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UNDERWATER TERRAIN NAVIGATION AND RECONNAISSANCE SIMULATOR

Emmanuel S. Psarakis

Naval Training Equipment Center
Orlando, Florida

September 1972

Technical Report: NAVTRAEQUIPCEN IH-198

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13. ABSTRACT

The continuing growth in the number of deep submersibles used by the Navy has created the need to design a simulator which will be used to effectively train pilots and scientific crews to man these submersibles.

The present method of training personnel is by actually making dives in the submersibles. This method is hazardous and costly, and the submersibles are not always readily available. The ideal method of accomplishing a true deep submersible simulation is by driving the simulator using the NSRDC (Naval Ship Research and Development Center) standard equation of submarine motion solved in a digital computer. In addition, various other submarine systems, such as ballast and trim systems, can also be readily simulated by solving appropriately designed equations in the computer.

This report describes how the orderly solution of the various equations, as well as all inputs and outputs to and from the system, cycle timing, etc., can be controlled by an appropriately designed computer control program. This program may also be used to introduce external effects to the simulator such as drift current effects and to reset or freeze the system as desired.

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NAVAL TRAINING EQUIPMENT CENTER

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SECTION I

INTRODUCTION

There is a need for a deep submersible simulator which can provide to the senses of its crew the illusion of the motion and other characteristics of a small submarine.

The deep submersible portion of the Underwater Terrain Navigation and Reconnaissance Simulator (UTNRS) located at the Naval Training Device Center provides a real-time simulation of the motion through water of a small submarine of the ALVIN, SEA CLIFF or SEA TURTLE types. This simulation will be used for research and to develop a trainer and improved training techniques for pilots and crews of deep submersibles.

The work described herein represents the effort of the Computer Laboratory to computerize the motion of the UTNRS Vehicle; that is, a set of equations of submarine motion will be solved on the digital computer and the results converted to analog voltage signals. These signals will be used to activate the motion system and drive various instruments and indicators.

A complete simulation program, capable of converting the current UTNRS analog simulation to a digital computer simulation, has been written. Various program units comprising the total simulation program have been written in the Sigma 7 assembly language. These programs have been debugged and tested, but interfacing the UTNRS simulator hardware to the Sigma 7 computer has not been accomplished.

SECTION II

SYSTEM DESCRIPTION

The UTNRS consists of a control cab, a motion system, an environment tank, a sound simulation system, an optics simulation system, a control monitor console, and a computer program. Reference 1 contains a detailed description of the entire UTNRS. The deep submersible portion, which consists of the control cab, instruments, and maneuvering controls, is briefly described herein for the convenience of the reader.

CONTROL CAB

The control cab, which is a mock-up of a real submersible pressure sphere, contains the trainee's control station in which all electronic support equipment is mounted. The trainee's control section contains vertically placed panels on which the various instruments, indicators, and maneuvering controls are mounted. The instructor's station contains a minimum of instruments and controls, which are used by the instructor to introduce special effects and emergency conditions (Note: the instructor's position is such that the instructor can view directly all of the instruments located in the trainee's station). The electronic support equipment is mounted behind panels and can not be seen directly by the trainees.

INSTRUMENTS

The instruments and indicators described are those related to the motion and those which will enable the pilots to sense the vehicle's attitudes; their function and range are given below:

Maneuvering Instruments

Depth Indicator	0-9000 ft.
Depth Rate Indicator	0-150 ft./min
Fathometer Indicator	0-6000 ft.
Gyro Compass Heading Indicator	0-360°
Speed Over Bottom Indicator	0-10 knots
Speed Through Water Indicator	0-6 knots
Main Thruster Speed	0-6 knots
Side Thruster Speed	0-2 knots
Auxiliary Thruster Speed	0-3 knots
Rudder Angle	0- ±90°
Stern Angle	0- ±40°
Bow Angle (Auxiliary Thruster Angle)	0- ±90°
Pitch Angle Indicator	0- ±30°
Roll Angle Indicator	0- ±30°

Ballast Trim Indicators

Main Ballast Indicator	On-Off Position
Variable Ballast Indicator	On-Off Position
Drop Weight Ballast Indicator	On-Off Position
Mercury Trim Pitch Indicator	On-Off Position
Mercury Trim Roll Indicator	On-Off Position

MANEUVERING CONTROLS

The maneuvering controls, which are located in the control cab panel and which enable the pilots to control the vehicle, are listed and described below.

MAIN BALLAST CONTROL. This control is used for an unpowered quick dive of the vehicle to great depths.

VARIABLE BALLAST (TRIM BALLAST CONTROL). After the vehicle has submerged to a given depth (both powered and/or unpowered descent), the pilots may use this control to make fine adjustments of the vehicle's depth position and to assist a powered ascent/descent.

DROP WEIGHT BALLAST. This control is used for a quick unpowered ascent to the surface by dropping weights in cases of emergency.

MERCURY TRIM PITCH CONTROL. This control is used to provide changes in fore and aft trim for better viewing angles and to assist in a powered ascent or descent.

MERCURY TRIM ROLL CONTROL. This control provides quick changes in the roll attitude of the vehicle for better viewing angles.

MAIN THROTTLE CONTROL. This control is used to provide changes in thrust to propel the vehicle through water.

ATHWARTSHIP THROTTLE CONTROL. This control provides for a sideways slow movement of the vehicle for better positioning over a target.

AUXILIARY THROTTLE CONTROLS. Two auxiliary thruster (right and left) controls provide for additional forward thrust or for adding on a powered ascent or descent of the vehicle. These controls act independently of each other.

RUDDER ANGLE CONTROL. This control provides for heading changes of the vehicle.

BOW ANGLE CONTROL. This control provides for changes in the thrust direction of the auxiliary thrusters.

STERN ANGLE CONTROL. This control is used to change the thrust direction of the main thruster in the vertical plane; the effect is a change in the pitch attitude of the vehicle. It also assists in a powered ascent or descent.

SECTION III

MATHEMATICAL MODEL REPORT

In order to make a simulation, a mathematical model of the object to be simulated must be available. A mathematical model is a set of equations which describe as accurately as required the motion and other characteristics of the object. The equations are solved either on an analog or digital computer and the results represent the object's behavior. A real-time simulation is obtained if the solution of the equations is restricted such that it is completed within a prescribed time interval.

The mathematical model selected for the UTNRS vehicle simulation is a set of six simultaneous differential equations which describe the six degrees of motion of a submarine. These equations were derived by the Naval Ship Research and Development Center (NSRDC), later simplified so they could be solved in a small digital computer, and then adapted to a submarine trainer by the Goodyear Aircraft Corporation, under Contract N61339-68-C-0050. See reference 2.

The modified submarine equations, though valid for a submarine trainer, were not fully suitable for a deep submersible simulation; thus, they were again modified at NAVTRADEVCEN (reference 3), to include the Auxiliary and Athwartship thruster effects, which are peculiar to a deep submersible.

The following paragraphs describe these equations:

HYDRODYNAMIC EQUATIONS

The equations for the hydrodynamic mathematical model consist of equations (1) through (6) of reference 3 and the following:

$$\dot{Z} = u\sin\theta + v\cos\theta\sin\phi + w\cos\theta\cos\phi \qquad (1)$$

$$\dot{X} = u\cos\theta\cos\psi + v(\sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi) + w(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi) \qquad (2)$$

$$\dot{Y} = u\cos\theta\sin\psi + v(\sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi) + w(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi) \qquad (3)$$

$$\dot{\theta} = q\cos\phi - v\sin\phi \qquad (4)$$

$$\dot{\psi} = (q\sin\phi + v\cos\phi)/\cos\theta \qquad (5)$$

$$\dot{\phi} = p + \dot{\psi}\sin\theta \qquad (6)$$

Where (1), (2), and (3) of the above equations are the kinematic relations which solve for the submarine position relative to a fixed reference system of axis (earth axis reference system), and equations (4), (5), and (6) are the transformation which changes the body axis velocities to earth axis velocities. The hydrodynamic coefficients and constants used in conjunction with the equations of motion are listed in reference (3).

BALLAST EQUATIONS

Three distinct ballast systems enable the UTNRS Vehicle 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 becoming negatively buoyant. The procedure for simulating the main ballast system follows:

At the surface the vehicle is in an equilibrium condition. In this case the weight of the vehicle and buoyant force are equal, i.e.,

$$W = B$$

where $\quad W$ = Weight of Vehicle in lb.,

and $\quad B$ = Buoyant Force in lb.

In the surface, the weight of the submersible is given by

$$W = VD_s$$

where $\quad D_s$ = Density of vehicle in surfaced condition,

and $\quad V$ = Volume of submersible in ft^3.

When submerged the weight of the submersible is given by

$$W = VD_d$$

where $\quad D_d$ = Density of vehicle in submerged condition.

The difference between D_s and D_d is that D_s is a function of air only in the ballast tanks, while D_d is a function of both water and air in the ballast tanks, the ratio depending upon the desired rate of descent.

The net effect of flooding the main ballast tanks is to increase its density; the vehicle thus becomes heavier and it descends below the surface of the water. It is assumed here, that W changes by an amount of 0.0142 lb. cycle (one cycle = 0.25 sec.); i.e.,

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

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, 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 vehicle in lb.,

W_u = Weight of submerged vehicle in lb.,

and W_w = Dropable 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 ft^3.

VARIABLE BALLAST SYSTEM. The variable ballast system allows small adjustments in depth to be made. This 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 vehicle may be affected which, in turn, cause the vehicle 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 trim the vehicle 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 is developed as shown in figure 1

MERCURY TRIM PITCH SYSTEM. The pitching moment acting on the vehicle due to the weights W_1 and W_2 in the mercury trim tank is:

$$M_p = W_{p_2} X_2 \cos\theta - W_{p_1} X_1 \cos\theta$$
$$= (W_{p_2} X_2 - W_{p_1} X_1) \cos\theta$$

The pitching moment, M_p, is counteracted by a restoring moment, M_B, due to buoyant force, B, acting through the metacenter, CB, i.e.,

$$M_B = Be = -B \, Y\sin\theta$$

For equilibrium:

$$M_p = M_B$$

or $(W_{p_2}X_2 - W_{p_1}X_1)\cos\theta = -B\ Y\sin\theta.$

Then

$$\frac{\sin\theta}{\cos\theta} = \frac{W_{p_2}X_2 - W_{p_1}X_1}{-B\ Y},$$

or

$$\tan\theta = \frac{W_{p_2}X_2 - W_{p_1}X_1}{-B\ Y} \qquad (7)$$

Assuming that the sum of W_{p_1} and W_{p_2} is constant, we may set

$$W_p = W_{p_1} + W_{p_2}$$

Now, for a maximum pitch angle θ, either

$$W_{p_1} = W \quad \text{and} \quad W_{p_2} = 0$$

or

$$W_{p_2} = W \quad \text{and} \quad W_{p_1} = 0$$

Assuming

$$\theta_{max} = 30°$$

$$W_{p_1} = W_p$$

$$W_{p_2} = 0$$

and substituting in equation (7) yields:

$$\tan 30° = \frac{W_p X_1}{B\ Y}$$

solving for W_p

$$W_p = \frac{B Y \tan 30°}{X_1}$$

where

$$X_1 = 6.83 \text{ ft,,}$$

$$Y = 0.22 \text{ ft,,}$$

$$B = 50,160 \text{ lb.,}$$

then

$$W_p = \frac{50160 \times 0.22 \times 0.57735}{6.83} = 983 \text{ lb.}$$

That is, an amount of 983 lb of mercury is needed to achieve a static maximum pitch angle of 30°. Assuming a rate of change of 0.25° per sec., the pumps must transfer: $\dot{W}_p = 983 \times \frac{0.25}{30} = 8.16$ lbs. of mercury per sec. The

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mathematical model for the pitch trim system then consists of the three equations:

$$\tan\theta = \frac{W_{P_1}X_1 - W_{P_2}X_2}{B\,Y}$$

$$W_{P_1} = W_{P_1} \pm \dot{W}_P$$

$$W_{P_2} = W_{P_2} \pm \dot{W}_P$$

MERCURY TRIM ROLL SYSTEM. An analysis similar to that of the trim pitch system yields the following equations for the mathematical model of the trim roll system.

$$\tan\phi = \frac{W_{R_1}X_3 - W_{R_2}X_4}{B\,Y}$$

$$W_{R_1} = W_{R_1} \pm \dot{W}_R$$

$$W_{R_2} = W_{R_2} \pm \dot{W}_R$$

$$W_R = W_{R_1} + W_{R_2}$$

Where

ϕ = Roll angle

X_3, X_4 = Distances in ft. of location of mercury tanks, from CG,

B = Buoyant force,

Y = Distance of center of buoyancy from CG,

W_{R_1}, W_{R_2} = Amount of mercury in each tank in lb.,

W_R = Total amount of mercury,

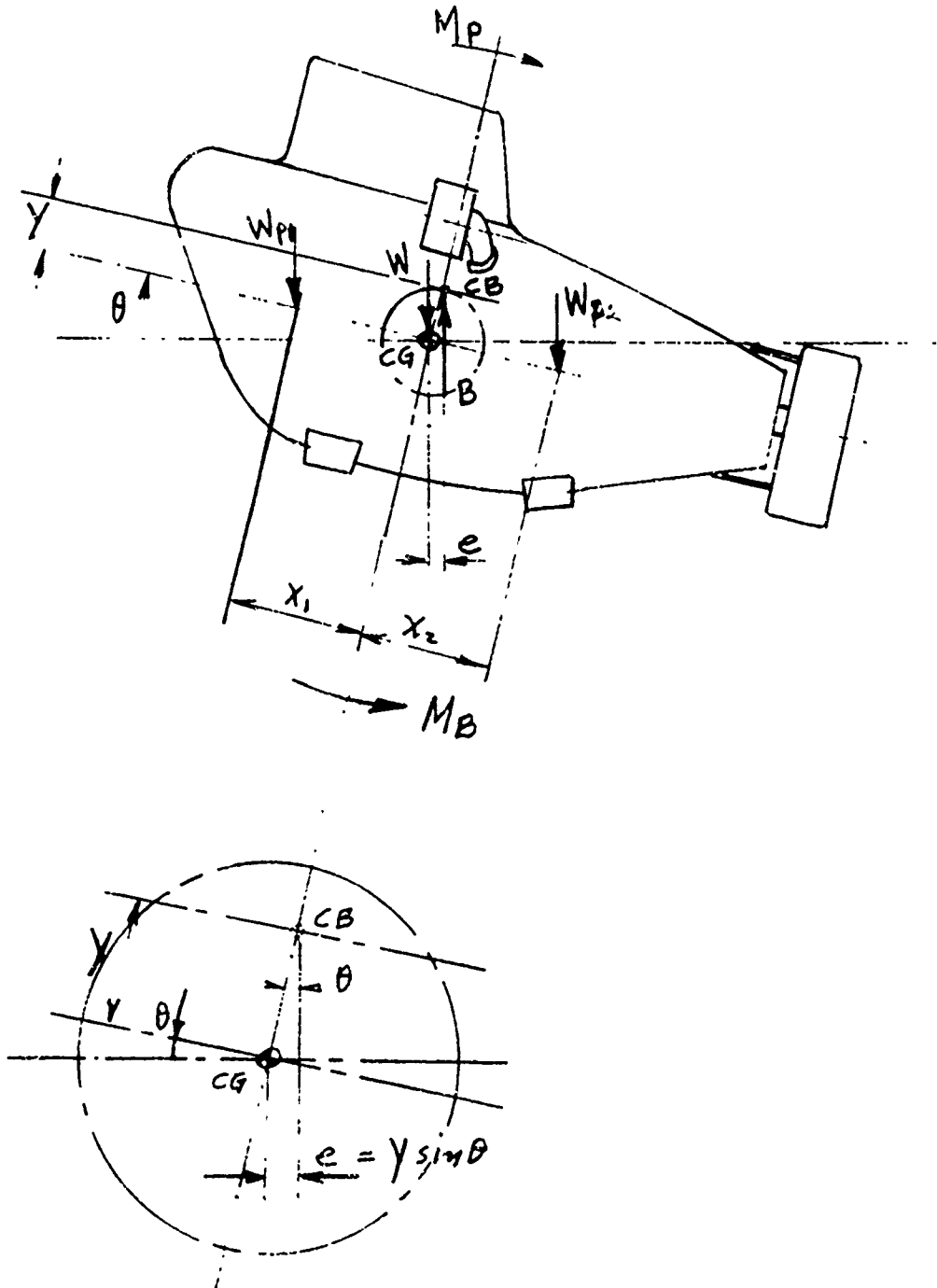and

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

Figure 1. Development of Trim Systems

SECTION IV

PROGRAMMING DESCRIPTION

This section contains information on the overall program organization of
the UTNRS simulation problem and briefly describes all program units and the
control program. In addition, it discusses the modes of operation of the
simulation program, timing requirements, computer environment, input/output,
and other information related to the effort of programming the UTNRS system
for the Sigma 7 digital computer.

PROGRAM ORGANIZATION

In order to meet the simulation objectives, the subroutines which
comprise the total simulation program must be loaded into the computer
storage and be performed in a specific order and time relationship. The
order of execution of the subroutines and the number of subroutines executed
in any one cycle result in three modes of operation. Any one of the modes
can be selected by the student or instructor at any time.

TIMING REQUIREMENTS. The solution of the simulation program in the digital
computer is not a continuous, but a stepped-out solution. Thus, the step
size (time interval) selected for each step must be such as to assure that:

a. No phase lag, at least not a large phase lag, will occur between
successive integration steps.

b. The accuracy of the results at each integration step is within a
specified limit.

c. The rapid input changes are not lost due to the slow input sampling
rate.

d. The movement of the instruments appears continuous despite the slow
output rate.

e. There is sufficient time to perform all program requirements including
input/output within a cycle.

For the realtime simulation of a slow-moving submarine, an interval of
50msec appears to be sufficient and was chosen for the simulation program
cycle time.

PROGRAM ORDERING. To avoid phase lag (which may cause instability in the
solution of the system equations in the execution of the various program
units), the simulation equations have been ordered as follows:

a. Hydrodynamic equations
b. Submarine system equations
c. Submarine instrument equations
d. Motion system equations

The mathematical model of the real-time simulation functions is shown in figure 2. The programs accept control inputs from the trainee and operate on these inputs to provide the necessary input values required by the mathematical model. In turn, the mathematical model equations operate with these inputs and provide the necessary outputs via the output processor to activate the motion system, instruments, and indicators associated with these outputs.

MODES OF OPERATION. A mode of operation consists of the sequential solution of all programs which make up one iteration in the real-time solution of the simulation problem. Three unique modes of operation have been established, the activation of each resulting in a distinct function of the simulation program. These are the normal, zero, and sink/freeze modes.

NORMAL MODE. The normal mode consists of those programs which are required for a real-time solution of the simulation problem. Under this mode, the various program's responses to the trainee inputs and these responses are converted by the programs to output signals necessary to drive the simulator for an unprogrammed mission. This mode of operation is shown in figure 3.

ZERO MODE. The zero mode overrides any other mode and results in the orderly reduction of the simulation parameters to the surfaced configuration of the deep submersible. This mode is initiated when the zero mode push button at the monitor console is depressed, or when the altitude voltage input is equal to zero. The zero mode is usually initiated to return the submersible to the surface or to clear any abnormal condition that may arise while operating the submersible. Initiation of the zero mode results in the following: (1) the hydrodynamics equations and the submarine system equations are bypassed; and (2) all quantities which are used to drive the instruments and motion system are reduced at a rate of $\frac{1}{60}$ of their current values per cycle until they become zero. This results in an orderly way of returning the instruments to their initial values. When all quantities are equal to zero, all parameters are reinitialized.

The vehicle configuration then corresponds to a submersible surfaced and at rest. The zero mode is shown in figure 3.

SINK/FREEZE MODE. This mode results in a suspension of the simulated motion of the vehicle by by-passing the equations of motion and the submarine systems equations; that is, current conditions are maintained as long as the freeze mode is in effect. This mode is activated by depressing the Freeze pushbutton on the monitor console. The Sink/Freeze Mode is shown in figure 4.

DESIGN OF THE CONTROL PROGRAM

The program responsible for the proper operation of the Deep Submersible Simulator in its real-time environment in the Sigma 7 is the mode and cycle control (MCC) program. The MCC program is designed to run under the XDS BPM Monitor.
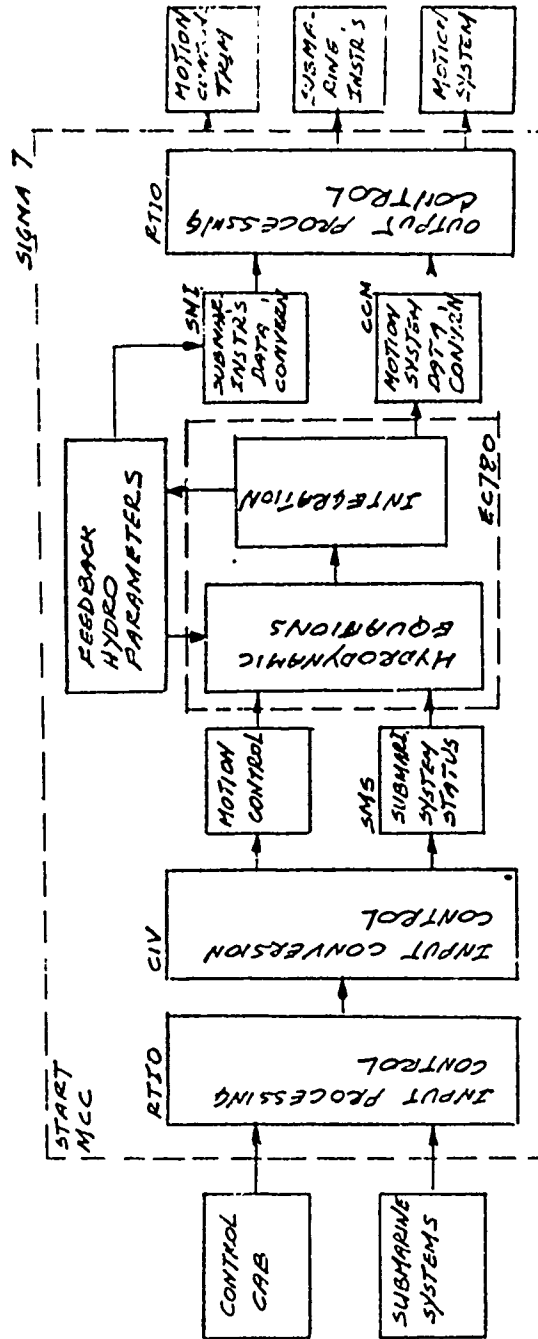
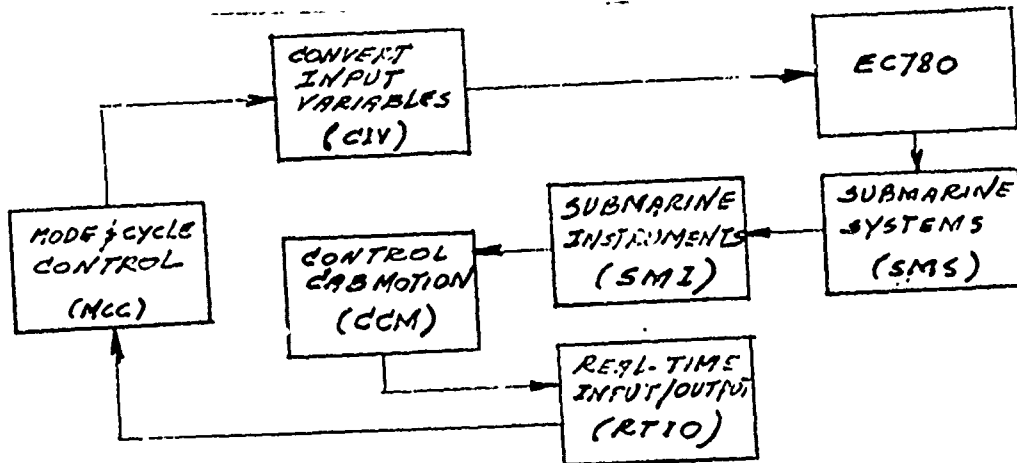Figure 2. Real-Time Function Diagram
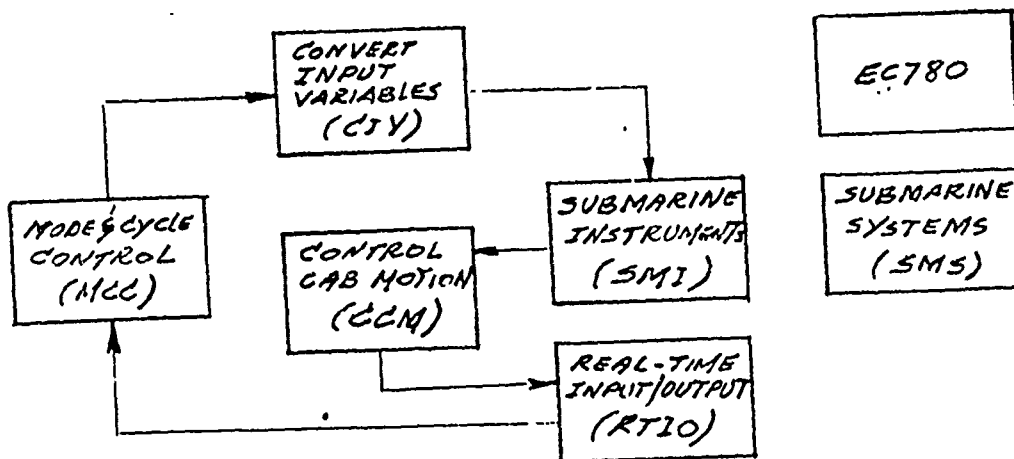
Figure 3.   Program Flow – Normal/Zero Modes

Figure 4.   Program Flow – Sink/Freeze Modes

LEVELS OF OPERATION. There are three levels of program operation in the deep submersible simulation program.

   a. The MCC program is responsible for the proper sequencing and real-time operation constraint of all other program units.

   b. The MCC program transfers computer control to the various programs in the proper sequence and time. After executing the specific function of each program, control returns to the MCC program.

   c. Subroutines which may be used by more than one program are entered directly by the program in operation; after completion of the subroutines function, control returns to the program which called the subroutine.

MODE DETERMINATION AND EXECUTION. The MCC program determines the operation mode at the beginning of each cycle. A test is performed and the results are indicated by the value of the parameter, MODE. The modes for the three programs, their priorities, and their respective mode values are as follows:

PRIORITY	PROGRAM MODE	MODE VALUE
1	Zero	2
2	Sink/Freeze	1
3	Normal	0

After the priority and the MODE value of a mode have been determined, the program MCC causes the execution of that mode cycle by maintaining three tables, one table for each mode. Each of the tables has as many entries as there are programs in the mode. The programs are ordered according to their sequence of execution. A particular mode is executed each program cycle as long as the mode value remains the same. Depressing the zero mode or sink/freeze push button at the control monitor console, will result in changing the mode value, thus altering the current mode. Figure 5 is a flow chart of the above procedure.

CONTROL OF PROGRAM CYCLES. The requirement of the deep submersible simulator is that one iteration must occur every 250 msec. This rate is controlled by the Sigma 7 counter interrupt feature. The frequency of the counter 3 count pulse is 8000 Hz or 125 μsec. At the start of each program cycle, a value of -2000 (which corresponds to 250 msec program cycle) is loaded into the symbolic location M1CLOCK, and the counter 3 count pulse and counter 3 zero interrupt are armed and enabled. At the occurrence of each 125 μsec count pulse (until the results becomes zero) the value at the location M1CLOCK is incremented by one. At that time, the counter zero interrupt occurs, and at that instant, a new program cycle starts. If the program time cycle fails to be completed before the 250-msec time expires, an error routine is entered to notify the operator.
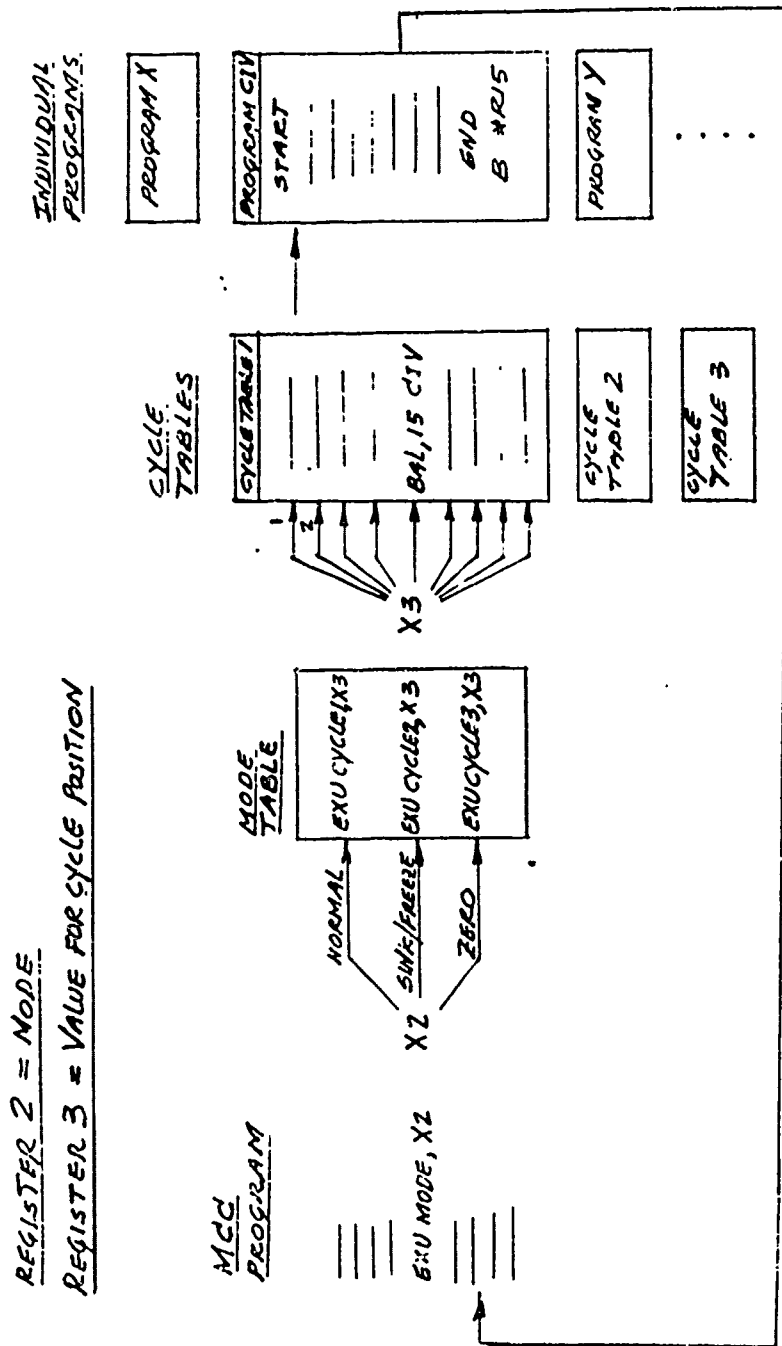
Figure 5. Program Control Sequence

BACKGROUND FOREGROUND PROCESSING. During each program cycle, there is a period of time not actually dedicated to solution of the simulation programs. During this time period, data processing which is not directly related to the simulation may be performed. This may include processing such as test data generation recording and outputting. This operation is defined as background processing, while processing related to the deep submersible simulation (real-time processing) is defined as foreground processing. Foreground processing starts at the beginning of the 250-msec time interrupt and continues until all operations in the cycle are completed. At that instant, the interrupt conditions are restored and background operations continue until the next 250-msec interrupt.

ZERO MODE INITIALIZATION. During the zero mode after the completion of each program cycle, the mode and cycle control program checks the speed and depth; when these parameters become nearly zero, MCC executes a portion of the program START to initialize the on-the-surface conditions.

INPUT/OUTPUT. All input/output (i.e., discrete and analog devices) are initiated by the program RTIO (Real-time Input/Output). Once the input/output is initiated, it continues asynchronously until all requested input/output operations have been completed. RTIO is executed once at the end of each program cycle in each of the modes.

START UP. The start of the simulation is initiated by a transfer to the location MCC$1. The start-up consists of those functions necessary to transfer the simulator to a status of a free-floating, on-the-surface, ready-to-dive submarine. Prior to the first program cycle, these functions initialize internal data values by entering the program START and reading via the RTIO program some external inputs.

The simulation is then ready to start. The interrupt and trap locations utilized by the program are initialized and the interrupts armed and enabled. The program is actually started by setting up the background environment and triggering the counter 3 zero interrupt. This results in entering the program to the first program cycle.

COMPUTER ENVIRONMENT. The mode and cycle control program maintains the Sigma 7 computer environment and is so designed that the coding is unique to each condition. All events in the simulation are initiated by the Sigma 7 interrupts and traps.

The response to the interrupts and traps is as follows:

POWER ON. This interrupt causes the mode and cycle control program to execute the start-up process.

COUNTER 3 - COUNT PULSE. This interrupt results in the addition of a one to the value in M1CLOCK symbolic location every 125 μsec. In real-time operation the value in M1CLOCK location will be reset to -2000 at the end of every program cycle. Thus M1CLOCK will increment to zero every 250 msec.

COUNTER 3 ZERO. This interrupt occurs every 250 msec and results in the start of a new program cycle. The parameter is incremented by one every program cycle. This results in a real-time clock with a 250-msec resolution.

MEMORY PARITY. The memory parity interrupt causes the mode and cycle control program to disenable the counter 3 pulse interrupt, to turn off the ready simulate levels, and to halt with an error indication.

POWER OFF. This interrupt causes the mode and cycle control program to save the current program status doubleword (PSD), save the contents of the general registers, turn off the ready simulate levels, and loop until the computer is shut down.

TRAPS. All traps, except the CAL1, CAL2, CAL3, and CAL4 are error traps. The occurrence of an error trap causes the computer to enter a specific trap handling routine, which saves the PSD by storing it in a specific memory locations, and a unique error code is returned. The traps and error codes are listed below:

       Non-allowed operation------------------------------------ 1
       Unimplemented instruction-------- ---------------------- 2
       Pushdown stock limit reached--------------------------- 3
       Fixed point arithmetic overflow--------------------- 4
       Floatir point fault--------------------------------- 5
       Decimal arithmetic fault----------------------------- 6
       Watchdog timer runout------- --------------- ----------- 7

ERROR ROUTINE. The simulation program is designed to operate under the Sigma 7 design constraints. Any violation of these constraints is considered as an error and so the simulation will halt. This is accomplished by the error subroutine of the mode and cycle control program. This error routine disenables the counter 3 pulse interrupt, turns off the ready-simulate levels, and halts the simulation with a particular error code displayed. The error routine is activated by executing the CAL4,0 instruction.

READY-SIMULATE LIGHT. The ready-simulate light serves to inform the monitor console operator that the program is operating in the real-time simulation mode, and to indicate that valid analog voltages are obtained from the computation. At the start of each real-time program cycle, the light is turned on; if in any program cycle the control over the computation is lost, the ready simulate light will be turned off.

MONITOR UTILIZATION. The simulation program will run under the Sigma 7 batch processing monitor. All interrupts necessary for the simulation are controlled by the mode and cycle control program, and they are initialized at start-up so that they override any interrupt control by the monitor. External or monitor console interrupts are not controlled by MCC. This allows effective monitor control of the standard I/O and of special routines which are activated through external interrupts. All traps are controlled by the batch processing monitor. The simulation program is designed such that the register block 1 is used by the background routine and register block 0 by the foreground routine. The mode and cycle control program controls the register block usage via the PSD when it responds to interrupts or traps. The 250-msec program cycle is always controlled by the mode and cycle control program. To do that, the counter, the I/O and external interrupts inhibits are activated via the PSD prior to specific programs when responding to interrupts or traps. The I/O and external interrupts are inhibited except when executing background processing.

The counter interrupts are inhibited during start-up process, interrupt of the program cycle, error routine, trap handling routine, power off interrupts, and memory parity interrupts.

PROGRAM UNIT DESCRIPTION

The various functions of the UTNRS simulator are accomplished by the sequential execution of the following program units.

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 submarine. It initiates all values necessary to transform the simulation programs to a known configuration (of the surfaced submarine). 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 (·) through (6) listed in reference 3 and equations (1) through (6) presented earlier in the mathematical model section of this report. The hydrodynamic coefficients and constants (which will be used in conjunction with the equations of motion) are those contained in the NSRDC Report Number 3148(U69-875). These 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. These coefficients are listed in appendix A, of reference 3. In addition, EC780 provides for updating velocities and positions of the vehicle 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, variable ballast system control, drop weight 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 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.

SECTION V

DISCUSSION

After the UTNRS simulation system was purchased from AMECOM, it was felt that the simple analog circuitry used by AMECOM to simulate the submarine motion, could not provide the high fidelity expected from a simulator which was to be used as a research tool for developing training techniques for deep submersible pilots and crews. It was then decided to improve the simulation fidelity by introducing hydrodynamic effects into the simulator.

The hydrodynamic effects were introduced by using a mathematical model consisting of a set of six six-degree-of-freedom equations of submarine motion. This set of equations provide three translational and three rotational motions along and around the body axis of a submarine.

The mathematical model selected describes the motion of a conventional submarine, and it was necessary to modify and adapt it to the slow motion of a deep submersible. In addition, provisions had to be made to include the deep submersibles side thruster and athwartship thruster effects. Also, two mathematical models had to be devised; one for the change in ballast and the other for the mercury trim in roll and pitch.

Generally, a submarine mathematical model may be used to describe the motion of several submarines. To use the model to simulate one particular submarine, a set of coefficients and constants which are peculiar to the submarine being simulated must be used in conjunction with the equations of motion. In the case of the UTNRS vehicle, the coefficients and constants used with the mathematical model were those of the AUTEC I (presently known as SEACLIFF) research vehicle. This is a deep submersible similar to the well-known ALVIN of the Woods Hole Oceanographic Instit e.

To test the validity of the mathematical model following its establishment, various computer programs were written and run on the Sigma 7. These runs were made in machine time, i.e., without regard to real-time constraints. Subsequently, all program units were integrated and the complete simulation program was tested as a unit. To accomplish this effort, the Sigma 7 computer was connected via the Sigma 7 special interface unit to the REAC 440 analog computer. The purpose of the analog computer was to simulate the function of the control console of the UTNRS vehicle control cab. Analog inputs entered the simulation program after being converted to digital form, and in return digital outputs, converted to analog voltages, were received by both the REAC and an 8-channel strip chart recorder. Thus, the simulation program was functionally checked and is ready for an actual hook-up to the UTNRS vehicle hardware.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

Based on the findings in the discussion section, it is concluded that the programs developed in this task would be usable in meeting the task objective, i.e., developing a deep submersible simulator.

It is recommended that these programs be utilized and an interface be made between the Sigma 7 computer and the UTNRS hardware.

Due to unavailability of performance data of deep submersibles such as AUTEC I and ALVIN, it is recommended that the system be tested and evaluated by experienced pilots of real deep submersibles.

SECTION VII

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