AUWE, NUSC has conducted a series of experiments using the compressed air tunnel facility at the National Physical Laboratory, Teddington, to support a flow visualization study to determine the effect of torpedo nose shape in the region where transition from laminar to turbulent flow occurs. Cooperation between NUSC and the U.K. in the propulsion field has been similarly of mutual benefit. A British team recently visited Center headquarters to finalize transfer of advanced propulsion hardware for a U.K. test-vehicle program, and British scientists have provided NUSC with important data on new electrical propulsion systems.

FIG. 8. His Excellency the British High Commissioner Peter Mennell is met upon arrival in February 1975 for a visit to the Atlantic Undersea Test and Evaluation Center by Cdr. Bruce Nicholls, Royal Navy Liaison officer assigned to AUTEC. Mr. Mennell was accompanied by his defense advisor, Cdr. David J. Cole, RN.

Britain and the United States have frequently cooperated in sonar research and development programs (Fig. 9). The first British exchange scientist, Mr. Robert M. Roberts, a Senior Scientific Officer at the Admiralty Underwater Weapons Establishment, worked in the System Development Branch, ASW Sonar Division during his tenure at NUSC (1969 - 72). At the same time, Dr. Wayne Strawderman, a Senior Project Engineer in the Submarine Sonar Division, took an assignment at AUWE, Portland. Mr. Roberts subsequently returned to New London in late 1972 to participate in sea tests aboard U.S.S. *Glover* and to present a paper on sonar echoes frequency/phase measurement at the 20th Navy Symposium on Underwater Acoustics, held under the auspices of the Chief of Naval Research and for which the Center served as host.

An important example of joint U.S./U.K. cooperation that may be cited is an active sonar exploratory development program conducted several years ago. Following two years of detailed planning U.S. and U.K. scientists embarked upon a six-week experiment to compare the performance of submarine sonars aboard a U.S. and a U.K. submarine. A purely research effort with no fleet systems involved, this experiment was arranged to determine how the two different arrays and processing systems would respond when the submarines echo-ranged on each other. Following rendezvous at Gibraltar, the two vessels sailed to the mid-Atlantic ridge, then on to Gosport, England. All measurements were made at the same time and over the same paths, and a wide variety of bottom conditions and topography were sampled. Each submarine served as target and searcher simultaneously.

NUSC's former Technical Director Harold E. Nash and his counterpart at the Admiralty Research Laboratory, Teddington, Middlesex, Mr. Edward Lee, were closely involved in initial planning and spearheaded the project from the start. Team leaders were Mr. J. E. Geary, chief engineer for the U.S., and Dr. D. D. Weston, chief scientist for the U.K. British analysts for the project, Messrs, R. P. Coghlan and P. A. Ching, along with Mr. Geary, prepared the final technical report on this cooperative experiment.

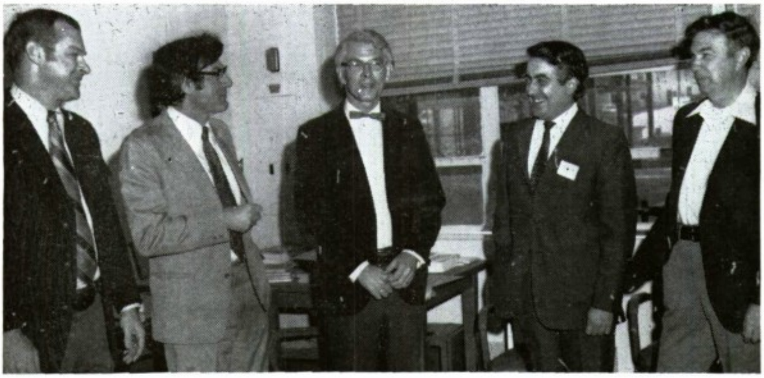


FIG. 9. AUWE Visitors. Visitors to New London in April 1975, Drs. John Wood and John Willis (second and fourth from left, respectively), Admiralty Underwater Weapons Establishment, Portland, Dorset, discussed some of their work and explored the possibility of a joint venture with NUSC. Pictured with the AUWE visitors are Dr. Wayne Strawdermen (left) former NUSC exchange scientist at AUWE, and other members of NUSC's Sonar Technology and Submarine Sonar Departments.

Officials representing the American and British navies recently concluded the eleventh annual scheduling conference dealing with the United Kingdom's use of the range facilities of AUTEC. Held at NUSC's AUTEC logistics headquarters in West Palm Beach, Florida, this conference focused on the use of AUTEC's deep-depth tracking ranges by Royal Navy ships over a period of several years and considered changes relating to policy and service, plans for system improvements, and such other topics as underwater targets and operations. Representing the U.K. were Captain Julian H. St. Aubyn-Sayer, RN, Ministry of Defence — Director General, Weapons-Navy, and Chairman of the U.K. AUTEC management group — and other members of the U.K. management group and British Navy Staff.

NUSC has provided support to various U.K. programs. Close cooperation was provided and tests were conducted at the Center and at AUTEC to insure the optimum selection and utilization of vessel tracking hardware for such U.K. exercises as the 1972 AUDACITY series (including OBJURGATE and the RAF trial EMPEROR) and the 1974 CONTRAST series. For OBJURGATE and INSPAN (part of CONTRAST), the Center provided target services for the evaluation of a new British ASW torpedo. NUSC representatives have conducted training sessions for U.K. personnel at the Royal Navy Armament Department, Ernestsettle, Devon, and have provided similar assistance in other instances.

Technology for Society

In recent years the Center has made important strides in utilizing its diverse talents and special capabilities to develop meaningful programs of technology transfer, environmental protection, and in other nondefense-area efforts. To meet and solve urgent environmental and sociological problems, the Center established an Office of Special Programs Development to apply NUSC's multidisciplinary technology and resources in the civilian sector at federal, state, and local levels. Over a hundred different technology transfer efforts have been conducted under this program since its inception.

Summary

The Naval Underwater Systems Center has conducted and pursues many varied programs that increase man's understanding of the ocean environment and provide effective utilization of ocean-engineering knowledge for both defense and nonmilitary purposes. These programs — along with those in systems research, development, test and evaluation — have significantly advanced underwater technology.

Acknowledgments

The author acknowledges the considerable assistance provided by colleagues and other staff members in the preparation of this article. In particular, thanks are extended to Dr. C. T. Kindilien and Mr. T. W. McCraw, Technical Information Department; Mr. C. L. Brown and Dr. D. H. Shonting, Ocean Sciences and Technology Department; Mr. G. R. Lopriore, Combat Systems Control Department; Mr. P. E. Moody, Launcher Department; Mr. T. F. Fishburn, AUTEC Program manager's staff; Mr. J. A. Wolstenholme, WSAT Trials branch and Capt. H. Oden, Chief Staff Officer at NUSC.

A HYDROSTATIC 'OVER THE STERN' 360° TRAINING PROPULSION UNIT FITTED TO A MINEHUNTER

G. Gardiner, NEL and R. Mulholland, MOD(PE)

Abstract

The development of a 145-hp podded multi-lobe ball/piston-motor and its adaptation as an 'over the stern' 360° training ship propulsion unit is described.

The results of harbour and sea trials are included. They show that a high degree of low-speed manoeuvrability and propulsion efficiency is achieved with this type of unit.

Introduction

In a minehunter it is important to be able to manoeuvre the ship at very slow speeds, especially so when station-keeping at sea. H.M.S. *Shoulton* was originally a Ton Class Minesweeper but during the late 1960s was converted to a minehunting role and is now extensively used as a trials vessel (see Fig. 1).

During the conversion a slow speed hydraulic propulsion system was installed. It consisted of two variable delivery pumps which supplied oil to two fixed displacement hydraulic motors which could be engaged to drive the main shafts of the ship through auxiliary gearboxes. In addition an 'over the stern' propulsion unit, also driven and steered by hydraulic motors, to give added manoeuvrability was fitted. The final drive to the propeller shaft was by bevel gearing.

A modified 'over the stern' propulsion unit comprising a hydrostatic multi-lobe podded motor driven by pistons with ball cam followers is the subject of this article. In this unit the motor is submerged and drives the propeller direct, eliminating intermediate shafts and gear assemblies.

Brief Description of Original Overstern System

The original overstern unit was supported on two vertical pillars fixed aft of the ship's transom. The unit could be rotated through 360° and thus manoeuvre and drive the vessel at slow speeds. Two fixed displacement axial piston swashplate motors mounted on the side of the overstern unit provided the steering and the propulsive power through gear trains. These motors were supplied with oil from an on-board diesel engine, gearbox and variable delivery axial piston swashplate pump system controlled from a bridge console actuator servo follow-up system. Provision was made for raising the unit on its two vertical support pillars when not in use. To allow for the raising and lowering the oil supply and return lines aft of the transom were articulated, see Figs. 2 and 3.

The propeller drive hydraulic motor displaced 22 in^3/rev and drove the propeller through a 5·09 : 1 double spiral bevel gear reduction. The maximum hydraulic motor speed was 1620 rev/min giving a propeller speed of 318 rev/min.

FIG. 1. H.M.S. *Shoulton*.

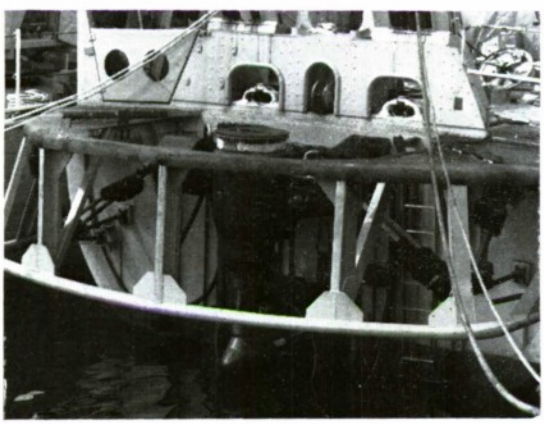


FIG. 2. Overstern unit in raised position.

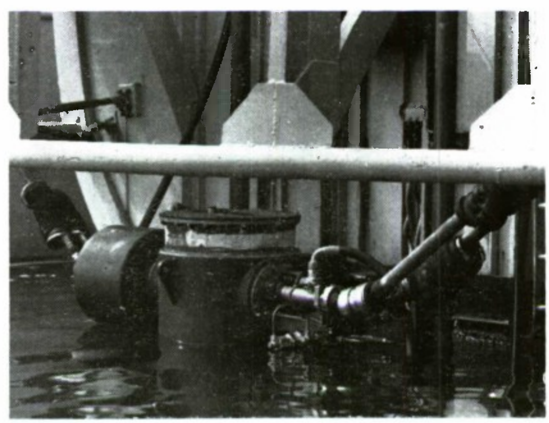
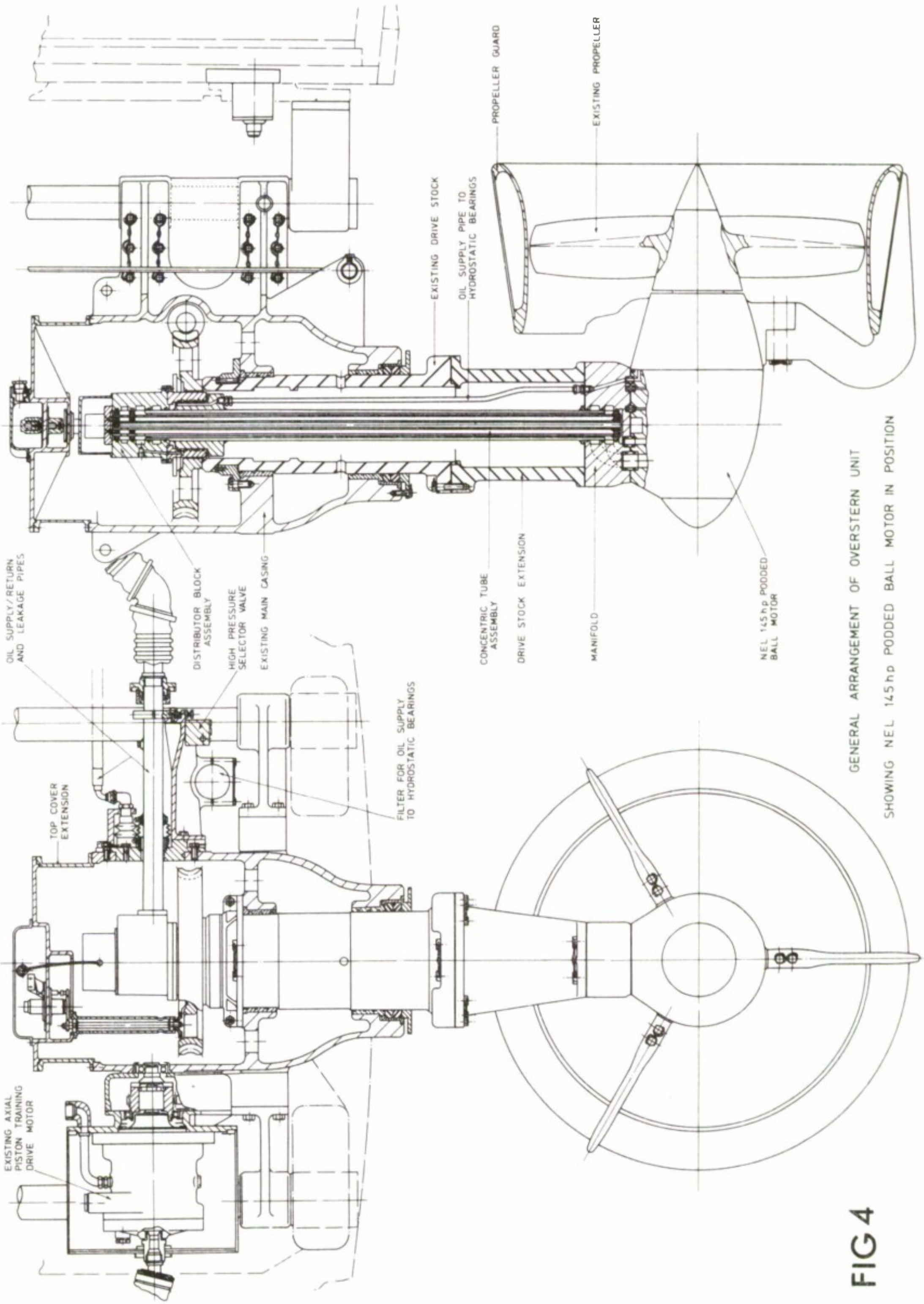


FIG. 3. Overstern unit in lowered position.

The steering motor was a $12\frac{1}{2}$ in³/rev unit rotating the overstern unit through a helical gear train to a worm shaft which meshed with a worm wheel bolted to the steering stock. The overall gear ratio was 115: 1 and the maximum training speed about 3 rev/min. As the hydraulic motor was reversible, steering angles could be obtained in both directions.

Oil supply to the steering and propulsion motors for the overstern unit was generated by an on-board system of variable delivery pumps, two $12\frac{1}{2}$ in^3/rev pumps operating in parallel and driven at 1795 rev/min supplying the propulsion motor and one $3\frac{1}{4}$ in^3/rev pump driven at 1539 rev/min supplying the steering motor. The pumps were driven from a gearbox which is powered by a Paxman Ventura diesel engine running at a constant speed of 1300 rev/min.

In the new unit the hydromechanical propeller drive is replaced by a multi-lobe ball/piston hydrostatic motor. The rotor of the motor extends beyond the casing and forms the propeller drive shaft (see Fig. 4), the unit being adapted to the existing controlling, training and raise/lowering device described above.



GENERAL ARRANGEMENT OF OVERSTERN UNIT

SHOWING NEL 145hp PODDED BALL MOTOR IN POSITION

FIG 4

Development of the 145-hp Podded Ball Motor

MOD (Navy) placed a contract with NEL to design and develop a propeller drive version of their radial multi-lobe ball motor. The power requirement was 145 hp at 220 rev/min.

Multi-lobe motor units have a number of advantages over a concentric ring or swashplate axial piston-type unit. One is that the pistons make multiple working strokes per revolution, thereby greatly increasing the torque to weight ratio. Another is that the cam profile is shaped to give constant torque.[1] The concentric ring or swashplate axial piston units develop a cyclically varying torque. With an appropriate selection of piston and cam lobe number the transverse loads developed between the pistons and cam can be balanced, thereby eliminating transverse loads on the shaft bearing. The criterion for balance is that : : number of pistons divided by the HCF of the number of pistons and number of cam lobes should be equal to or greater than three. For continuous operation the number of pistons divided by the number of cam lobes must not be equal to two.

The choice of the number of cam lobes in a motor is governed largely by the life expected of the motor. As the number of cam lobes is increased the curvature on the cam becomes smaller and this results in high contact stresses between the balls and the cam, hence reducing the fatigue life.

The combination of six pistons and four lobe cams had been found by NEL to be the most economical in terms of space and cost and gives an acceptable life for most applications.

The main parameters of the 145 hp podded ball motor are as follows:

Cylinder diameter		2·125 in
Ball diameter		1·875 in
Radial distance to centre of ball	at idc	3·1875 in
	at odc	3·9015 in
Stroke of piston		0·714 in
Displacement per revolution		121·55 in³/rev

Failure from fatigue will ultimately occur in any component which is continuously subjected to repeated stresses and although some engineering materials have an endurance limit below which failure from fatigue will not occur, rolling contact bearings do not exhibit an endurance limit.

The balls and cam ring in all multi-lobe ball/piston type motors are subjected to Hertzian-type contact stresses of a similar nature to those in a ball bearing and the type of fatigue failure experienced in ball bearings is also found in multi-lobe ball/piston motors. The fatigue life is affected by the material and the surface finish of the rolling contact elements, the ratio of the cam track radius to the ball radius, the curvature of the cam and the working pressure of the motor. At NEL equations were derived for the cam track in both radial and axial multi-lobe ball/piston motors which are based on the ISO recommendations for evaluating dynamic load ratings of rolling bearings and modified to include the special operating features of ball motors. The predicted B10 life (*i.e.* the life which 90% of this design of motor would be expected to survive without any pitting failure), of the 145-hp podded ball motor can then be calculated.

A typical life specification for drives of this type of duty is as follows:

Life: 10000 hours	15% at 85 - 100% power	
	25% at 55 - 85% power	
	30% at 15 - 55% power	
	30% at 0 - 15% power	

Oil pressurised hydrostatic bearings of the double conical type were chosen as they have two features which make them attractive for this application.[2] One is their ability to withstand high axial and radial loading, the other is their low noise and vibration characteristic. The main design parameters are as follows:

Axial thrust capacity	16300 lbf
Viscous friction loss	0·42 hp at 440 rev/min. Fluid viscosity 58 cSt
Oil flowrate	2·85 gal/min at 2000 lbf/in² supply pressure
No of recesses per cone	6

Axial bearing stiffness at 2000 lbf/in² supply pressure $10{\cdot}92 \times 10^6$ lbf/in (measured)

The oil flow and axial loading characteristics of the double conical hydrostatic bearings are shown in Fig. 5. They indicate an oil flowrate of 2·84 gal/min at a supply pressure of 2000 lbf/in² and an oil viscosity of 60 cSt. The theoretical prediction of the bearing flow was 2·85 gal/min at nominal bearing clearances of 0·002 in with an oil supply pressure and viscosity of 2000 lbf/in² and 58cSt respectively.

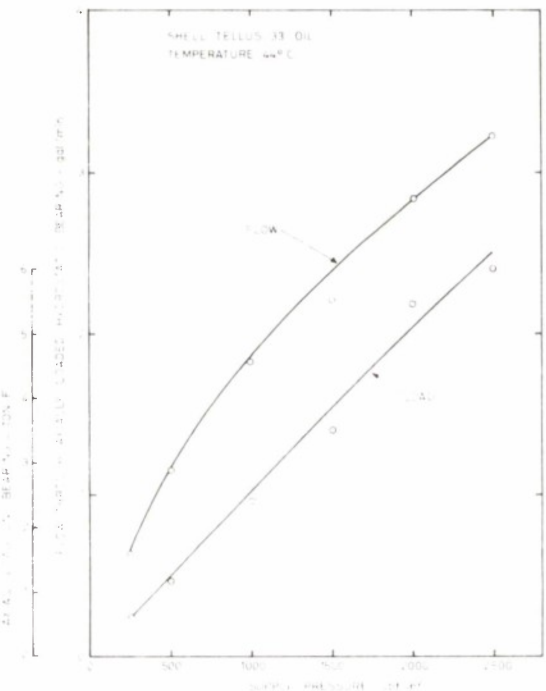


FIG. 5. Oil flow and axial loading characteristics of double conical Hydrostatic bearings.

Prior to the design study for the 145 hp podded ball motor being undertaken for the MOD (Navy), NEL had developed and tested a range of multi-lobe radial ball motors. In these motors standard ball bearings were used as pistons. To keep wear rates to acceptable limits, especially when operating at high pressure, expensive materials and heat treatment processes had to be used. Attempts to find a means of reducing cost and improving motor efficiency were investigated. One solution was to fit short cylindrical pistons so that the balls acted purely as cam followers and were not in contact with the cylinder walls. The increased efficiency is obtained by using short cast iron pistons. Unfortunately the spherical seats of the cast iron pistons wore rapidly when the motor was operated at high pressure and speed and further development work on the design and construction of pistons was necessary.

Nevertheless the improvement in performance was such that development of suitable piston designs could give worthwhile benefits. Also the construction of all motors might well be simplified as larger manufacturing tolerances on cylinders and pistons could be accepted and cheaper materials could be used for the

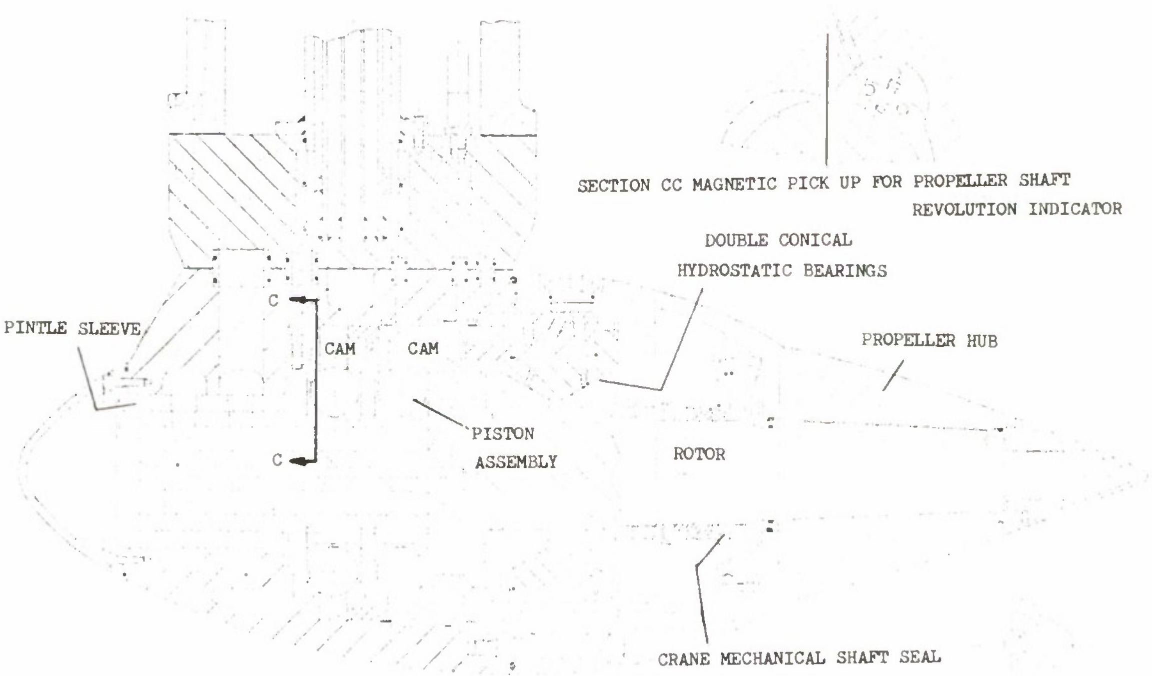


FIG. 6. Cross section through NEL 145 h.p. Podded ball motor showing manifold and lower end of concentric tube assembly.

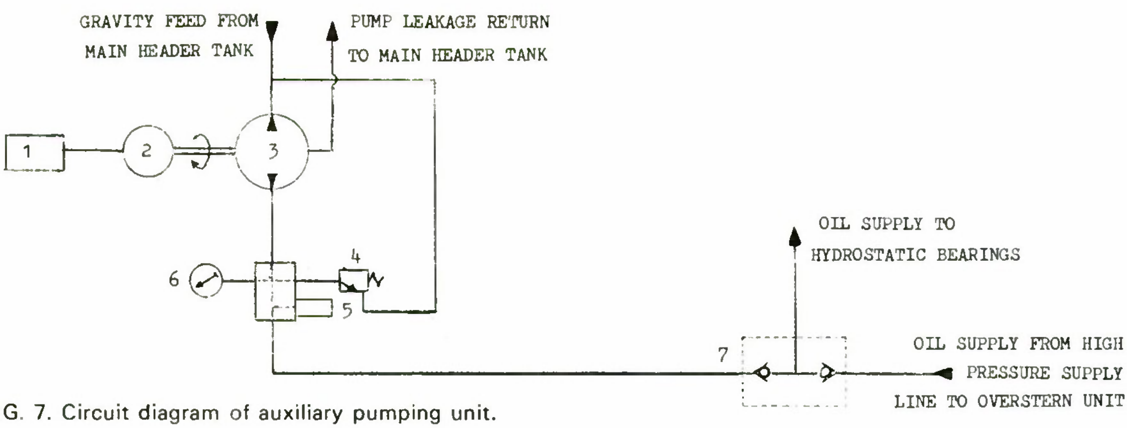


FIG. 7. Circuit diagram of auxiliary pumping unit.

cylinder block. In addition a piston/ball construction had the further advantage that fatigue of the cam would not result in seizure of pistons in the cylinders as is often the case with ball motors. Development of various piston configurations were undertaken. Pistons made from meehanite, hardened and ground tool steel and gun metal with various surface treatments were tested but with limited success. Low friction materials were sprayed on to spherical seals in an attempt to reduce wear but this was also unsuccessful. NEL then patented an idea for injection moulding a suitable plastic into a metal piston. After proving the viability of the injection moulded plastic pistons on smaller units the technique was adopted on the 145-hp podded ball/piston motor unit.

A further Navy requirement was that the motor should be capable of doubling its speed when operated in the reverse mode without requiring higher fluid flow. This is achieved by making one cam moveable so that one bank of pistons operate against a concentric track, effectively halving the displacement of the motor.

Full power dynamometer tests were carried out at speeds up to 440 rev/min with no appreciable drop in motor performance when running in one bank.

In this application as an overstern unit the two speed facility with reverse was not used, but could be for other applications. Maximum performance and thrust in any direction is achieved by 360° training.

Description of the 145-hp Podded Ball/Piston Motor Overstern Unit

A general arrangement of the overstern unit is shown in Fig. 4. As stated earlier the unit was adapted to the original steering stock which is supported in the original main casing. To achieve this adaptation a concentric tube assembly, distributor block assembly and manifold were designed to form the oil supply/return and leakage passages for the motor. A separate oil supply passage for the hydrostatic bearings is employed and can be seen as a separate pipe running between the distributor block assembly and the manifold block. Drillings in the distributor block assembly, manifold block and the motor casing carry the oil to the hydrostatic bearing jets.

Fig. 6 is a section through the NEL propeller drive unit. The rotor constitutes both the cylinder block and the propeller shaft. The cylinder block comprises two rows of piston bores of six bores per row. Each bore has a nominal diameter of 2·125 in. The piston assemblies comprise a sleeve of 2·125 in nominal diameter containing a plastic seat on which bears a standard ball bearing steel ball of 1·875 in diameter. The steel ball is retained in the piston sleeve by a circular section spring steel circlip. Two four lobe cams which are in axial alignment with the piston bores in the rotor constrain the piston assemblies in the piston bores. Each cam has a stroke of 0·714 in and is fixed to the motor casing. Oil is ported to the piston assemblies by a pintle sleeve located in the main body of the motor and drilled passages in the rotor communicate with the piston bores. Timing of the motor is achieved by ensuring correct angular alignment between the pintle ports and the cam lobes. The action of high pressure oil to the piston assemblies forces the steel ball of each piston assembly against the cam and the reaction between the cam and steel ball causes rotation of the rotor which turns the propeller.

The double conical hydrostatic bearing, Fig. 6, transmits the propeller thrust and supports the rotor and propeller weight. Each one contains six equi-spaced pockets, the flow to each pocket being controlled by an orifice jet. The oil supply to the bearing is taken from the high pressure supply to the motor when it is running.

A standard mechanical shaft seal manufactured by 'Crane' prevents sea water entry to and oil escape from the motor, Fig. 6.

Because the propeller blade tips are below the water line even when the overstern unit is in the raised position and not in use, the rotor must have bearing support at all times when the ship is at sea. An auxiliary pumping unit installed in the pump compartment in the ship provides the oil supply to give this bearing support. It comprises a 1½ hp 200/220 V dc electric motor driving a Vickers vane pump PVQ-PSSO-06CR-20. The pump is mounted on a manifold which houses a maximum oil pressure relief valve and oil low pressure switch. A pressure gauge indicates the pump operating pressure. Oil supply to the pump is by gravity feed from the main header tank in the pump compartment. The supply from the pump is fed to a high pressure selector valve on the over stern unit which selects the higher of two supply pressures, *i.e.* high pressure supply to the overstern unit when it is running and from the auxiliary pumping unit when the overstern unit is not in use. The output from the high pressure selector valve is fed to the hydrostatic bearings via a filter mounted near the valve, see Fig. 4. A circuit diagram of the auxiliary pumping unit is shown in Fig. 7. The oil low pressure switch operates the visible and audible alarms in the machinery control room, pump compartment and bridge should the oil pressure drop below the required level. A circuit diagram for the oil low pressure alarm system is shown in Fig. 8.

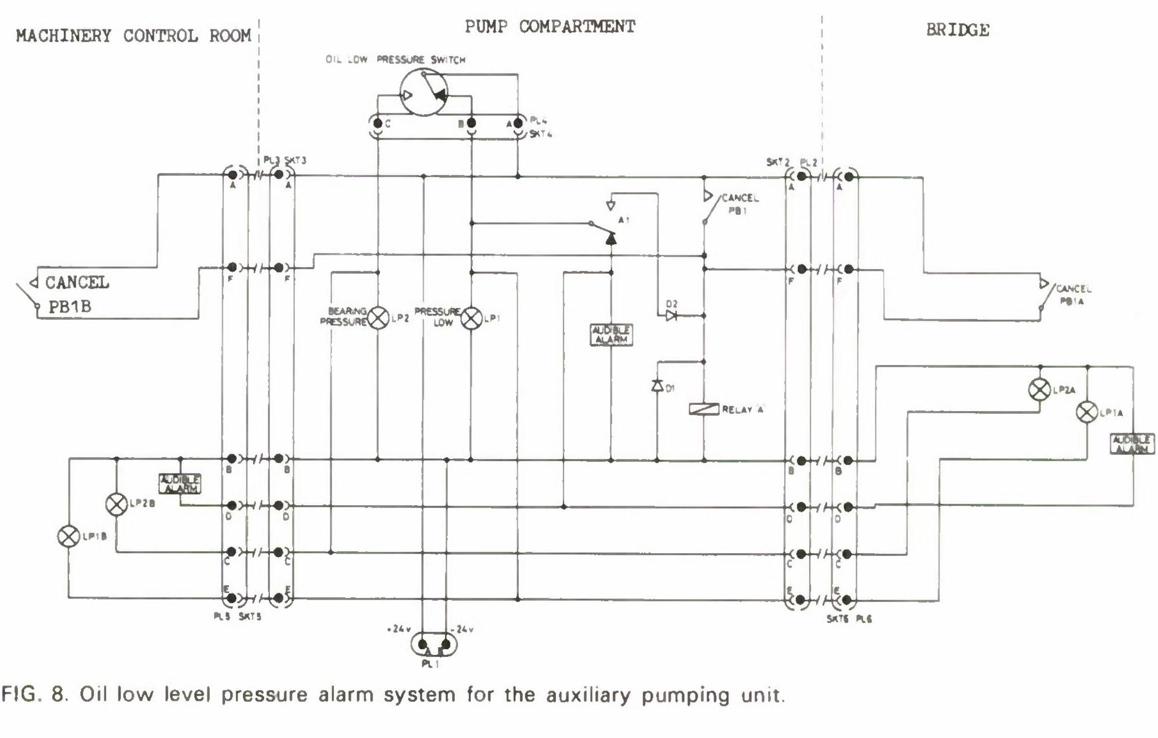


FIG. 8. Oil low level pressure alarm system for the auxiliary pumping unit.

Propeller speed is measured by a magnetic pick-up in the motor body, Fig. 6. The sensor probe of the pick-up is fixed adjacent to the rotor surface which has six slots cut into it. Every revolution of the rotor produces six voltage changes from the pick-up. These signals are amplified and fed to a frequency-to-voltage converter mounted in the tiller flat. The output of the frequency-to-voltage converter is fed to a meter mounted in the bridge console and calibrated to show propeller speed in revolutions per minute.

Ship Trials

After installation a successful programme of harbour and sea trials was carried out. The results of the harbour trials are shown in Figs. 9, 10 and 11.

The static pull of the overstern unit operating in the ahead mode was made by the ship pulling a dynamometer connected to a bollard. The results are shown in Fig. 9. The corresponding motor differential pressures are shown

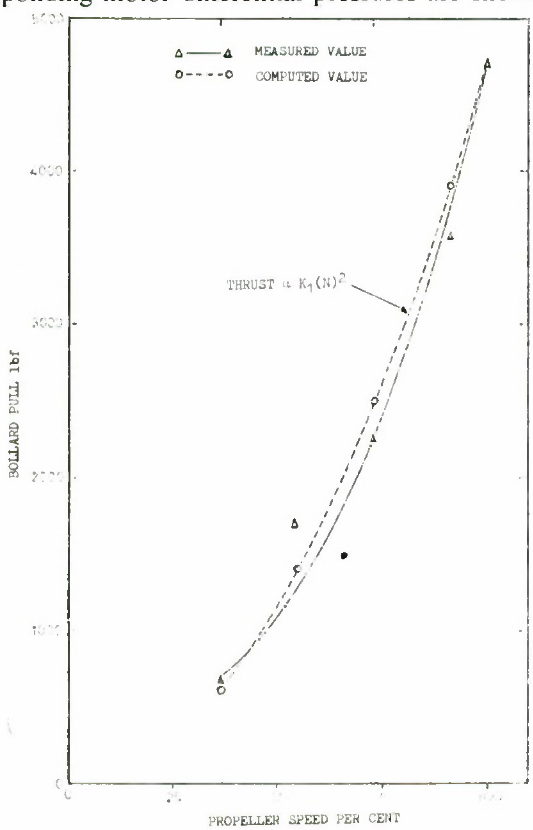


FIG. 9. Bollard pull tests — Bollard pull against propeller speed.

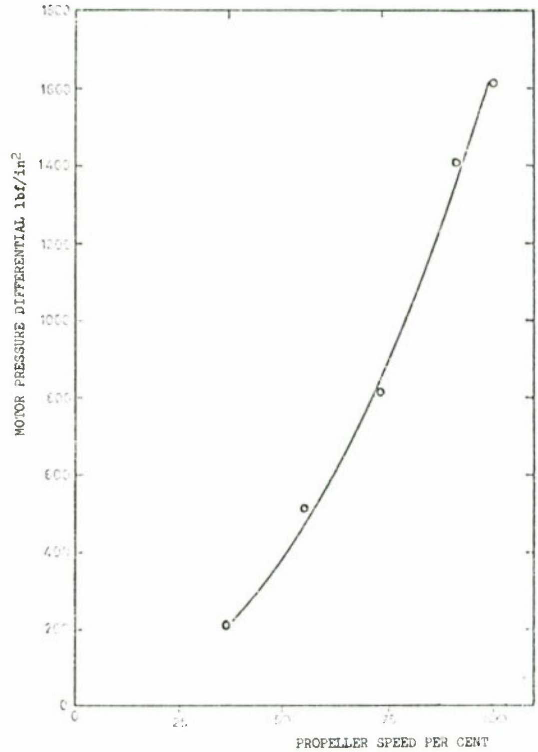


FIG. 10. Motor pressure differential against propeller speed.

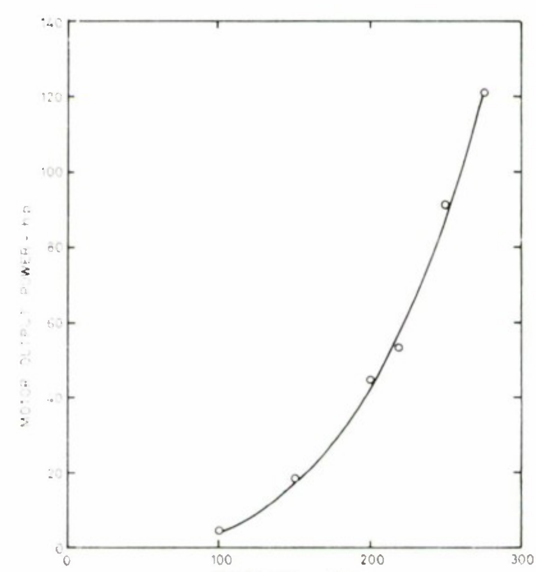


FIG. 11. Power output of motor for corresponding pressure differentials and propeller rev/min.

in Fig. 10. By reference to dynomometer test results the corresponding horse power being developed by the motor at these pressure differentials and speeds can be extracted. These are shown in Fig. 11.

A theoretical curve extrapolated from the maximum value of bollard pull has been added using the propeller thrust.

$$. T = C_T \rho N^2 D^4$$

Simplified this gives T is proportional to $K_1(N)^2$.

A figure often quoted for a mechanical drive with a ducted propeller is 31 lbf/hp. The maximum thrust obtained during these trials was 38·8 lbf/hp which is efficient and highlights the advantages of the constant torque multi-lobe ball/piston motor hydrostatic drive housed in the propeller boss.

The time taken for the overstern unit to rotate through 360° in both directions was 20 seconds at maximum propeller speed.

To ascertain the ability of the ship to maintain station using the overstern unit solely, an exercise was conducted with the ship in a fixed position relative to a buoy. The distance of the ship from the buoy was measured by a light hand line calibrated in yards. The first series of tests were conducted in a 21 - 28 knot wind and a half knot tide. The second series was conducted in a 3 - 5 knot wind and 1·5 knot tide. The r.m.s. error was found to be ±2·18 yards. These trials confirm the ability of a ship fitted with an overstern unit to station keep in a seaway to a very high accuracy.

An interesting manoeuvre conducted by the captain during this series was a trial when the tide rate slackened. The main motors were put to astern and counteracted by the overstern unit going ahead at the same rate allowing a positive control of the hover to be maintained in still water and light wind conditions.

Conclusions

A multi-lobe hydrostatic podded ball/piston motor of 145-hp has been successfully developed for installation into the boss of the propeller of an overstern unit. The application of the hydrostatic transmission system enables great flexibility of installation and the design of the motor into the propeller boss enables the maximum utilisation of the power available. This is confirmed by the increase of ship speed by the hydrostatic drive over the mechanical drive by 1·3 knots.

The principles of a hydrostatic motor for operation submerged in the sea have been developed, and the design of units of increased power is possible.

The application of a fully rotatable ducted propeller unit to provide controlled vector thrust to a ship creates a dimension of low-speed ship handling that is not otherwise available. For these reasons the hydrostatic motor was adapted for installation in H.M.S. *Shoulton* to assist in the mine hunting role and the low speed handling requirements. The facility to be able to raise the unit clear of the water at higher speeds removes the drag. Also a replacement unit could be installed in about one day without the ship needing to be dry docked. Due to the unit being installed on the transom it is vulnerable to mechanical damage and a more satisfactory type of installation may be a unit which is fully rotatable but which is lowered through the bottom of the boat within the confines of the hull.

Acknowledgements

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AUTOMATION OF LARGE ELECTRO-MECHANICAL SYSTEM TESTING

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Abstract

A case history on the application of ATE and other test procedures to large electro-mechanical system testing is presented. The final solution involves a combination of ATE (Automatic Test Equipment), BITE (Built In Test Equipment), SCCT (System Computer Controlled Test), and MCT (Manual Controlled Test).

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Introduction

System testing may be automated in at least four different ways:

(a) automatic test equipment may be provided, driven by tape or by a dedicated mini-computer

(b) where the system under test is itself computer controlled, the computer may be used on a time-shared basis, and integrated with appropriate hardware

(c) existing hardware instrumentation with interface problems already solved, such as a Fourier Response Analyser (FRA), may be controlled and results processed by a dedicated mini-computer

(d) special-to-type test hardware may be developed which automates specific existing tests, and either removes the human operator subjective assessment of test results, or provides a quantitative basis for the assessment. The hardware essentially includes a data processing stage.

All four approaches are competitors for the testing of shipborne equipment, especially when it is remembered that testing is required at the research and development, manufacturing procurement, routine maintenance, breakdown, and refit phases of system life.

The article considers the level of automation appropriate to the testing of large electro-mechanical systems, and in particular the influence of particular design, manufacture, assembly, and quality assurance philosophies in choosing an optimum level appropriate to a particular case study.

Role of ATE in Ship System Testing

The manner in which test automation is implemented in any given situation depends on many factors, only some of which may be quantified. For ship-borne applications, some of the more unusual factors have already been reviewed[1]. Dockyard applications of ATE for sub-assembly testing have been reported[2], and it is easy to see how on a volume and available skills basis such equipment is justified. At sea, however, certain manual skills must be retained and practised since in many situations the only viable back-up to an automated facility is the human operator.

Much skilled manpower is required for fault location in a system which has failed checkout. This is therefore an obvious area in which ATE might well provide substantial savings in test time and manpower, provided we know exactly which factors are important in a given application, since even if a universally applicable diagnostic tool became available overnight, there is no guarantee that it would be universally used. Table I lists some of the factors which may influence the system user away from some theoretical ideal solution. What is needed is the simplest way to return the system to a state in which it will perform as the designer intended. If a sophisticated test and data processing procedure is necessary, then it must be used, but the rule should be to do the least that can be got away with consistent with the functioning of the system. For example, a simple instrument servo-mechanism can be cheap, and *if* the optimum spares inventory level is known, the best method of fault finding may be to recognise that a fault exists from failure of the checkout test, and then to throw away the old servo and fit a new one. Here the role of ATE would be straightforward and for modern, high quality servos would necessitate only a few simple tests, which for maximum effectiveness would yield dynamic performance data. As the system under test grows in complexity, so do automatic test requirements change, as will be seen in the case study, leading to combinations of ATE (Automatic Test Equipment), BITE (Built-In Test Equipment), SCCT (System Computer Controlled Test), and MCT (Manual Controlled Test).

Access Point Considerations

There is little doubt that maintenance of many systems at present in service is hampered by the provision of an insufficient number of access points for injection and monitoring of test signals. Extra access points would simplify checkout and fault diagnosis, and a design guide laying down certain minimum requirements has already appeared[3]. On the other hand, it has been argued that provision of additional access points, will, in itself, reduce the reliability of the system under test[4], since more components are required, although this effect has yet to be quantified. The absence of a reasonable number of access points means that static tests are of limited value in maintenance, and this data deficiency is overcome by using advanced test methods and computer diagnostic routines. For example, pseudo-binary noise signals may be used to stimulate a system under test. System checkout[5] and fault diagnosis[6] is then accomplished from input-output cross-correlation function only,

TABLE 1.

Grouping of Factors Influencing System Fault Location Philosophy.

Group 'A'	Group 'B'	Group 'C'
What matters as a result of fault occurrence?	*Hindrances in putting system right?*	*Kind of things to be put right*
1. Physical damage caused?	1. Availability of manpower	1. Component failures
2. Inconvenience?	2. Technical quality of manpower	2. Machine failures
3. Danger?	3. Spares availability	3. Sub assembly failures
4. Cost of damage?	4. Local repair facilities	4. Wiring faults
5. Cost of repair?	5. Availability of test equipment	5. Dry joints/plug-socket failures
6. Speed of repair?	6. Availability of supporting documentation	6. Intermittent faults
7. Ability to take emergency action?	7. Time available	7. Modification inflicted faults
8. Fact that fighting unit is prejudiced?	8. Lack of money	8. Interference from adjacent equipment
	9. Lack of practice or training of personnel	9. Mechanical defects
	10. Access points	

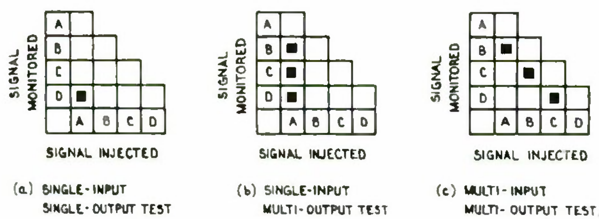

FIG. 1. Test point matrices.

the fault diagnosis being achieved using a computer based voting technique.

To develop a methodology for studying access point problems, we propose the concept of the 'test point' or 'access point' matrix which distinguishes between 'signal inject' and 'signal monitoring' capabilities, and also reduces conceptual problems in understanding test routines for complex systems. Fig. 1 shows some typical examples. For consistency, the horizontal variable in the matrix is the 'signal inject' point, and the vertical variable in the matrix is the 'signal monitor' point. The points listed are those associated with definable signal flows in the system, whether or not they are physically accessible. Thus the single-input single-output test of Fig. 1(a) corresponds to an example already mentioned[6] in which many components may be located between consecutive access points. The single input, multi-output case, Fig. 1(b), permits fault location by intermediate observation, but the signals are not necessarily well conditioned for this purpose since they will have been operated on by upstream components and therefore changed in properties. Finally, the multi-input, multi-output arrangement of Fig. 1(c) permits the conditioning of the test signal to suit local needs at the expense of providing a dual-purpose access point. An example of the matrix applied to an existing system designed for manual dynamic test is shown in Fig. 2. This system appears in block diagram form in Reference 7. Test AJ is the overall system transfer function which may be used for check-out purposes. To locate faults in the network transfer function BC, a different range of test frequencies must be used compared with AJ tests, so that it is not sufficient to inject at A and monitor at C. B must therefore be an injection point. Similarly, the power amplifier and metadyne transfer function must be tested by injecting at E and measuring at F and G.

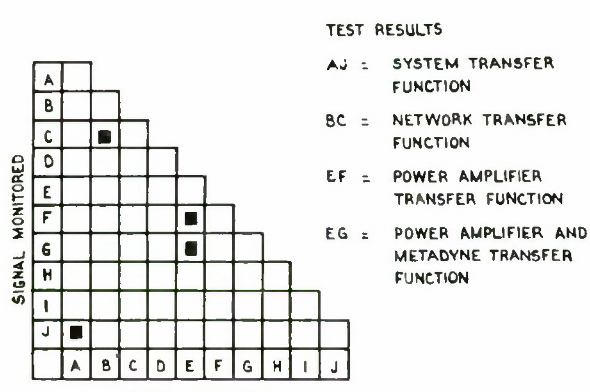

FIG. 2. Test point matrix for large electro-mechanical servo not designed for testing by ATE.

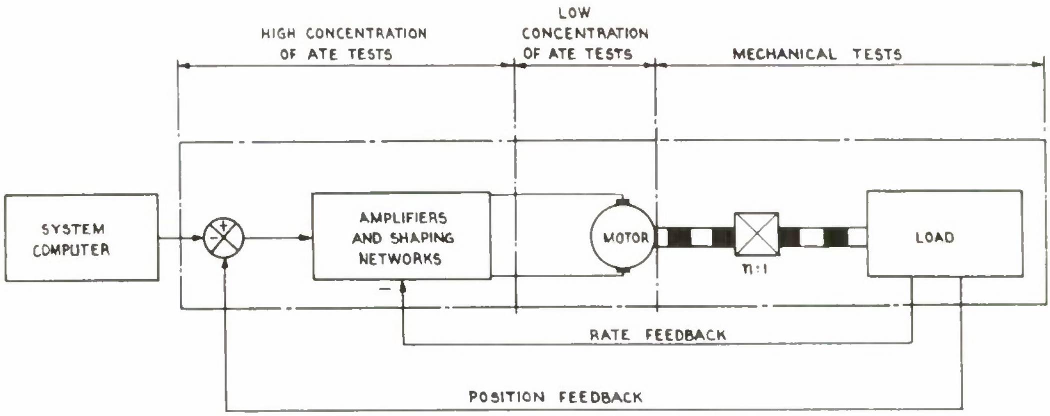

FIG. 3. Block schematic of large electro-mechanical system.

It is not feasible to drive the metadyne by injecting at F, which is therefore an observation point only.

Description of a Typical System

The example used to illustrate this article is a servo-mechanism suitable for use within the radar system of Reference 1 and to which some degree of automatic testing has been applied. Fig. 3 shows the servo-mechanism in block diagram form. It can be operated from a system computer; *via* BITE; or from the radar itself, and controls a mass of several tons. The performance specification defines permitted errors for certain test conditions. ATE is used to test the complete system, rather than just the servomechanism part. From Fig. 3 it is seen that there is a high concentration of ATE tests in the control amplifier region, because here there are many circuits and modules, the latter being the desired fault location level. In contrast the power end of the servomechanism has litle circuitry and therefore few ATE tests. Standard modules are used wherever possible, resulting in a high degree of reliability and providing the maintainer with the opportunity of interchanging similar modules between systems in the fault finding situation. These servomechanisms are not provided with any means of tuning so that all servos out of the factory should be as near identical as possible. To achieve this, stringent quality control is applied at all stages of precision manufacture. It is also particularly important for the mechanical part of the system to be well designed so that initial operating characteristics are maintained for long periods of time. Fig. 4 shows the mechanical tests necessary to achieve this aim and set an initial performance standard which matches the constancy of electrical performance so readily achieved by using operational amplifiers.

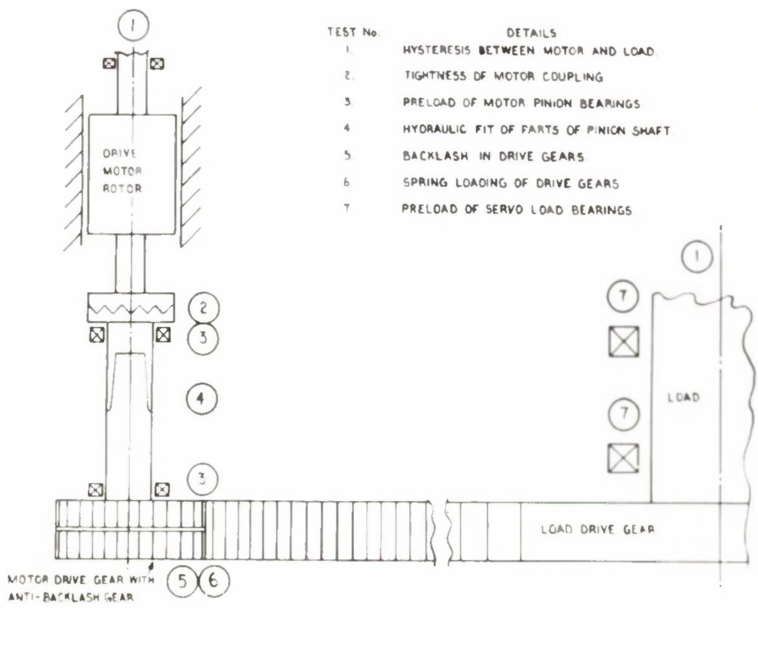

FIG. 4. Typical mechanical tests.

TABLE 2.
Current Test Philosophies.

Test philosophy	*Test stimulus*	*Display*	*Function of test*	*Frequency of test*
ATE	DC voltages etc.	Lamp and numerical displays for go; no-go with 3 tolerance levels	Routine maintenance	Daily
Manual controlled BITE	Step, ramp, harmonic injection to rate and position loops	Pen records of system error	Routine maintenance	Bi-monthly
System computer control	Fixed level sine wave	Lamp display for go; no-go	Confidence immediately prior to use	As required
System computer control	Simulated real inputs	Pen records of system error	'Fingerprints' performance definition and system comparison	On commissioning before/after refit
Manual controlled mechanical	Steady torques	Displacement dial gauge	QA in manufacture and special maintenance	During build, before/after refit

An Example of Current Test Philosophy

Two major principles dominate the test philosophy for the servomechanism described in the previous section. Firstly, confidence in performance must be demonstrable, and secondly, if the performance is not acceptable, the maintainer wants to know how to correct the performance as quickly as possible, subject to the factors already listed in Table I. Dynamic performance methods such as frequency response, pseudo-noise excitation and correlation to estimate transient response, etc, are well known[8], and need not be reviewed here. It is sufficient to say that a dynamic test procedure is the most meaningful test for confidence in system performance since it is more representative of real life, and that the results of such tests, suitably processed, are helpful in fault location if other tests are hindered by lack of access points. Fig. 5 shows some typical dynamic error pen records, whilst Table 2 categorises the testing undertaken on the servomechanism, and when such testing takes place. It may be observed that manual BITE, ATE, SCT, and mechanical tests are all included in order to establish, for a system which initially worked correctly, whether it is working incorrectly, and if so, how the malfunction may be corrected.

The ATE tests are carried out daily in accordance with a pre-determined programme, taking about 1 minute for the servo tests (power supply voltages, amplifier zero thresholds etc.), and 15 minutes for the complete system. Since signals are injected into the loop during ATE tests, care must be taken to ensure

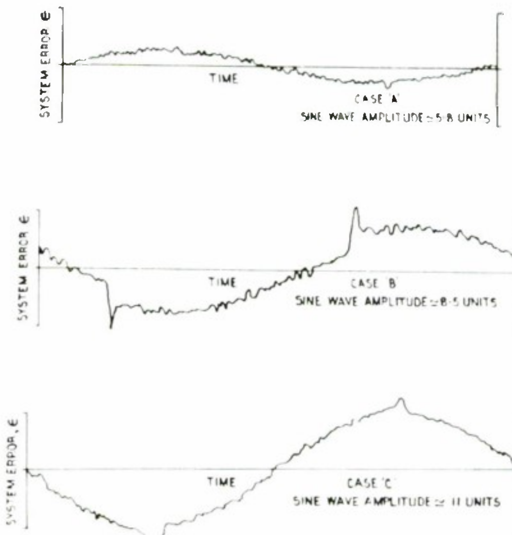

FIG. 5. Records of error channel dynamic tests.

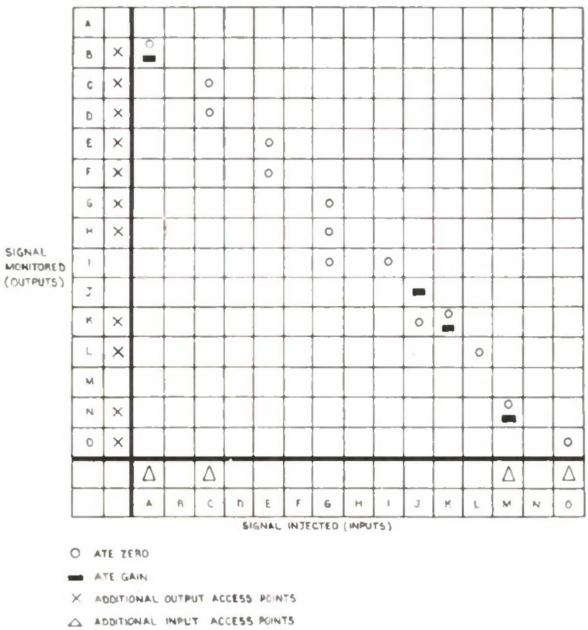

FIG. 6. Access point matrix for system tested by ATE.

that tests which modify the servo loop are inhibited during normal operation, nor must ATE test signals be allowed to cause damage by misuse of test facilities, particularly at the high power end of the loop. ATE checkout tolerances are set at three discrete levels, so that a certain amount of trend detection can be undertaken with a view to determining when corrective action is required.

Fig. 6 shows the test point matrix for the servomechanism. This is totally different from the matrix of Fig. 2, since many more test points are provided in order to facilitate fault location to module level *via* simple ATE static tests. Additionally, further access points are provided which are independent of ATE testing; indeed it will be seen in the next section that the servo panel allocated within the ATE does not have the spare capacity to cope with further test points. Comparing Fig. 6 with Fig. 1, it can be seen that the real system possesses some diagonal properties suggesting multi-input, multi-output test point philosophy in the main. The test point matrix is a very simple way of analysing complex systems, and should provide a very useful aid at the design stage. This point is illustrated by comparing Figs. 6 and 7, the latter being a relatively small part of the complete circuit diagram, appropriate to access points J, K, and L only.

ATE Development in a Typical System

The first stage in the development of ATE on a particular system is to decide what ATE testing is essential, and what is desirable. This provides a first estimate of the number and kinds of tests needed. An essential requirement for progress is the parallel preparation of such estimates for all sub-systems at an early stage of system development, often before the final configuration of any sub-system, such as the servomechanism, is known. In tracing steps in the evolution towards the final test set, it could well be that a decision to buy out ATE, rather than develop equipment 'in-house' will have a fundamental effect on the end result[9], so that the case history described herein may have an inbuilt bias.

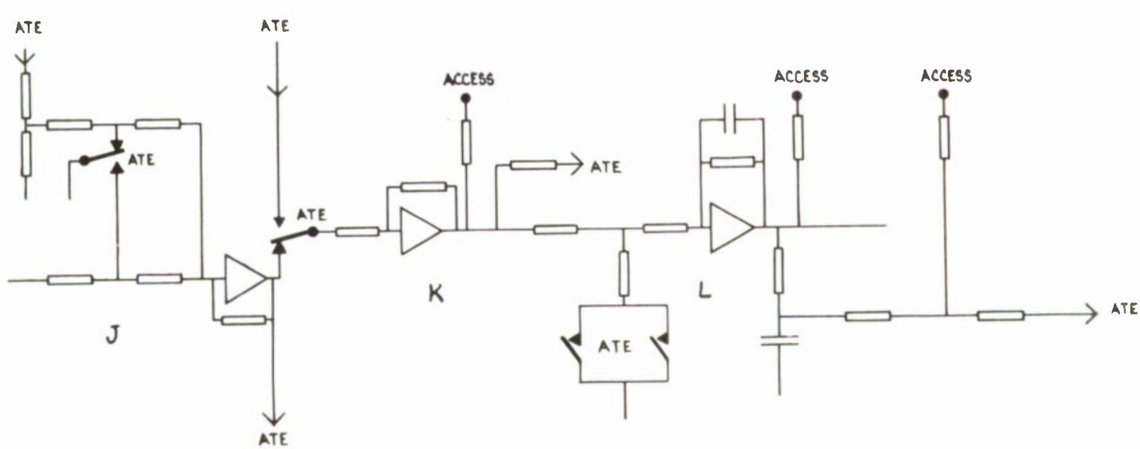

FIG. 7. ATE test circuit.

TABLE 3.

ATE Development.

1 *What tests?*	2 *ATE capacity*	3 *Competition*	4 *Refinement*	5 *Finality*
Estimates lead to ATE capacity	Capacity becomes fixed as design proceeds	Changes in requirements; addresses given up to other sub-systems	Some tests incompatible; others found necessary	Compromise reached
Servos 5 a.c. 7 d.c. 12 amp zero 14 + gain 14 − gain				Servos 1 a.c. 7 d.c. 12 amp zero 3 + gain 1 − gain 2 a.c. gain

Fig. 6 shows that ATE tests may be grouped into zero checking and gain measurement categories, the former being the more common. This was not the original intention because it was decided at the outset that ATE testing should be aimed at the location of faults down to the level of an amplifier and its associated feedback components. In the event, many network faults (although not their location) demonstrate their presence without tests being necessary. The quick repair is therefore to change the relevant plug-in printed wiring board. Eventually, the facilities, location, and capacity of the ATE become finalised. On the way, the original estimate of test addresses might have been rejected, leading to a rearrangement of test philosophy. For example, in Fig. 6 it can be seen that a short circuit is put on the inputs of amplifier G, but the related measurements are made on G, H, and I. This area represents an interconnection of amplifiers. A fault indication at G could mean conclusively a fault in that amplifier, but a fault indication from H or I would require further manual investigation.

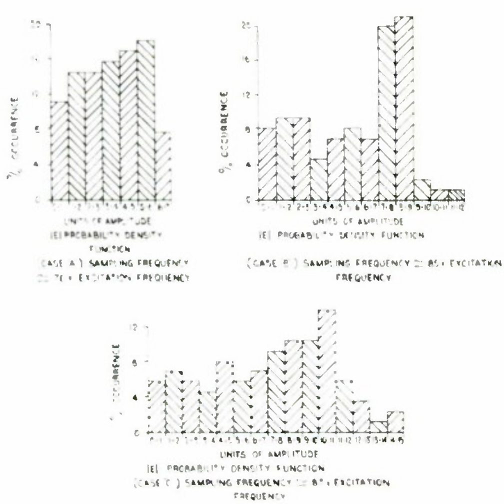

FIG. 8. Automation of 'finger printing': error distributions resulting from low frequency sine wave test.

Once the capacity of the ATE is fixed, new tests may only be introduced at the expense of existing tests, or by cutting back on facilities allocated elsewhere in the system. A factor inducive to change in plans during the development phase of the system concerns the physical integration of centralised ATE (with requirements for wiring, cable runs, and cabinets, etc.) with the physical system. Only then do all the sources of incompatibility emerge, leading to further modifications of tests and interlock circuits. Table 3 summarises a typical case history including the final compromise solution in which 26 automated tests appear in contrast to the intended 52 tests. It is interesting to note that the quantity of d.c. voltages and amplifier zero checks have not changed, although the exact details may well have altered.

At what stage in ATE development does the servo engineer say no, when under pressure to give up more addresses? This is difficult to answer, especially if the design shows that faults are not likely to occur very often, so why have expensive test facilities if all they do is show that the system is correct? Strangely, perhaps, at first sight they are required because if things go wrong only rarely, manual skills cannot be sufficiently practised. Thus ATE is justified for both high and low reliability systems, in the first case to supplement skill levels and in the second case to cope with high workload.

Automation of 'Finger Printing'

We have seen from Table 2 that naval systems require dynamic 'finger printing' for maintenance records used in inter-ship comparisons. At present the comparison is not automated, since performance is stored on a pen recorder as previously seen in Fig. 5 The system maintainer assesses quality from this particular trace *via* three subjective judgements. Firstly the peak error in the linear mode must be acceptable, secondly the superimposed noise must be acceptably small, and thirdly, the end-of-roll spike signifying non-linear behaviour must be reasonable. If 'finger printing' is automated, then the best judgement amongst all maintainers may be established as a permanent standard. In any proposed method of automating finger printing it may well be important to retain the existing stimulus of precise standard since considerable experience on ancestral systems can then be put to immediate good use. Selection of a different stimulus in order to simplify signal generation, measurement data processing or other good reasons should not be undertaken lightly, since the decision will carry with it the necessity of large scale simulations or field trials to establish confidence in the new test method[5] which would otherwise be unnecessary. One suitable technique is to sample the system response and display the probability density function of the modulus of system error[10], as shown in Fig. 8. The subjective judgements may then be replaced by a definitive profile leading to a toleranced histogram. In practice, the histogram is obtained by counters set to record the number of times samples are within specific error bands. The test need not be restricted to a sine wave stimulus, or to error channel measurements.

Epilogue

Electromechanical system testing will be governed by constraints dependent on the particular application. Nevertheless, certain general points emerge from the case study described in the article:

1. Irrespective of how many access points are provided, the necessity of dynamic testing of the servomechanism to demonstrate performance remains.
2. High quality design and manufacture can eliminate the need for tuning facilities, thus simplifying the maintainers task to fault location and direct replacement. However, an added financial cost must be borne during the system procurement phase, and mechanical tests now loom large in importance.
3. An adequate number of test access points must be provided at the system design stage, thus avoiding costly modifications later on. As a minimum, all modules should have at least a monitoring test point.
4. The test point matrix is a useful short-hand aid to assist the system designer in interpreting complex circuit drawings in terms of test requirements.
5. There is likely to be sufficient pressure on ATE capacity to ration the number of test access points which may be used for this purpose. A judgement is therefore likely to be needed on test priorities long after initial plans are drafted.
6. It is the job of the design engineer while details of the system are still fresh in his mind, to make the best possible forecast of the necessary tests required at all phases in the life of the system.
7. In a complex naval system, ATE is unlikely to totally eliminate the requirements for manual skills. The best test programme is therefore one which optimises the sum of the contributions from both sources.
8. Although a system computer is available for control purposes, it is of only limited, but valuable use to the maintainer. Inevitably, the computer is oversubscribed and in the event of conflict of interests the maintenance role must take second place to the operational role.
9. BITE is still an effective tool for any routine maintenance requiring dynamic test procedures.

Acknowledgement

Is given to the Director ASWE for permission to refer to MOD work. Views expressed, of course, are those of the authors and do not necessarily represent any official policy on any matter.

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AN INVESTIGATION INTO SIMPLE ADAPTIVE CONTROL SYSTEMS

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Abstract

This article describes a project undertaken by the author as part of the final year syllabus for a first degree in Electrical Engineering. The project was to design and build a simple Adaptive Control system and to go on to investigate some performance characteristics of it. The adaptive system was developed by first considering a single parameter optimal system. The optimal system was built and tested, then used as the basis for the more complex, two parameter adaptive arrangement. The development of this system together with the tests carried out on it and the conclusions drawn from these tests and observations, are all described. The article ends with a brief comparison of analogue and digital adaptive approaches.

Introduction

Man-made control systems have been in existence since Hero first designed his thermally activated devices. However, it is only in the past 25 years with rapid advances in high speed aircraft flight and, in particular, space exploration, that traditional methods of control have proved inadequate. Modern control theory developed several ideas to meet these new problems, amongst which optimal and adaptive control are to be found. Optimal control was the first of these two to be developed, and adaptive control, at its simplest, may be regarded as the evolution of the optimal approach. Many methods are now available for producing adaptive systems *viz.* linear systems with compensation for invariant parameters; systems with relay control; various feedback methods and many more, but the most popular approach seems to be that employing a model as a reference to provide the ideal response. An analogue or digital system may be designed for the model, but in the main part of the work carried out, an analogue type was used. This was primarily because of the closer physical relationship of an analogue model to the actual system and also the relative ease with which such a system may be checked stage by stage.

Optimal and Adaptive Systems

With optimal control, it is assumed that the problem dynamics are fully known and may be described by linear or non-linear differential equations. The solution is then effected (in the case of a two-parameter situation) by fixing one parameter at a pre-determined optimum value and varying the other to produce an overall optimum performance in accordance with some design criteria.

The question arises, what can be done when no compromise between the design objectives of a system is possible which results in an acceptable, fixed parameter arrangement and yet where pre-programmed adjustments cannot be made because of lack of knowledge relating system performance to time? Such systems designed to accomplish specified objectives under greatly varying operating conditions are termed Adaptive or Self-Adaptive. Adaptive control may be defined as: 'The process of changing the properties of a system which allows it to achieve the best, or at least an acceptable functioning under varying environmental conditions'. For Adaptive Control there are at least two variables.

The Development of the Optimal System

(1) *Designing the Model.* Clearly it was necessary to have some system on which to base the optimal controller. The system chosen was a servo assembly type SA1B, manufactured by Feedback Ltd, England. This was convenient, because tests and measurements could easily be carried out on this laboratory apparatus. Once the paramenters were known, an analogue model could be designed to certain desired specifications; this was to provide the model reference. In its simplest form, the servo could be considered as a second order system. Accordingly, the design was made in terms of: (a) speed of response, (b) steady state errors and (c) oscillatory response. It was found that ω_n (natural frequency) of 50 rad/sec and ξ (damping ratio) of 0·45 gave a satisfactory performance, *i.e.* they provided what was considered to be the best response available from the servo. These were the values chosen initially, later they were modified. The model was built up on the Solartron HS73A Analogue computer. After scaling the system was as shown in Fig. 1.

Such a scheme enabled gain and damping ratio to be adjusted easily for testing purposes. Tests were carried out with the conventional square wave, ramp input and sinusoidal input to ensure response was as desired.

(2) *Designing the System.* It was realised considerable interfacing problems would arise between the analogue and the servo when using the analogue as the reference for the servo system. Therefore, it was decided to use another analogue model to represent the real system initially and to try to interface the actual servo when the controller had been made to operate. For simplicity, the system chosen was identical to the model.

Designing the Analogue and Servo Systems in Parallel

Although as mentioned before, there were interfacing problems, it was thought desirable at this stage to drive the analogue model and actual servo from the same signal source and compare responses without effecting any control other than manual adjustment of parameters. This showed several limitations of the servo which had been overlooked when considering it as the basis for the analogue model.

By not exceeding 1·5v. input step, the servo was considered a linear device. However, it is in fact, subject to several undesirable non-linear effects:

(i) Saturation of power and pre-amplifiers.
(ii) Insensitivity band (sensitivity limit) of amplifiers.
(iii) Threshold of servomotor-coulomb friction effects.
(iv) Hysterisis of magnetization curves of the motor and resultant saturation.
(v) Inherent non-linearity of the mechanical characteristics of the motor-gear transmission backlash or stiction.
(vi) Granularity of the follow-up or feedback potentiometer.

Hence, although servo and analogue could be adjusted to give the same result at a particular operating point, discrepancies over the operating range became apparent.

One machine unit for the analogue was 100 V., whereas the servo amplifier saturated at 1·5 V., hence a reduction of voltage was necessary before applying the signal to the servo. The model was controlled in compute and reset modes by clocked logic and this was used to provide the input to the servo since a logical 1 was a 24 V. step. This 24 V. being divided by 10 and finally controlled by a potentiometer before being applied to the servo. Amplification of the servo output was necessary for an adequate display alongside the model output. A gain of 100 was used but inevitably this increased noise, necessitating the use of 0·01 µF capacitor acting as a filter.

There was a certain amount of stiction in the pen recorder used and this produced an increase in damping. Gear backlash produced a flattering of response peaks.

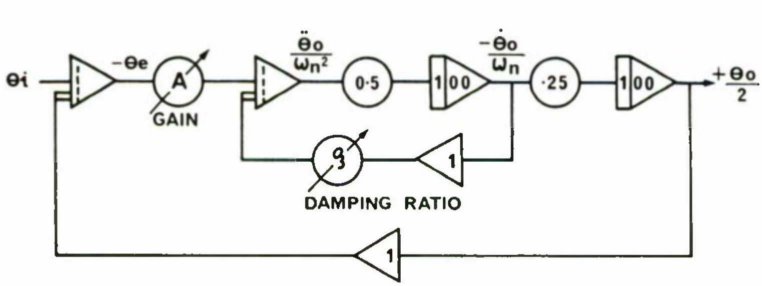


FIG. 1. Block diagram of model reference system.

The traces shown in Fig. 2—were taken from the servo test. The output trace compared well with that from the ideal model. Allowing for the fact that the u-v recorder has little inertia, whereas the pen recorder has both stiction and inertia, the magnitude of the system's first overshoot was larger than expected. This was due to inaccuracies in the system and the fact that the percentage error setting of the servo was based on values of constants evaluated previously and therefore not wholly accurate. There was evidence of both stiction and backlash in the traces. There was also noise, some from motor brushes —'brush ripple', as may be seen on the unfiltered traces.

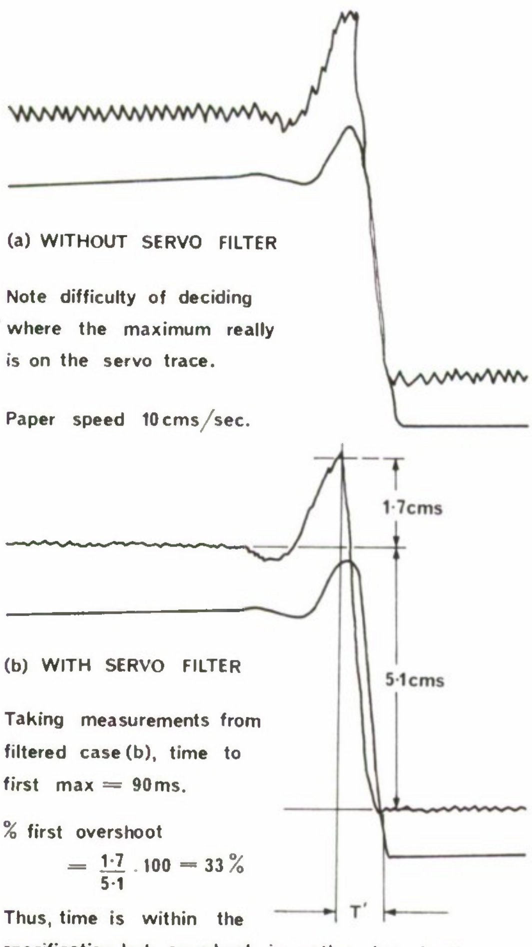


FIG. 2. Analogue Model trace and servo system trace × 100.

Performance Index Considerations

It may be deduced that the mode of operation is to compare the outputs from system and model, then from this, to produce some driving function which adjusts the system's parameters until its output is the same as the model; that is, there is no error between the two. Some means of measuring the difference between outputs is necessary. This difference (or error) signal is then operated on to produce the Performance Index (P.I.). The P.I. may be defined as: 'A functional relationship involving system characteristics in such a manner that the optimum operating conditions may be defined from it'. Clearly the choice of P.I. is fundamental to the whole problem. A great deal has been written on the subject[1] and a great many P.I.'s have been developed for various uses. However, the three simplest are:

- (i) $\int edt$ Integral of error with respect to time
- (ii) $\int e^2dt$ Integral of error squared with respect to time
- (iii) $\int e^2.tdt$ Integral of error squared weighted by time with respect to time.

It was decided to experiment with these initially before proceeding to greater complexity.

Consider the response of two second-order systems with different parameters, to a common step input. The response of each may not be the same; there may be an error between the outputs. The function of the P.I. generating device is to reduce the error, by means of the controller, to zero.

The error is represented by $\int edt$ so that when this integral goes to zero, the controlled system output would be the same as the model. This was the simplest of all the P.I.'s and was chosen initially. There is however, one grave disadvantage with this, in that $\int edt$ is made up of +ve. and −ve parts which at certain points sum to zero, despite the problem's being incorrect. The problem then locks on to an incorrect solution. Fig. 3 shows this. The difficulty was overcome by using $\int e^2dt$ as the P.I. In this way, all errors were +ve., and when $\int e^2dt$ was zero, the problem was solved. $\int e^2dt$ as a P.I. is considered to have poor sensitivity, although it proved adequate in this case. The concept of +ve and −ve areas of error is explained at great length in [2].

Investigation of Integral of Error

It was necessary to find the effect on the system of changing gain and damping ratio as these were going to be the varied parameters of the Adaptive system. Initially only ξ was varied, thus making a single parameter, optimal system, gain being fixed at its predetermined optimum value. Tests were carried out on the system which had been patched up on the analogue. A step input was applied as test signal. Fig. 3 was produced from the results. Fig. 3 also shows the effects of variations in gain. It may be seen that the only line to pass through $\xi = 0{\cdot}45$, is the one of gain value 1—the optimum value. All other zero crossing points represent non-optimum solutions, causing lock on to occur. No such lock on occurs when using $\int e^2dt$ as P.I.—see Fig. 8 following—although it is not possible to tell in this case whether ξ is too high or too low as it is with $\int edt$. This point will be discussed later.

The Selection of the Iteration Procedure

The chart (Fig. 4) gives the design sequence for a system which automatically adjusts the variable parameters to their desired values and hence produces the required controlled system output. See also [3] and [4] for a discussion of iteration procedures.

Iteration is the process by which a sequence of runs is made, each one being dictated by some recursive formula. Given n initial parameters xj, a recursive formula after run (k–1) can have the form:

$$(xj)_k = \int j \left\{ (x_1)_{k-1}, (x_2)_{k-1} \ldots (x_n)_{k-1} \right\}$$

and the process converges if each

$$(xj)_k \rightarrow (xj)_{k-1} \text{ as } k \rightarrow \infty.$$

Iteration is generally carried out either by using some fixed step size method or by using proportional correction. The former method, although generally easier to implement, has the disadvantage that large errors need many steps for correction, or if the steps are large, there is inevitably a residual error. Proportional corrections speeds the solution by correcting large errors quickly and residual errors can be made negligible. For these reasons, proportional correction was the method adopted.

The proportional correction was implemented using a controlled integrator. The controlled integrator provides a correction proportional to $\int edt$. The mode of operation of these various units is described in[5].

The system gain was controlled by potentiometer. The initial condition allowed a value of gain remote from the desired value to be inserted from which to start the iteration procedure.

Fig. 5 shows the results of varying the gain of the controlled integrator. It is interesting to note the time taken to obtain a solution.

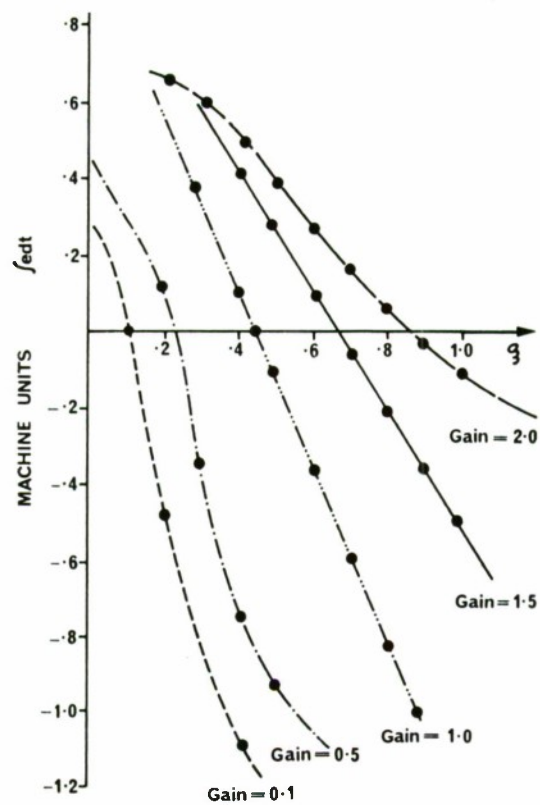


FIG. 3. Graph of $\int edt$ against ξ for various values of gain.

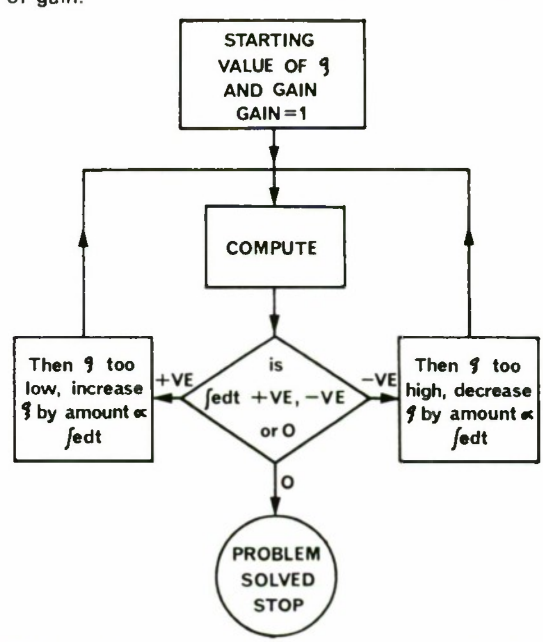


FIG. 4. Flow diagram of Iteration sequence for ξ adjustment.

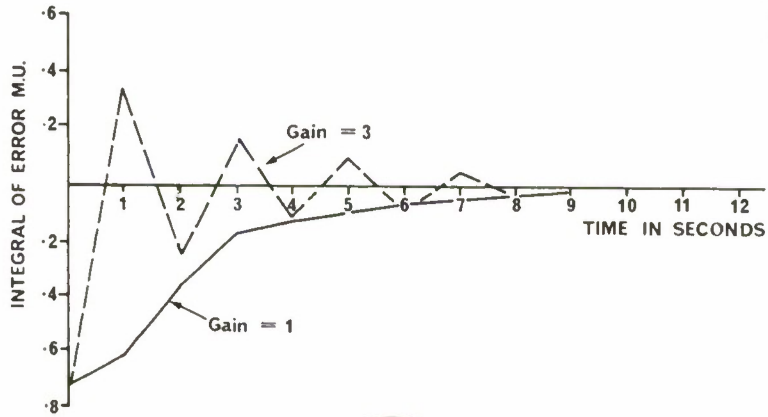
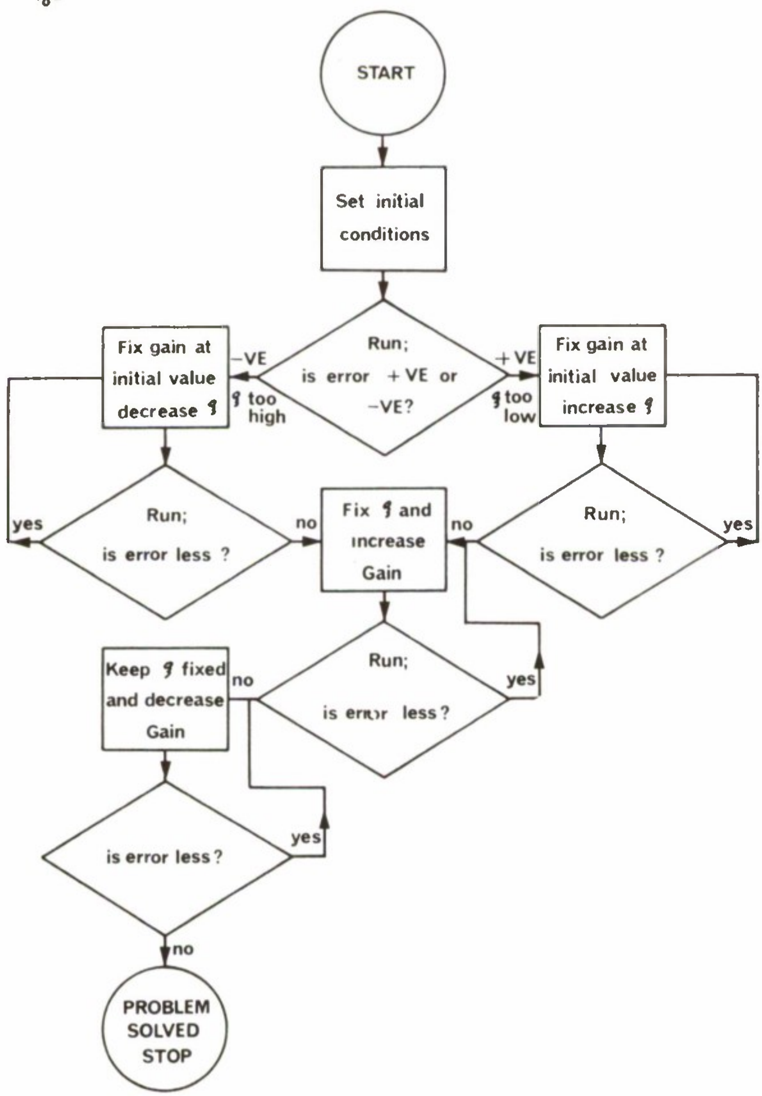


FIG. 5. Performance index for successive iterations for various values of gain.



The sign of ∫edt determined the direction in which the iterating steps were to proceed in order to reduce the error.

Advances towards the two-parameter search

The controller must move the operating point from the initial condition to the point in the centre of the contours (Fig. 7). There are basically two methods of doing this:

(a) Pattern search.

(b) Random search.

The former uses the fixed step size and was rejected for the same reasons as on the previous occasion.

The latter has a proportional correction and the solution proceeds in a series of steps. The flow chart (Fig. 6) shows the method.

FIG. 6. Block diagram of Two-Parameter search.

Some indication of system behaviour in response to changes in gain was now sought. Until this time, ξ had been the only varied parameter. Fig. 3, see earlier, was produced at this stage. It was found that when gain was too high, edt was +ve and ∫edt was —ve when gain was too low, hence the opposite sense to that for ξ. It was at this time that the P.I. was changed from ∫edt to $\int e^2 dt$ to prevent the lock on situation shown in Fig. 3. However, the sign of ∫edt was preserved to ensure the correct direction of iteration. Thus the full P.I. was $\int e^2 dt$ plus the sign of ∫edt. To make the new P.I., a multiplier was simply inserted before the controlled integrator.

Figs. 7 and 8 show $\int e^2 dt$ against varied parameters. Fig. 7 in particular shows the closed curves associated with the two variable concept.

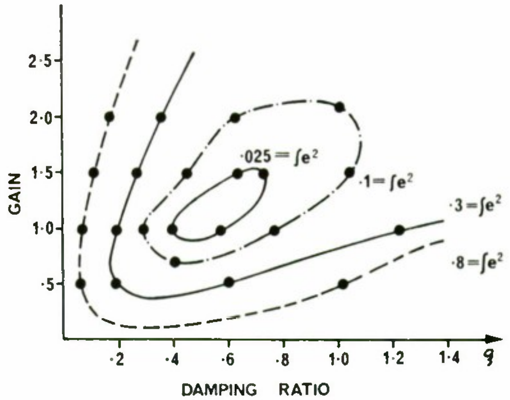


FIG. 7. Graph of gain against § showing contours of constant P.I.

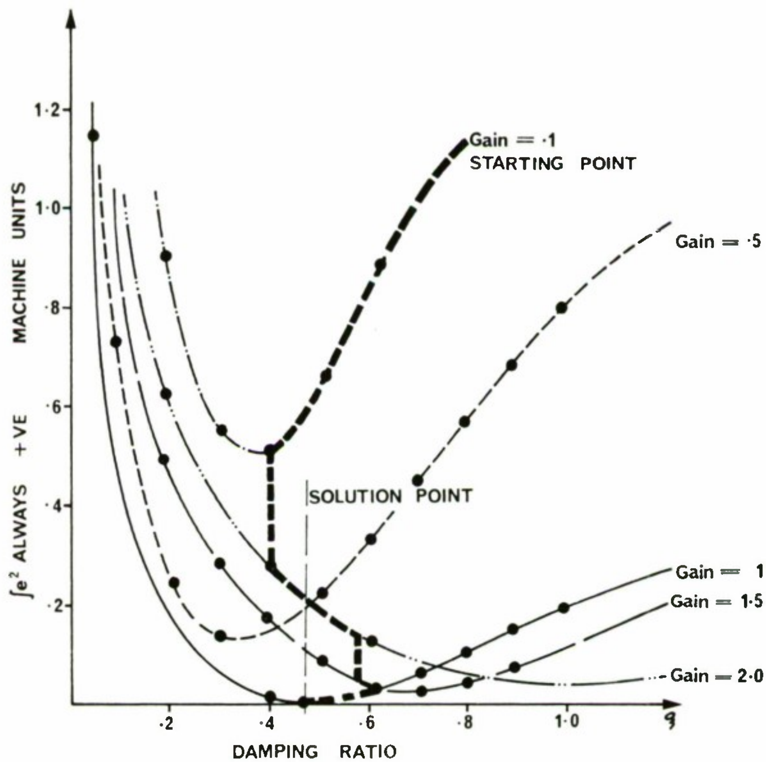


FIG. 8. Graph of $\int e^2 dt$ against § for various values of gain(w).

The Two Parameter Search Technique

Having decided on the type of adaptive controller and collected all the relevant data from tests, it now remained to design a controller to operate in the random search manner. The controller was naturally quite complex so that it was found much easier to design it stage by stage and, having tested each part, to assemble it.

Earlier it was stated that the object of the controller was to move the operating point from some initial condition to the desired value of parameters by adjusting each parameter in turn, in other words, to proceed in a series of steps. The difficulty arises in deciding at which points to change from one parameter to the other. To simplify reasoning, it was decided to use a

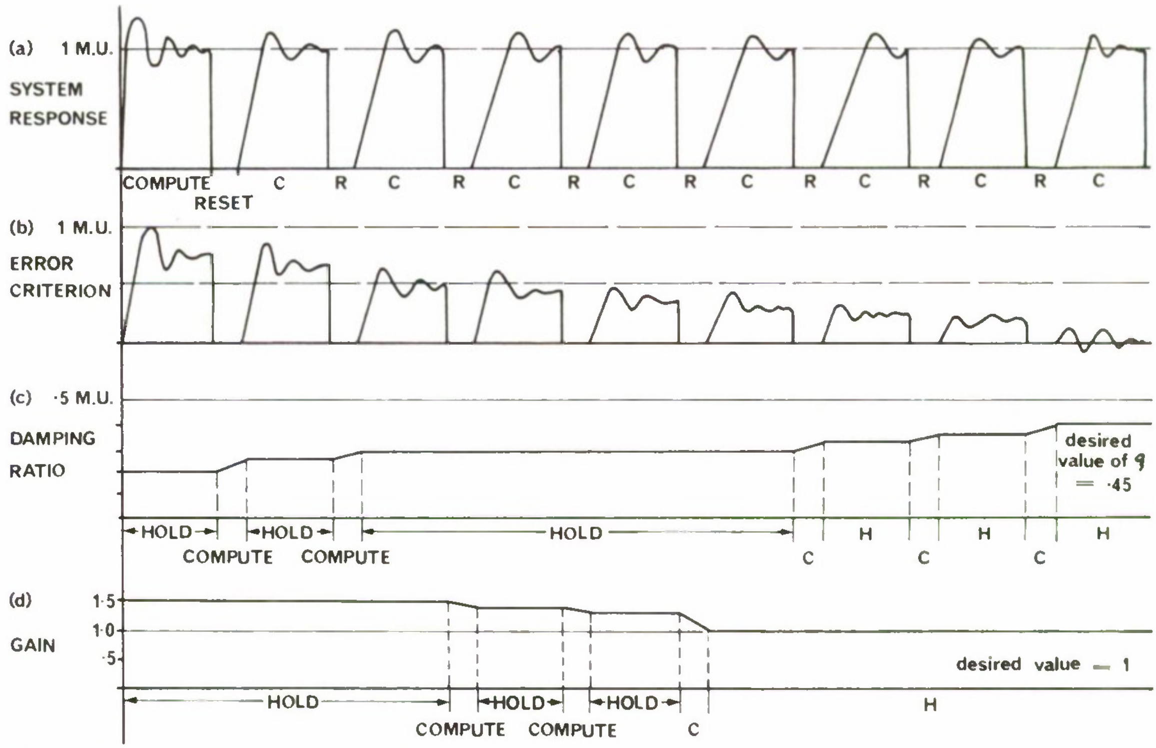


FIG. 9. Theoretical 2-Parameter Iteration.

specific set of initial conditions, namely those shown in Fig. 8. In this case, gain was as low as it could ever reasonably be at 0·1. As ξ had been the varied parameter in the single parameter search, it was decided the new controller would begin by iterating ξ before switching to gain. Consider the operation as shown on the graph: from the start point X, the damping ratio is adjusted and the solution passes along the constant gain line to point A. Switching must take place at this point to adjustment of gain, otherwise the problem will lock on and hunt about this minimum. Switching is then arranged to take place at 0·5x (previous value of $\int e^2dt$). In this way, the solution moves down the curves as shown by following lines of constant gain and constant damping ratio in turn.

The circuit for performing this iteration used a comparator together with a means of storing and feeding back the last value of $\int e^2dt$. The sign of $\int edt$ was still used to decide whether gain or ξ were too high or low and hence to ensure the correct iteration direction.

Testing and Patching the Two-Parameter System

The system was quite complex by now. Units were tested individually and then connected together. There was virtually no spare capacity on the analogue computer and, at this point, reliability problems arose. Despite redesign and a certain amount of simplification, the problems persisted and no satisfactory result was ever achieved. There appears below a drawing and explanation of the expected system response.

Theoretical Results (as depicted in Figure 9)

(a) System Response. Starts with too high a gain and too low a damping ratio. Solution approaches the ideal as iterations proceed. Compute/Reset times may be adjusted, but compute times must be long enough to allow a steady value to be reached. Correcting iterations take place during reset times. These must be long enough to allow a sufficiently large correction to be made each time.

(b) Error or P.I. trace. This is $\int e^2dt$ and is always +ve. There is an initial transient followed by a steady value. As iteration proceeds, $\int e^2dt$ decreases. Starting at $\int e^2dt = 0\cdot8$ m.u., ξ is iterated while gain remains fixed at its initial value. Subsequent $\int e^2dt$ traces show a reduced value until the 0·5 m.u. level is reached which is the predetermined criterion to change parameters. Then $\int e^2dt$ reduces until 0·25 m.u. is reached at which there is another change.

This is a proportional correction, so that as the system trace approaches the ideal, the amount by which the error is reduced becomes less at each iteration.

(c) Damping Ratio. Initially at 0·2, the required value is 0·45. ξ is iterated first and the steps are shown, these take place while the problem is in reset. While the problem computes, the value of ξ is held. This proceeds until $\int e^2 dt = 0{\cdot}5$ m.u., at which point ξ is held at the value it has reached, and the gain is iterated until the next pre-set criteria is reached, where the switch is made to ξ again. From the trace, it may be seen the desired solution is produced after two iterations.

(d) Gain Trace. As ξ is the first parameter to be iterated, gain remains fixed at its initial value of 1·5. It remains at this value until the first error criterion is reached, the gain is adjusted while ξ remains fixed as shown.

Thus from these traces, it may be seen how, by a process of iterating one parameter to some predetermined point, and then the other, the error criterion may be reduced to zero and the desired trace produced.

Digital Technique Investigations

These were carried out on an IBM 1130 computer using the continuous system modelling program [6, 7, 8]. This program uses digital methods to simulate an analogue system. As such, it provided a useful comparison with the direct analogue approach and the step-by-step method of digital calculation gave some useful insights into one or two anomalies encountered with the analogue.

The principal drawback was the long solution time. While the analogue is a parallel device with all the units operating simultaneously to produce a solution, the digital computer operates on each set of equations in turn. Although the C.P.U. handles individual calculations very rapidly, these are done in a series manner and the resulting overall time for a solution is longer. Digital solutions are more accurate but the accuracy of $\pm$ 1% obtainable with the analogue was adequate in this case.

Conclusions

(a) By basing the analogue model on a real servo system, a useful parallel was established which ensured that a physically realizable system was used all the time. Work on the analogue computer showed the single variable controller to be comparatively straightforward to build and operate. There was sufficient spare capacity on the computer to allow components to be changed over when they went wrong. The greatly increased complexity of the two variable search used all the computer capacity, and this lack of available spares caused problems. The obvious conclusion to be drawn for a controller of this type is that the computer must be sufficiently large to accommodate the problem and still have spare capacity.

(b) In spite of difficulties encountered with equipment, the work carried out demonstrated the viability of using the analogue computer as an adaptive controller. It was particularly suited to the model reference type of system under consideration.

(c) Some work was done using the CSMP on the digital computer, but there was not time to build a full controller. A useful insight was provided though. This is the recommended approach to anyone thinking of investigating this topic further. Clearly, a faster operating digital computer, say the 'Sigma 6' system, would be a great improvement when using the CSMP method.

(d) A considerable number of publications concerning adaptive control were read. Although every author seemed to have his own idea of what Adaptive Control means or precisely what it does, the general concensus seems to be that this is potentially the most useful and fascinating area of automatic control presently being examined. There are not a great many applications of it at present, but one interesting example is the C1WS (Close In Weapon System) made by General Electric using a simplified adaptive controller. Fire control would seems to be a logical and extremely useful application of an adaptive system.

(e) By way of a conclusion, adaptive control, together with its potential of learning systems, can be thought of as human ingenuity's nearest yet approach to that most perfect of control mechanisms: the human body.

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SOME THOUGHTS ON BAYES' THEOREM, BAYES' POSTULATE, RANDOMNESS AND FUZZINESS

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Abstract

Many people have difficulty with the concept of probability. Some, mistakenly, do not. Subjective probability and randomness are the main topics dealt with here, with particular reference to Bayes' theorem and postulate. An attempt is made to relate the idea of fuzziness to the paradoxes that arise. Reference is made to a recent book which explores the theories of probability with great thoroughness, but finds no satisfactory resolution of the mysteries.

Introduction

In unpublished research working papers[1,2,3] I have recorded some of my views on difficulties that arise in dealing with probability. In particular, I have commented on the importance of clarity in statements about prior knowledge and randomness. Although, after much thought, and attention to the thoughts of others, absolute clarity still appears to be unattainable, it may help others if I present some of the ideas that have helped me to overcome further conceptual difficulties. I also quote as references books which have encouraged me to believe that my earlier statements have not been wrong. This does not imply that I am satisfied that I have expressed my ideas adequately either then or now.

This article starts with some simple, yet confusing, uses of Bayes' Theorem and leads to an examination of Bayes' Postulate of equiprobability, when nothing is known to the contrary[4]. Various ways in which one can be deceived, by the arguments through which subjective probabilities are arrived at and by the forms in which 'information' is provided, are discussed. The 'reliability' of statistical significance tests depends very much on prior assumptions and on what is understood by randomness, and the pitfalls here are briefly discussed.

Finally, because I believe that the concept of fuzziness has to be introduced to explain why some probabilities, which seem to exist conceptually, cannot be usefully measured, I have included a section summarising exchanges on this subject between myself and Professor D. J. White of Manchester University[5]. This is far from conclusive, but it is important because, if those who set great store on the measurement of subjective probabilities are, in fact, forcing a particular framework of prior knowledge onto a decision-maker, without his being clear as to what this framework is, they should not be surprised if he later denies that the measurements reflect his beliefs.

This article, therefore, collects together various related ideas which may help readers to resolve some difficulties and to appreciate others. The debate on probability, both philosophical and mathematical, is of long standing and the end is not in sight. There may not be an end.

Bayes' Theorem and Bayes' Postulate

A Bridge Player's Problem

The problem may be stated as follows:

An opponent has Ace, King of a suit *or* Ace alone *or* King alone, on prior assessment. The Ace is played. What is the probability of his having the King also?

This can be restated more generally, and interpreted suitably for discussion:

Person A has X alone (X), Y alone (Y) or X and Y (XY). No extra knowledge of what he has is held by Person B, who interprets this lack of knowledge in the sense of Bayes' Postulate, namely that, on his understanding (H) of the situation

$P(X/H)=P(Y/H)=P(XY/H)=\frac{1}{3}$.

A is then required to show X or Y. He shows X. What are B's posterior probabilities?

From Bayes' Theorem,

$P(X/H, X \text{ shown}) \propto P(X/H)P(X \text{ shown}/H, X)$

and there are two similar equations with the same proportionality constant for B's posterior probabilities of Y and XY.

But

$P(X \text{ shown}/H, X) = 1$

$P(X \text{ shown}/H, Y) = 0$, and

$P(X \text{ shown}/H, XY)=\frac{1}{2}$.

The last equation again uses Bayes' Postulate, namely that randomness of choice of X or Y is, for A, represented by the equiprobability state. This is a secondary prior probability estimate by B.

B may now deduce posterior probabilities

$P(X/H, X \text{ shown}) = \frac{2}{3}$

$P(Y/H, X \text{ shown}) = 0$, and

$P(XY/H, X \text{ shown})=\frac{1}{3}$.

This result can seem surprising if we argue (falsely) in the following way. A has to show X or Y. The fact that he shows one rather than the other gives no new information. The posterior state is that he may or may not have Y. The two non-zero posterior probabilities are, therefore $\frac{1}{2}$ and $\frac{1}{2}$!

The fallacy lies in assuming that there is no new information. X will be shown in *all* cases where A has X, but in only *half* the cases where A has XY. So if we consider the cases in which X is shown, these will be a subset of the set of all possible prior cases (in the total set, X and XY are equally represented). The subset has only half the number of XY cases as it has X cases and the posterior probabilities, as obtained from Bayes' Theorem, are thus justified. What is in fact unchanged, since either X or Y must be chosen, is the probability of XY.

The actual assessed posterior probabilities are, however, dependent on the Bayes' Postulate interpretation of 'no knowledge', which will be discussed later.

A Biased Coin Problem

There is no knowledge of a chosen coin except that it has an equiprobability of being, in so far as nothing is known to the contrary,

(a) biased so as to fall heads always,
(b) biased so as to fall tails always, or
(c) a normal balanced coin (50/50 heads/tails).

It is spun and falls heads. What are the posterior probabilities of (a), (b) and (c)?

This is, conceptually, the same problem as the bridge player's problem. It is perhaps an easier example to deal with, since, in the bridge player's problem as originally stated, it is possible to be misled by thinking about what other cards the player holds, although these are irrelevant to the problem as stated. It would of course be possible to state it differently, so that other cards were important, and this would affect the prior probabilities.

Discussion of Prior Probabilities

In either of the above problems, suppose that one were to insist, in the posterior state, that there was a 50/50 chance of one or the other of the two remaining possibilities being true. If the logic is to be consistent, one can calculate the *implied* prior probabilities. Note, however, that it is perfectly 'rational' to be 'inconsistent', provided that this assumes a shift of ground (for example, a sudden realisation that H contained something extra or different). A study of inconsistency may conclude "it is *as if* the decision-maker had thought as follows . . .", although it must be accepted that he may not have thought much at all, or he may have just made a mistake. On the other hand, there are many documented examples of consistent 'inconsistency', which imply non-acceptance of the *prescriptive* axioms of the analyst.

Reverting to the argument from prior to posterior probabilities, if one accepts the equiprobable choice for A in the case XY, posterior probabilities $\frac{1}{2}$, 0, $\frac{1}{2}$ imply prior probabilities $\frac{1}{4}$, $\frac{1}{4}$, $\frac{1}{2}$. In the bridge-player example, this would be a somewhat surprising prior (unless one were to add, to H, something indicated by the bidding). In the coin example, if the 'no knowledge' was so expressed as to make it possible that the coin was biased or not biased in a 50/50 way, the priors would be reasonable. How the problem is stated and interpreted is very important.

Now suppose that the $\frac{1}{3}$, $\frac{1}{3}$, $\frac{1}{3}$ priors are correct but that the prior probability of choosing X from XY is p. The posterior probabilities of X, Y, XY are now

$$\frac{1}{p+1}, 0, \frac{p}{p+1}.$$

Therefore, if B expected X *always* to be chosen from XY (an Ace played, rather than a King, from Ace, King), he would correctly hold to posterior probabilities ($\frac{1}{2}$, 0, $\frac{1}{2}$). An equivalent assumption for the coin problem is not applicable, although it would be reasonable to doubt the precise statement (c).

It is also possible to rationalise posterior probabilities by changing both the primary ($\frac{1}{3}$, $\frac{1}{3}$, $\frac{1}{3}$) *and* secondary ($\frac{1}{2}$, $\frac{1}{2}$) prior probabilities appropriately.

Finally, we can express doubts about the validity of the equiprobable 'no knowledge' assumption, but it is more instructive to do this by recalculating posterior probabilities on other assumptions.

An Alternative to Bayes' Postulate

If we have 'no knowledge', it seems reasonable to assume a uniform distribution of prior probabilities over the appropriate probability space. From this point of view, Bayes' Postulate uses an *expected* probability: we are here concerned with the probability density of probability estimates (and I have used such uniform probability distributions elsewhere)[6]

Suppose that p, the probability of choosing X from XY, is distributed as

$$dp, \quad 0 \leqslant p \leqslant 1,$$

and let the primary prior probabilities remain as before ($\frac{1}{3}$, $\frac{1}{3}$, $\frac{1}{3}$). We now have

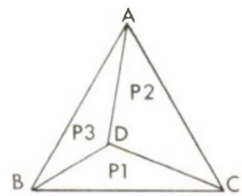
$$P(XY/H, X \text{ shown}) = \int_0^1 \frac{p\,dp}{p+1} = 1 - \log_e 2,$$

so that, instead of $\frac{1}{3}$, we now have 0·307.

Suppose now that p is deterministically $\frac{1}{2}$, but that the primary prior probabilities (p_1, p_2, p_3) are uniformly distributed, subject to $p_1+p_2+p_3=1$. $p_1=P(X/H)$, $p_2=P(Y/H)$, $p_3=P(XY/H)$, and, in particular, p_2 is independent of p_1: later we look at the plausible assumption that $p_2=p_1$. We have, then,

$$P(XY/H, X \text{ shown}) = \int_{0 \leqslant p_1+p_3 \leqslant 1} \frac{\frac{1}{2}p_3}{\frac{1}{2}p_3+p_1} 2dp_1dp_3.$$

Note that the joint probability distribution of p_1 and p_3 is given by $2dp_1\,dp_3$, $0 \leqslant p_1+p_3 \leqslant 1$. This may be determined from the geometrical presentation of p_1, p_2, p_3 as being three triangular areas of a unit area equilateral triangle (homogeneous coordinates) – the point D which represents p_1, p_2, p_3 has to be considered as uniformly distributed over the equilateral triangle.



An additional check is given by integrating over the probability space, *i.e.* showing that

$$\int_{0 \leqslant p_1+p_3 \leqslant 1} 2dp_1dp_3 = 1.$$

The posterior probability, P(XY/H, X shown), is therefore

$$\int_0^1 \left[p_3 \log_e(\tfrac{1}{2}p_3+p_1) \right]_{p_1=0}^{p_1=1-p_3} dp_3,$$

$$= \int_0^1 p_3 \log_e \left(\frac{1-\frac{1}{2}p_3}{\frac{1}{2}p_3} \right) dp_3,$$

which can be shown to be $2 \log_e 2 - 1 = 0{\cdot}3863$. Similarly, P(X/H, X shown)=0·6137.

If we treat the two prior probability statements as uniform distributions, we get

$$P(XY/H, X \text{ shown}) = \int_0^1 -\left[\frac{p}{1-p} + \frac{p}{(1-p)^2} \log_e p \right] dp.$$

(Note that this reduces to $2 \log_e 2 - 1$ when p is deterministically $\frac{1}{2}$). The integration is awkward but, numerically, we get

$$P(XY/H, X \text{ shown}) = 0{\cdot}343,$$

which, as might be expected, lies between the other two estimated values. Taking $p_1=p_2$ as a prior assumption, but letting p_3 vary uniformly from 0 to 1, since for any p_3 P(XY/H, X shown) $=\frac{1}{2}p_3/(\frac{1}{2}p_3+p_1)$, and since $2p_1+p_3=1$, we obtain

$$P(XY/H, X \text{ shown}) = \int_0^1 p_3 dp_3 = \tfrac{1}{2}.$$

Thus, if we take a choice from XY as 50/50 *and* we assume a uniform distribution of primary prior probabilities, subject to X and Y being always equally likely, we *do* reach posterior probabilities of $\frac{1}{2}$, $\frac{1}{2}$!

In the bridge player's problem, this treatment of prior probabilities is not an unreasonable interpretation of the lack of knowledge. In the coin problem, it would depend very much on the precise way in which the problem was posed. The trouble is that, despite the fact that nothing is known, it is necessary to state this lack of knowledge explicitly and each explicit statement implies (differently) that there is *some* knowledge after all. If there is no explicit statement, some statement is implicit in the treatment used in the analysis, which may well be wrong if the subjective prior probabilities are not those of the analyst.

Acceptance of Bayes' postulate, or any other postulate, without careful examination, is seen to be a hazardous procedure in this simple example. What might happen in more complicated cases is likely to be just as troublesome. But as a final confusion, reverting to the $p_1 = p_2$ variant of the bridge player's problem, it may be noted that the *expected* values of the prior probabilities are $\frac{1}{4}$, $\frac{1}{4}$, $\frac{1}{2}$; this does not mean that XY is considered as more likely *always* than X or Y, which was why, when we discussed prior probabilities, the *fixed* prior probabilities of $\frac{1}{4}$, $\frac{1}{4}$, $\frac{1}{2}$ did not seem a reasonable interpretation. Pope found that "a little learning is a dangerous thing": Bayes (indirectly) implies that it may be the saving grace.

Keynes[7] in a book highly praised by Russell[8], examines a problem which superficially resembles those discussed here and which if misinterpreted, gives the same posterior probabilities (equiprobability of alternatives being assumed). A pair of cards is chosen, each at random from a separate pack. One is shown as black. What are the posterior probabilities that the pair are both black *or* red and black? The answer $\frac{2}{3}$, $\frac{1}{3}$ is obviously wrong: since the two are independently chosen, the posterior probabilities must be $\frac{1}{2}$, $\frac{1}{2}$. The error here is that there are *four* possibilities of equal probability, red-red, red-black, black-red and red-red. If we lump the middle two together we get something conceptually similar to the biased coin problem, but with prior probabilities $\frac{1}{4}$, $\frac{1}{4}$, $\frac{1}{2}$ for two red, two black and one of each. With these priors, Bayes' Theorem yields the correct answer, $\frac{1}{2}$, $\frac{1}{2}$,

This I would class as a technical error rather than a form of deception, although it will be seen that there must be a hazy borderline between the two. The following sub-sections deal briefly with the Bayesian aspects of four types of deception, deliberate, accidental, semantic and self-deception.

Deliberate Deception

A decision-maker (DM) is largely undecided on a YES/NO problem, but he tends to favour NO. He has an analysis department, but (unfairly?) he does not trust it. The senior analyst knows this. He also has arguments which, to him, strongly suggest YES. The arguments are based on complicated analysis, they will not be easy to expose, and the analyst doubts whether they will carry much weight with the DM. The analyst knows, however, that, when he has had independent support from an equally suspect source, the DM has been swayed. He therefore arranges to have "independent" views expressed, as well as his own, and the DM decides YES. Whether the analyst and his confederate have appreciated the case correctly is immaterial. What has happened is that the sub-Bayesian process of the DM has identified new information where none existed. He has gone through a process of judgement which his experience made him believe to be sound, but which he would not regard as sound if he knew what had happened. He has been deceived and his decision-making prerogative usurped through an understanding of his decision processes. I would make no moral judgements. That such a procedure "has to be" contemplated says little for the analyst/DM relationship and it is pointless to talk of 'wrong' actions in a 'wrong' situation, without full specification.

Accidental Deception

Accidental deception occurs when information received (h) appears to add to prior knowledge (H). False information is another issue: a mistake has occurred, but given that mistake, the subsequent logic may be impeccable (as it is when the 'mistake' is deliberate as in the previous paragraph).

Suppose then that there are two possible hypotheses, q_1, q_2, and that, based on H (which in a non-explicit manner contains h), these are seen as equiprobable. Let the probability of h, given q_1 and H-h (the explicit prior knowledge), be p_1 and the probability of h, given q_2 and

H-h, be p_2. The posterior probabilities are $p_1/(p_1+p_2)$ and $p_2/(p_1+p_2)$, although there is no real cause for their altering from $\frac{1}{2}$, $\frac{1}{2}$.

Transformations of this kind are very likely to take place in the mind of a DM in complex situations. An analyst who tries to estimate a DM's prior or subjective probabilities must therefore ensure that he 'knows' the DM's H, so that information is not used twice over. I have drawn attention to the importance of H in subjective probabilities in an earlier unpublished paper[1].

Semantic Deception

Prior and posterior probabilities can be in error because of semantic confusion. The following artificial example illustrates the point. The police wish to know if a person seen at the scene of a crime was 'small' or 'tall', 'man' or 'woman'. A first reliable witness indicates "*definitely*, not a small woman" (H). At this stage there appear to be three possibilities, tall woman, small man, tall man, and prior probabilities might be taken as equal ($\frac{1}{3}$, $\frac{1}{3}$, $\frac{1}{3}$). A further reliable witness says "*definitely*, tall". Posterior probabilities become ($\frac{1}{2}$, 0, $\frac{1}{2}$).

The above argument interprets the prior statement to mean "not both small and a woman", with 'small' and 'tall' taken as absolutes, independent of the categories 'man' and 'woman'. But, alternatively, the prior statement could imply *either* a small man *or* a tall woman – prior probabilities ($\frac{1}{2}$, $\frac{1}{2}$, 0). The second statement can only be interpreted as an impression of tallness and we have posterior probabilities (1, 0, 0) – indeed, the woman seems likely to be more than usually tall!

Not only are statements of the type quoted here ambiguous, but words like 'small' and 'tall' are fuzzy, and differently fuzzy depending on the related noun. When subjective probabilities are sought from a DM through inadequately defined propositions, the latter are also fuzzy, and this can be more serious since the interpretation is not the analyst's and is not available explicitly for reconsideration. This aspect is considered further in a later section.

Self-Deception

Suppose, in relation to a given coin, two exclusive hypotheses are to be tested:

q_1 : the coin is 'normal' – probability of heads, 0·5; and

q_2 : the coin is 'biased' — probability of heads, 0·55

H, the prior information available to the experimenter, is that the biassed coin may have been replaced by a true coin. The experimenter, knowing the circumstances, thinks this is *very* likely, but, influenced by a pre-experimental stage, decides to keep 'an open mind' and sets his prior probabilities at $\frac{1}{2}$, $\frac{1}{2}$. The results of 100 trials give a 60/40 result for heads (h):

$$P(h/q_1) = {}^{100}C_{40}\,(\tfrac{1}{2})^{100}, \text{ and}$$
$$P(h/q_2) = {}^{100}C_{40}\,(0{\cdot}55)^{60}\,(0{\cdot}45)^{40}.$$

The ratio of these two is approximately $1/e^2$, so that the posterior probability of q_2 is almost 90%. The experimenter is now almost convinced that the coin is the biased one: he has forgotten that he was originally *very* doubtful. Had he stayed so, the evidence to date would not have had such an effect – he may well have retained his former belief.

Prior beliefs in the likelihood of ESP have had a hypnotising effect on the interpretation of statistical results and on their significance. On the other hand, those prejudiced against ESP dismiss evidence in favour of ESP as 'freaks of chance'. As a 'disbeliever', I have long advanced arguments similar to those of Spencer-Brown[9] which I have discussed before[2], and which I comment on again in the next section below. Now, to my surprise, I am joined by 'believers'. Hardy *et al.*[10] have found that results similar to those previously advanced as evidence of ESP *can* be obtained "by chance" and this has markedly affected their probability assessments. In effect, they are questioning their prior beliefs about randomness as applied to finite samples.

Randomness and Probability

Randomness and probability are connected in a circular definition. Each is defined through the other, the dilemma being 'circumvented' by more and more complicated treatments, but never being adequately resolved. What is intuitively wanted is a concept which defines 'anything can happen', so that randomness in theory could be regarded as a satisfactory concept. Unfortunately, such a concept presupposes some idea of equiprobability and also leads to sequences of events which have patterns not easily regarded as random, or, at least, not desired as a finite, "representative", section of a 'random' process. And if 'chance' *has* to provide sequences that surprise us, it is also *not* surprising that they occur.

One way of expressing the dilemma more precisely is as follows. Consider an infinite sequence of the integers 0, 1, 2, . . . , 9. The set of all such sequences can be regarded as the set of real numbers from 0 to 1 written as decimals. A random choice of sequences implies equiprobability of choice from the real numbers. Let a 'successful' sequence be defined as one in the interval 0 to p and an 'unsuccessful' sequence as one in the interval p to 1^-, thus defining the probability of success, p. Probability not only seems to depend on equiprobability but, also a second dilemma occurs.

The real numbers are not countable, and no Lebesgue measure is defined, so that the *ratio* of successes to non-successes is not decidable. In other words, even though p is conceived as a probability, it cannot be obtained as the limit of a ratio. Thus, while Spencer-Brown's argument[9], that the ratio for a finite number, n, of samples can be made anything by taking n large enough, seems well justified, the theoretical concept that it "suddenly" becomes p as n becomes infinite is of questionable meaning.

Fine, in a recent book[11], has argued, in a comparable but different way to Spencer-Brown, that probability as a limit is unsatisfactory, on the basis that the process of convergence to a limit cannot be determined. Not only does Fine disagree with Bernoulli's theory of "probability as a ratio", but also he finds fault with *all* existing theories. He seems to have the greatest sympathy with the concept of subjective probability seen as an equivalent gamble, but he doubts whether such probabilities always exist in a meaningful way and whether, even if, conceptually, they do exist, they are measurable (one probability may not even be relatable as greater or less than another).

From my, admittedly prejudiced, standpoint, Fine's book seems to be the most thorough and valuable exposition available, although it might be claimed that, in the end, Keynes and Spencer-Brown have said most of what can be said of the paradoxes that arise whenever a deep discussion of probability is attempted. At the end of Fine's book, a passing reference is made to Zadeh's earlier papers on fuzzy sets—Fine seems to imply that the idea of fuzziness is an alternative way of looking at the concepts of chance, whereas it is more properly seen as a classification of vague concepts.

It is with a summary of some ideas, not yet thoroughly investigated, of the link between the concepts of fuzziness and probability, that this article ends, although it does not offer any conclusions.

Fuzziness and Probability

In 1973, I sent a paper[12] which was a simplified statement of Zadeh's concept of fuzzy sets to Professor D. J. White. I suggested to him that one might escape from some of the insistence on obtaining subjective probabilities (for Maximum Expected Utility approaches to decision making) on the grounds that these were not measurable in a meaningful way, since the concept of subjective probability was fuzzy, and the relevant H could be fuzzy in the extreme. The following gives the essence of the ensuing correspondence[5].

White doubted the usefulness of fuzziness in decision-making, since in assessing the consequences of an action one required some statement of the variation in consequences subsequent to various actions. If we take the concept of *credible* deterrence, then, if we cannot define credibility, how can we evaluate the consequence of credibility? We must have some measurement process for the credibility function, however difficult justification and meaning might be. White had considered how the degress of membership might be used, but did not find anything which differed essentially from methods used in value theory. He also observed that there are many calculi which are similar to the fuzzy calculus and mentioned specifically Shackle's degree of surprise, which he has dealt with elsewhere[13].

In my reply, I tried to tie the idea of fuzziness more closely to the subjective probability/decision-theory controversy. On credibility, I considered that there was definition *when* action was taken, but, prior to a decision, one was trying to put ideas into two mutually exclusive and exhaustive sets, credible and not credible. The degrees of membership of these sets are measures of satisfaction with the eventual response decision, but there is not any obvious way of putting numbers to these degrees of membership. White had commented "I assume it is either credible or not credible, since if there are degrees of credibility the position may change and the meaning may change": this seems to echo "they will sometimes be seen to be members of the set and sometimes not, even to the same person and without any change of circumstances"[12]. I remarked that one might add "apparent" before "change", since fuzziness is "in the mind". I discussed also the dangers of trying to add definition to a concept which was usefully fuzzy, in some sense: as we removed the fuzziness, we might also remove the concept. Janet Harris, seeking to describe such an attempt to measure precisely, had used the phrase "Walking deeper into the wood, shouting 'there is no wood' "!

I did not regard the introduction of fuzziness as helping to make a more discriminating choice, but merely as showing why the choice is so difficult. Consider the probability, p, of a future action of a certain type, given that some action of that type would occur. If we take the sets $0 \leqslant p < \frac{1}{2}$, $\frac{1}{2} \leqslant p \leqslant 1$, p will *not* necessarily be seen as belonging unequivocally to one or other of these sets. To try and measure a subjective probability in some circumstances will merely represent a forced opinion at a moment of time and in an undefined state of mind.

Discussion between myself and Janet Harris on degrees of membership, and the density functions that could be associated with them (see contours, paragraph 7 of reference [12]) provided the following thoughts:

(a) Degree of membership of a set might be described in terms of what we called "anguished" time — the time, t, actually taken with wrestling with the problem of choice, with due consciousness of the fuzziness involved, and with the intention of making, as quickly as possible, a decision seen as important to future behaviour. Such a degree of membership (with a choice between two sets) would have the form

$$\tfrac{1}{2}(1 \pm e^{-\lambda t}),$$

where the $\pm$ refer to whether the eventual decision was that represented by 1 or 0. The time is conceptually measurable only: λ is a scaling factor. It will be noted that when $t=0$, we behave as if there was no fuzziness.

(b) It seems that there might well be zero probability of the degree of membership being 0 or 1. In many cases, the density function of degree of membership may be uniform (flat), so that there is total uncertainty about the categorisation of future environments in probabilistic terms ("fuzzy in the extreme" as used in the first paragraph of this section).

White replied that a higher proportion of words could now have a mutually accepted meaning! On the general plane he had no argument: definitions can be incomplete. The background theory to any particular measurement procedure is, however, always the central problem. Since I had referred to measures of satisfaction, this implied that I had some notion of a value measure, and, if so, this was a stage toward an appropriate theory.

He accepted the point about relating fuzziness to the difficulty of choice. But, after some general comments relating to absence of theory, he remarked that, if some of my more general statements could be expanded, we might move towards theory. I had said " . . . the concept (fuzziness) offers a way of thinking that is relevant to the choice of a decision theoretic framework" and " . . . (what I have said) has a pragmatic rather than a theoretic flavour. Theory and actuality are always different in some way, but fuzziness, if present and ignored, can lead to the use of an incorrect theoretic process for decision, one that requires definite set membership". White also commented that "Pragmatism is OK until you want to know if it is OK!" He referred again to Shackle's theory (which is incomplete). Its main raison d'être was to deal with the difficulties of being unable to conceive of the exhaustive set of environments without which subjective probability is an unwieldy concept. He agreed that there was some fuzziness somewhere about the concept of subjective probabilities and to resolve it one needed a theory. Savage's theory does *not* require subjective probabilities (although it was noted in later discussion between us that it does arrive at 'things' which behave *as if* they were probabilities —and are often referred to as such). It may however be that one can argue against the Savage axioms[13].

Finally, White made this point about the Savage theory. If one argues that people are not sure of some preference, the theory is not invalidated, *provided that* an exhaustive set of hypotheses is specified and the outcome measures are available. However, the "probability" problem only becomes a "fuzzy set" problem if we are arguing about whether or not certain numbers are "probabilities".

While I can, in a loose sense, agree with this (and I should add that White's point was qualified by two question marks), it seems to dodge the issue, since I would have to go back to the provisos and wonder where the hypotheses and outcome measures were coming from. The fact is that if fuzziness does exist, there are measurements for which no scale exists.

Finally, it could be suggested that arguments that would include the notion of fuzziness within a decision-theoretic framework (in the sense of accepting imprecision in some way) might, on the one hand, be independent of a need for a satisfactory theory of probability but, on the other hand, might be necessary to it.

Final Comment

As I said earlier, there are no conclusions. I would welcome comment and criticism of any points made. It is easier and more comfortable to accept that probability is well enough understood to be useful, because trying to understand it makes its applications less sure. And having gone so far in my own attempts I cannot now return to my earlier, complacent, state. If the reader is also disturbed, the article is worthwhile.

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(The DOAE Research Working Papers may be borrowed on application to the Library, DOAE, Parvis Road, West Byfleet, Surrey.)

CARD—Computer Aided Report Drafting

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The use of lists of buzz-words which may be selected at random to form allegedly meaningful combinations is well known. The purpose of this note is to draw attention to a possible extension of this principle[1], which would facilitate the construction of complete sentences, and thus simplify the drafting of technical reports[2].

As an example of the method, consider the tables of phrases listed below:

A

1. It has to be admitted that
2. As a consequence of inter-related factors
3. Despite appearances to the contrary
4. Unless the present trend is reversed
5. Using the principle of cause and effect
6. Assuming the validity of the present extrapolation
7. Using the results of recent studies
8. It is now proven beyond a shadow of doubt that
9. Worrying though the present situation may be

B

1. real determination to achieve success
2. embarking upon a large-scale experiment
3. access to greater financial resources
4. pursuit of international recognition
5. ocean science
6. new computations involving non-linear equations
7. excessive concern with administrative problems
8. new measurements
9. information presented in JASA

C

1. should serve only to add weight to
2. will inevitably lead to a refutation of
3. can yield conclusive information on
4. might usefully help to resolve
5. must take into account
6. will unfortunately mean the end of
7. should ensure further support for
8. could result in confirmation of
9. refutes the current thinking regarding

D

1. the need to acquire further computing facilities.
2. efforts to improve working conditions.
3. Rayleigh's results.
4. design of a prototype leading to production at a later stage.
5. Tennyson's assertion that 'Science moves, but slowly, slowly'.
6. some divergencies in normal mode theory.
7. the desire to encourage certain promotions.
8. the future of acoustics in the UK.
9. proposals concerning surface ship sonars.

Taking one phrase from each of the four tables in turn according to a selected four-digit number leads to sentences such as:—

Despite appearances to the contrary, information presented in JASA should ensure further support for proposals concerning surface ship sonars (3979). Using the results of recent studies, new computations involving non-linear equations could result in confirmation of Rayleigh's results (7683). It has to be admitted that real determination to achieve success must take into account the need to acquire further computing facilities (1151). However, unless the present trend is reversed, access to greater financial resources will unfortunately mean the end of efforts to improve working conditions (4362).

Selection of the phrases may be left to a random number generator.

It may however be noted in the above examples that the addition of some punctuation marks or conjunctions is sometimes desirable to improve the flow, and the optimum method of achieving this within the computer deserves further study. Clearly the tables may be modified as necessary to make them more appropriate for the particular topic. A possible extension of the method would of course be to select complete sentences for random combination

The technique would have two primary advantages. Firstly, it would simplify the writing of technical reports, and would reduce any irritating worries about style*. Secondly, if the technique became widely used, reports could be stored simply on computer memories, thereby significantly reducing the demands for library space. There may of course be some difficulties in implementing such a radical scheme. Furthermore, it has to be admitted that embarking on a large-scale experiment could result in confirmation of the need to acquire further computing facilities. But what further proof do we need of its usefulness?

* Certain authors appear in fact already to have used the technique, though without any formal recognition of the basic principles.

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[2] Nature 258, 465 (Dec. 1975).

This article and the following three letters are in response to the Appreciation to Sir Charles Wright, K.C.B., O.B.E., M.A., M.C., published in the January issue of this Journal. — Editor.

WITH SCOTT TO THE ANTARCTIC

W. F. Fry

W. F. Fry was a member of the *Discovery* Investigations from 1929 to 1943 and in this capacity made three cruises to Antarctica during 1933 - 1939 in RRS *Discovery II*, being awarded the Polar Medal. In 1943 he joined Professor Blackett in the Admiralty's Directorate of Operational Research where he served until retirement from the RNSS in 1970, when he transferred to OS10 to review scientific papers for release to the PRO. His 'second' retirement took place at the end of last year.

Charles Seymour Wright became interested in Antarctica whilst a research student at the Cavendish Laboratory, Cambridge, during 1908 - 10. It was after he became a member of an informal club of research students that he became friendly with T. Griffith Taylor (later appointed geologist, together with Raymond Priestley to the British Antarctic Expedition). In a foreword to the Edward Wilson *Terra Nova* Diary published 1972(1) Sir Charles Wright as he was then, explained the circumstances which aroused his interest. 'Griffith Taylor, the physiographer, and I were research students together at Cambridge. He was an Australian working on palaebotany on the Great Barrier Reef and I was a Canadian doing research at the Cavendish Laboratory. 'Griff' was a friend of Douglas (later Sir Douglas) Mawson who had been to the South Magnetic Pole with the Shackleton 1907 - 9 expedition. Taylor persuaded Mawson to come and talk to a small scientific group at Cambridge. At that time I was doing some research on penetrating radiation which I thought might be quite different in the Antarctic. I naturally at once applied for the post of physicist. I was promptly rejected. Griff Taylor then persuaded me to walk with him from Cambridge to London to see Captain Scott and Wilson and at the same time to see if we could walk the fifty miles in ten hours. The upshot was that I was accepted by Scott on Wilson's advice. Later when the whole party was aboard the *Terra Nova* on her way South from New Zealand and met with Antarctic pack ice, I found myself taking great interest in the flat topped icebergs of the south so different from those I had seen in the north. To cut a long story short Dr. Bill (Wilson) engineered my re-appointment as the expedition's glaciologist which meant that I became eligible for field work away from headquarters'.

The *Terra Nova* sailed from West India Dock on 1st June, 1910, for what has since become known as 'Scott's Last Expedition'. The ship eventually arrived in McMurdo Sound in early January and the shore party took up their quarters in the hut that had been built at Cape Evans.

Captain Scott quickly organised two sledge parties: (a) under Scott himself to lay a large depot on the Barrier for the Polar journey and (b) the first western journey for a geological exploration of the region between Dry Valley and Koettlitz Glacier. This latter party was under the command of Griff Taylor with Wright, Debenham and Keohane in support. After six weeks away from base the two parties joined at Hut Point (old Discovery hut) to await the freezing of the sea to allow passage back to Cape Evans. Wright was an invaluable asset for such work since he was an expert in traversing snow-clad country, for he had often spent his vacations from Toronto University surveying in the Canadian backwoods.

In his own report on General Physics in Volume II of Scott's Last Expedition[2], Wright divides the field covered in Pure Physics by the Expedition into:—

(a) Magnetic Observations.
(b) Atmospheric Electricity.
(b1) Potential Gradient.
(b2) Radioactivity of the Air.
(b3) Natural inonisation in closed vessels.
(c) Pendulum observations.

In a summing up of 'Work and the Workers' an extract from Scott's Personal Journals[2] under this heading says: 'Wright, good hearted, strong, keen, striving to saturate his mind with the ice problems of this wonderful region. He has taken the electrical work in hand with all its modern interest of association with radioactivity'. During these long dark winter months Wright was fully occupied with his scientific researches and indeed Scott remarks on 1st July, 1911, 'Wright has been swinging the pendulum in his cavern. Prodigious trouble has been taken to keep the time, and this object has been immensely helped by the telephone communication between the cavern, the transmit instrument and the interior of the hut. Wright tells me that his ice platform proves to be five times as solid as the piece of masonry used at Potsdam. The only difficulty is the low temperature which freezes his breath on the glass window of the protecting dome. I feel sure these gravity results are going to be very good'.

So with the gradual passing of the winter months the final preparations for the southern journey began and in October 1911 Scott writes: 'One of the greatest successes is Wright. He is very thorough and absolutely ready for anything. Like Bowers he has taken to sledging like a duck to water and although he hasn't had such severe testing, I believe he would stand it pretty nearly as well. Nothing seems to worry him and I can't imagine he ever complained of anything in his life'.

The Polar journey began in earnest on 1st November and Wright leading the pony Chinaman was a member of the First Supporting Party. The story of this journey is well-known and after the ascent of the Beardmore glacier which had been a tremendous task, Scott writes that at Camp 42 Upper Glacial Depot on 20th December, 85°3'S: 'I have just told off the people to return tomorrow night: Atkinson, Wright, Cherry-Garrard and Keohane. All are disappointed — poor Wright rather bitterly I'm afraid. I dreaded this necessity of choosing — nothing could be more heartrending . . '. The First Supporting Party finally reached Cape Evans, having covered the return 500 miles in 37 days.

With the non-return of the Polar Party by the scheduled date, 27th March, it soon became evident that some misfortune must have overtaken them and, in the words of Ponting in his Great White South[3], 'owing to terrific weather and fall of winter it was not until the following spring, 30th October, 1912, that a search party in command of Surgeon Atkinson was able to set out under the guidance of Mr. C. S. Wright who was a skilled navigator. By the evening of 11th November they had covered the 140 miles to One Ton Depot and the next day, having travelled 11 miles further, found the tent'.

References

[1] Diary of the *Terra Nova* Expedition to the Antarctic 1910-12. Edward Wilson. Edited from original MSS in Scott Polar Research Institute and British Museum by H. G. R. King. Published 1972.

[2] Scott's Last Expedition. Vol. I being the journals of Capt. R. F. Scott, RN, CVO. Vol. II being the reports of the journeys and the Scientific Work undertaken by Dr. E. A. Wilson and the surviving members of the Expedition. Published 1913.

[3] The Great White South. (Ponting, H. G. FRGS). Published 1921.

See also: The Worst Journey in the World. (A. Cherry-Garrard). Published 1923.

CORRESPONDENCE

Journal of Naval Science

To the Editor

Dear Sir,

I, the last Head of the RNSS would like to pay tribute to the first Chief of the RNSS, Sir Charles Wright, especially for his creation of that service. His great contribution I believe was not in the conception, it was not particularly novel, but the carrying to fruition.

The part allocated to civilian scientists in the inter war years by a Royal Navy very conscious of its power was modest, in part due to the fact that the Navy depended for its strength on heavy engineering. What is now ASWE was at that time roughly the experimental department of HM Signal School controlled by the Experimental Commander. The great days of radar were just beginning and the role that technical superiority in complex weapons could play was but dimly appreciated. The potential contribution of the scientist and innovator was thus undervalued except by the more far sighted naval officers. Those of us in Radar had little contact with Sir Charles who appeared as a remote figure descending from Whitehall on very rare occasions. We little appreciated that even at that time he was preparing the ground for the RNSS. By 1946 helped by the great impact science made during the war the RNSS was launched. It is difficult to remember the events of thirty years ago but for most of us it gave a great boost to morale. It was pleasant to be recognised and the concept gave promise of horizons far wider than those of the experimental departments of the various Schools. Whilst it is doubtful if all the high hopes have been fulfilled, it was a great step forward.

Now the RNSS is no more, it has had a short life but an effective one. We should therefore pay tribute to Sir Charles for his vision and for his steadfastness in instigating its birth.

D. STEWART-WATSON

To the Editor

Dear Sir,

My first contact with Sir Charles Wright was when he succeeded Dr. C. V. Drysdale as Superintendent of ARL when I was a very junior officer. He invited my wife and myself to dinner in June 1932 at his home in St. Georges Hill, Weybridge where we were very cordially welcomed and entertained by Mrs. Wright. We vividly recall a large woollen carpet covering the drawing room floor which had been handmade by Mrs. Wright. My wife who was 'expecting' our first born, and therefore somewhat nervous at the thought of dining with the Superintendent was soon put completely at ease in the comfortable atmosphere of the Wrights. This may provide a glimpse of their charming characters.

During this period at ARL Dr. Wright gave a talk to the Staff and families on his experiences in the Antarctic with Scott and I have always remembered one anecdote he quoted when showing slides of the ice floes they encountered. A sailor had ventured too far on pack ice when a killer whale was sighted from a higher vantage point and it was approaching the sailor at full speed, probably taking him for a seal. The other members of the party quickly hauled the chap to safety and his mate's comment was, 'His bloody face was as white as a bloody sheet'.

He took a great interest in one's day to day work but never intruded on the work policy being pursued which in my case was gyroscopic stabilisation and not in Sir Charles line of country for detailed oversight. When he became DSR one saw even less of him but he always retained his friendly contact with staff. Whilst serving in the British Navy Staff in Washington DC from 1960 - 1964 Sir Charles visited Washington to give a lecture to a US Scientific Institution and we were able to entertain him and his daughter, then living in Washington, to dinner at our flat in Arlington. Later on when I was on an official visit to Victoria, BC I was entertained to tea by Sir Charles and Lady Wright just a short time before his wife's death. He was then spending the winters at La Jolla, California and working or advising at Scripp's Institute whilst returning to Victoria for the summer period. I last saw him when he was again in Washington and he attended our farewell party.

NORMAN WARREN

To the Editor

Dear Sir,

My association with Sir Charles Wright goes back to the time when I was only a small boy, because I always remember my father telling me stories of his experiences with Sir Charles way in the distant past. The chief one I remember is, that before the Scott expedition to the Pole there was a campaign to raise funds and my father and Sir Charles were in a coach with Scott signing autographs. It would be interesting to know how many people have Scotts signature in Wrights handwriting. My first actual contact with Sir Charles was when as a schoolboy I was taken by my father to ARL where I met him — it would be about 1929. I was impressed by his jocular manner because on his desk was a matchbox which he handed to me and when I opened it Jack-in-the box jumped out of it. I also remember Sir Charles for his kindness to his staff. One year he lent us his bungalow at Ferring near Worthing, called 'Muscoco' which I subsequently found is a place near Toronto so he must have had some sentimental reason for calling it 'Muscoco'. My memory of the bungalow is that it was very primitive as is the home where he died, because my great memory is that in order to get water you had to operate a hand pump 300 times. My father often took me to the Physical Society Exhibitions and when we got there we nearly always saw Wright and Wood (A. B. Wood) and my father would say 'Oh there's Wright, he's at it again, he's leg-pulling as usual' and he would be quizzing someone about a piece of apparatus that he himself knew a lot more about than anyone else.

After that time I had no personal contact with Sir Charles during the War or after for some time, but my father was always very close to him. When I next met Wright it was when he visited AUWE soon after we moved down from Havant and we had an official cocktail party and drinks with the various Canadian visitors, and Sir Charles was one, at our house. The reason for its being at our house was a number of the other people hadn't got houses yet, they were all living in digs and things.

Now my next contact with Sir Charles was when we went on a holiday to Canada in 1970 to see the Rockies and we thought we'd look him up and have a meal with him, when we made contact he invited us to stay with him. When we got there we found he was living in a very small bungalow on the edge of a cliff with a delightful view over the sea which is between Vancouver Island and the mainland of Canada, now this bungalow only had one bedroom in it and he and his daughter, moved out of that room and slept out in an old hut so that we could have their bedroom. Next door to this hut there was another old hut which Sir Charles had converted into a laboratory, full of power points, and outside there was a terrific amount of junk that he had just moved from his house in the States and all the stuff he'd removed was just piled up in a heap. Included in this junk there were the skis that he had used on the Polar expedition. Oh! And the number of things he said he was going to do — that was in 1970, when he was 83 — he said he was going to build a boat also he was doing a lot of his own work such as fencing in the bungalow. The fence ran along the edge of the cliff and one day, Pat Wright, his daughter, wondered where he was — he'd fallen down the cliff. A little while later his beaming head appeared and Sir Charles all covered in blood arrived at the top.

He got into an argument with his daughter Pat because he wanted to show us his arbutus trees and he had got them floodlit much to the annoyance of his daughter who was very fond of animals and she didn't want the birds who were nesting in the eaves of the bungalow disturbed. Needless to say, Sir Charles won the argument. Actually Pat who's fond of animals, does animal illustrations for the Hudson Bay Company.

He was 83 years old when he finally retired, he had been spending six months at the Scripps Institute and six months at Esquimault, and he had just given all that up and retired to the bungalow. He used to have a house in Victoria and another in the States, and as I hear it, when he removed his furniture from the States to Salt Spring Island he hired a removal van and drove it himself. Now, one of the difficulties he was having on Salt Spring Island was that he couldn't find enough water. His well kept drying up and he was having water diviners and boring done but couldn't find enough water and that reminded me of his bungalow at Ferring when one had to pump 300 times so I immediately joked and said 'Oh this reminds me of Muscoco'. Sir Charles said, 'Muscoco, what are you talking about boy?' and then Pat said 'Don't you remember Father the bungalow at Ferring'.

Since 1970 we kept in touch with Sir Charles and we have always had a Christmas card from him. Our last contact with him was indirect, and rather strange. We were on holiday in the Far East and were staying at a small hotel in Colombo. There were only two other people in the hotel at the time and they started talking to us and they said that they'd come to Colombo to take animal photographs for Canadian television and that they had just come from Victoria, so since they were interested in animals, we asked them if they knew Pat and their eyes lit up and they said that only a fortnight ago they had had tea with Sir Charles and Pat after interviewing him for a programme about his life to be shown on Canadian television.

ALEC BUTTERWORTH

Dear Sir,

J.N.S. Vol. 1, No. 4, Page 310

Mr. Corben's comments on narrow band analysis of vibration data would appear to be a little out of date.

Real Time Analysers such as the Federal Scientific (Nicolet) and Spectral Dynamics ones using time compression techniques are not time consuming to use, will output frequency data in several convenient forms and are 'suitcase' portable.

As to the economic aspects of this; a RTA is comparable in price to a 14 channel instrumentation recorder. A tape recorder is not needed when the RTA is used on site.

Yours faithfully,

J. F. Edwards

Military Vehicles and Engineering Establishment

Dear Sir,

The proposal to use a portable tape recorder as the data link between vibration measured on machines in a ship's compartment and a shore-based analyser and computer facility was made for practical reasons. I am aware of the time-compression analysers and regularly use one of the types recommended by J. F. Edwards. There are a number of points in favour of machinery health monitoring in the fleet being carried out by a team based on shore (there are also some disadvantages), and an essential feature of the proposed equipment was that it could be transported (by air if necessary) and used at any site where R.N. ships are operating, by one man. On board, the equipment has to be moved around to the various machinery spaces and this usually involves the use of vertical ladders. As measurements will often be required whilst the ship is in a dockyard, and power supplies may be interrupted, the equipment must be independent of external power supplies. On the basis of portability and battery operation the tape recorder has to be a single or twin-track machine with a suitable frequency response. The multi-track recorder has few if any advantages over the smaller unit, when one man has to transport and rig the measuring chains; recording time is rarely limited as the visit will be timed for a suitable period when most machines are running, or, can be run at short notice.

On the question of time on site, the analysis time must be compared with the, say, one minute required to make the tape recording. Although the Real Time Spectrum Analyser may display 250 or 500 line analyses in a few seconds, time is consumed in reading off and manually logging the frequencies of interest for comparison with past or future results. This is a tedious task and subject to human error when many analyses have to be made. If the narrow band analysis of, say, one Hz is required above the 250 or 500 Hz range of the trace, another unit, the translator, must be added to the equipment. To avoid the manual logging yet another unit and a tape punch are required. Data recorded by manual logging or a Polaroid photograph is not directly suitable for computer processing or storing.

Yours faithfully,

F. Corben

Admiralty Engineering Laboratory

Admiralty Underwater Weapons Establishment

Obituary

After a relatively short illness **Frank Evans** died at his home in Weymouth on Saturday, 14th February, a few weeks before his scheduled retirement at the age of 63 after 36 years' service.

Frank joined the Admiralty in 1940 and was first employed in the Mine Design Department on countermeasures equipments. These included redesigning the Fessenden Submarine Oscillator and developing a Water Siren as sweeps against acoustic mines. He was also associated with the development of remotely controlled enemy mine dismantling equipment. Subsequently he worked on the design of a 10 inch diameter 60 feet long Air Gun developed to simulate the deceleration forces sustained by mine and depth charge components on water entry.

In 1942 the Admiralty sent Frank to Harland Engineering Company at Alloa to take charge of the design construction and trials of an ahead thrown anti-submarine weapon (PARSNIP) which finally led to SQUID, the first ahead thrown non-contact A/S weapon introduced in the Royal Navy. Originally this weapon was fitted forward of the bridge of the ship but subsequently it was required to be fitted on the quarter-deck. This resulted in changes in ballistic and structural design and extensive land and sea trials with which Frank was closely involved.

At the end of World War II Frank wrote the Historical Record of the establishment's A/S weapon programme. Soon however he was involved in the design construction and evaluation of SQUID's successor LIMBO. In order to develop the internal ballistics of the weapon he designed a special Test apparatus for determining the optimum loading density and venting ratio factors when burning cordite propellant in a two chamber system as a trials facility. The evaluations meant Frank spending some considerable time at sea; six weeks in the Arctic in 1949 and extensive trials at South Rona in 1950 bear witness to this.

In 1952 Frank turned his talents to the design of arming units and impact firing pistols for PENTANE an air dropped torpedo but before long he was yet again involved in mine countermeasures activities.

From about 1953 onwards his duties became more administrative, in general acting as deputy to Dr. F. F. Butterworth. Subsequently he acted as technical assistant to the Director of what is now AUWE. On promotion to PSO in 1971 Frank became responsible to the AUWE Management for scientific staff, personnel and administrative matters. He also assumed responsibility for staff training and became secretary of the Local Career Development Panel.

Although invariably overloaded with work Frank always found time to give advice or information to staff. He commanded the full respect of everyone because of his interest in, and knowledge of, the establishment and of the Service. He was always sympathetic and coupled this with a fair and firm treatment of individual problems.

"Throughout his life he put Service interests first although he played a very active part in the Weymouth Arts Centre and the Local Church Council. His energy and application were a fine example to all staff. His valuable service was recognised in 1974 when in the Queen's Birthday Honours List he received the Imperial Service Order. Moreso the pity that he did not live to enjoy a well earned retirement. His many friends and colleagues extend their deep sympathy to his wife and family."

Mr. S. D. Mason was appointed Head of Sonar Dept. AUWE from Deputy Director Underwater Weapon Projects (Ship Systems).

Mr. D. A. White was promoted to DCSO and appointed Deputy Director Underwater Weapon Projects (Ship Systems).

Visits of senior staff were as follows:

23 March Dr. W. H. Penley, Controller R&D Establishment and Research.

26 March Vice-Admiral R. P. Clayton, Controller of the Navy

29 March Dr. D. H. Davies, Assistant Chief Adviser (Projects)

30 March Rear-Admiral A. G. Watson, Assistant Chief of Naval Staff (Operational Requirements)

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Admiralty Oil Laboratory

The Quadripartite Meeting on Naval fuels and lubricants was held in Australia in May and was attended by Dr. D. Wyllie, Mr. C. E. Carpenter, Dr. M. H. Holness and Mr. R. E. Penfold. Mr. C. E. Carpenter went from the Quadripartite Meeting to Japan to attend the 9th World Petroleum Congress that was held in Tokyo. Meetings of European Committees were held during the year; Mr. C. E. Carpenter attended the 18th Meeting of the Commission European Normalisation Working Group No. 19 held in Paris in April, and Mr. R. E. Penfold was a member of the UK delegation at the Engine Lubricants Technical Committee of the Co-ordinating European Council held in the Hague on 14-17 April.

Mr. C. E. Carpenter attended the Meeting of the Naval Fuels and Lubricants Working Party, as member of the UK delegation, held in Brussels on 15-20 June. In October Mr R. P. Langston attended the 22nd Meeting of the Engine Lubricants Technical Meeting that was held in Rome.

To ensure that the laboratory was fully aware of political as well as the technical problems associated with petroleum products Mr. R. P. Langston attended the Wilton Park Conference on the subject of 'Oil and other commodities: the politics of producer and consumer needs' that was held from 22 February to 6th March.

At the 3rd International Tribology Conference held at Paisley College of Technology on 21-25 September, Mr. P. R. Eastaugh in collaboration with Mr. J. Ritchie, Mat R10 MOD (PE) presented a paper on 'Improved Fluids for Submarine Hydraulic Systems' reproduced in the January edition of this journal.

Several members of the staff attended one day symposia, notable among these was that held at University College, Cardiff on April 17, on the subject 'Disposal of Oil Waste' attended by Mr. C. E. Carpenter. In November Dr. M. H. Holness attended the symposium 'Environmental Regulations: An International View' and another at the Chemical Society 'Health and Safety at Work in Chemical Plants and Laboratories'. On 8 January Mr. R. G. Collis attended the symposium held at the University of Sheffield, the subject being 'The 3rd Analytical Atomic Spectroscopy Symposium'.

In keeping with our up-dating of technical information Mr. P. R. Eastaugh attended a two-day IME Conference on Piston 'Ring Scuffing' held on 13-14 May.

Visits of Senior staff were as follows:

8 October 1975
Captain K. B. Birkett DD Eng (M)

7 November 1975
Dr. D. H. Parkinson DGERPA

11 February 1976
Mr. R. J. Daniel DG Ships

16 March 1976
Dr. W. H. Penley CER

16 March 1976
Mr. B. W. Lythall DCERA

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Royal Naval Physiological Laboratory

Dr. H. V. Hempleman, Supt RNPL has been awarded the Albert R. Behnke Jr., Award of the Undersea Medical Society.

The formal presentation has yet to be made but could possibly take place in the USA in May 1976.

March 1976 - Dr. H. V. Hempleman, Supt/RNPL visits USA and Canada to represent DR/UW at The Office of Naval Research (Workshop, on High Pressure Biomedical Research) Naval Coastal Systems Laboratory, Panama City to discuss deep diving, followed by a visit to DCIEM, Toronto, Canada for discussions on the same topic.

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