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A MODEL FOR THE SUBMARINE DEPTHKEEPING TEAM

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SUMMARY

One of the few real examples that exist of cooperative control of a relatively fast (compared to economic systems) system occurs in the depth control loop of a submarine. Two operators sit side by side viewing essentially similar displays in an arrangement that is much like a conventional aircraft cockpit. One of these operators has direct control of the forward planes and the other has direct control of the stern planes. By tradition each is assigned a distinct control task; the forward planesman controls depth and the stern planesman controls pitch (attitude). Obviously these controls are not independent and a high degree of coupling exists.

The most difficult task the depthkeeping team must face occurs during periscope-depth operations during which they may be required to maintain a submarine several hundred feet long within a foot of ordered depth and within one-half degree of ordered ptich. The difficulty is compounded by the facts that wave generated forces are extremely high, depth and pitch signals are very "noisy" and submarine speed is such that overall dynamics are slow.

In late 1979 we began a study leading to a mathematical simulation of the depthkeeping team based on the optimal control models that have proved successful in many other applications. This work will be described, including a solution of the optimal team control problem with an output control restriction (limited display to each controller).

I. INTRODUCTION

Modern submarines bear little resemblance to their WW I and II ancestors. Prior to the advent of the nuclear age, submarines were basically enclosed surface ships capable of submergence for short periods of time and substantially faster on the surface than below. A typical modern submarine is built to operate and function totally submerged for essentially indefinite periods. Circular cross section hulls and improved hydrodynamic shaping has resulted in a reverse of the WW II standards and the new subs are much faster below the surface than while surfaced.

Despite substantial advances in almost every other area of submarine operation, steering and diving control procedures have changed relatively very little over the years. True the displays are high reliability devices and the planes/rudder hydraulic systems are faster and quieter but man functions in the loop much as he did before. In fact, the steering and diving control of a modern U.S. Navy submarine is one of the few examples of a team effort for the control of a small dynamic system. In this paper we will discuss the most demanding of the functions of the steering and diving team; that is, accurate maintenance of depth, trim (pitch), and heading while operating at periscope depth in a heavy sea way; and our efforts to model their procedures. The remainder of this paper contains the following material:

Section II describes the Near-Surface Depthkeeping (NSDK) control problem in more detail and discusses the roles of the team members.

Section III describes an Optimal Control Modeling approach for solution of this problem.

Section IV presents the results of a preliminary experimental study and describes the follow-on efforts.

II. THE SUBMARINE CONTROL PROBLEM

Over the past several years we have been investigating many aspects of submarine control including display effects and workload. However, the most difficult task, from the operators' viewpoint, is the periscope depth operation. There are several sources of difficulty including:

(1) Control of a large physical system (perhaps 300 to 400 feet) with very slow dynamics.

(2) A narrow operational band; too deep and observation capability is lost, too shallow and detection may result.

(3) The presence of extremely large disturbance forces due to sea waves. These are of two types: first order forces which resemble zero-mean, narrow band, Gaussian processes; and second order forces which resemble the first order

processes past through a square law detector (squaring device). The second order forces always act upwards and tend to "suck" the submarine towards the surface.

(4) The presence of (relatively) high frequency noise on all displays which is the direct or indirect result of first order wave action.

(5) A relatively low skill level and rating (compared to pilots of military aircraft) of the helmsman/planesmen.

In order to cope with these difficulties the U.S. Navy has evolved a procedure that has as its goal the de-coupling of the primary control axes of depth, pitch and heading. There are five personnel involved in the near-surface depthkeeping (NSDK) operation whose duties and responsibilities are as follows:

Officer of the Deck: The OOD is generally responsible for the overall well being of the ship. He will issue orders directly to the Diving Officer of the Watch for depth and trim. He also issues orders directly to the helmsman for heading control. A typical set of orders would be: "Helmsman, xx degrees right rudder, steady on course xxx degrees." The helmsman replies: "Helm aye" and then, when the course is reached, "Steady on course xxx degrees."

Diving Officer of the Watch: The job of the DOOW is to attain and maintain ordered depth. He does this be exerting direct control over three other personnel--the stern planesman, the fairwater planesman, and the Chief of the Watch. One of his major roles is training and admonition.

Chief of the Watch: The COW is in charge of the Ballast Control Panel (BCP) and he ballasts and trims the ship in response to orders from the DOOW. He does this moving water fore and aft (for trim) and to and from the sea (for ballast).

Stern Planesman: The role of the stern planesman is to maintain ship's angle (pitch) using the stern planes (located near the rudder) in direct response to commands from the DOOW.

Fairwater Planesman: Under normal conditions the fairwater * planesman has two separate and distinct responsibilities.

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* The bridge fairwater, now called the "fairwater" or "sail" is what was called the "conning tower" on the older ships. The fairwater planes are mounted on this structure so that they do not extend beyond the beam of the ship.

First, in his role as planesman, he will be tasked to maintain ship's depth in direct response to orders from the DOOW. Second, in his role as helmsman, he is responsible for attaining and maintaining ship's heading in direct response to orders from the OOD.

The physical arrangement of the personnel is as follows. the OOD moves freely through the control room but is usually fairly near the periscope (which is located amidships) from which position he can observe all of the control activity. Slightly forward and to port (left) is the diving control station which somewhat resembles the pilot/co-pilot seats, controls, and displays in an aircraft (no windows, of course). The DOOW sits slightly behind and centered on the planesmen. The Ballast Control Panel is still further to port and the COW sits facing this panel which can also be easily monitored by the DOOW.

The fairwater planesman's role is obviously the more difficult of the two as he receives orders from two sources to control two axes of motion. Fortunately the vertical and horizontal plane motions are only very lightly coupled and, for all practical purposes, he may consider them to be orthogonal. However, the pitch and depth motions are very closely coupled via the dynamics of the ship and correction of depth errors by the fairwater planesman influence pitch angle and the correction of pitch errors by the stern planesman influence depth. The nature of this interaction and the manner in which the planesman solve their problem was the primary interest of our study.

In order to focus the intensity of the effort it was decided to attempt to model only steady state operation and exclude the evolutions involved in coming to the surface and submerging after the operations were complete. As a result of extensive interviews and at-sea observation of procedures we concluded that, again emphasizing steady state operational conditions, the OOD and the COW contributed little to the moment-to-moment control activity. The OOD, once having given orders for depth and heading, would not interfere in the routine unless unusual circumstances occurred. The COW, having trimmed and ballasted the ship to the DOOW's satisfaction, would only monitor ship's status. Therefore our preliminary experiments included only the DOOW and the two planesmen.

From further observation of crews during the preliminary experiments, augmented by further interview data, we concluded that the role of the DOOW was primarily admonitory. That is, he intensified the efforts of the planemen by issuing commands/warnings such as:

* Watch your depth!
* It's starting to come up!
* Maintain your angle!

and so forth. From this we concluded that, were the planesmen more skilled, the role of the DOOW during steady state operation would be minimal. This was confirmed by noting that there was considerably less communication in low sea states than in high sea states and that little or no communication occurred between the DOOW and the planesmen when the planesmen had considerable experience. The DOOW transferred his much more extensive skill and experience to the planesmen and also served to motivate them should their attention lag. Therefore, we reasoned, the model could take into account the effects of the DOOW by simply employing a slightly higher "skill factor" or attention parameter than would otherwise have been used. The DOOW was also eliminated from the modeling procedure.

Having reduced the diving team to its two essential members it only remained for us to quantify the nature of the inter-relationships between them. We again intended to rely heavily upon interview data to provide insights in this regard. Indeed all of our interviewees (most of whom had, at one time or another, actually been involved in planesman/helmsman training) emphasized the importance of cooperation between the planesmen. Both during training and at-sea operation, planesmen are urged and encouraged to "cooperate" and not to "fight" each other. However, when we attempted to pin down exactly in what way the planesmen were to cooperate we received no satisfactory answers. Apparently "cooperation" was a vague concept and the over-riding rule was an attempt at independent control of depth and pitch. We decided to make the tentative assumption, until the data should prove otherwise, that cooperation, as such, was a myth. That is, while each planesman is aware of the other's activities, he does not attempt to aid the other in achieving his performance goals. Each planesman establishes his own performance goals and attempts to meet these while in control of a dynamic system which is made up of both the ship <u>and</u> the other planesman. In fact, we postulated that should the planesmen be completely isolated from each other and from displays of the other's behavior and controlled states, their responses would not be substantially different. Unfortunately we did not have the opportunity to design and conduct a set of experiments which would have conclusively demonstrated the truth of falsity of that assumption.

III. FORMULATION OF THE MODEL STRUCTURE

The conclusion that cooperation is largely a myth heavily influences the resulting model structure. Beginning basically with the Optimal Control Model (OCM) as proposed by Kleinman (Ref. 1), the model structure shown in Figure 1 was derived. Having had good success with an OCM approach for single person submarine control in the past we elected to continue along this path as far as practicable. For example, the lack of cooperation implies that the planesmen have different performance functionals (control goals). In addition there are other items to be considered with regard to observation and utilization of data. The most basic of these are summarized in Table 1. In Table 2 we present further differences between the human and the optimal controller. As these latter limitations and differences are well known they require no further elaboration at this point.

Figure 1

**OPTIMAL CONTROL MODEL (OCM)
FOR SUBMARINE NSDK EVALUATION**

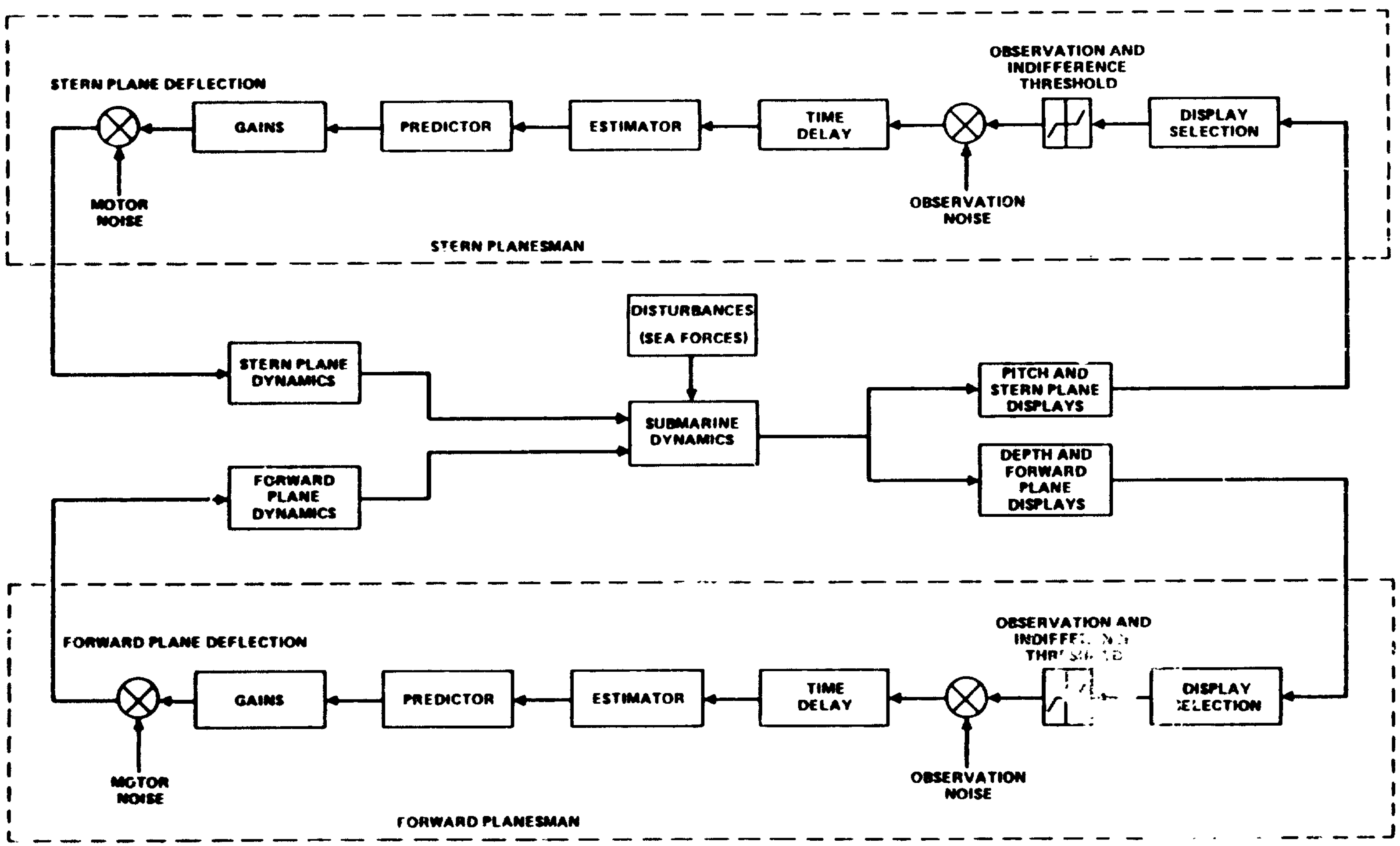

TABLE 1

COMPARISON OF OPTIMAL AND HUMAN TEAM STRATEGIES DURING NEAR SURFACE DEPTHKEEPING

Optimal Controller Strategy	Human Strategy
The optimal controller considers that both planes operate in harmony and utilizes a single performance function to derive its control law.	The fairwater and stern planesmen's goals (performance functions) are different which may result in conflict.
The optimal controller "observes" all states and uses this information in the control laws.	The fairwater planesman observes depth information only and the stern planesman observes pitch information only. Neither attempts to construct the others states from his limited observations.
The optimal control law uses gains on all states for both controllers.	The forward planesman's control law uses depth and depth rate only while the stern planesman's control law uses pitch and pitch rate only.

TABLE 2

COMPARISON OF OPTIMAL CONTROL AND HUMAN LIMITATIONS

Optimal Controller	Human Constraint
Optimal system's observations are "noise free" (neglecting sensor noise).	Humans observe imperfect instruments and are subject to observation and indifference threshold phenomenon.
Optimal controller has perfect knowledge of submarine dynamics.	Human's knowledge of submarine dynamics is imperfect and a strong function of training and experience.
The optimal controller observes all states simultaneously and is able to utilize the information so obtained.	The human can effectively observe only one display at a time and must allocate his attention appropriately.
The optimal controller gives full "attention" to the task at all times.	Humans are subject to lack of attention due to mental fatigue, boredom, stress, or lack of motivation.

The structure shown in Figure 1 is at variance with the standard Linear-Quadratic (LQ) controller (and the human models resulting from it) in two major respects:

(1) Each control has its own performance function. In the present case these are independent.

(2) The control law is based on a limited set of states.

The combination of these deviations from standard LQ control theory is one aspect of team theory and/or decentralized control theory. While literature on these topics is easily found little or no practical applications or solution techniques is evident. In the limited space here we could not present the details of the techniques we used to solve this particular problem. An outline of the approach may be, however, instructive. An initial set of gains is determined, by an appropriate start-up technique, for one of the controllers. This set of gains, plus the system open loop dynamics, represent the system to be controlled by the other controller whose gains are then easily computed by standard techniques. This set of gains is then used to update the original guess on the first controller's gains and the process is repeated iteratively until sufficient convergence takes place. This iterative procedure is embedded in a further iterative procedure (due to Wenk, Ref. 2) for computing the optimal output control (state limited) feedback problem.

Having determined a computational procedure for solving the requisite control problem there remained only the selection of the various model parameters. These are:

(1) The control and state weighting matrices.
(2) The indifference thresholds.
(3) The Total Attention Parameter (TAP).

The Total Attention Parameter (TAP) is simply a divisor of the baseline observation noise derived from previous display related experiments (-20.0 db). By varying the TAP from unity towards zero the observation noise increases which, in turn, decreases the performance of the model. This decrease in performance may be thought of as arising from any of several causes such as boredom, lack of motivation, and so forth. Based on previous experiments we expected to be able to match the human data with a TAP in the range of 0.5 to 0.75. The diagonal elements of the weighting matrices would simply be the inverse of the variances of the measured human performance and thresholds would be approximately one-half of display graduations.

Unfortunately this straight-forward procedure did not duplicate the experimental data available. In every case the performance of the model was substantially superior to crew performance unless the TAP was reduced to unreasonable levels. After a considerable period of investigation it was concluded that the error did not reside with our assumed model structure and gain selection procedures. However, based to a large extent on detailed studies of strip chart records, it was postulated that the lower than expected performance of the crews was attributable to a relative lack of motivation which was manifested by higher than normal indifference thresholds. Because it is not unreasonable to suppose that the TAP and the indifference thresholds would be related when motivation was low, we sought to form an ad hoc relationship between the two that would explain the available data. The form of this relationship was suggested by the form of the Random Input Describing Function (RIDF) for the threshold in the range of interest. The TAP and the RIDF for the threshold interact in such a way as to imply that they could be related by:

$$\text{Indifference Threshold}_i = K_{1i} - K_{2i}(\text{TAP})^2$$

It should be amphasized that this relationship was selected for mathematical tractability and may have to true anthropomorphic basis.

The K_{ni} were selected by (the admittedly) arbitrary procedure of assuming that the normal threshold (½ major graduations) could be used for a TAP of 0.8 and that the thresholds would be four times as great when the TAP was 0.2. It is only necessary to vary the TAP until the desired level of performance is attained. The validity of the approach could only be determined by its ability to predict performance in conditions other than that used for tuning.

IV. PRELIMINARY EXPERIMENTAL RESULTS

A preliminary experiment was conducted for the purpose of providing data for model tuning. In this preliminary experiment only the vertical plane states of depth and pitch were controlled. (The total control problem will be addressed in a later study). Eight crews controlled a simulated U.S. Navy attack class submarine under two conditions; Sea State A at X knots and Set State B at Y knots. For the first case the TAP of the model was varied until the model's average RMS depth error equalled that of the average RMS depth error of all crews. Weighting matrices based on this condition were used to generate the data shown in Table 3A. (All data has been normalized so that the value for the human results is unity for every variable in order to preserve the unclassified status of this report.) By agreement with the Navy we are only required to match pitch and depth data but we have reported control data also. Exactly the same model parameters were used to predict performance in the other condition, Sea State B at Y knots, as shown in Table 3B.

V. CONCLUSION

Based on the preliminary results it certainly appears that our decision to proceed using an OCM approach was more than justified. The team modeling problem can be very complex but the OCM structure allowed us to attack the problem in a fairly coherent manner. At the present time the Navy is planning a much more elaborate set of experiments which

TABLE 3

COMPARISON OF MODEL AND HUMAN PERFORMANCE

TABLE 3A

SEA STATE A AT X KNOTS
(HUMAN DATA IN PARENTHESES)

	Depth Error	Pitch Error	Stern Plane	Fairwater Plane
Average RMS	0.990 (1.000)	1.007 (1.000)	1.149 (1.000)	1.019 (1.000)
Standard Deviation	0.076 (0.073)	0.065 (0.073)	0.072 (0.362)	0.070 (0.161)

TABLE 3B

SEA STATE B AT Y KNOTS

	Depth Error	Pitch Error	Stern Plane	Fairwater Plane
Average RMS	0.991 (1.000)	0.929 (1.000)	0.679 (1.000)	0.684 (1.000)
Standard Deviation	0.123 (0.097)	0.079 (0.106)	0.057 (0.273)	0.041 (0.188)

will include both depth and heading control along with other variables to fully validate the OCM approach. Perhaps we'll be back to tell about this next year.

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