Space and Deep Submergence Vehicles: Integrated Systems Synthesis

JACOB L. MEIRY*
Massachusetts Institute of Technology, Cambridge, Mass.

The extension of man's capabilities to explore the ocean depths and to utilize the abundant resources contained therein is one of today's most challenging technological problems. The difficulty in accurately keeping track of position on or under the wide expanses of the sea is one of the significant aspects of this endeavor. Specifically, precise navigation is an absolute necessity for such operations as the search for and recovery of objects from the ocean floor. The design of integrated marine guidance, navigation, and control systems is an outgrowth of aerospace technology adapted to inner space missions. The impact of mission requirements upon the synthesis of guidance, navigation, and control in deep submergence and space systems is illustrated by a comparative study of the Apollo and the Deep Submergence Rescue Vehicle.

Introduction

NAVIGATION, guidance, and control of space vehicles are problems of precise fuel management. Since orbital mechanics constrain the trajectory of the spacecraft, the duration of a space journey is a function of the selected mission phases. Space navigation and guidance are then undertakings in optimal fuel consumption. In contrast, marine vehicle missions are quite often time optimal problems constrained by the configuration characteristics of the vehicle and the performance of its propulsive units. Electrical power, the equivalent of chemical fuel in space applications, can be consumed while available at a rate compatible with requirements for minimum time steering. Thus, in general, performance goals for space and deep submergence systems emphasize the difference in their respective mission profiles. This distinction between the objectives of navigation, guidance, and control systems in space and deep submergence vehicles is the subject of discussion here.

Navigation and guidance systems are designed to provide accurate information about the craft position and velocity in a selected reference coordinate frame. This knowledge about the state of the vehicle is subsequently processed to command course changes. In the context of space applications, navigation is usually referred to as measurement and control of the spacecraft position and velocity during periods of free fall. Guidance, on the other hand, is the task of vehicle state measurements and steering course commands for periods of major thrusting.

The distinction between guidance and navigation in deep submergence is not quite as obvious and certainly cannot be related to vehicle acceleration. One refers to the information about the state of the submersible, position, velocity, and attitude as outputs of the navigation system. With the vehicle under manual control, the hydronaut navigates the submersible; a major computer controlled maneuver is called "guidance." A parallel between celestial navigation and deep submergence navigation is easily established if one recalls that spacecraft navigation is indeed translation and attitude control based on information measured by the navigation system. Of course incremental translation and attitude control is precisely the task of the hydronaut at the controls of the submersible. The guidance problem for space and deep submergence vehicles is essentially identical; as a matter of design, it is a boundary value maneuver, executed while subjected to time or fuel consumption constraints.

For illustrating the impact of mission requirements upon the synthesis of navigation, guidance, and control systems, a comparative study of similarities and differences between space and deep submergence systems is quite illuminating. The Apollo and the Deep Submergence Rescue Vehicle (DSRV) are selected as representative of the state-of-the-art in their respective fields. First, let us examine the mission trajectories for the two vehicles. Figure 1 summarizes the total Apollo mission and its phase subdivisions. An interesting feature to note is the presence of short accelerated maneuvers (heavy lines in Fig. 1) spaced between substantially longer coasting periods. This aspect of the Apollo mission, which is characteristic of all spacecraft voyages, has a significant bearing upon the synthesis of the guidance, navigation, and control system aboard the vehicle. Note that spacecraft missions are preplanned and vehicle maneuvers are known in advance. The basic objective of the navigation, guidance, and control system is then to force the spacecraft through its predetermined trajectory.

The Deep Submergence Rescue Vehicle, as indicated by its name, is a deep diving submersible designed to rescue the crew of a disabled submarine settled on the bottom of the ocean. A whole range of subsidiary functions such as search, oceanographic exploration, and object retrieval are also feasible with this craft. This will be the deepest diving maneuverable submersible in the United States. Figure 2 is an illustration of a typical rescue mission of the DSRV. Specifically, two phases are distinguished during rescue: 1) a rapid transport leg between the mother ship or the surface vessel and the site of the distressed submarine, and 2) an accurate, tightly controlled spatial approach to the distressed vessel.

To effect rescue, controlled mating to a disabled submarine is the design goal and the critical test of the DSRV navigation, guidance and control system. The two mission phases of the rescue operation carry a distinct dynamic characterization based on the forward velocity of the submersible. The transport leg, being the cruise phase, is carried out with high velocity, and the hover regime is maintained while mating is attempted at very low velocities of approach. The necessity for these two operational regimes, cruise and hover, for the

Presented as Paper 68-473 at the AIAA 3rd Marine Systems and ASW Meeting; submitted May 6, 1968; revision received November 25, 1968. The information presented in this paper resulted from the cooperative efforts of the many individuals associated with the Apollo Guidance and Navigation Program and the Deep Submergence Systems group at the Massachusetts Institute of Technology Instrumentation Laboratory.

* Assistant Professor of Aeronautics and Astronautics.

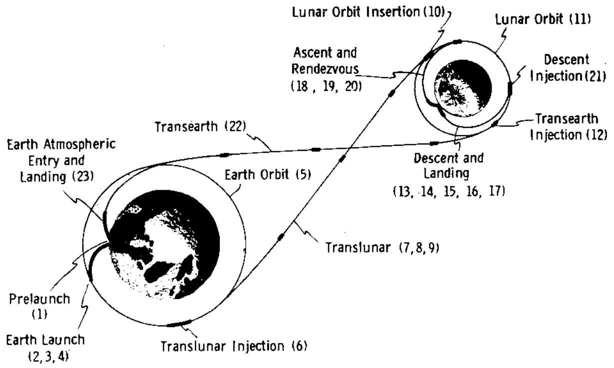

Fig. 1 Apollo mission.[1]

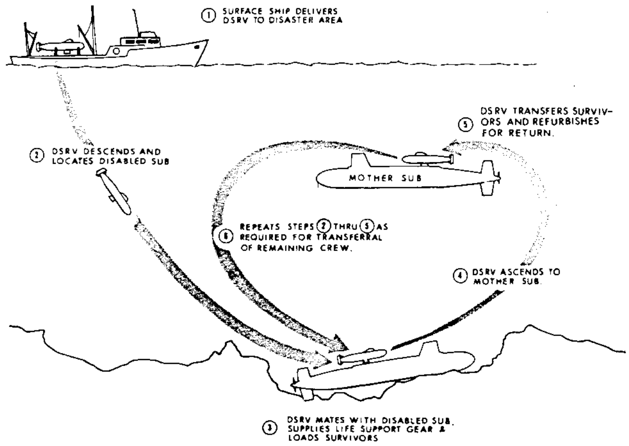

Fig. 2 Deep submergence rescue vehicle mission.

DSRV is a dictate of the projected mission of the submersible. However, the implications on the design of the submersible systems are far reaching. To assess the impact on the control system, for example, it is sufficient to mention the need for alternate propulsion means during cruise or hover with the added complexity of the control system which is called to act upon characteristically different vehicle and effector dynamics.

Navigation and Guidance

Given the specific set of navigation sensors with which a space or marine vehicle is equipped, the definition of sensor configurations and the processing of the information gathered from them constitutes a particular solution to the navigation problem. Ideally, the best solution to the navigation problem will take into account all the pertinent information available to provide the most accurate indication of position and velocity possible. Realistically, the designer is limited in his definition of the information processing by the computer memory capacity and the requirements for real time indication and availability of the navigation system outputs. An important question then is the relation between mission and navigation hardware configurations. In conclusion, our search is for the link transforming specific conceptual requirements to operational guidance, navigation, and control systems.

The rescue mission phases of the DSRV presented previously highlight some of the subtle demands imposed upon its systems. One such requirement for the successful completion of mission objectives for marine vehicles is the ability to record accurate history of the vehicle trajectory. Obviously, this feature is indispensable when the vehicle is called to carry out efficient search operations and to return to the target area. This additional requirement reflects what is perhaps the distinguishing characteristic between the navigation problems in inner and outer space. Indeed, for the most part during the journey of a spacecraft (that part occurring during free flight) the vehicle trajectory is relatively predictable; continuous measurement of the position and velocity of the vehicle is unnecessary, and relatively infrequent updates or corrections of the vehicle position and velocity are required. The converse, of course, is true for the DSRV. These remarks indicate that greater information handling capabilities are required for marine navigation systems than for comparable space systems.

The physical aids available for navigation are also quite different for marine and space applications. The astronaut has a variety of natural landmarks at his disposal, such as the earth, moon, sun, and other celestial objects. By taking optical measurements of their positions, he can fix his location in space with sufficient accuracy and determine the attitude of his spacecraft. If necessary, he can also rely heavily on ground link telemetry and voice communications to provide him with the necessary information to complete mission objectives.

Nature does not provide so well for the hydronaut in this respect. Excessive propagation losses of high frequency radiation in ocean waters rule out the extensive use of electromagnetic radiation. Moreover, natural landmarks are not usually available, due in part to the restricted visibility underwater, thus eliminating optical aids for the hydronaut. As a result, man-made objects such as acoustic transponders and homing beacons are often supplied. In conclusion, navigation systems for marine vehicles have to operate as self-contained units, and in this respect transponders and beacons do not alleviate the problem since prior precise calibration of the net is a prerequisite for their use.

Navigation and Guidance Instrumentation

The Apollo navigation system is illustrated in Fig. 3. Inertial instruments measure thrust acceleration along three mutually orthogonal, nonrotating axes. The Apollo guidance computer then carries out integrations and gravity calculations in real time throughout the entire mission. In space flight these computations, although very accurate, are made on an open-loop basis. Since the majority of the mission trajectory is in free fall, there is no real need for the continuous use of the inertial measurement unit. Open-loop computations indicate the availability of navigation outputs, spacecraft position and velocity, obtained by integration of the vehicle equations of motion. Navigation output updates are performed whenever external measurements are made, but this is an infrequent event.

Navigation of space vehicles was shown to be a software task with position and velocity information provided, and with no need for sensor measurements. Guidance, on the other hand, is a steering task during major maneuvers. Here, in addition to efficient data processing, a knowledge of thrust

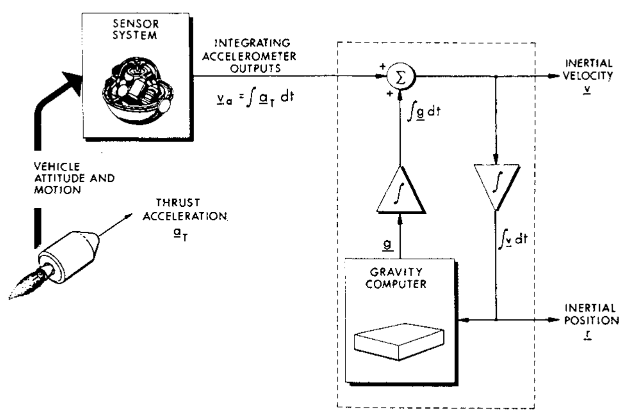

Fig. 3 Apollo navigation system.[2]

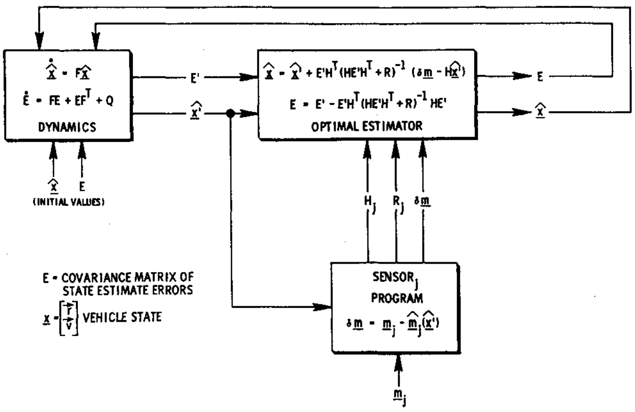

Fig. 4 DSRV position and velocity computation.

acceleration is needed. The astronaut, borrowing marine techniques, utilizes the space sextant for an in-flight alignment of the inertial measurement unit in order to provide the navigation system with the proper sensors for measuring thrust acceleration. Thus navigation and guidance in deep space require optical measurements, thrust acceleration knowledge, and computational capability aboard the spacecraft.

In marine navigation, the relaxing assumption of vehicle operation in a forcefree environment does not exist. There is a continuous need for measurement updates in marine navigation systems. The Deep Submergence Rescue Vehicle navigation system is a set of sensors collectively utilized to provide the best indication of vehicle position and velocity. A sufficient complement of navigation data for a submersible is a measurement of its velocity in a known reference frame. Therefore, ground velocity measured along three orthogonal body axes and resolved into components in geographical coordinates is the only information required for navigation. The doppler sonar navigator, a unit similar in operation to a doppler radar unit, and the inertial navigator of the DSRV are the sensors needed to accomplish these measurements. Thus, one common feature which is effectively utilized by both space and marine navigation systems is that of inertial stabilized instruments. However, the inertial systems differ in their configurations due to the difference in their application. The Apollo system contains three gyroscopes to maintain the inertial reference and three accelerometers to measure acceleration in three degrees of freedom. A marine vehicle operates at all times in the gravity field of the earth. To avoid gyro tumbling in this gravitational field, it is desirable to constrain the inertial platform to the horizontal at all times. This instrumentation also has the advantage of eliminating coordinate transformation calculations in the navigation computer and provides for direct readouts of the yaw, roll, and pitch of the vehicle from the inertial system gimbals. For a system maintained in this orientation, a third accelerometer is relatively useless for long-term navigation since there is a basic instability in mechanizing the third degree of freedom in the vertical direction. Thus, only two accelerometers are used for the inertial navigator of the DSRV. An additional difference between the inertial systems is in their stability. As indicated previously, the Apollo inertial measurement unit is used only during the powered phases of the spacecraft flight. The inertial navigator of the DSRV, on the other hand, is continuously needed to provide resolution of doppler velocity information and attitude control. Consequently, more accurate control of gyros is required for marine inertial navigation than for space navigation. Moreover, additional care must be exercised to provide for torquing the inertial navigator at earth rate.

In addition to the inertial navigator and the doppler velocity sensor previously mentioned as members of the DSRV navigation sensor suit, there are two depth pressure gauges, an altitude/depth sonar, a velocimeter which measures the speed of sound necessary for doppler velocity calculation, and the possibility for a network of acoustic transponders placed in some known geometrical pattern on the ocean floor. Of course, once the coordinates of these transponders are determined, they fulfill the function of the natural landmarks available to the space navigator. It is apparent that the DSRV navigation sensor suit provides redundant information in order to achieve increased system reliability. The solution to the navigation problem then depends upon the definition of the processing of the sensor's information such that all pertinent data is incorporated into the computation of the present position and velocity of the vehicle, and the use of techniques for this incorporation which process this information in a mathematically optimal fashion, taking full advantage of redundant sensor information and the past history of vehicle maneuvers during a given mission.

The solution to the navigation problem for the DSRV has been accomplished by formulating it as an estimate of the state of a dynamic system. The state of this dynamic system is the position and velocity of the vehicle, for which an estimate is found by using a weighted least squares recursive algorithm to process the navigation sensor measurements. Implicit in the solution of the problem as a least squares procedure is the definition of system optimality. The optimal system is that which indicates the minimum least squares deviation from the true position and velocity of the vehicle.

The techniques developed in the space program, and for the Apollo mission in particular, for handling navigation sensor measurements have found ready application in the DSRV. These techniques consist of optimal incorporation of the sensor measurements with their statistical uncertainties into a linear estimate of the position and velocity of the vehicle. The method takes full advantage of redundant information contained in the measurements. In the DSRV navigation system, all the sensor measurements are incorporated into the position and velocity estimate using the mathematical algorithm shown in Fig. 4.

Finally, the navigation problem reflects upon the organization of the computer systems for marine and space vehicles. The outstanding reason for many of the differences between the systems stems from the fact that the mission objectives of the Apollo and the DSRV vehicles are drastically different.

The Apollo software system is created from a preplanned mission with vehicle maneuvers known in advance. The basic goal here is to force the vehicle through its desired trajectory. The input/output interface is therefore designed to provide data from the various sensing devices to the guidance system only at unique time slots during the mission. Because of temporal accuracy constraints, inputs to the computer system are wired directly to a predetermined core location in order to provide the latest data with the shortest possible access time.

The DSRV system has an unknown mission profile and consequently requires a software and input/output system that is general in nature in order to provide service to a variety of situations. Consequently, the DSRV central processor computer is equipped with erasable core. Similarly, for the

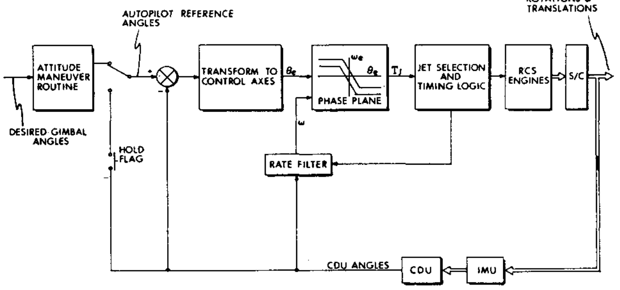

Fig. 5 Apollo coasting flight control.[2]

DSRV system the accuracy requirements are much less stringent due to the relatively low velocity and short distances involved. This relieves the timing constraint on data access. The general nature of the system, however, involves a larger data processing task than Apollo.

The buffered input/output system of the DSRV suits these requirements rather well. (No input/output buffering is necessary for Apollo.) Data access takes more time because of the number of instructions that must be executed to satisfy the interface requirements of the buffer system. The flexibility allowed by the buffered system, however, eases the burden of the data processing task by allowing mass storage and retrieval of data, thus providing the ability to operate with a minimum memory configuration.

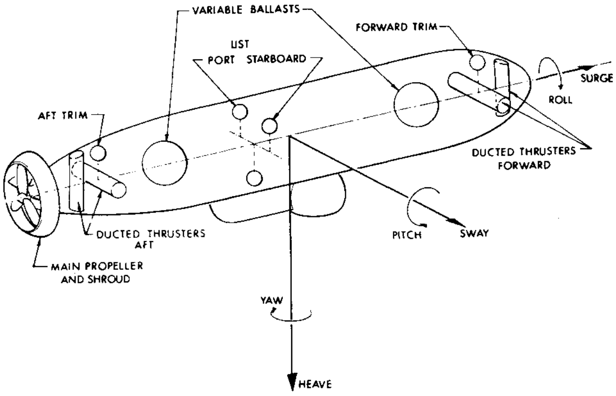

Fig. 6 DSRV effector system.[3]

Control Systems of Apollo and the DSRV

The dramatic difference between operation in outer and inner space is apparent in the control system design of the Apollo and the DSRV. For the Apollo spacecraft, coasting flight control is exercised during the majority of its trajectory. No significant forces act on the spacecraft for these periods and control over the vehicle involves attitude control only. The effector system for attitude control is a group of reaction jets with minimal cross-coupling, if any. Digital autopilot control, as illustrated in Fig. 5, operates the rockets based on attitude and attitude rate information with the crew aboard able to select a variety of modes such as attitude hole, rate command, or direct acceleration command via a hand controller.

For powered flight control, the digital autopilot of the Apollo spacecraft orients the vehicle thrust vector in response to guidance commands. However, the acceleration vector is usually along the longitudinal axis of the spacecraft, and the powered flight control problem again becomes one of attitude control. Note that autopilot control in the Apollo system is a function of the guidance computer aboard the spacecraft.

The Deep Submergence Rescue Vehicle belongs to a new class of submersibles. Characteristic of the group are mission requirements calling for control over the precise spatial orientation and translation of the vehicle. When equipped to maneuver in six degrees of freedom, the submersible performance is expected to remain invariant with respect to environmental disturbances, the degree of hydrodynamic cross-coupling affecting the dynamics of the vehicle and the coupling of effector forces and moments along and about the vehicle axes. The integration of a human operator as a monitor and active controller of the submersible is an additional constraint to reckon with in the design of the DSRV control system.

The prime mission of the DSRV is mating to the distressed submarine. Failure to mate is a failed mission regardless of the outcome of any other functions the DSRV is called to perform. In this context the design of the DSRV control system, the operator's displays, and the procedures for mating are synonymous with the design of the control, display, and computer systems for any mission of the DSRV. One can easily demonstrate the fact that any task other than mating will utilize only part of the maneuvering capability, the display precision, the sensors available on board, and the tight control of the submersible necessary for successful mating. One immediate observation is that the human pilot cannot control the coupled, uncompensated six degrees of freedom of the submersible within the prescribed error envelope at mating, regardless of the degree of sophistication built into the display system for the operator. Similarly, effecting a fully automatic mating is ruled out at the present time since information about the attitude of the distressed submarine is unavailable in a form suitable for processing as a signal input for the DSRV autopilot. The design for mating resorts then to a man-machine execution of the mission.

Conceptually, the mating process is a combination of pattern recognition and maneuver to mating orientation. Both tasks are assigned to the hydronaut aboard the DSRV, with the integrated display and control panel and the control system designed to provide the capabilities required by the operator. To perform efficiently, the hydronaut is to be confronted with a sequence of single-axis control tasks or uncoupled, frequency distinguishable multi-axis control situations. To decide efficiently, the operator must be relieved of the burden of continuous control of the DSRV in order to counter disturbances forcing the submersible off target. To be a tight active controller, the human operator must provide minimal dynamic compensation to the control loops.

The design goals for the DSRV control system are set to insure compatibility of the system with the mission requirements and the role imposed on the human operator. To this end, the control system includes the following features: 1) six rate (inner) loops compensated for hydrodynamic coupling in the vehicle dynamics and for effector coupling; 2) three translational and three attitude (outer) loops to effect hover conditions in the presence of steady state disturbances; 3) single-axis human operator rate control in six degrees of freedom with aided tracking as required.

While the design goals of a control system are a declaration of intent, the system performance is a function of vehicle dynamics, the characteristics of the propulsion system, and the environment in which the DSRV operates. Hydrodynamic cross-coupling between vehicle degrees of freedom is quite prevalent in the dynamic model of the DSRV. The absence of predominantly large forward velocity during hover precludes linearization of the mathematical model. To effect six degrees of freedom independent control, decoupling of vehicle dynamics is imperative.

Limitation of available electrical power and space severely constrains the performance of propulsion systems for submersibles in general. This effect is even more pronounced for the propulsion system of the DSRV, since maneuverability and dynamic stiffness are of prime importance to the vehicle mission. Specifically, the ratio of force to mass or torque to moment of inertia (the maximum accelerations of the DSRV) is extremely small. In addition, the dynamic range of the effectors is quite limited, and, of course, the propulsion effector dynamics are nonlinear and sluggish. These facts render any control system extremely susceptible to effector saturation.

The propulsion system of the DSRV is presented in Fig. 6. A reversible main propeller thrusts the vehicle along the surge axis, ducted thrusters provide sway and heave forces, and yaw and pitch moments, while mercury shift systems are utilized for roll control and steady-state torques about the pitch axis. Two variable ballast tanks are used to achieve neutral buoyancy of the DSRV as a function of depth. All the effectors are proportionally controlled with the exception of the pitch mercury system. The propulsion system for this hover configuration is a source of simultaneous generation of forces and

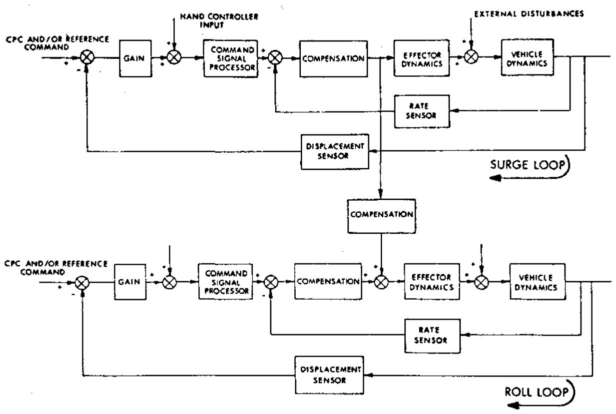

Fig. 7 Dynamic decoupling of the DSRV.[3]

moments to introduce axis cross-coupling. Accelerating or decelerating the main propeller induces a moment about the roll axis. Indeed, this cross-coupling between surge and roll motions should be minimized, since the roll control moment is limited by the pumping rate between the list tanks and the short moment arm.

The ducted thrusters, in turn, produce simultaneous forces and moments on and about the center of the DSRV. With ideal thrusters located symmetrically with respect to the center of gravity of the vehicle, two coplanar thrusters are to be used to generate a pure force or a moment on the submersible. In actuality, however, the moment of the thruster is not equal to its force multiplied by a lever arm due to the fact that the thruster is disturbing the flow pattern around the DSRV. And more critical to the design of the DSRV control system is the inequality of moments produced by identical forces generated at the forward and the aft thrusters. As a matter of fact, the aft thruster exhibits torque sign reversal for part of its dynamic range, the magnitude of the effect being a function of DSRV forward speed. Finally, the destabilizing pitch moment of the locked shroud while the submersible is maneuvered along the negative surge axis (backward motion) is another effector dynamic cross-coupling to reckon with. This moment increases as the square of the backward speed with the shroud acting as a lifting surface.

The environmental disturbances acting on the DSRV are primarily caused by ocean currents. In deep water, away from close-by boundaries, freestream currents exert steady forces and moments on the DSRV as a function of vehicle attitude. However, in the presence of boundaries such as the ocean bottom or the disabled submarine, these disturbances are time variant and a function of the spatial relation between the DSRV and the boundary. These disturbances are especially crucial during the mating procedure while they shift from repulsion to suction with steep relative altitude gradient.

To the list of vehicle dynamic cross-coupling, effector coupling, and proximity effects, the contribution of the human operator characteristics must be added as an additional performance requirement affecting the design of the hover control system. Since the response of the DSRV to commanded inputs is inevitably sluggish, the hydronaut resorts to bang-bang or pulsed commands in an attempt to separate cause and effect in the state of the submersible. This control policy of the operator presents a significant drawback to the operation of the control system in view of the fact that this tendency leads to effector saturation.

The hover control system of the DSRV is designed to effect the desired performance goals while minimizing the vehicle sensitivity to the various disturbances just discussed. The synthesis of six independent loops closed on three angular rate and three translational velocity components measured in vehicle axes is intended to provide axis decoupling. Thus, separate control over each degree of freedom is achieved when six vehicle rates may be independently and individually controlled. It is rather easy to recognize that rate feedback is used to insure system stability and to reduce cross-coupling, due to nonlinear terms in the vehicle dynamic model, to acceptable levels. High gain rate loops will also eliminate the effects of nonlinearities and change of polarity of the ducted thrusters provided that these effectors are commanded proportionally above a certain threshold level. For small input commands, six rate feedback loops do, indeed, decouple the degrees of freedom of the DSRV with the exception of crossfeed between surge and roll. Due to the relatively slow response characteristics of the roll effector mercury system, roll rate feedback is inadequate to counter the disturbing moment generated by the main propeller. The resort to feedforward techniques commanding the roll mercury system in relation to the rate of change of the command signal to the main propeller renders the desired small signal decoupling between the surge and roll degrees of freedom of the DSRV.

The functional block diagram of the hover control system for surge and roll is presented in Fig. 7. The rate feedback loops just discussed are easily recognized as the inner loops in Fig. 7. As indicated before, these loops include high gains to render them insensitive to vehicle and effector cross-coupling, and they are properly compensated for stable operation with small command signals. Moreover, the high loop gain leads to a system which is also quite insensitive to external disturbances. However, this feature of the control system along with other performance characteristics is lost as soon as saturation occurs in the effectors. Since saturation renders open loop control, it will cause large perturbations in the state of the DSRV. Effector saturation can be a result of excessive external disturbances or excessively large commanded rates. While persistent saturation attributed to disturbances will limit the operational envelope of the DSRV (restrict operation when water currents are strong), saturation of effectors called by large commanded rates may be reduced to occurrence with low probability via the use of a network designated command signal processor. The command signal processor is a first-order filter with limiters on the magnitude of the commanded rate and its derivative. A second-order filter is utilized in surge in order to satisfy the decoupling criteria in the roll control loop. Examination of Fig. 7 reveals the fact that command signal processing circumvents the nonlinear control policy of the human operator since operator inputs through the hand controllers are processed by the limiting network.

The closure of six outer feedback loops on vehicle angular rotations and translations in body coordinates insures the hovering feature of the DSRV and provides added stiffness to the control system to counter external disturbances. Since steady disturbances will cause a constant offset of the DSRV from a reference hover state, a proportional plus integral compensation is used in the rate loops to eliminate these errors. Integral compensation is similarly effective in reducing the sensitivity of the DSRV to low-frequency time variant disturbances.

The control of the DSRV in cruise is regulation of attitude and speed of the submersible. Inasmuch as the hydronaut's prime interest is navigating the vehicle between targets, the importance of rotational and translational control in body axes is lost. Steering of the vehicle with control over the pitch and yaw angles at high forward velocities is the main concern. Significantly, at these velocities the ducted thrusters, which are the prime effectors for the hover regime, are no longer efficient thrust and moment producers. Thus, the emphasis is shifted to the characteristics of the moving shroud to control the attitude of the DSRV. Based on these assumptions, the cruise control system of the DSRV is synthesized around four feedback loops. Attitude is controlled with inner rate loops and outer angular rotation feedback. Moreover, roll control is designed as a regulator, set to null roll rate and roll angle. Forward velocity is maintained with a feedback around the surge velocity component of the DSRV. In form, the cruise control system is very similar to the configuration outlined for hover control. Here again, high gain rate loops, command signal processing, attitude feedback, and feedforward signals between surge and roll effectors render the desired system performance.

DSRV Control System Organization

With the stability and controllability of the DSRV inherently assured by synthesis, the full realization of the control system potential is predicated upon the integration of system components and features into one cohesive and systematic operational unit. To that effect, man-machine communication with the control system, system performance in case of a failure, and information flow to the hydronaut are of enormous importance. The previous section brought to light the dynamic distinction between operation in hover or in cruise. Regardless of the manner in which these control configurations are implemented, the system required navigation inputs to maneuver the DSRV. These commands are generated either automatically by the central processor computer aboard the submersible, or by manual control of the hydronaut. In this context, during a computer guidance mode, the DSRV is navigated under program control, along one specific trajectory generated by the central processor computer. Aided manual mode, on the contrary, places the responsibility of steering the vehicle with the hydronaut. This mode classification is highlighted in Fig. 8, which presents the functional relations of the DSRV control instrumentation.

The hierarchy of hardware organization as designed by the Massachusetts Institute of Technology Instrumentation Laboratory is designed to assure minimal performance degradation due to a single failure in the system. At the pinnacle, the system is a digital differential analyzer (DDA) autopilot interfaced to the inertial navigator, a prime package of rate gyros, and a doppler sonar unit. An immediate level of backup for these sensors is available. After a failure of the DDA, the hydronaut is provided with a minimal analog system to insure mating capabilities with favorable environment, and operated in conjunction with visual displays. As a result of a subsequent failure, the hydronaut is faced with proportional control of the effectors via the hand controllers with no vehicle compensation. On-off control of each effector with switches is a last resort prior to emergency jettison.

As indicated previously, the implementation of the DSRV hover and cruise control loops is undertaken with a digital differential analyzer. It is recognized here that this is a novel approach to the mechanization of control systems. However, the choice between a solid state analog computing system and a digital processor strongly favors the digital system, if one considers the amount of computation required for a full control system synthesis. If at the same time due consideration is given to the nature of the computations, namely a considerable amount of low drift integration and substantial amounts of trigonometric transformations, the conclusion is reached that analog implementation would, if feasible, require a disproportionate amount of hardware.

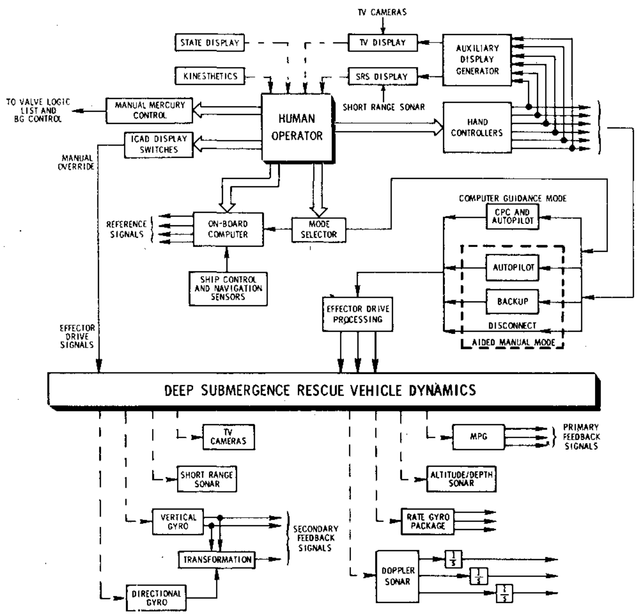

Fig. 8 DSRV control instrumentation.[3]

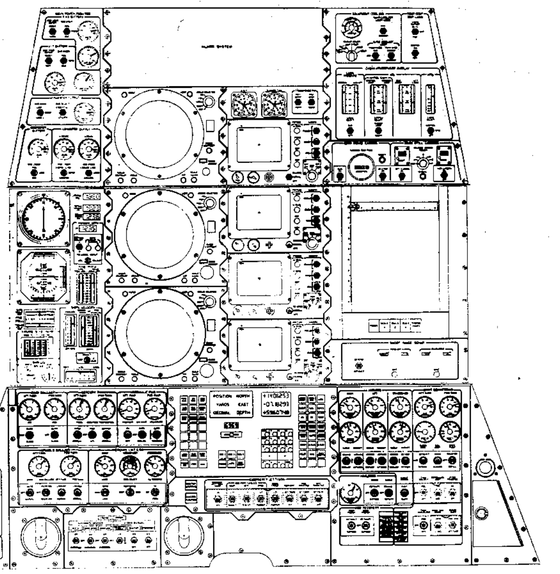

Fig. 9 DSRV integrated display and control console.[3]

Moreover, the flexibility and versatility inherent in digital processing and implemented through software is a significant factor when one considers the uncertainties that are present in the knowledge of the behavior of the vehicle over a wide range of environments while performing a variety of missions.

The case for digital processing is also considerably enhanced by the availability of a proven design for a digital differential analyzer. This type of computer is best suited to the computational nature of the problem. In addition to the fact that integration is a prevailing operation in the synthesis of the control loops, and that coordinate transformations are abundant, the real time nature of the control problem and the associated speed requirements impose the DDA solution.

The backup control system is used in the event of a failure of the autopilot DDA or a double failure in the feedback sensors. This is a minimal analog system based on the use of video information, angular rate feedback, and open-loop translational control of the DSRV, while still capable of effecting rescue. Degraded performance as compared to the prime system is, of course, acceptable. Even in the event that the rescue mission is aborted, the requirement exists to mate the DSRV to a mother submarine, possibly in the presence of a current. Degradation of performance in this context implies that the mating procedure might consume more time than in the prime configuration and that the DSRV operator would have to service individual degrees of freedom more frequently while manipulating the vehicle. Here again, as with the autopilot DDA, the hydronaut navigates the DSRV via two 3 angular degrees of freedom, proportional hand controllers. In this manner, rotation of the hand controller will command submersible rate, proportional to the attitude of the controller.

Subsequent failure places direct control of the effectors with the hydronaut. This is the disconnect configuration where signals proportional to hand controller rotation regulate the acceleration of the DSRV. Finally, as the most reliable and least sophisticated scheme of DSRV control, a set of on-off switches are available to activate effectors. These are indicated in Fig. 8 as manual override and manual mercury control.

Figure 9 is a picture of the integrated control and display console for the crew of the DSRV. The bottom panel is the horizontal control shelf providing the hydronaut seated on the left with all the controls of the system in his immediate reach. In the center of the control shelf one finds the computer display panel for communication with the central processor computer and initiation of the computer guidance mode. With the two-hand controllers and the mode selection panel in between them, the hydronaut masters the aided manual mode of the control system. The mercury systems and the effector switches are also readily accessible on the control shelf.

The midpanel is vertical to provide the visual information for navigation and control. The left panel is a state display panel designed to present vehicle attitude and effector operation data. Sonar and TV monitors relay obstacle and target information and the navigation plotter is useful for repeated rescue trips. The top overhead sloping panel includes the alarm system, where malfunction of the navigation and control system sensors, among others, is indicated.

References

[1] "Space Navigation, Guidance and Control," Rept. R-500, June 1965, Massachusetts Institute of Technology Instrumentation Lab., Cambridge, Mass.

[2] Martin, F. H. and Battin, R. H., "Computer-Controlled Steering of the Apollo Spacecraft," E-2159, Aug. 1967, Massachusetts Institute of Technology Instrumentation Lab., Cambridge, Mass.

[3] Meiry, J. L., "The Control System of the Deep Submergence Rescue Vehicle," Fourth National ISA Marine Instrumentation Symposium, Cocoa Beach, Fla., Jan. 1968.