A VARIABLE BUOYANCY CONTROL SYSTEM FOR A LARGE AUV

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Abstract

A large Autonomous Undersea Vehicle (AUV), the *Seahorse*, has been designed, constructed, and tested by the Applied Research Laboratory at Penn State University (ARL/PSU) for the Naval Oceanographic Office (NAVO). The vehicle is required to launch in shallow water, hover at zero speed, and dynamically maintain trim over the course of the mission. The vehicle is equipped with a two tank Variable Buoyancy System (VBS) to meet these requirements. The resulting control problem is one where the control variable and the sensed variable are off by three derivatives, there are significant delays, and forces are nonlinear (including discontinuous) and highly uncertain. This paper describes the design of the VBS and the control software operating in two modes, depth control mode and trim control mode. In-water test data and simulation results are presented to illustrate the performance of the VBS controller. The paper provides practical insight into the operation of an AUV with a VBS.

Introduction

A large Autonomous Undersea Vehicle (AUV), the *Seahorse*, has been designed, constructed, and tested by the Applied Research Laboratory at Penn State University (ARL/PSU) for the Naval Oceanographic Office (NAVO). The design requirements for the *Seahorse*, seen in Figure 1, specify a nominal mission duration of 300 miles or 72 hours. The nominal vehicle sensor package includes a side-scan sonar, a conductivity-temperature-depth (CTD) sensor, and a GPS/Doppler aided inertial navigation system. Propulsion and hotel power are provided by a large number of D-cell batteries packaged in watertight canisters throughout the vehicle.

Figure 1: The *Seahorse* AUV

Due of the very large size of the vehicle and low operating speeds, small changes in trim resulting from battery replacement, sensor exchanges/additions, and water temperature variations can result in significant drag-induced energy penalties over the duration of a mission. In order to eliminate the need for operators to verify and adjust the trim of the vehicle prior to each mission, a two-tank variable buoyancy system (VBS) has been incorporated into the design. In an attempt to keep cost to a minimum, the design uses a single speed motor and a positive displacement pump. Valves must be moved to control whether water is pumped in or out of each tank, or whether the tanks are closed to the outside or open to sea-water. The valves and pumps must be sequenced to ensure that the pumps do not operate against a closed head and to control the direction of flow. Besides dynamically trimming the vehicle, the VBS is also used to meet a requirement to hover in the water column at zero speed, and to launch the vehicle from the surface. In shallow water it was found that surface capture effects caused the vehicle to be sufficiently heavy at the time it left the surface so that a conventional control law failed because it allowed the vehicle to get halfway to the bottom before the pumps could be reversed. All of these aspects of the vehicle and its operation combine to result in a control problem where the control variable is proportional to a constant (except wrt sign) rate of acceleration, the sensed variable is related to position, there are significant delays, and forces are nonlinear (including discontinuous) and highly uncertain.

This paper first describes the design and modeling of the VBS. The performance of the VBS model is demonstrated by comparisons with in-water test data. Next, the design and implementation of the VBS controller in its two operational modes, depth control mode and trim control mode is described. One previous control approach has used the combination of an extended Kalman filter to estimate motion variables, a linear compensator to compute the required lift and moment, and a trim plane to map these into one of nine pump state combinations [1] and [2]. Another has proposed a fuzzy logic-based controller for depth control [2]. In this design, the AUV is launched from the surface using the VBS depth controller implementing a PD-type control law in conjunction with the fins, once fin authority is attained. Logic and filtering are used to sequence operational modes and to reject low frequency disturbances such as waves. Vehicle trim is achieved and maintained by the VBS trim controller that uses a model-based approach to determine the force/moment combination that would trim the vehicle using a moving average of the pitch angle and elevator angle. The linearized state-variable models of the pitch plane dynamics used for the design of this controller are the same as those used for the Autopilot design; so additional model identification is not required.

Finally, in-water test data are presented to illustrate the performance of the VBS controller. While the depth control strategy presented here is shown to be more than adequate to launch the vehicle, it does not satisfy strict depth control requirements (e.g. hovering) in that a limit cycle exists. A modified VBS depth controller design that shows, in simulation, improved hovering capabilities is the subject of current research and in-water testing of this controller is planned. The benefits of the approach presented in this paper lie in the intuitiveness and simplicity of the design and the robustness as evidenced by the performance of the VBS controller in both fresh and salt water. The paper provides practical insight into the operation of a VBS with an AUV and discusses actual operational experience. To our knowledge, no published papers consider the significance of the surface capture phenomenon on the design of a VBS control system, especially in very shallow water.

Design and Modeling of the VBS

The main requirements of the VBS are:

1. Launch the vehicle from the surface,
2. Change depth without using the fins, and
3. Dynamically maintain vehicle trim in the face of differing payloads and changing environments for efficient power usage.

To achieve these requirements, the AUV has fore and aft VBS components each consisting of a reservoir, a pump and associated plumbing, and control hardware/software. Each VBS reservoir is essentially a rubber inner tube into (out of) which water can be pumped to increase (decrease) the vehicle's in-water weight. To keep costs to a minimum, the design uses a motor operating at a fixed rpm and a positive displacement pump resulting in a constant pump rate. Valves must be moved to control whether water is pumped into or out of each tank, or whether the tanks are closed to the outside or open to sea-water. The valves and pumps must be sequenced to ensure that the pumps do not operate against a closed head and to control the direction of flow. The VBS can be operated in ambient conditions in excess of 1,000 feet depth and each pump subsystem is currently set to add (remove) 20 pounds of water per minute. The reservoir housing and the hardware assemblies, including pumps, valves and controllers, are seen in Figure 2.

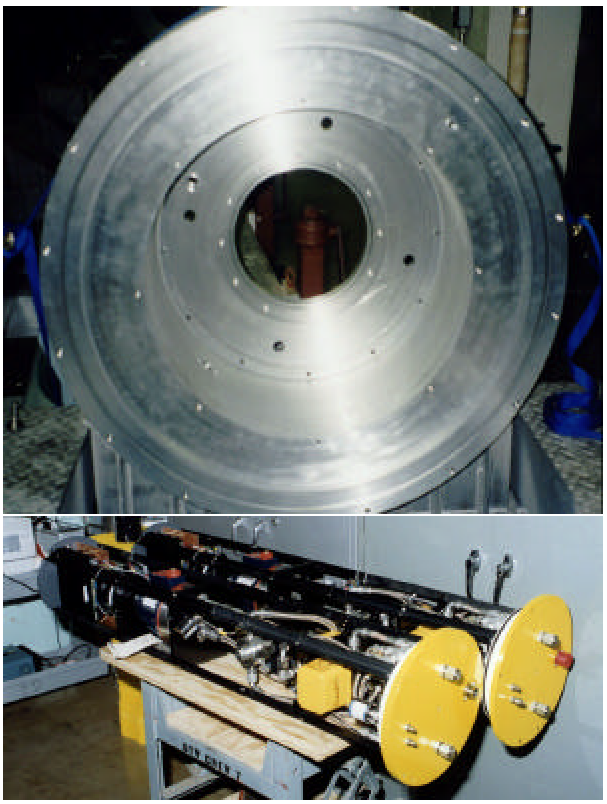

Figure 2: VBS reservoir housing and hardware

The VBS model for the *Seahorse* is shown schematically in Figure 3. The tank commands from the VBS Controller (+1 = pump in, -1 = pump out, 0 = close valves) are fed into the *Valve Motion* block that simulates valve motion by delaying the commands by 5 seconds. These delayed commands are then multiplied by the pump gain (20 lb/sec = 0.1512 Kg/sec) and input to limited integrators which simulate the pumping of water into or out of the tanks by adding or subtracting mass respectively. The integrators are limited between 0 and 200 lbs (90.72 Kg). Water masses are then mapped into water levels by a relationship determined by the geometry of the bladders.

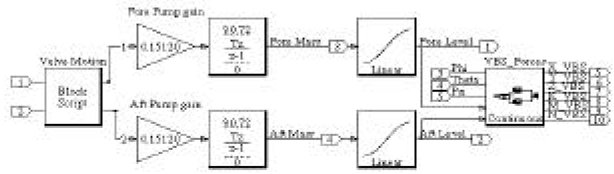

Figure 3: Block Diagram of VBS Model

The *VBS Forces* block uses the water level in each tank and the geometry of the bladder (inner radius, outer radius, and thickness) to compute the mass of water in each tank, and (X_{cg}, Y_{cg}, Z_{cg}), the location of the CG of the water in each tank with respect to the origin of the vehicle coordinate frame. These physical properties are then used to compute forces (F_x, F_y, F_z) and moments (K, M, N) in the vehicle frame as detailed below in Eq.(1), where W is the weight of water, and ϕ, θ are roll and pitch Euler angles respectively.

$$
\begin{aligned}
X &= -W\,Sin(\theta) \\
Y &= \ \ W\,Sin(\phi)Cos(\theta) \\
Z &= \ \ W\,Cos(\phi)Cos(\theta) \\
K &= \ \ WY_{cg}\,Cos(\phi)Cos(\theta) - W\,Z_{cg}\,Sin(\phi)Cos(\theta) \\
M &= -W\,X_{cg}\,Cos(\phi)Cos(\theta) - W\,Z_{cg}\,Sin(\theta) \\
N &= \ \ W\,X_{cg}\,Sin(\phi)Cos(\theta) + WY_{cg}\,Sin(\theta)
\end{aligned}
\qquad (1)
$$

The VBS forces are added to the hydrodynamics forces, multiplied by the inverse of the inertia matrix and integrated to compute the motion of the vehicle. The contribution of the inertia of the VBS tanks to the potential forces (so called “added masses”) is also taken into account. Test data indicates that the vehicle needs to be significantly negatively buoyant to sink below the surface; approximately 10 Kgs of extra water are necessary to overcome the so-called *surface capture* effect. This phenomenon and the shape of the nose of the AUV prevent the vehicle from being able to dive from the surface using the control fins alone even when near neutral buoyancy and forward speed are achieved. To simulate the surface capture effect a force of 100N is added to the weight-buoyancy portion of the hydrodynamic model in the negative Z direction (upwards) while the depth is less than 0.5 m. Details of the vehicle model including the hydrodynamic model and propulsor model are not in the scope of this paper and are not included here.

The VBS Controller

At low (or zero) vehicle speeds, vehicle pitch and depth dynamics are approximately decoupled. We therefore approach depth and pitch (or trim) control separately. The requirements for the VBS as outlined in the previous section are achieved by a VBS controller that is designed to operate in one of two modes: *depth control mode* or *trim control mode*. In depth control mode, the VBS controller is able to launch the AUV from the surface, achieve depth changes without using the fins, hover at a commanded depth, and lift the vehicle off the bottom if necessary. Vehicle launch is performed in combination with the *Autopilot* that commands the fins and the propulsor, and is scheduled by a *Supervisor* whose logic is also described below. In trim control mode, the VBS controller ensures that the vehicle maintains dynamic trim at all times, under changing environments and payload.

Depth Control Mode

The VBS depth controller either pumps water into or out of both tanks equally, or turns both pumps off. This affects the weight-buoyancy force acting on the vehicle (since the ballast tanks are not equidistant from the CB this also effects the torque acting on the vehicle but this is handled by the VBS trim controller described next.) A constant pump rate results in a constant derivative of force acting on the vehicle, i.e., the third derivative of the controlled variable, depth. While this seems to indicate that knowledge of the accelerations experienced by the vehicle is necessary for good control and stability [1,2, and 3], we show that a simpler control structure achieves most of the performance requirements. A schematic of the discrete time VBS depth controller operating at a 1 second sample rate is seen in Figure 4. The depth controller has the general form of a proportional-derivative (PD) controller. The proportional gain is selected to saturate at a depth rate command of 0.1524 m/sec (6 inches/sec) at depth errors greater than or equal to 20 m. Depth information is available directly from a pressure depth sensor and depth rate is derived. There is no derivative gain, however, the depth rate error is quantized based on a threshold to generate one of the following commands: +1: pump in to both tanks, -1: pump out of both tanks, or 0: close valves and turn off pump.

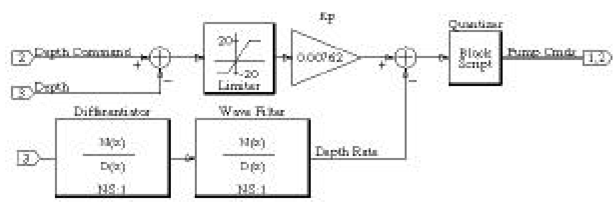

Figure 4: VBS Depth Controller

Trim Control Mode

Another important function of the VBS is to maintain the AUV in dynamic trim while underway. While this is certainly useful in situations where the vehicle's net buoyancy varies from mission to mission, it serves a much more important function in compensating for changing environmental factors. Many of today's operational AUVs do not use VBS trim controllers; some, like the HUGIN, because they do not have changing payloads, and others, such as the AUTOSUB, because they are trimmed in a seawater tank before each mission. As will be seen later, however, even a small variation in water temperature during the mission can cause significant changes in the buoyancy of the vehicle. This is important from an energy standpoint since, for the longer missions that this vehicle is designed for, using the fins to maintain level flight not only reduces fin availability for maneuvering but also depletes valuable and limited power resources.

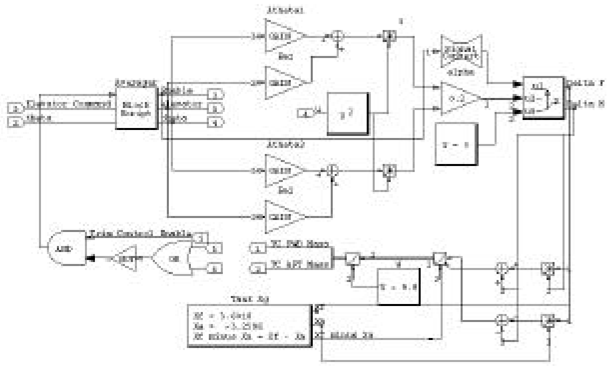

Figure 5: The VBS Trim Controller

The VBS trim controller used in the *Seahorse* is model based and is seen schematically in Figure 5. A running average of pitch angle and elevator deflection is maintained by the *Averager* block (data when the vehicle is maneuvering is excluded.) The Averager uses a (settable) deadzone of one degree for both pitch angle and elevator deflection. This has the beneficial effect of removing oscillations within the trim controller, but allows pitch angles and elevator deflections of less than one degree to go uncompensated for. Models of the pitch-plane dynamics parameterized by forward speed are derived from a coefficient-based hydrodynamics model:

$$\begin{bmatrix} \dot{w} \\ \dot{q} \end{bmatrix} = \left[u \begin{bmatrix} Z_w \\ M_w \end{bmatrix} \quad u^2 \begin{bmatrix} Z_{\delta e} \\ M_{\delta e} \end{bmatrix} \right] \begin{bmatrix} w \\ \delta_e \end{bmatrix} + \begin{bmatrix} \Delta F_{VBS} \\ \Delta M_{VBS} \end{bmatrix} \qquad (2)$$

Equilibrium of Eq. (2), and recognizing that the vertical velocity may be expressed as a function of pitch angle yields the following expression for the force and moment combination that the VBS trim controller must generate to trim the vehicle for the current averaging interval:

$$\begin{bmatrix} \Delta F_{VBS} \\ \Delta M_{VBS} \end{bmatrix} = -\varepsilon\, u^2 \begin{bmatrix} Z_w & Z_{\delta e} \\ M_w & M_{\delta e} \end{bmatrix} \begin{bmatrix} \theta \\ \delta_e \end{bmatrix} \qquad (3)$$

where, ε is a "belief factor" that represents the confidence in the validity of the models. $e = 0.2$ has proven adequate for the *Seahorse* as demonstrated by test data below. Given the geometry of the AUV and the physical locations of the forward and aft VBS tanks, ΔF_{VBS} and ΔM_{VBS} are easily converted into the differential masses required in each VBS tank. The models of the pitch plane dynamics used for the VBS trim controller (Eqs.(2) and (3)) are the same as those developed for the design of the autopilot and additional model identification is not required.

Vehicle Launch Supervisor

Vehicle launch from the surface is accomplished using the VBS depth controller in conjunction with the Autopilot. The finite state machine *Supervisor* seen in Figure 6 provides scheduling and coordination.

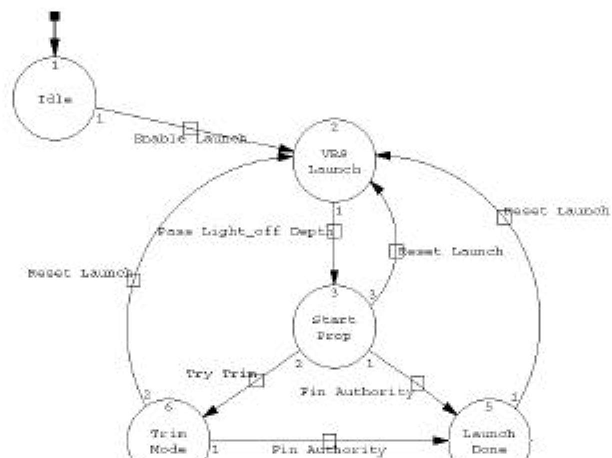

Figure 6: Vehicle Launch Supervisor

The following sequence of steps illustrates the Supervisor logic:

1. The Supervisor is initialized in the *Idle* mode where nothing happens.
2. An *Enable Launch* signal triggers a state transition to the *VBS Launch* state where the VBS is enabled in depth control mode with a commanded *launch depth.* The VBS depth controller starts to ingest ballast in order to sink the vehicle.
3. When the vehicle passes the mission specific *light-off depth*, the Supervisor transitions into the *Start Prop* state where

the autopilot is also enabled with the *launch depth* as a depth command and the mission specific launch speed command. No heading command is issued at this stage to the Autopilot so all fin authority may be used to achieve and maintain launch depth. The Supervisor allows the *launch depth* and *light-off depth* to be different.

4. The next state transition is dependant on the vehicle's forward speed. Once forward speed exceeds 1 m/sec a state transition to the *Trim Mode* state occurs. In this state, the VBS is taken out of depth control mode and placed into trim control mode. In-water test data shows that fin authority is achieved at forward speeds greater than or equal to 1.5 m/sec. If fin authority is achieved the Supervisor transitions into the *Launch Done* state where the VBS remains in trim control mode and the autopilot is enabled for all commands including heading commands. If, however, the vehicle is substantially out of trim, it is possible that the fin authority threshold forward speed of 1.5 m/sec is not achieved. In this case the Supervisor will remain in the *Trim Mode* state where the VBS will attempt to trim the vehicle until fin authority is achieved.

VBS Controller Performance

At the time of this writing, the *Seahorse* is undergoing sea trials off of the USNS Bruce Heezen and the IX-508 in the Gulf of Mexico. Several missions have been executed, the longest being about 6 hours. The data presented in this section is from some of these tests and illustrates the performance of the VBS controller.

Figure 7 demonstrates vehicle launch both in simulation and an in-water test. Here, the ability of the VBS depth controller along with the Autopilot and Supervisor to launch the *Seahorse* in shallow water is seen. This figure also validates the VBS model, the hydrodynamic model of the vehicle, and the propulsor model. The depth oscillation roughly between 70 seconds and 130 seconds is due to the following reasons:

- The VBS depth controller is still active and is in fact removing ballast to compensate for the excess ballast taken on to overcome surface capture.
- The vehicle is pre-ballasted to ensure a nose up attitude at launch. This causes the vehicle to head toward the surface when the propulsor is activated.

The "plateau" in the data between 130 seconds and 145 seconds is due to the fact that the vehicle has climbed very close to the surface and is feeling the effects of surface capture again. The simulation model does not capture this effect, but models the rest of the launch sequence adequately. The difference in vehicle depth at the surface is due to the fact that the model floats higher than the actual vehicle. After 145 seconds, the VBS depth controller takes the vehicle below the surface again and there is now enough forward speed, and consequently enough fin authority to allow the autopilot to hold depth and pitch angle near the commanded values. The commanded speed is 2.05 m/sec (4 Kts), but this is not achieved because the vehicle is out of trim (zero attitude is held by a positive elevator deflection.)

Other work [3] has presented VBS based vehicle launches that display better overshoot and no oscillations. This method however, is based on obtaining measurements of vertical velocity and estimating vertical acceleration, does not account for delays due to valve motion, and does not consider shallow water launches. The launch procedure used for the *Seahorse* is necessary to enable vehicle launch in shallow water of depth less than 8 m (25 feet), a design requirement. In deeper water, and without actuator delays, comparable results are obtained. A limit cycle, however, still exists due to the nature of the control problem. A modified depth controller currently under development uses an estimate of vertical acceleration in computing the control and shows much better depth control in simulation.

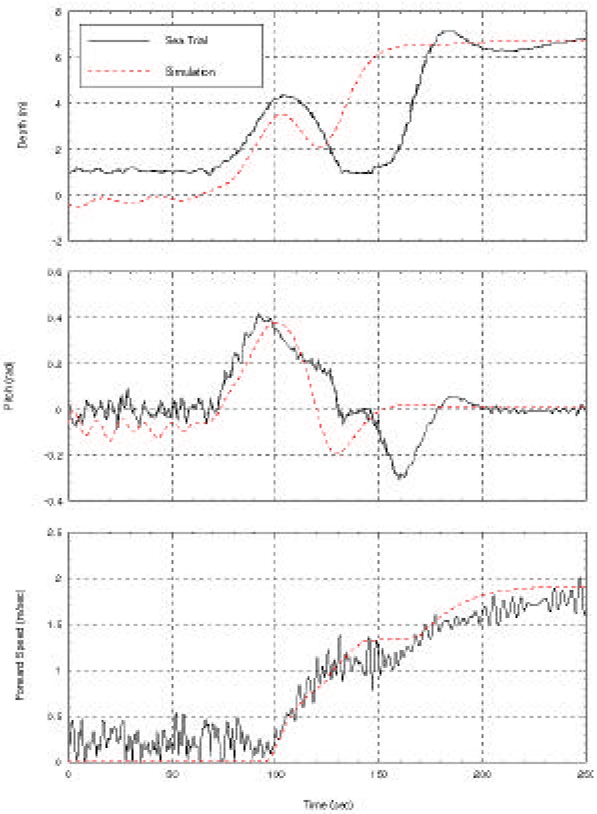

Figure 7: Vehicle Launch

Vehicle missions have been designed to conduct a *trim run*, level flight without any turns, for about 15 minutes before the start of the actual mission to ensure that the vehicle is trimmed for the duration of the mission. Although not currently implemented, it is proposed to maintain the trim information in the VBS controller so that if the vehicle is required to surface for a GPS fix using the VBS, the relative difference in water levels between the forward and aft tanks is memorized. When the vehicle dives after the GPS fix is obtained, the relative bias in the forward and aft VBS tanks is restored and fine-tuned by the VBS trim controller. Figure 8 illustrates VBS trim controller performance. This data is from a different sea trial of the *Seahorse* than the one shown in Figure 7. An averaging interval of 60 seconds is used here.

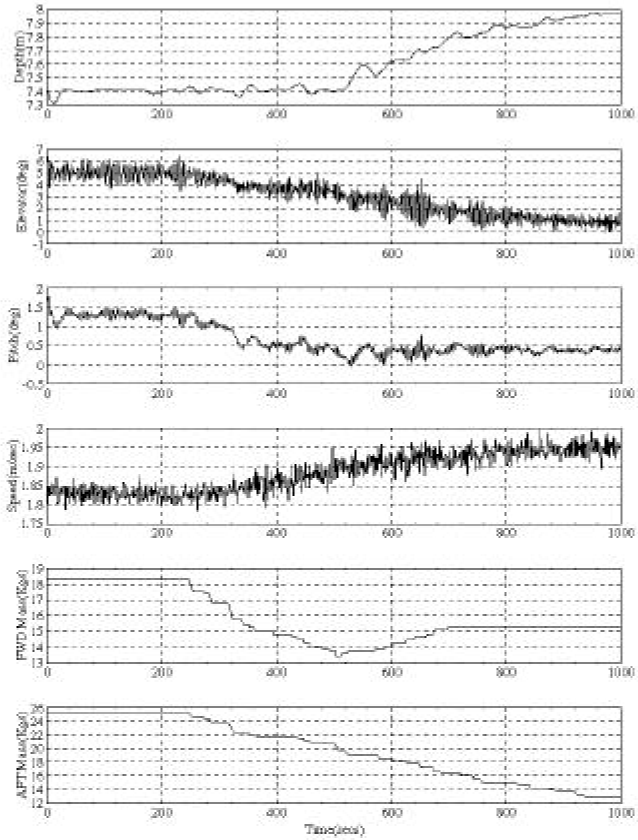

Figure 8: VBS Trim Control

At the beginning of the plot in Figure 8 the vehicle is substantially negatively buoyant and out of trim. Over the subsequent 15 minutes, the trim controller adjusts the water levels in both VBS tanks to leave the vehicle in a trimmed condition with both pitch angle and elevator deflection within the acceptable limits of one degree. At this stage, the vehicle is very slightly negatively buoyant. Besides lower energy consumption, the trimmed vehicle also achieves better depth control, frees up control authority for maneuvering, and more closely approaches the commanded speed (2.05 m/sec) as is also seen in Figure 8.

Figure 9 illustrates another commonly occurring scenario where the VBS trim controller contributes toward more efficient energy usage. This data is from yet another mission different from that used in Figure 7 and Figure 8. In this mission the vehicle is commanded to dive from a depth of ~7 m to a depth of ~9 m at a mission time of about 1200 seconds. This depth change seems to have taken the vehicle below an existing layer located at about 9m and into water that is colder by about 2^{o}C. This cooler, denser water causes the vehicle to be more buoyant and therefore go out of trim (note elevator and pitch angles.) The VBS trim controller detects this out of trim condition and takes on ballast, differently fore and aft, to bring the vehicle back into trim by a mission time of approximately 1600 seconds. This situation recurs, in reverse, at about a mission time of 7200 seconds when the vehicle is commanded to climb back to a depth of ~7 m.

Conclusions

This paper has presented a design for a variable buoyancy system and the associated controller for a large AUV. The VBS controller operating in depth mode is shown to be adequate to launch the AUV in shallow water in concert with the Autopilot and a launch Supervisor. The VBS trim controller is shown to dynamically maintain the AUV in trim under a variety of operating conditions freeing up control authority for maneuvering, increasing vehicle speed and enhancing depth control. All of these factors contribute greatly toward more efficient usage of limited power resources resulting in longer missions. This is of notable importance since a change in water temperature of just 2^{o}C is seen to have a dramatic effect on vehicle trim and by extension, efficiency. Current work is focused on a VBS depth controller that will enable the AUV to hover at zero forward speed. A design that works adequately in simulation has been arrived at and in-water tests are planned.

Acknowledgements

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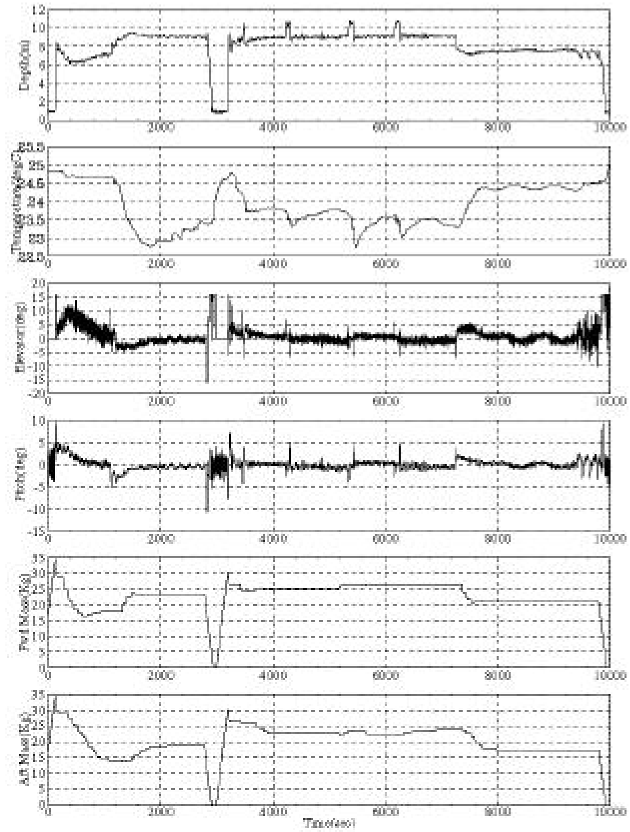

Figure 9: VBS compensation for temperature related buoyancy changes

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