Analysis and development of a buoyancy-pitch based depth control algorithm for a hybrid underwater glider

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***Abstract*—The hybrid glider augments a Slocum electric glider with a propeller based propulsion device enabling new modes of operation. One of the new modes available is constant depth flight. The glider has two mechanisms which lend themselves to a control scheme for depth control, a ballast system and an internal mass shifting mechanism for pitch control. This paper examines the use of a ballast depth controller and a pitch based depth controller. The detailed implementation of both controllers is described and experimental results are presented.**

I. Introduction

Over the last ten years autonomous underwater gliders have become increasingly commonplace in oceanographic research. The success of underwater gliders is to a large extent due to their ease of operation and their low operational cost, which is a result of their autonomy, range and endurance characteristics[1]. Gliders use an active buoyancy control system combined with a set of fixed wings to move vertically and horizontally, in a saw tooth like pattern through the water column [2], [3], [4]. The endurance of these underwater vehicles varies from weeks to several months and even longer in the case of the thermal glider [4]. In contrast, currently available propeller driven autonomous underwater vehicles (AUVs) achieve an endurance ranging from hours to days. This stark contrast can mostly be attributed to a purpose built system and to the low speed at which the gliders move [5] and [6]. Gliders typically move at horizontal speeds of about 0.3 m/s compared to propeller driven AUVs which typically move at average speeds greater than 1.0 m/s. The low speed capability can create significant problems when operating in areas of strong water currents which exceed the glider's maximum forward speed. If the direction of the currents is known a priori or measured in situ [7] the missions can be designed to either avoid these areas or to take advantage of them. In this case the operator must redirect the glider to better deal with the current by moving away from that region or, in the case of significant vertical stratification, try to operate below/above the expected layer of highest lateral velocities. However, in the case of unknown currents they can pose a significant risk to the successful execution of the mission plan. These issues have given rise to the idea of the hybrid glider which combines the gliding behaviours of traditional underwater gliders with the behaviours of propeller driven AUVs.

The hybrid gliders described in this paper refer to standard 200m *SLOCUM* gliders built by Teledyne Webb which have been augmented with an auxiliary, propeller based propulsion module [8]. Memorial University's propulsion system is integrated into the glider at the rear of the vehicle, replacing the 500 gram emergency drop weight as shown in Fig.1. Tests performed on Teledyne Webb Research's in-house glider have a dual drop weight and thruster configuration.

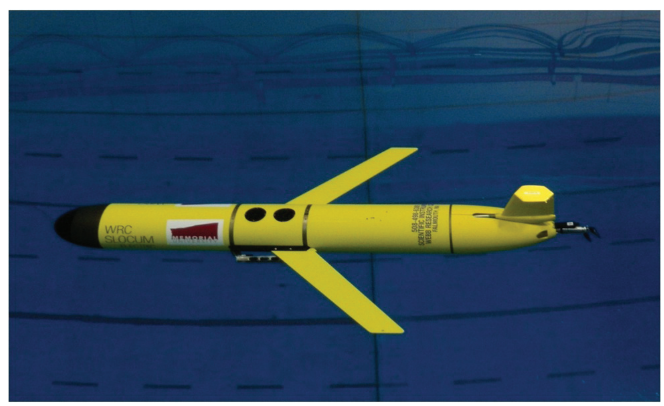

Fig. 1. Image of the Memorial University hybrid glider configuration.

The integration of the propeller based propulsion system allows for horizontal flight and higher flight speeds approaching 1m/s. Since level flight was not possible prior to this addition new controllers had to be developed to make use of this new capability. In terms of actuation the *SLOCUM* glider has a rudder for steering control, a buoyancy engine and an internal mass shifter, i.e. pitch battery, to control pitch and depth. During regular glider operations the internal mass shifter is used to change the axial location of the centre of gravity within the gliders reference frame and therefore the resulting pitch angle. The buoyancy engine, located in the nose cone of the glider not only changes the overall weight in water of the glider, enabling the glider to sink or rise, but also moves the relative axial location between centres of buoyancy and gravity, again resulting in a significant pitching moment.

In this paper two depth control schemes, one using buoyancy change and the other using internal mass shifting, are presented with experimental results. The ballast based depth control method was derived from a drift-at-depth behavior developed previously by the manufacturer augmented with a pitch controller to maintain zero pitch. The second control scheme is based on the internal mass shifting mechanism. By combining the forward velocity provided by the propeller-driven propulsion system with a controlled pitching angle of the vehicle the depth may be controlled. This controller is termed the pitching depth controller. The strengths and weaknesses of the ballast depth control method and the pitching depth controller are examined and experimental results are presented.

II. Ballast Depth Control

For the ballast depth controller the drift-at-depth behaviour was used as it includes a pitch controller and depth controller. Depth control is primarily achieved using the buoyancy control, and the internal mass shifting mechanism compensates any pitching moment created by the change in buoyancy to maintain level flight. For this approach, the primary contribution of the thruster is in the horizontal direction. While this results in a slower overall depth controller, this may allow the vehicle to make less frequent corrections in depth positioning.

The pitch controller runs on every control cycle, making adjustments to the pitch battery position to maintain zero-degree pitch. The ballast is only adjusted if certain requirements are met:

- the pitch error is within the specified deadband
- enough time has elapsed since the last buoyancy pump command

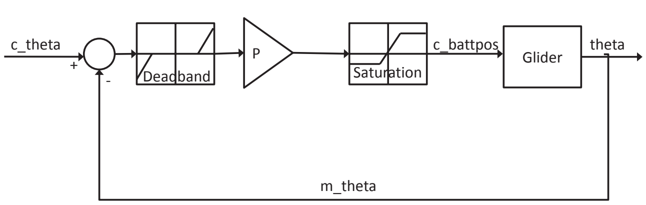

Fig. 2. Diagram of pitch controller

The pitch servo control consists of a proportional gain feedback controller with several control elements based upon system and actuator dynamics as shown in Fig. 2. Pitch angle m_θ is measured by the attitude sensor and compared to the desired pitch angle c_θ. A controller deadband on pitch error not only incorporates limits due to attitude sensor resolution, but also protects against excessive servoing. If pitch error $c\_\theta - m\_\theta$ is within the pitch error deadband $\theta\_deadband$, then no control action is taken, and the software sets a delay for the next control action calculation. This incremental delay serves as an energy conservation technique: if the current battery position is achieving good results, then do nothing. If the pitch error is outside of the deadband, then that error is multiplied by a proportional gain p and converted to the desired change in mass shifting mechanism position. There is a limit on the maximum change in position per control calculation cycle. This value is then sent to the motor driver. Within the motor driver are deadband and saturation limits on the mass shifting mechanism position.

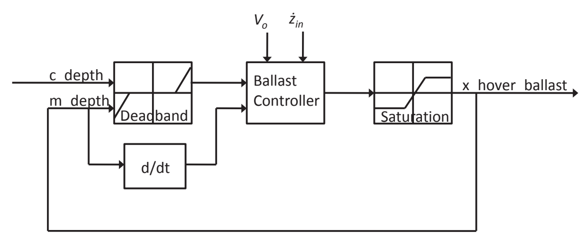

Fig. 3. Ballast depth controller structure

A diagram of the depth controller structure is shown in Fig. 6 where c_depth is the desired depth control point and $c\_deadband$ is the depth deadband for determining the hovering zone. The initial $x\_hover\_ballast$ value V_0 based upon previous tests was used. The controller steps $x\_hover\_ballast$ by the ballast pump delta value δ_{bp} depending on which state it determines the glider to be in. If the glider is outside of the hovering depth zone defined by c_depth and $c\_deadband$, the controller will decrement $x\_hover\_ballast$ if it is above the depth zone and moving up and will increment $x\_hover\_ballast$ if it is below the depth zone and moving down. If the vehicle is inside the depth zone there are two additional states in which the controller will change $x\_hover\_ballast$, moving down too quickly and moving up too quickly. The controller determines these states by comparing the measured depth rate $\dot{z}$ with the hovering depth rate $\dot{z}_h$ which is calculated using the user configurable input hovering depth rate gain $\dot{z}_{in}$ as in

$$\dot{z}_h = \dot{z}_f \dot{z}_{in} \quad (1)$$

where the factory set hovering depth rate $\dot{z}_f$ = 0.0475 m/s by default. If the glider is moving up and $|z|$ is greater than the $\dot{z}_h$, the glider is moving up too fast and $x\_hover\_ballast$ is incremented. Similarly, if the glider is moving down and $|z|$ is greater than the $\dot{z}_h$, the glider is moving down too fast and $x\_hover\_ballast$ is decremented.

Tests were performed to demonstrate the depth controller for various thruster inputs. For each test, the glider was commanded to dive to depth using the buoyancy pump only. Once the lower bound on the target hovering zone was reached, the glider transitions to horizontal flight mode. The thruster was commanded to turn on a specified number of seconds (60) after the transition to allow the controllers time to settle.

Figure 4 demonstrates the settling time for the pitch controller to transition from diving to horizontal flight. The pitch stabilises fairly quickly. However, there is a fair amount of overshoot of the depth target, as the horizontal flight controller is only activated once the glider reaches the beginning of the target hover zone (9m), and the vehicle dynamics are slow to respond to the reversal in commanded ballast. In addition, the depth controller takes a while to reach the target depth zone, due to the vehicle "pancaking" up as the pitch controller maintains a zero-pitch angle.

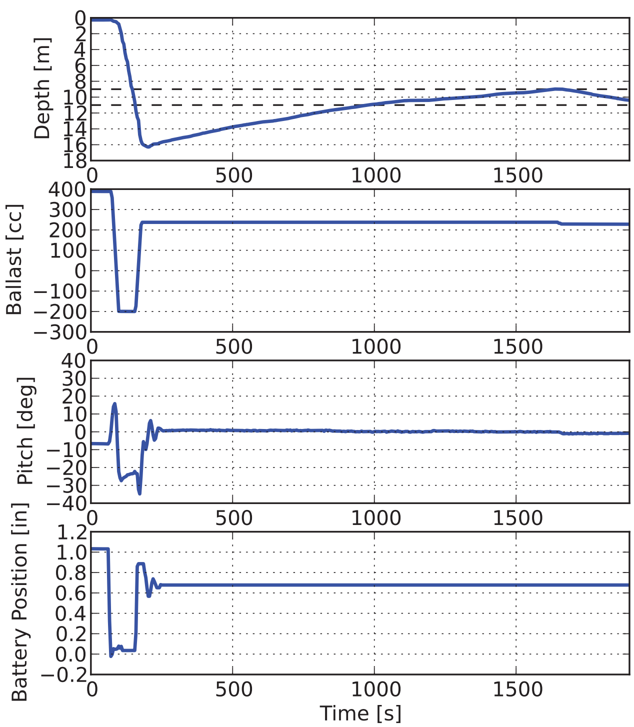

Fig. 4. Ballast depth control, depth and pitch controller performance to maintain depth within ±1 m for dive to horizontal flight transition. Vehicle has a forward speed of approximately 0.4m/s.

Fig. 5 shows the changes in buoyancy required to maintain a tight deadband around the commanded depth (±1 m). For this well-balanced glider, the resulting changes in pitch angle were within the specified pitch error deadband (±3 deg), such that no resulting pitch battery movements were required.

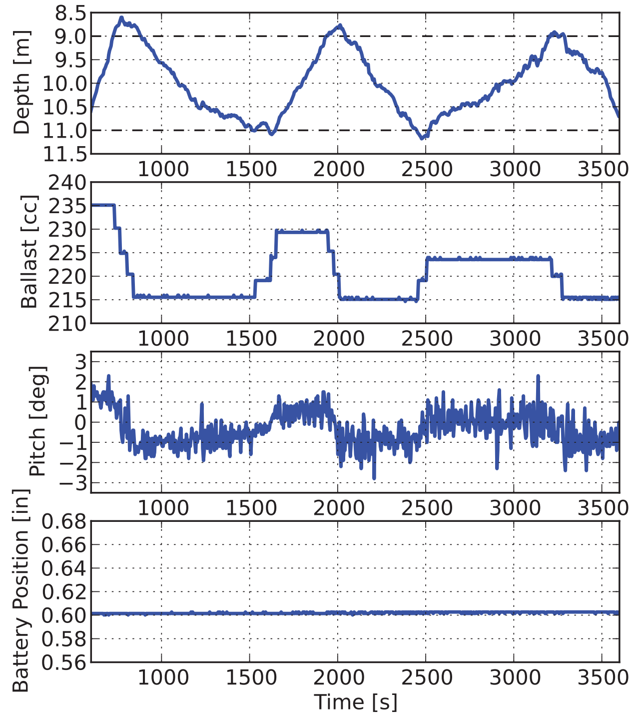

Fig. 5. Ballast depth control, depth and pitch controller performance to maintain depth within ±1 m, with ballast pump delta value δ_{bp} = 5 cc. Vehicle has a forward speed of approximately 0.4m/s.

Preliminary results suggest that the controller has the ability to maintain depth within an acceptable depth deadband. However, long term mission viability will depend on a control scheme that minimises actuator movements in order to save energy. Future tests will focus on the ability to maintain a tighter deadband on target depth (<1m), as well as tuning control parameters. Because the depth controller relies primarily on the change in vehicle buoyancy to create vertical position change, it is vital that the controller utilise the ballast pump as effectively as possible. A proportional-derivative controller on depth error for the ballast pump delta value δ_{bp} has been developed. This alternative approach may improve the settling time as well as the ability to maintain a tighter deadband on target depth.

III. Pitching Depth Control

The pitching depth controller uses the internal mass shifting mechanism to control the vehicle to fly at a constant depth. Several effects come into play to change the depth of the vehicle from a pitching motion. The glider is only subjected to lift forces when flying with an angle of attack. When the vehicle is ballasted to be neutrally buoyant the angle of attack during steady state maneuvers is zero. The lift force only acts to change the depth therefore during dynamic maneuvers before the vehicle reaches steady state. For small changes in depth or disturbance rejection the dominant depth change mechanism is expected to be from lifting forces. However, at steady state the dominant change in depth mechanism is expected to result from the vehicle driving forward at a non zero pitch angle.

To investigate the suitability of using the mass-shifting mechanism to control the depth a simple proportional-derivative controller is implemented. The input to the controller is the vehicle depth error and the depth rate. The output of the controller is limited and sent to the mass-shifting mechanism. The mass-shifting mechanism movement results in a change in pitch causing the vehicle to change depth when coupled with the forward velocity from the propeller based propulsion system. This arrangement is shown in Fig. 6.

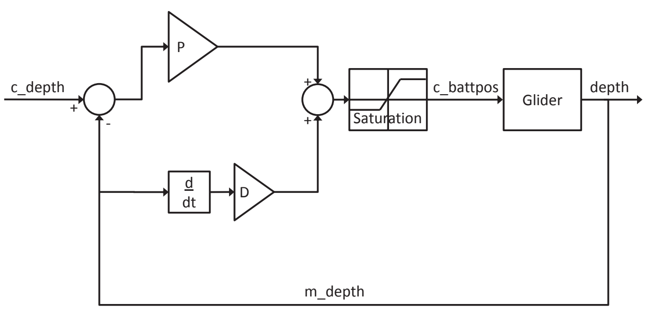

Fig. 6. Pitching depth controller structure

The pitching depth controller was tuned during field tests in Holyrood Bay, Newfoundland in July of 2012. All of the tuning tests were run with an estimated vehicle advance velocity of around 0.75 m/s. During the tuning process several factors regarding non-ideal trimming was found to affect the steady state depth error of the vehicle as shown in Fig. 7. To correct for this effect the mass shifter position at steady state during a mis-trimmed flight, around 0.25 inches, was used as the zero point for the controller. Additionally, the vehicle had difficulty diving from the surface when the propeller based propulsion system was in use. To overcome this difficulty the ballast was used to dive down to around 7.5m after which the ballast was set to neutral and the pitching depth controller used for the remainder of the flight.

To tune the gains of the controller a series of step response tests were run starting with a low proportional gain and zero derivative gain. The proportional gain was doubled until under-damped behaviour was visible. Using a proportional gain with an underdamped response a similar process was used to select the derivative gain, starting with a low value and doubling it in each test until the step response was visibly damped from the proportional gain only test. In this case the tuning objectives were to have minimum overshoot, reasonable disturbance rejection and zero steady state error. Several of the step response from this tuning process are shown in Fig. 8.

A close up of the tuned step response is shown in Fig. 9

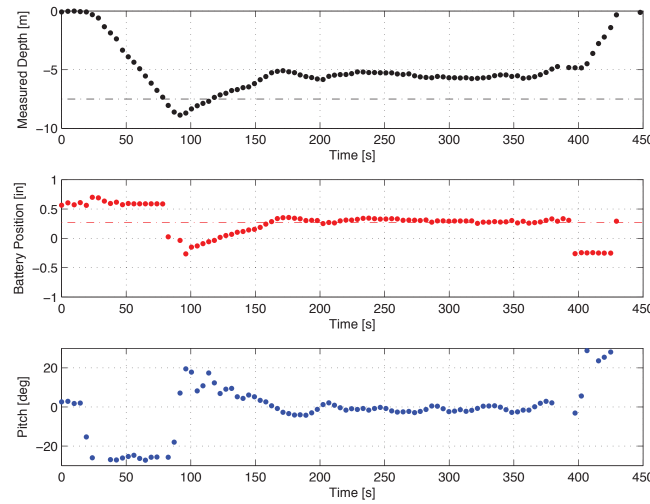

Fig. 7. Initial low proportional gain flight test for a commanded depth of 7.5m showing the steady state error due to the vehicle mis-trim

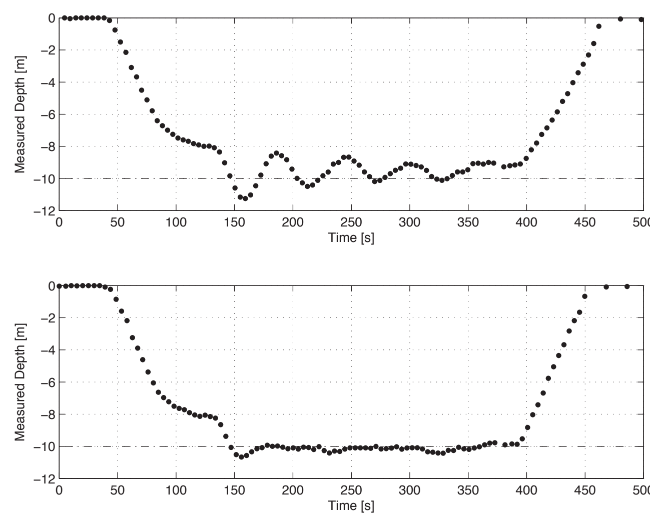

Fig. 8. Pitching depth controller tuning for a commanded depth of 10m. Top: Under-damped response with proportional only. Bottom: Tuned response with the same proportional gain and a moderate derivative gain

from which the overshoot is around 0.6m, the steady state error is minimal and the disturbance rejection is reasonable. The peak to peak error from the commanded depth after settling is 0.53m and the RMS value is 0.16m over 5 minutes.

The pitching depth controller shows a decent ability to control the glider at a constant depth while underway from the propeller based propulsion system. The PD controller used to examine the suitability of the pitching method suffers from sensitivity to the trim and ballast of the vehicle. Specifically a mis-trim was shown to result in a steady state depth error. It is expected that a mis-ballast will result in a steady state pitch error as the buoyant force will be counter-acted by the lift force of the vehicle, requiring an angle of attack. For level flight this requires the vehicle to maintain a pitch offset.

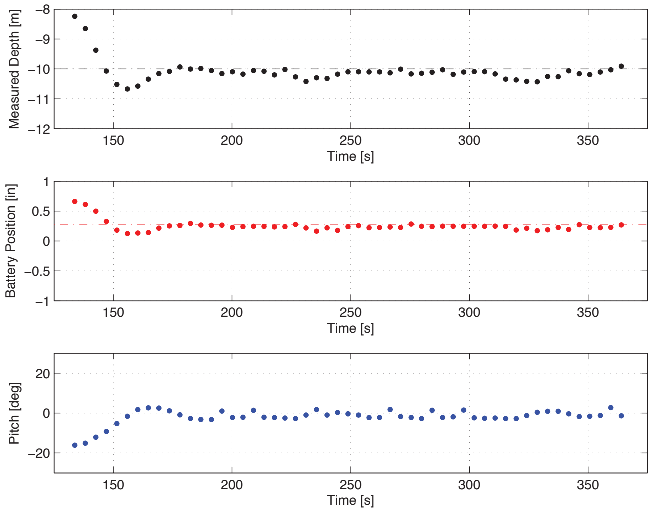

Fig. 9. Close up of the depth and battery position for the tuned step response where the commanded depth is 10m

Fig. 10. Hybrid glider setup for sensor calibration. Fluxgate magnetometers are installed on each of the wing-tips of the glider.

IV. Conclusion

In conclusion two different controller schemes for the *SLOCUM* hybrid electric glider have been examined. Both methods have shown their practically and achieved stable flight conditions in a desired depth band. Tradeoffs between the two schemes exist in terms of robustness with respect to mis-trim and/or non-neutral ballast conditions, response-time and energy consumption. Typically the response time for the ballast depth controller is of an order of magnitude larger than that of the pitch driven depth controller, making it less suitable for a trajectory controller. Similarly the energy consumption to perform the ballast based depth control is significantly higher than the pitch based depth control [8]. This is due to the fact that the buoyancy engine has to work against the pressure differential between ambient and internal pressure while the internal mass-shifter has only to overcome the friction of linear driving mechanism and a fraction of the pitch batteries weight. On the other hand the pitch based depth controller relies on accurate trim and ballasting conditions. It is close to impossible to exactly trim and ballast a glider due to measurement inaccuracies for the conditions encountered at sea, due to changes in temperature, salinity and pressure. The trim error will result in a steady state depth error from the desired depth while the ballast error will result into non-zero pitch angles from the pitch controller in order to compensate for the errors and maintain the desired depth. However, this non-zero pitch angle will come at the cost of increased drag and therefore reduced advance velocity, resulting in smaller range.

A combined controller that takes the advantages of each of the two controllers and brings them together into a single design would be highly desirable. A Linear Quadratic Regulator (LQR) would be a first candidate for such a controller design, providing an efficient way of scaling the controller gains based on energy based weighting matrices. As a natural extension of the depth controller an attitude controller is being currently developed using the onboard forward looking altimeter.

The first missions using the depth controlled flight capability will be to conduct repeated magnetic survey at constant depths. The magnetic data will be used to identify temporal and spatial fluctuations in the earth magnetic field around a test site. Magnetometers have been integrated in the wing-tips of the glider[9], see Fig. 10 and calibration of the installed sensors is underway.

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