SIMULATION OF A DEEP SUBMERSIBLE

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A number of deep submersibles have been used by the United States Navy recently in various operations, such as for research in Marine Biology, Oceanography, Underwater Rescue Missions, and Underwater Terrain Reconnaissance.

Deep submersibles are slow moving, blunt-body shaped, small submarines manned, usually, by a crew of two to four men. They lack the plane control surfaces which conventional submarines use for control. Instead, most deep submersibles use side thrusters (propellers) mounted symmetrically with respect to the vertical plane and above the center of gravity.

Currently, crews to man and operate these deep submersibles are trained by making actual dives in these vehicles. This method of training, besides being costly, possesses a certain factor of risk. A more effective and safer method of training could be provided by a simulator which would simulate all the functions of an actual deep submersible, as well as its motion characteristics through water. Such a simulator was designed and built for the United States Navy Training Equipment Center (NAVTRAEQUIPCEN). The simulator consists of a spherically shaped structure (control cab) which is mounted on top of a motion system. This structure contains all the controls and instruments necessary for the operation of the simulator and provides room for two trainees and an instructor. The motion system provides for movement of the control cab in longitudinal, lateral and vertical directions, as well as for roll, pitch and yaw. The signals necessary to drive the motion system are generated in a digital computer by solving the equations of a mathematical model. The computer signals are transformed to electrical impulses and accepted by the hardware of the motion system in a specially designed interface.

This paper describes the development of the mathematical model of the deep submersible simulator. This model consists of a system of six, six-degrees-of-freedom differential equations of motion, six equations which solve for the position of the deep submersible relative to a fixed reference system of axes and the Euler angles transformations, and some additional equations which provide for ballast changes and trim control for the small submarine.

The standard mathematical model for submarine motion developed by the Naval Ship Research and Development Center (NAVSHIPRANDCEN) was used as a basis. The NAVSHIPRANDCEN equations of submarine motion describe the motion of a conventional, fast moving submarine equipped with plane control surfaces. These plane control surfaces are the stern and bow planes which enable a submarine to dive or rise, depending on the angle between these planes and the plane which contains the x and y body axes of the submarine. In contrast, a deep submersible is a slow moving (4 knots maximum speed), almost spherically shaped, is controlled by two auxiliary side thrusters instead of plane surfaces, and is capable of a slow sideways movement which is used to better position the submersible over a target. Thus, it was necessary to modify the standard mathematical model to provide for these particular motion characteristics of the deep submersible. In addition, equations were derived to provide for ballast changes necessary for submerging and surfacing, and for static trim changes in pitch and roll which are used to tilt the deep submersible such that better viewing angles are provided for the crew.

Following the development of the mathematical model, a digital computer program was written to solve the equations of the mathematical model, and other programs to provide inputs from analog control devices, as required by the computer, and to provide outputs to drive the hardware of the simulator. In addition, a control program was written to schedule the order of execution of the various programs and to control the computer functions so that the computer program would run in real time. The aggregate of the various programs constitute the deep submersible real-time simulation program.

In addition, this paper discusses the computer storage and timing requirements and the numerical integration techniques used for the solution of the system differential equations. The paper also discusses various tests performed for the verification of the mathematical model and the results of these tests. Recommendations for improving the performance of the simulator are also included.

Simulator Training Requirements

The deep submersible training device consists of a control cab, a spherically shaped structure similar in design to the pressurized sphere which contains the life support systems and control equipment of an actual deep submersible. The control cab is mounted on a motion system which is capable of moving forward, backward, up, down, as well as to pitch, roll or yaw.

The motion system and control cab are sitting on top of an environmental tank filled with water in which models of ocean bottom terrain are installed and various conditions of visibility and lighting are reproduced to simulate direct visual photographic and TV views of the sea environment.

The design of the simulator is such that it permits quick changes in layouts to adapt it to any training situation. It provides a controllable environment in which any specialized training objectives may be met. These include maneuvering and positioning the deep submersible precisely relative to an object and training crews in the use of mechanical arm manipulators, sampling devices and oceanographic instruments.

The main purpose of the simulator is to provide training for trainees to control the motion of a deep submersible and also to use equipment which may be installed in a deep submersible to conduct various research and study programs in the ocean environment. Such training will involve the use of navigational equipment to determine positions and to follow a preset mission pattern. During the training cycle, realistic views of ocean bottom terrain will be provided both directly and by television cameras, as well as related sound displays from acoustic sensors.

Simulator Systems Description

The simulator is divided into five major subsystems. These are the Control Cab and Motion System, Simulation of the Ocean Environment, Optics and Television Camera, Control and Instrument Simulations, and Sonar Simulations.

The Control Cab and Motion System consists of the control cab which provides the physical environment for the trainees and instructor and the motion system which consists of a structure of rails, pivots and drive motors which cause the control cab to translate in three directions and to rotate around its body axes. The signals for the motion of the control cab are provided by an analog computer via a special interface system. These signals reflect the controls manipulated by the trainees, the characteristics of the deep submersible, and the simulated ocean parameters, such as currents, turbulence, etc.

The Simulation of the Ocean Environment subsystem includes equipment required to simulate a given oceanographic environment. These are a three-dimensional 1:60 scale model of a typical ocean bottom terrain, located at the bottom of a large shallow water tank, and other special equipment with which a variety of characteristics of the deep ocean environment may be simulated.

The Optics and Television Camera subsystem provides the simulation of a deep ocean environment which is seen through the portholes by the crews of an actual deep submersible. These presentations are unprogrammed and respond to the deep submersible's attitude and translating motions. The equipment consists of an optical system which extends into the water tank from the control cab, a closed circuit TV system and various controls. Trainees are also able to take photographs of the simulated ocean environment.

In the Control and Instrument Simulations subsystem, the operational controls and instrument indicators for the trainee's and instructor's consoles are included together with the electronic equipment and controls to activate the displays. The vehicle responds to the trainee's operation of the controls and the displays reflect these responses. Not included here are the displays for other subsystems such as the sonar displays and TV monitors.

The Sonar Simulations subsystem consists of displays, controls and electronics which are necessary to simulate the effects of the depth/altitude, the side scanning and the terrain avoidance sonar, as well as the doppler navigator and the underwater telephone.

System Mathematical Model

The two subsystems of the simulator, the "Control Cab and Motion System" and the "Control and Instruments Simulation", provide for the motion of the simulator. The basic function of these subsystems is to provide to the senses of the trainees the illusion of the motion characteristics of a small submarine. This is accomplished by moving the controls in the control cab for various maneuvers. The responses to the trainees are indicated by changes in the position of the control cab and the control console instruments. The control cab and the control console supply inputs to and receive outputs from the simulation program. As the pilot trainees go through the maneuver motions, the controls provide inputs to the simulation program. Based on the current position of the controls and the past history of the deep submersible's course, the new state of the course (i.e., rate of descent/ascent, depth, speed, etc.) is determined by the simulation program and these values are returned to the instruments and indicators of the control console and the motion system drives.

The simulation program is a digital computer program which solves the equations of the system's mathematical model in real time; that is, at a rate which is equivalent to the rate of position changes of an actual small submarine in motion.

The development of the mathematical model of the deep submersible was based on the standard NAVSHIPRANDCEN equations of motion for a submarine. However, substantial modification and additions to these original equations were required to provide a useful deep submersible simulation. The following modifications and additions were made as part of the project.

Hydrodynamic Equations

The standard NAVSHIPRANDCEN equations provide for the motion of a conventional submarine equipped with bow and stern planes and one propeller mounted at the stern of the submarine, which produces a thrust along the longitudinal axis of the submarine. In contrast, a deep submersible is equipped with a stern propeller mounted in a shroud. The shroud rotates around a vertical axis, producing changes to the deep submersible's heading due to the changes in the direction of thrust. In addition, two auxiliary propellers (side thrusters) are mounted approximately 2 feet above the center of gravity of the deep submersible and symmetrically with respect to the vertical plane which contains its longitudinal axis. A third propeller (athwart-ship thruster) provides for a slow sideways motion of the deep submersible. To account for these motion characteristics, various terms were added to the hydrodynamic equations.

Ballast Equations

The main function of the ballast equations is to provide for changes in the weight W of the deep submersible; thus, the deep submersible may dive or rise as desired.

The NAVSHIPRANDCEN mathematical model does not provide for changes in the weight of the submarine; thus, a complete ballast system was designed by E.S. Psarakis and equations were derived for three distinct ballast systems to enable the deep submersible to submerge, change depth, and to surface whenever desired. These systems are:

Main Ballast System

The main ballast system enables the vehicle to submerge rapidly to great depths. This is accomplished by flooding its main ballast tanks and taking in large amounts of water; thus, the deep submersible becomes negatively buoyant.

The net effect of flooding the main ballast tanks is to increase the deep submersible's density, thus becoming heavier and descending below the surface of the water. It is assumed here, that W changes by an amount of 0.0142 lb. per cycle (one cycle = 0.25 sec.); i.e.,

$$\dot{W} = 0.0142 \text{ lb/cycle}$$

where $\dot{W}$ is the rate of descent/ascent. This corresponds to the rate of descent/ascent of an actual deep submersible. When W reaches its maximum value, W from then on remains constant and the vehicle descends at a constant rate.

Drop Weights Ballast System

The drop weights ballast system permits the vehicle to quickly stop at a desired depth or to ascend, depending upon its buoyancy. This is accomplished by dropping weights, which were attached to the submersible prior to its descent from the surface.

The mathematical model for the drop weights ballast system simulation consists of the equation:

$$W_{new} = W_u - W_w$$

where W_{new} = New weight of deep submersible in lb.

W_u = Weight of submerged deep submersible in lb.,

and W_w = Droppable weight in lb.

W_W consists of several items which can be dropped individually. Their total weight is equal to V_1 D_W, that is, equal to the weight of the maximum amount of water which can be taken inside the main ballast tanks. Here, D_W equals the water density and V_1 equals the volume of ballast tanks in cubic feet.

Variable Ballast System

The variable ballast system consists of an oil reservoir and a pair of flexible ballast tanks, which expand or contract to contain a larger or lesser amount of oil as desired. By changing the volume of the variable ballast tanks, small changes in buoyancy of the deep submersible may be affected which, in turn, cause the deep submersible to ascend or descend to a new depth.

The mathematical model of the variable ballast system consists of the equation:

$$W_{new} = W_u \pm BVAR$$

where BVAR = Variable ballast in lb., with a maximum of 800 lb.

Mercury Trim Equations

The mercury trim system is used to control the pitch and roll of the deep submersible in forward motion and to obtain statically better pitch and roll viewing angles. This is accomplished by pumping mercury from an aft tank to a fore tank for pitch, or from a starboard tank to a port tank for roll. The mathematical model for the trim system was developed by Emmanuel S. Psarakis as shown below:

Mercury Trim Pitch System

The mathematical model developed for the pitch trim system consists of the equation:

$$\tan\theta = \frac{W_{p1}X_1 - W_{p2}X_2}{BY}$$

$$W_{p1}^{(n+1)} = W_{p1}^{(n)} \pm \dot{W}_p$$

$$W_{p2}^{(n+1)} = W_{p2}^{(n)} \pm \dot{W}_p$$

where θ = Pitch angle

X_1, Y_2 = Distance in feet of locations of mercury pitch tanks from CG

B = Buoyant force

Y = Center of buoyancy from CG

W_{p1}, W_{p2} = Amount of mercury in each pitch tank in lb.

W_p = Total amount of mercury

$\dot{W}_p$ = Rate of change of mercury in pitch tanks in lb/sec.

Mercury Trim Roll System

A development similar to that of the trim pitch system yields the following equations for the mathematical model of the trim roll system.

$$\tan\phi = \frac{W_{R1}X_3 - W_{R2}X_4}{BY}$$

$$W_{R1}^{(n+1)} = W_{R1}^{(n)} \pm \dot{W}_R$$

$$W_{R2}^{(n+1)} = W_{R2}^{(n)} \pm \dot{W}_R$$

$$W_R = W_{R1} + W_{R2}$$

where ϕ = Roll angle

X_3, X_4 = Distance in feet of location of mercury roll tanks from CG

B = Buoyant force

Y = Distance of center of buoyancy from CG

W_{R1}, W_{R2} = Amount of mercury in each roll tank in lb.

W_R = Total amount of mercury

$\dot{W}_R$ = Rate of change of mercury in roll tanks in lb/sec.

Integration Methods

The numerical integration method to solve the differential equations of the mathematical model was selected by considering a trade-off between accuracy, stability and speed of integration.

Accuracy depends on the amount of truncation and round-off errors present in the calculations. Stability of an integration method depends on the ability of the integration method to control these errors so that they do not increase with integration time. Speed of an integration method depends on the complexity of the method and the integration interval. For real-time simulations, it is necessary to perform all computations within a specified integration interval, while stability and accuracy is maintained.

Based on the criteria described above, various integration methods were considered and tested. Among them was the 2nd Order Adams Formula (predictor type).

$$X_n = X_{n-1} + \frac{h}{2} (3\dot{X}_{n-1} - \dot{X}_{n-2}).$$

This method yielded favorable results as compared to other more complex integration methods, and thus it was selected as the method for the solution of the differential equation.

The integration interval used with this method was 250 milliseconds. This yields a frequency of 4 cycles per second.

Programming - Mode and Cycle Control (MCC)

MCC controls system timing, coordinates the cyclical execution of all programs and responds to error conditions. Specifically, MCC provides real-time control by activating and maintaining the 250 msec interrupt; provides simulated real-time control by continually cycling through the programs without regard for the 250 msec time restraint; maintains an internal clock, which is updated once each program cycle; controls execution of the complete program cycle according to a program mode; and provides an error code for external communication.

Real-Time Input/Output (RTIO)

This program initiates and maintains communication with the on-line simulation equipment by updating all inputs and outputs once every program cycle. The input/output process, once initiated by the Central Processor Unit (CPU), continues asychronously with the computation process until all outputs for the next cycle have been completed. The program contains all instructions and control words required to initiate and control the I/O process and analog conversions. It also detects any I/O conditions which may cause a halt of the simulation.

Convert Input Variables (CIV)

At the start of each program cycle, CIV converts all external input variables to the format and units required by the various other programs. Specifically, it converts the analog and discrete inputs, stored previously to the required format and units. It acknowledges all discrete switch changes from the monitor console by setting or resetting the corresponding indicator outputs. It determines water current effects for introduction into the equations.

Start-Up (START)

This program performs the transition of the simulation system from an inactive state to an active state equivalent to that of a surfaced deep submersible. It initiates all values necessary to transform the simulation programs to a known configuration of the surfaced deep submersible.

It tests the I/O system for proper equipment configuration and set-up before activating the program. It also insures that the start-up transition is performed to eliminate problems such as undesirable equipment effects or sudden physical changes which might be hazardous to personnel.

Equations of Motion (EC780)

This program, which is written in FORTRAN IV language, simultaneously solves the modified six-degrees-of-freedom equation of submarine motion, the three kinematic relations and the three Euler equations which transform the body axis velocities to earth axis velocities. These are the equations discussed earlier in the Mathematical Model.
The hydrodynamic coefficients were obtained from captive model tests of a half-scale model of the AUTEC-I Vehicle (a deep-dive research vehicle, presently known as SEACLIFF), while investigating the dynamic stability and other characteristics of that vehicle. In addition, EC780 provides for updating velocities and positions of the deep submersible and for returning the velocities to zero when operating in zero mode.

Submarine System (SMS)

This program introduces to the simulation the effects of those submarine systems that change the current configuration of the vehicle. These effects result either from pilot action or monitor console operator action. The program simulates the effects of the mercury trim pitch, mercury trim roll, main ballast system control and the effects of introducing water currents into the solution of the equation of motion.

Submarine Instruments (SMI)

The SMI program transforms the current solution results of the computer to the form required for OUTPUT to the instruments. It must perform the conversions and scaling necessary to obtain the correct dial rotations for output.

Control Cab Motion (CCM)

This program converts the signals necessary to activate the motion system and move the deep submersible along and around the three axes as determined by the hydrodynamic and submarine system equations. The program performs the conversions and scaling required by the motion system hardware.

All programs described in this section are written in the Sigma 7 Assembly (Meta-Symbol) Language, except the EC780 program, which is written in FORTRAN IV, as noted earlier.

Tests and Evaluation

To verify the validity of the equations of motion of the deep submersible and to test the overall performance characteristics, certain tests were made in accordance with specification of the Naval Ship Research and Development Center related to the study of submarine system equations. These standard tests consist of the following maneuvers: Meander, Vertical Overshoot, Steady Submerged Turn, RPM Versus Speed, Acceleration/Deceleration, Longitudinal Trim. These maneuvers are performance tests for conventional submarines. Three of these maneuvers were performed for the deep submersible. They are described below.

Meander

This maneuver demonstrates the capability of a submarine to recover from a rise or dive without the use of primary control surfaces or any emergency ballast changes. It evaluates the longitudinal stability of the submarine.

The submarine moves at a given speed and course until a steady level flight is achieved. It is then disturbed from its neutral pitch angle by deflecting the sternplanes (auxiliary pod in the case of the deep submersible) a fixed amount in either rise or dive. When the submarine reaches a preselected pitch angle, the planes are returned to their original neutral position. The planes are held fixed while the submarine pulls out and resumes a condition of steady level flight. The pitch angle trajectory furnishes both visual and quantitative evaluations of the longitudinal stability of the submarine.

Meander tests were run with various command speeds. The maximum diving plane angle was 20 degrees.

Steady Submerged Turn

In this test the submarine response to a rudder action in a horizontal plane maneuver is investigated; specifically, loss of speed, steady turning diameter, roll angles and the time necessary to accomplish a 90-and 180-degree change of heading are investigated. Throughout this maneuver, the command speed remains fixed. An autopilot in the computer program maintains depth as constant as possible. The controls remain fixed until steady, level flight at the selected speed is achieved. Then, the rudder is deflected to a given angle and held fixed. During the maneuver, the results collected from the computer programs were the following: a. rudder angle (DR), b. pitch angle (θ), c. roll angle (ϕ), d. heading angle (ψ), e. forward speed (u), f. depth (z). The results obtained from these preliminary tests were examined quantitatively and found to be satisfactory.

Additional and more systematic tests were performed after all program units were completed, individually tested, and finally integrated to form the complete real-time simulation program for the deep submersible training device system. These tests were performed as follows:

Analog voltage inputs originating from the REAC-550 Analog Computer of the NAVTRAEQUIPCEN Computer Laboratory Facility, converted to digital numbers, entered the simulation program. The program operated with these inputs, under the 250 msec real-time constraint, and the outputs produced, converted to analog voltages, were received by various voltmeters an an eight-channel strip-chart recorder.

Acceleration/Deceleration

This test determines the deep submersible's response to change in values of the command speed. The deep submersible was held at a constant depth of 600 feet. The command speed was initially zero, then was increased at 1-knot increments up to a maximum of 4 knots, at equal time intervals of 180 seconds. The command speed was then reduced in 1-knot decrements down to zero at the same time interval. The results were observed in a voltmeter and good agreement in the time intervals, both for acceleration and deceleration for each command speed increment, resulted.

Conclusions and Recommendation

The objectives of the work which led to this paper were: 1. To obtain a suitable mathematical model for implementation to a Deep Submersible Trainer; 2. To develop a Real-Time Simulation Program using the equation of the mathematical model; and 3. To interface the Digital Computer and the Hardware of the Trainer via the Simulation Program.

The objective in 1. was met successfully. The standard NAVSHIPRANDCEN equations of submarine motion were modified to include the effects of the side thrusters and of the athwart-ship thruster which moves the deep submersible sideways. In addition, a set of ballast equations were derived by which the weight of the deep submersible could be changed, such that changes in depth can be effected. Finally, a mathematical model for the mercury trim system was derived, such that static angle changes in pitch and roll may be effected. The mathematical model simulates accurately the functions of a typical deep submersible such as the SEACLIFF.

Deep submersibles are inherently unstable in horizontal motion at speeds in excess of 3 knots. To maintain a straight, level flight, it is necessary to trim the vehicle in pitch by pumping mercury fore or aft, as it appears necessary. The mercury trim system, developed by Emmanuel S. Psarakis, was proven to be effective in maintaining horizontal stability. It is actually part of the training to acquire these skills to operate a deep submersible.

The objective in 2. was met with complete success. All program units comprising the total simulation program, described by name and function, perform orderly. Extensive real-time runs made, after the program units were integrated to form the simulation program, indicated a trouble-free operation.

The objective in 3. was not met due to the deferment of the project to a later date. However, the hardware of the control cab and motion system were simulated by the REAC 550 Analog Computer of the NAVTRAEQUIPCEN Computer Laboratory Facility. In this simulation, the analog computer was interfaced to the Sigma 7 Digital Computer, such that it could be used to generate analog voltage inputs (such as throttle, ballast, rudder, etc.) to the simulation program. These inputs were varied by potentiometers so that various maneuvers could be performed. The outputs from the simulation program were, in turn, received by various digital voltmeters and an eight-channel strip-chart recorder. Using this procedure, the mathematical model was verified and all the results were obtained.

It is recommended that additional work be performed to develop a universal mathematical model for deep submersibles, a model which would describe the motion of various types of deep submersibles. Furthermore, it is recommended to accumulate experimental data from the actual operations of deep submersibles so that this data may be compared to the performance of simulators. Finally, it is recommended to perform captive model tests on various deep submersibles in order to obtain the hydrodynamic coefficients and constants to be used in conjunction with the equations of motion of the mathematical model in simulations.

ABOUT THE AUTHORS

MR. EMMANUEL S. PSARAKIS was born August 17, 1923 in Iraklion, Crete, Greece. In May 1941 he graduated from Tenth High School of Athens. From April 1942 till April 1945, he worked for an aircraft factory in Fuerth in Bayern, Germany as a displaced person. During this time interval, he also spent one year in a concentration camp near Nuernberg. In 1946 he went to Belgium, where he worked as a coal miner for approximately a year. He then returned to Germany, and in 1948 he enrolled in the Technical School of Nuernberg, where he received an Associate's Diploma in Mechanical Engineering in 1951. After working for 2-1/2 years as a design engineer with an automobile manufacturing company in Nuernberg, he emigrated to Montreal, Canada in 1953.

During the 5 years of his residency in Montreal, he worked with Canadian Vickers Company and Montreal Locomotive Works Company as a Stress Analyst. He enrolled in the Evening Division of Sir George Williams University during this time interval, and in September 1957 received the degree of Bachelor of Science with a major in Mathematics and a minor in Physics.

In May 1958 he entered the United States as an immigrant and resided in Akron, Ohio for nearly 5 years. During this time, he worked for three different industrial firms as a design engineer. He also enrolled in the Graduate School of the University of Akron in 1959, and in 1962 received the degree of Master of Arts, with a major in Mathematics. He became a naturalized citizen of the United States in 1961.

After a 2-year residency in Philadelphia, Pennsylvania he came to Orlando, Florida where he worked for Martin-Marietta as a research engineer and mathematician until 1967. During this time he taught various courses in Mathematics at the Education Division of the Martin-Marietta Company, at GENESYS of the University of Florida, and later at Rollins College.

In September 1967 he joined the Naval Training Equipment Center as a mathematician. From September 1968 until the present, he has pursued his work toward the degree of Master of Science in Engineering, with a major in Computer Science, and in June 1972 he received this degree.

Mr. Psarakis is a member of the American Mathematical Society and the American Hellenic Educational Progressive Association (AHEPA).

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