HYBRID SIMULATION OF A SUBMARINE FEATURING A MANEUVERING PHYSICAL MODEL DYNAMIC DISPLAY

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Introduction

The operation of a small submersible constitutes a large scale system in action. The number and variety of subsystems and components are many and diverse in nature and in function, with numerous inputs and excitation functions present, some deterministic, others stochastic. Both man and machine must operate together in various degrees of semi-automaticity, controlling with intermittent and continuous signals traversing interconnected multiple feedback loops containing non-linear elements.

The environment itself is adverse, consisting of pressure, corrosion, poor visibility and requiring life support. Undersea currents, with turbulence and time varying flow, together with cross-coupling effects on the vehicle render the motion and attitude of the craft highly non-linear. Yet it is paramount that all parts of this sophisticated system (including man) contribute to the common goal of a successful underwater mission, be it search, exploration, recovery or oceanographic research.

To minimize cost and ensure meaningful operation, engineering effort must be guided and supported in the pursuit of improved design and increased efficiency of the deep submersible. Pure analysis alone, directed toward solving a non-linear, time-varying, cross-coupled multi-loop type of problem cannot treat more than a few simplified aspects of the entire systems problem. Although various portions of each subsystem may be susceptible to hand techniques, the dynamic analysis of the subsystems operating together in real time will require the assistance of simulation as a tool for investigation. Only through this use of simulation techniques implemented on suitable computing machinery can the engineer obtain the information and data necessary for analysis, design and synthesis that is consistent with economy.

This paper describes some major features of a hybrid simulation of undersea vehicles performed under company-funded programs over the last three years in the Re-entry and Environmental Systems Division.

Simulation in General

Formally, simulation might well be defined as "attaining essence without reality." More practically, the salient features of a device, process or system, either real life or proposed, may be simulated for reasons of convenience and economy in study and design by constructing an "entity" or model of some kind which is analogous to the object being observed in the sense of being able to imitate its behavior or characteristic (e.g., reproduce phenomena likely to occur under imposed specified condition, actual or feigned).

Simulations may be classified as either direct or indirect, total or partial, and physical or mathematical. (These partitions are not mutually exclusive, but may exist in various combinations.)

A direct simulation obeys the physical laws governing the action, while an indirect version describes the phenomenon. A mathematical simulation involves a set of equations represented by software on the computer while physical refers to actual hardware involvement in some manner in the simulation.

A total simulation includes the entire system, either represented directly by the entity itself in a mock exercise or indirectly by a mathematical model undergoing computation. A partial simulation (also called a test or physical simulation) includes actual hardware subsystems or components (or their non-mathematical replicas) in its organization. It attempts to create, under the investigator's control, operating conditions similar to those actually postulated to exist. The class of partial simulations thus includes subjecting scaled (physically, dynamically or in some other sense) models to actual or simulated environments.

In this paper, the term "hybrid simulation" implies utilization of both analog and digital computers in a combined mathematical/physical partial simulation of an undersea craft.

Hybrid Simulation Laboratory

It was Luther Burbank, the famed horticulturist, who said (while perhaps speaking in another context), "Hybrids are what make the world go forward."

The advantages of a hybrid type of simulation are numerous. They include:

- Assignment of different sections of a problem to each computer. For example, path calculations may be done digitally for high resolution, while controls are simulated on the analog for flexibility in design.
- Different functions may be assigned each type computer. Integrations may be performed on the analog to ensure a continuous output, while function generation by table look-up may be done digitally.
- Continuous graphical output may be provided by the analog while accurate, tabular printouts are available from the digital computer in may different formats.
- Logic or decision functions, scale changing, editing and choice can be done by the digital computer,

- Incorporation of real hardware as part of the simulation. Most hardware can readily be connected into the analog, and hybrid operation allows it to connect readily to the digital computer. Similarly, digital components such as samplers and quantizers can be included.

- The inclusion of "man-in-the-loop" to serve as an error-correcting mechanism in the overall system.

Our Hybrid Computing Facility is undergoing a transition period between the present operating system and a greatly expanded system.

The present operating system configuration employs a GE 235, which operates as a dedicated computer when in the hybrid mode and accesses the analog conversion equipment through the Datanet 63, a special interface developed to our specifications. The timing, control and routing of the information is centered in the hybrid computer linkage, which contains 32 multiplying digital-to-analog channels (MDAC's) and a 32 channel multiplexed analog-to-digital converted (ADC) equipped with sample and hold amplifiers for simultaneous sampling without skew. The conversion equipment can be routed through the "SWITCH" system, a relay-actuated computer-controlled switching matrix that allows any or all of six analog computers to access the GE 235. Software has been developed which allows the sequential time sharing of the various hybrid jobs with a turn-around time on the order of ten seconds for previously compiled programs. Compiling a new program necessitates stopping the execution of real time jobs in the present system. The hybrid software package written for the GE 235 is primarily concerned with data conversion, scaling, logical sensing, and analog mode control.

The new hybrid system utilizes the existing analog computers, conversion gear and a new GE 635 computer. Access to the 635 will be via an ASR 35 teletype which will control loading and execution of the hybrid time critical jobs, under the GECOS III operating supervisor. The hybrid programs will operate as high priority batch programs which will not be swapped during execution. Communication to the analog equipment will be through a special master mode module to minimize bookkeeping. Dynamic debugging will be possible using DAC, a direct access option.

The system will expand the capability of the present system to include the full computational capability of the GE 635, including 131K words core memory, 16 magnetic tapes, and disc files. A line printer will be located in the Hybrid Lab. for convenient data access. Since standard 600 line software is to be used, communication and linkage to other programs will be simplified, allowing the use of a common data base in many instances. The timing and control of the clocked data transfer will continue to be an external function, with an interrupt line used to request the central processor when the data transfer is complete.

The Carco Flight Simulator (or flight table) is a precision electro-hydraulic positioner which dynamically simulates the angular flight motion of space and undersea vehicles in testing inertial components and systems.

It is a three-axis gimbaled flight table with each gimbal driven independently in either rate or position mode. The outer and middle gimbals have a $\pm 120^{\circ}$ displacement, while the inner gimbal can spin continuously up to 100 rpm, and can mount test packages up to 250 lbs., 18" diameter and 21" in length.

The mathematical model in the hybrid simulation provides the resulting motion commands to drive the Flight Table representative of the motion. Actual sensors mounted on the Table sense the rotational motion, and the output is monitored and/or fedback to close the loop within the simulated vehicle problem.

The Hydraulic Laboratory permits evaluation of vehicles employing hydraulic actuator devices. For example, missiles possessing movable aerodynamic control surfaces can be included in the simulation by mounting the hardware actuators on the test stands and subjecting them to variable loads, driven by the simulation problem output. Output data of the actuators is either evaluated or used close loop to drive the simulated surfaces in the problem.

The "Hunley" Submarine Simulation

A hybrid simulation of a manned small submersible combined with optical/TV seafloor and sonar displays has been both operational and evolving over the past three years. The basic purpose has been threefold:

- Investigation of control and stability problems of submersibles when slowly moving or hovering in an undersea environment.
- Study of sonar simulation and bathymetric navigation.
- Identification of human factors interfaces among the displays and controls.

The simulation functions are separated into those performed on the analog equipment and those performed in the digital computer. (Figure 1)

The analog portion contains both the symbolic and the linear quickened displays to the pilot, his control and other manual inputs, adjustable current compensation, turbulence or random fluid motion, two major propulsion systems (as well as an energy linear six-degree-of-freedom differential equations of motion, incorporating hydrodynamic data corresponding to the characteristics of the submersible vehicle being simulated.

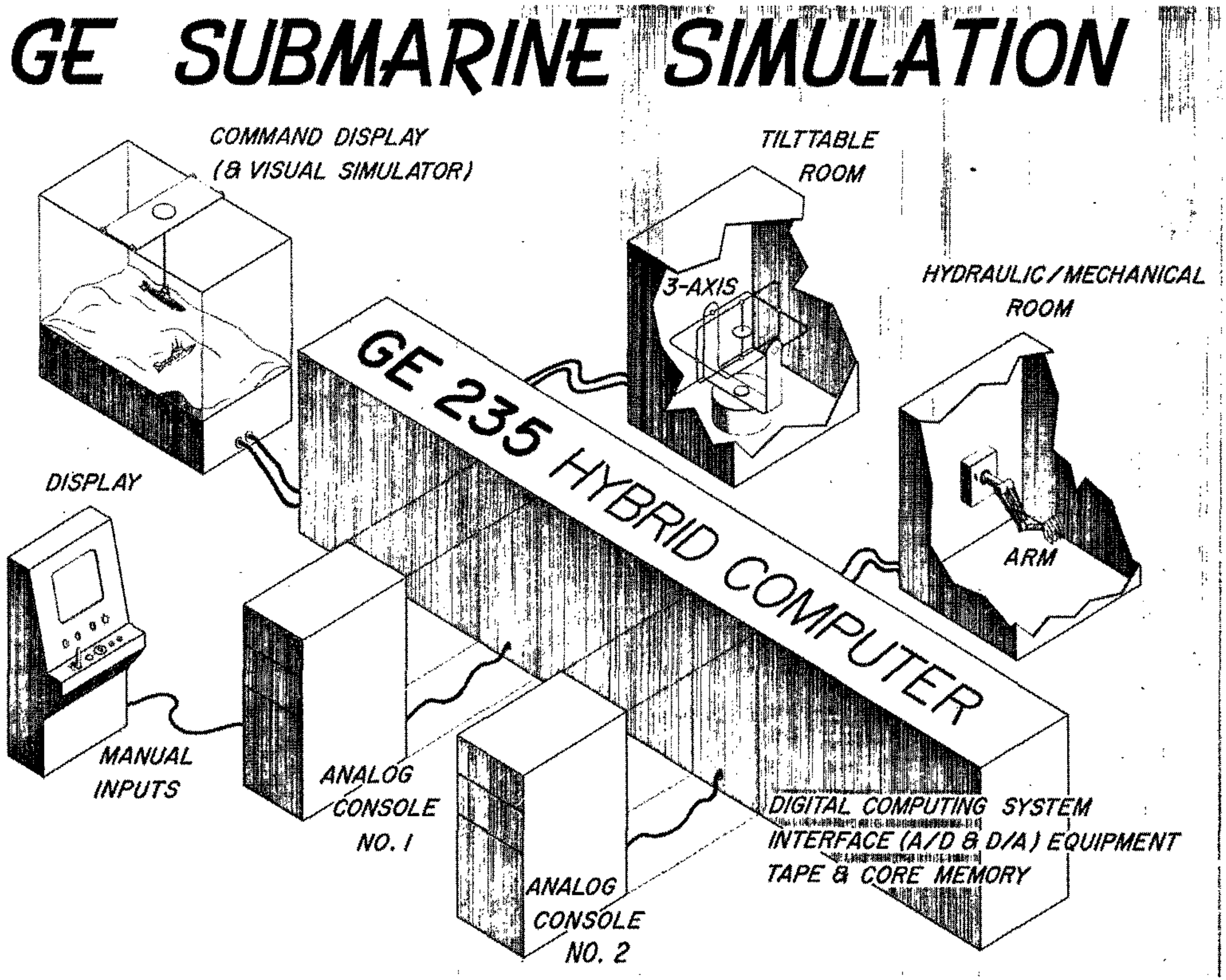

Figure 1. Conceptual View of Hybrid Simulation Facility

The digital portion contained a dual time-scale prediction model and display, an automatic terminal homing control system with adaptive parameters and self-learning aspects for minimum energy approach on repetitive approaches, and the several sonar activities, which will be discussed later.

Flexibility in the simulation layout permits ready growth expansion as well as ease of modification for special purpose studies.

A) Control Station

A small, fixed base cockpit contains the seat, control sticks, various manual intervention inputs and controls, and displays. The pilot operates the submarine in accordance with instrument readings, displays, and two simulated porthole views (forward or down) using a closed circuit TV monitor; all interfacing with the simulation equipment and computer.

Since the simulated vehicle enclosure is fixed, the kinesthetic effects of translation and rotation the pilot experiences must be induced visually. The simulated "out-the-porthole" view has six degrees of freedom and correlates with the simulated motion of the craft, as discussed later herein.

B) Propulsion

The Haselton Tandem Propellor System[1,2] was modeled using a pair of large hub-to-tip diameter counter-rotating propellors, normal or canted, located forward and astern of the submersibles' center of gravity, equidistantly. Individual propellor blade pitch can be varied collectively and cyclically to produce axial and transverse forces for both propulsion and control in the six independent degrees of freedom (together with possible inadvertent couplings occurring as the result of hull-propellor interactions).

The other propulsion system modeled is the conventional Polaris FBM submarine type, involving stern propellors with fixed tail fins mounting movable rudders and elevators for stabilization and control in cruising operations.

C) Hydrodynamics

The hydrodynamic coefficients must represent the undersea craft operating over a considerable dynamic range and speed variation, and undergoing maneuvers. Included in the simulation are some real fluid effects such as currents (while virtual mass effects are separately included in the equations of motion), unsteady or time-varying flow effects, and random fluid or turbulent forces.

The undersea current is inserted in the horizontal plane, and requires the pilot to hold the submarine against the current manually, resulting in fatigue. If it is assumed that the current components can be measured, and the vehicle's hydrodynamic characteristics are known, then a current compensation circuit can be activated so that automatic commands can be generated for the tandem propellor system to provide proper forces so that the pilot's control sticks can be returned to neutral.

Underwater turbulence is simulated by white noise produced by a Gaussian noise generator. The noise is filtered to give a peak frequency response of about 0.6 hz, and is added to the current flow at the desired level.

D) Control

Manual control of submarine maneuvers is accomplished for both type propulsion systems thru the use of dual separate control column hand sticks,[3] providing manual intervention inputs into the autopilot, which converts and correlates these commands into appropriate signals to propellor blades, fins, etc.

A vertical hand stick controls vehicle translation motion. Horizontal lateral motions (surge, sway) are governed by fore-aft and side deflection of the stick. Vertical motion (heave) is controlled by stick twist right-left for up-down.

A horizontally mounted control stick, parallel to the vehicle's centerline, controls the three rotational orientations (roll, pitch and yaw). The stick is rotated in the same sense as the desired rotation, as if the operator's hand could actually grasp the submarine aft hull.

E) Analog Quickening

The outputs of the two control sticks to the autopilot are tapped off and processed to provide "quickening" of the symbolic display to the pilot, i.e., the submarine position symbol on the display moves as the vessel would move if the offset stick position were maintained, whereas the actual boat response may lag up to several seconds.

This type of quickening is equivalent to rate feedback, furnishing lead information to the pilot in the sense of predicting the consequences of his present control actions in advance. His response is considerably improved as a result of the quickened display, particularly in mating and docking.

F) Fast Time Model

If the small submarine carries an onboard digital computer, then the commanded forces and moments from the autopilot, resulting from control stick inputs, can be inserted as forcing functions in a software program modeling the simplified hydrodynamic equations of motion of the submarine. The onboard computer then calculates the vehicle's future states (location, attitude, velocities) on a fast-time scale relative to real time and displays the information pictorially to the pilot. In this way the consequences of his present control action are predicted ahead more accurately than in analog quickening

The predictive time span ahead, from 1 to 14 seconds, can be varied automatically as the range decreases to some stationary target object on the ocean floor, such as in mating and docking, search and recovery, and obstacle avoidance.

In addition to providing the pilot with display information, the fast-time model output is also used in an automatic terminal control system with a non-linear on-off autopilot.

G) Autopilot

The function of the autopilot is to accept command inputs and convert them into appropriate and compatible decoupled signals to the propulsion, steering and stabilization subsystems, for the purposes of controlling depth, turn and heading. Inherent constraints on power levels, angles and rates are included in the autopilot, as well as the additional chore of modifying the vessel's response. The command inputs may be either manual or automatic, arising from an attitude reference platform or an unmanned navigation or guidance/control subsytem. The autopilot itself exists in two versions: linear or proportional and non-linear or on-off control, depending on which command input-output is desired.

H) Symbolic Displays

External sensing of the immediate environs is represented by three types of displays presented to the pilot: symbolic, "out the porthole/TV" and sonar. The latter two types will be discussed later.

The symbolic display scope is a 17" single gun cathode ray oscilloscope with an associated time sharing switching circuit set to allow 16 separate X-Y traces to be displayed. Each trace is on 1/16th of the time and the repetition rate is 1 khz, resulting in a sequence of dotted traces forming outlines of desired shapes and traces. The retention of the CRT is sufficiently high to provide a "good" picture, but not so high as to create a retrace problem.

A symbolic (or virtual) display is of the "outside-in" type in which the pilot can consider himself outside the submarine, viewing the overall scene as a spectator. (This is in opposition to the visual or real world pictorial display of the "inside-out" or "out-of-the-porthole" type exemplified by the pilot's TV monitor.)

Such a symbolic display must be referenced to the real world initially. In reality, this is accomplished by the actual submarine predropping at least three transponders around the stricken sub or other bottom point of interest and using on-board range trilateration computations. The initial hover over the stricken sub permits its location to be ascertained and the origin of the resulting reference grid shifted to that point.

A typical scope symbolic display consists of two distinct pictures presented on the left and right side of the scope face. (Figure 2) On the left side are the side and top view of the pilot's own moving submarine symbol and a fixed stricken submarine symbol, if mating and docking is the mission objective.

The top left view depicts the view of the stricken sub symbol positioned at the origin of the X-Y plane, bow pointed vertically. "Own sub" symbol is movable, and its position on the scope is the quickened, not the actual, position. Mating is accomplished in this lateral plane by maneuvering own sub symbol until superposition and continued coincidence of the two sub symbols occurs. (The result of pitching is indicated in this top view by fore-shortening of own sub symbol. Yaw changes the symbol's heading, and roll is disregarded).

The bottom left side of the scope shows the side view of the two submarine symbols. Conning towers distinguish the symbols from the top view. Mating occurs by decreasing the Z height of own sub until coincidence of the fixed and moving sub symbols occurs and is maintained. (Mating is taken here to mean the rescue sub is brought down to within, say, 5 to 10 feet above the stricken sub hatch, and the remaining descent is made manually using sonar or closed circuit TV. If the rescue sub touches any part of the stricken submarine, a hard "stop" built in the program occurs, to prevent passage.) In this symbolic side view, any yawing results in fore-shortening own sub symbol. Roll is ignored.

The right side of the scope displays the actual range error in its three components existing between own sub and stricken sub. The axes lengths shorten, remain stationary or lengthen depending whether own sub is closing, hovering or receding from the stricken sub, based upon the range trilateration calculations with the (three or more) predropped ocean bottom tranponders.

The Z error axis has both a coarse and fine scale. The latter is calculated from the returns of a simulated very short range mating and docking sonar (which would be installed interior to the mating bell on the actual submarine). In some runs, the fine Z error axis is tilted right or left from vertical to indicate own sub roll attitude.

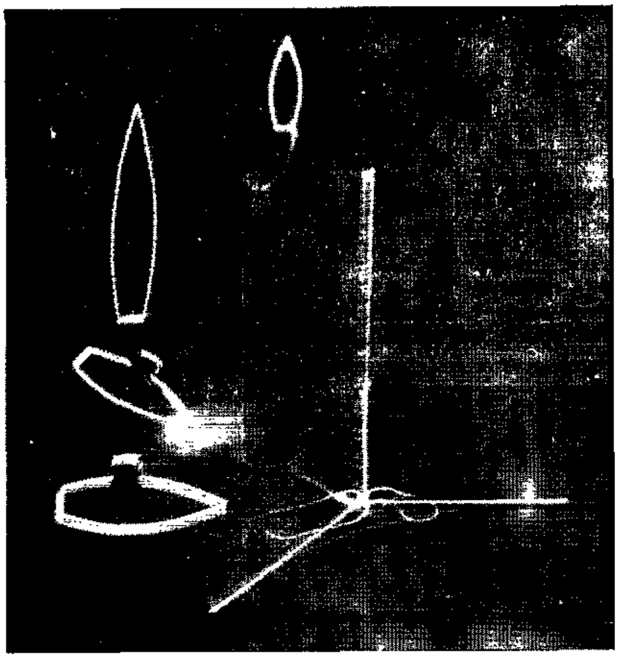

Figure 2. CRT Dual Symbolic Display to Pilot

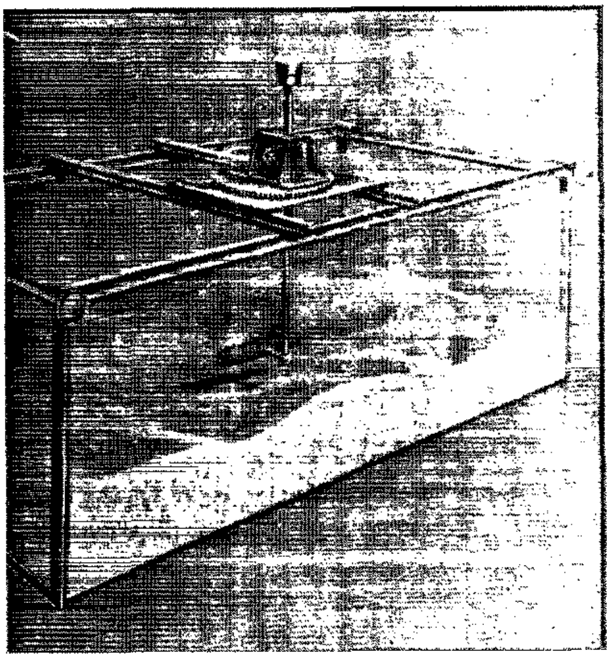

Figure 3. Command Display Unit

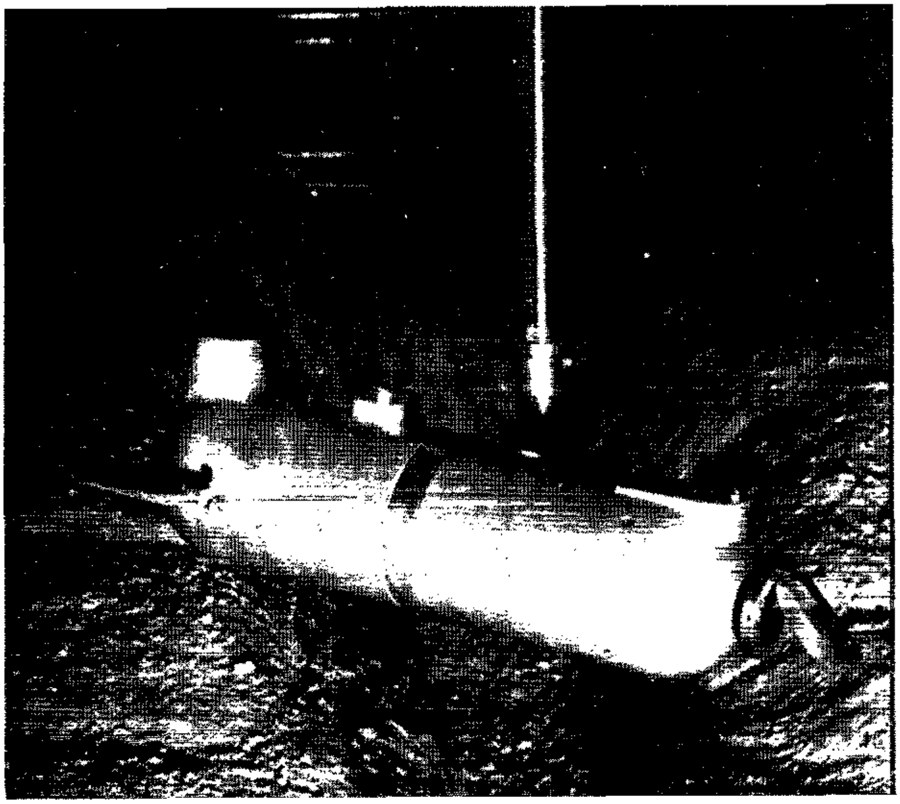

Figure 4. Model Submarine Maneuvering Over Scaled Ocean Bottom

Command Display Unit

The Command Display Unit (CDU) is an actual physical exhibition of a scaled model submarine, capable of omnidirectional dry maneuvering and motion in three dimensions and full six degrees of freedom, as driven electromechanically by the hybrid computing system which is simultaneously calculating the proper translational/rotational commands in accordance with the mathematical equations of motion. (Figure 3)

The CDU consists of a rectangular shoebox framework 12 feet long, 6 feet wide and 4 1/2 feet high. It mounts two horizontal parallel rails (hereafter referred to as N-S rails) on top, on which a movable platform can slide linearly forward and backward in the N-S direction.

This movable platform itself mounts two parallel 6 foot rails (hereafter termed the E-W rails) upon which a carriage can move crosswise in the E-W direction. The platform and carriage together can occupy any point in the X-Y horizontal plane within the overall framework. A vertical rack and pinion gear drives a hollow rod up and down, with the scale model submarine attached to the lower end of the rod translating in the vertical direction.

The three rotational degrees of freedom are obtained as follows:

A) Yaw motion is obtained by turning the rod right and left. (Actually the rod is offset attached to the turntable on the carriage, but the axis of rotation is through the center of the submarine model.

B) Pitch motion is provided by a motor mounted on the vertical staff, transmitting its torque by an inner rod in the center of the vertical shaft. A small gear converts this into pitch motion, rotating the model.

C) Roll motion is achieved by a motor within the model itself, mounted in a non-rolling center section which rotates the front and back portions of the model together.

Within the CDU cage on the bottom is a sculptured model of the ocean floor, accurately carved, finished and painted. It represents a section of the Continental Shelf, ranging in actual height from 2 inches at one end to about 30 inches in the other. It contains a deep gully, with sloping sides and is covered with sand for a realistic appearance. (Figure 4)

This ocean bottom model has been accurately scaled. A 3" by 3" grid element matrix in the horizontal plane has been mathematically overlaid, yielding rectangular matrix blocks sized to 1500 feet with depth data quantized to the center of each element. The resulting numerical description of the bottom is used internally in the computer for sonar simulation and automatic navigation.

For the "out-the-porthole" display to the operator, a one-inch videcon tube is housed within the scaled model submarine looking out forward through the nose of the submarine with a closed circuit TV monitor mounted at the pilot's control station. A flip-up mirror mounted at a 45° angle on the scale model in front of the TV pick-up lens permits the camera either to look directly ahead (for obstacle avoidance) or vertically down (for bottom searching or mating/docking). The resulting TV monitor display is in true perspective and varies with the motion of the simulated vehicle. This type of real world effect, based on using the narrow field of view inherent in the actual TV equipment aboard a submersible does not require extensive "wrap around" large display projections or theatrical inputs.

In addition, the TV monitor information can be stored on video tape for later play-back for demonstration or critique.

For the "outside-in" display feature, the omnidirectional maneuvering of the scaled submarine provides total observation capability since the Command Display Unit serves as an observation post for audience walk-around. Vehicular orientation motion and relative positions over the ocean bottom are executed by the scaled model, providing a basis for rating pilot performance.

Sonar Simulation

In the development of the manned submersible training simulation a need has arisen for realistic sonar representations corresponding to operational conditions and for use in conjunction with bathymetric navigation charts. As an outgrowth of the past two years investigation of methods for representing and storing terrain features in digital computers for the realistic simulation of signal returns, corresponding sonar sensor signal and ocean bottom representations were modeled and programmed for inclusion in the real-time hybrid simulation of a maneuvering submersible vehicle.

An operational submarine sonar device, i.e., a narrow beam-width fathometer was modeled for simulation. It provides ocean depth-below-keel sounding measurements by transmitting acoustic signals and measuring the time interval until the ocean bottom return signal is received. The simulation generates sonar signal propagation data consistent with vessel position and attitude, and the ocean floor information in previously digitized and stored form.

Two different modes of operation, Manual and Correlation are available. In the Manual Mode, the submarine pilot maneuvers the craft from his console. The sonar simulation generates signal output consistent with the submarine's instantaneous position, speed, depth, rate of descent, attitude, signal power level and return pulse stretchout.

Other digital routines representing inherent signal modification by the discretized ocean bottom model, sonar signal scattering, and providing hardware signal detection and echo measurement culminate in the following displays.

Ocean depth is shown simultaneously on a permanent paper chart display and on a lighted digital display. The paper chart display indicates: ship (keel) depth below water surface, ship latitude and longitude as obtained from the onboard Ship Inertial Navigational System (SINS), and the ocean bottom profile from the processed echo data.

The lighted digital display performs an electronic counting operation in the interval between the end of transmission (start pulse) and detection of the bottom echo (stop pulse). The result is transferred to an indicator circuit which drives appropriate digit lamps for a registered numerical display of depth below keel in fathoms.

An unusual feature involves the use of the closed circuit TV system which, operating in parallel with the hybrid computer and displays, provides a "view" of the ocean bottom model consistent with that which is processed in the digital computer. In effect, a view of the ocean floor is shown on a TV display while the computer, at the same time, is processing simulated sonar data which had "echoed" from that same portion of the ocean floor working with digitized terrain data. This parallel operation is accomplished by the use of the Vidicon camera mounted in the submersible model.

In the Correlation Mode of operation, automatic bathymetric navigation by the submarine is demonstrated, i.e., an unmanned navigational fix technique using bottom profile matching is shown to be feasible.

It is assumed that in this mode of operation, the ocean bottom in the immediate vicinity of the submarine has already been well mapped. The submarine's gross location is known from its inertial guidance system. A more accurate position ("fix") will be obtained by taking a series of sonar soundings and comparing these with onboard computer stored map data.

Entry into the Correlation Mode is made by a sense switch on the analog console. The submarine yaw, pitch, and roll angles are nulled to zero values, and a constant velocity is maintained. The present simulation, for convenience, has assumed a constant heading, along a matrix column during the correlation run, but this will be changed in the future, in order to accommodate error effects. The digital computer compares the sonar "soundings" with the stored bottom data and prints out the fix point in terms of the coordinates of the matrix element over which the readings were initiated. It is anticipated that updated position information will be used on-line, in order to illustrate full unmanned navigation (and course correction) capability.

Multiple real time displays were designed to ensure the operator's awareness of the automatic process.

On the 17" Symbolic Display scope a split screen provides two such displays. On the left, a large rectangle represents a view of the selectively bounded ocean bottom in the horizontal plane, and the submarine is displayed in outline form, in this rectangle, with rough coincidence to its actual position. The circle around the submarine represents the projection of the sonar echo signal at the submarine cruising depth. If the submarine and the ocean floor were exactly level, the submarine would be centered within the circle. When the center of the submarine falls outside the circle, an indication of "no return" from the sonar is made, and the other displays have corresponding indications, in parallel.

The right half of the scope depicts the submarine depth and the distance to the ocean floor. The top line represents the surface of the ocean and serves as the reference. The side view of the submarine moves in accordance with the vertical height of the submarine from the ocean surface. The bottom line represents the ocean bottom as determined by the sonar echo indication. It is subjected to an update each time a return signal is sensed, and is, thus, quantized in time.

An 11" x 17" X-Y plotter is used to simulate a strip chart recorder, having a variable paper speed proportional to the submarine horizontal velocity. Four signals are plotted on the paper: the ocean surface (for reference); the submarine (keel) depth; the indicated depth of the ocean floor (from the processed sonar signal); and the actual depth of the ocean floor.

Audible clues to the sequencing of the sonar readings were given by the use of a short duration 800 hertz signal, in accordance with the outgoing and incoming sonar pulses. Two separate sense lights indicated which signal is being heard, since no effort has been made to render them audibly distinguishable. If no return signal is received, there will be no audio indication or light clue.

The digital depth meter, discussed earlier is also operable, reading depth in fathoms.

Acknowledgement

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