Depth Control of an Autonomous Underwater Vehicle, STARFISH

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***Abstract*—We present a depth controller design for a torpedo-shaped autonomous underwater vehicle (AUV) known as STARFISH. It is common to design an AUV to be positively buoyant, so that it will float to the surface in case of power failure. However, most depth controllers are designed with a neutral buoyancy assumption by regarding the extra buoyancy as a disturbance. In this paper, we study the effect of buoyancy on both pitch and heave dynamics of an AUV, and propose a controller scheme that specifically compensates for the effect. We propose a simplified model for pitch dynamics that takes into account the buoyancy of the AUV. We identify the parameters of the model from field data from a closed loop depth maneuver. We adopt dual loop control methodology with inner pitch control loop and outer depth control loop. The inner pitch controller is designed using sliding mode control (SMC) with integrator effect to overcome a constant offset term due to positive buoyancy of the AUV. Then, a simple proportional controller is designed in the outer loop for depth control. Positive buoyancy of the vehicle will induce heave motion of the AUV. Thus, in order to maintain depth, the AUV need to be pitch down at certain angle. An adaptive feedforward controller is designed to compensate for this angle. The dual loop design with inner SMC and outer proportional control with feedforward loop was shown to be effective through experiments in both lake and sea.**

***Index Terms*—Autonomous Underwater Vehicle (AUV), Sliding Mode Control, Positive Buoyancy.**

I. Introduction

A. The STARFISH AUV

The Small Team of Autonomous Robotic "Fish" (STARFISH) project [1] at the ARL of the National University of Singapore (NUS) has developed modular low-cost AUVs that may be used in teams for collaborative missions. The STARFISH research program was started in 2006, and has conducted numerous successful lake and sea trails. The STARFISH AUV was designed to be modular at the mechanical, electronic and software level. The detail description of the hardware architecture can be found in [2]. The STARFISH AUV is a torpedo-shaped AUV with a diameter of 0.2m. The base AUV is 1.7m in length and comprises of a nose section, a command, control and communication section and a tail section. Typically, the AUV also carries a sensing payload or a navigation payload. Results presented in this paper are from an AUV with an advanced navigation payload that increases the total length to 2m. The AUV with the payload weighs 50kg in air. The AUV is trimmed to be positive buoyant by 0.6kg in order for it to float to surface in case of system failure and also to keep the WiFi, GPS, and GSM communication antennas above water surface during surface runs. The STARFISH AUV is controlled using two rudder fins and two elevator fins. All fins are designed using NACA 0012 axisymmetric profile with span of 0.115m $\times$ 0.15m that will generate 11N of lift at 5°angle of attack when cruising at 3knots. The fin angle is limited to $\pm 12°$to avoid stall.

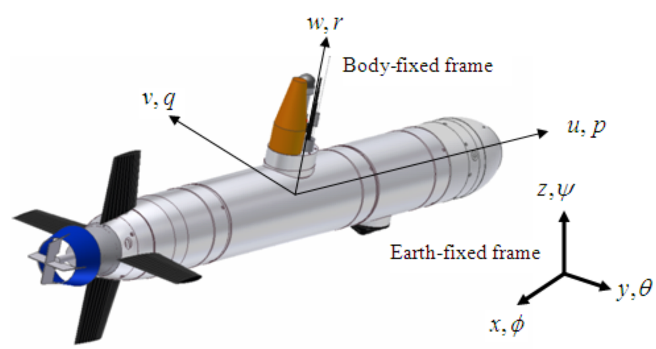

Fig. 1. Reference Frame of STARFISH AUV.

B. Control methodology

Generally, the motion of an AUV can be described using six degrees of freedom differential equations of motion [4]. These equations are developed using two coordinate frames shown in Fig. 1. Six velocity components $[u, v, w, p, q, r]$ (surge, sway, heave, roll, pitch, yaw) are defined in body-fixed frame, while the earth-fixed frame defines the corresponding positions and attitudes $[x, y, z, \phi, \theta, \psi]$.

Due to hydrodynamics forces, these equations are highly nonlinear and coupled, are therefore impractical for use in controller design. In practice, the system is commonly decomposed into three non-interacting subsystem – the speed subsystem, the steering subsystem and the diving subsystem [5], [6], [7]. This paper only focuses on the diving subsystem of the STARFISH AUV.

We adopt dual loop control methodology [8] with an inner pitch control loop and an outer depth control loop. In the dual loop design, the depth controller generates a desired pitch angle which becomes the input to the pitch controller. The pitch controller then decides the elevator deflection δ_s, based on the desired pitch angle. This idea is illustrated in Fig. 2. The inner pitch controller is designed using sliding mode control (SMC) methodology [9] and discussed in section IV. In section V, we discuss an adaptive feedforward control loop which is designed to compensate for pitch angle during a constant depth maneuver. The feedforward loop simplifies the heave dynamics and allows proportional controller to be designed for outer depth control loop.

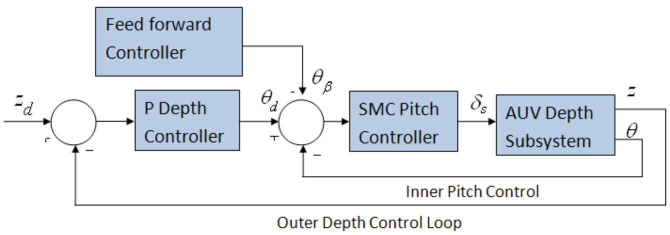

Fig. 2. Dual loop control for depth subsystem.

II. Depth Subsystem Modeling

The notation used in this paper is in accordance with SNAME [10]. Restricting our discussion to the diving plane (x-z plane), the equation of motion for heave and pitch are:

$$m(\dot{w} - u_0 q) = Z \quad (1)$$

$$I_y \dot{q} = M \quad (2)$$

The heave external force Z and pitch moments M consist of hydrodynamics added mass, linear damping, cross flow drag, munk moment and effect of elevator plane deflection. In addition, there is righting moment in pitch due to the vertical distance between center of mass and center of buoyancy $BG_z = z_G - z_B$. There is also excessive positive buoyancy of the vehicle $\Delta B = B - mg$ that acts in z-axis.

$$Z = Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} + Z_w w + Z_q q + Z_\delta \delta_s + \Delta B \quad (3)$$

$$\begin{aligned} M &= M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} + M_w w + M_q q \\ &\quad - mg(z_G - z_B)\sin\theta + M_\delta \delta_s \\ &\simeq M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} + M_w w + M_q q \\ &\quad - mgBG_z\theta + M_\delta \delta_s \end{aligned} \quad (4)$$

From kinematics analysis in x-z plane with assumption of small pitch angle,

$$\dot{\theta} = q \quad (5)$$

$$\dot{z} = -\theta u_0 + w \quad (6)$$

Substituting (3) and (4) into (1) and (2) respectively and combining with (5) and (6), we can write the following state space representation using state variable $w(t)$, $q(t)$, $\theta(t)$, and $z(t)$:

$$\begin{bmatrix} \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 \\ c_{21} & c_{22} & c_{23} & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & -u_0 & 0 \end{bmatrix} \begin{bmatrix} w \\ q \\ \theta \\ z \end{bmatrix} + \begin{bmatrix} d_1 \\ d_2 \\ 0 \\ 0 \end{bmatrix} \delta_s + \begin{bmatrix} e_1 \\ e_2 \\ 0 \\ 0 \end{bmatrix} \Delta B \quad (7)$$

By assuming that the value of $c_{21}w$ to be constant as heave velocity does not fluctuate significantly during a run, the linear model in (7) reduces to:

$$\begin{bmatrix} \dot{q} \\ \dot{\theta} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} c_{22} & c_{23} & 0 \\ 1 & 0 & 0 \\ 0 & -u_0 & 0 \end{bmatrix} \begin{bmatrix} q \\ \theta \\ z \end{bmatrix} + \begin{bmatrix} d_2 \\ 0 \\ 0 \end{bmatrix} \delta_s + \begin{bmatrix} c_{21}w + e_2\Delta B \\ 0 \\ 0 \end{bmatrix} \quad (8)$$

Thus, the pitch dynamics is

$$\dot{\theta} = q \quad (9)$$

$$\dot{q} = c_{22}q + c_{23}\theta + d_2\delta_s + C_b \quad (10)$$

$$C_b = c_{21}w + e_2\Delta B \quad (11)$$

The above derivation of the depth subsystem model follows the derivation in [11] closely but takes into the consideration that the AUV is positive buoyant. From experimental measurements, the resulting heave velocity is around 0.13m/s and therefore not negligible. In [11], the heave velocity is small (less than 0.05m/s). The heave velocity introduces cross flow drag and munk moment which result in an offset term C_b that needs to be compensated by the pitch controller.

III. System Identification

There are two objectives of identification. Firstly, we need to find the values of the four unknowns: c_{22}, c_{23}, d_2, C_b in (10). These unknowns are needed when designing the pitch controller. The second purpose is to validate the proposed pitch model and show its superiority over the model without the offset term C_b.

Identification was done by recording the elevator input angles and the AUV's pitch response during a closed-loop depth maneuver. The AUV is commanded to rapidly change the depth set-point in order to excite a large range of the pitch dynamics. However, the AUV has to maintain constant heading, constant speed and small roll angle during the maneuver. One such data set is shown in Fig. 3. The figure shows that the AUV had a surge velocity of 1.3m/s and a heave velocity of 0.13m/s, both measured by the Doppler Velocity Log (DVL). The depth changed between 1m and 3m. At the same time, the AUV pitched up and down between -0.05rad and 0.2rad in response to changing elevator plane angle. The elevator was operated at the maximum deflection of 0.23rad for most of the time.

Simulated pitch responses are obtained by feeding in the elevator angle data to (10). The initial state conditions of the model were matched to the filed data. Then, the four unknowns are identified by minimizing the difference between simulated response and the field response. This process can be carried out several times for different set of recorded data to obtain an average result.

Referring to Fig. 4, both 2nd order models (with or without the offset term) are able to capture general trend of experiment pitch response for about 125 seconds of total 1250 recorded pitch data (data is recorded at 10Hz). The model with the offset term fits relatively better as compared with the one without that term. The sum square errors are reduced from 3.96 to 2.27 as shown in Table I. The existence of an offset term is consistent with the expectation that the fins need to turn to a certain angle to maintain a pitch angle during constant depth run.

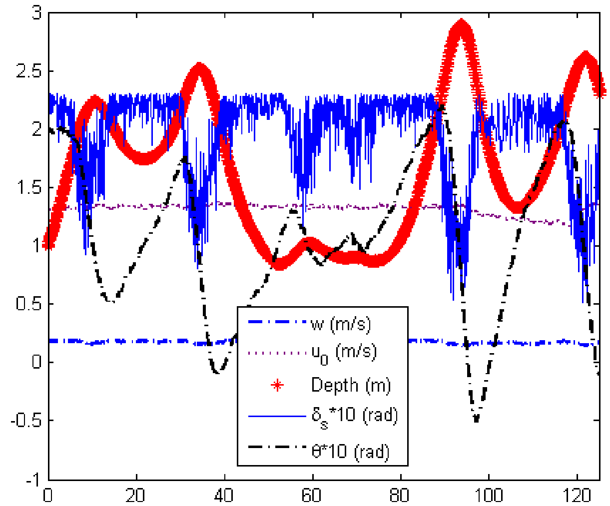

Fig. 3. Elevator angle and pitch response for identification.

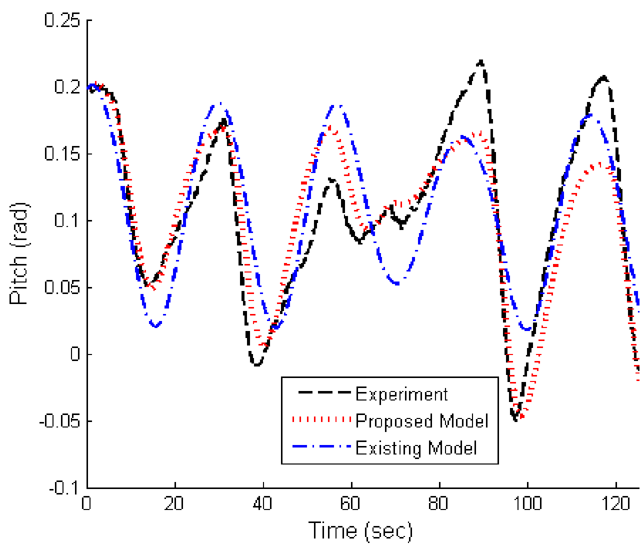

Fig. 4. Comparison of experiment pitch response and simulated pitch response for two different models.

IV. SMC Pitch Controller

From the previous section, four unknowns in (10) have been identified using experiment data. Although the model provides a reasonably good fit to the data, the pitch dynamics of AUV will change when different payloads are installed on the AUV.

TABLE I
Sum Square Error for different models

Model	Sum Square Error (rad^2)
$\frac{\theta(s)}{\delta_s(s)} = \frac{K_\theta}{s^2+2\zeta_\theta w_\theta + w_\theta^2}$	3.96
$\frac{\theta(s)}{\delta_s(s) - C_b/K_\theta} = \frac{K_\theta}{s^2+2\zeta_\theta w_\theta + w_\theta^2}$	2.27

SMC as a form of variable structure control has been applied successfully by many researchers in AUV community [6], [7], [8]. Compared to classical control, SMC design has proven to be effective in handling the nonlinear AUV dynamics with uncertain models operating in unknown environments with strong wave and ocean current disturbances. One of the early works using SMC in underwater vehicles has been reported in [12], [13]. Through computer simulation, the authors show that SMC design produces extremely robust controllers in controlling EAVE, a remotely operated underwater vehicle (ROV). Similarly, in [14], the authors proposed a multivariable sliding mode control of their ROV which demonstrated robustness against parametric uncertainty. The application of SMC in AUVs with more streamlined hydrodynamics characteristic as compared to ROVs is reported in [8] with their MUST vehicle. In [6] and [7], the authors presented an adaptive multivariable sliding mode control based on state feedback with decoupled design for speed, steering and diving of an AUV. The controller design was successfully implemented on NPS ARIES AUV as reported in [15].

In this paper, we design an integrator sliding mode controller with specific consideration to eliminate the constant offset term that appears due to the positive buoyancy of the AUV. Let us define the state

$$\begin{aligned} x_1 &= \theta - \theta_r \\ x_2 &= q \end{aligned} \tag{12}$$

By substituting (12) in (10), we get:

$$\begin{aligned} \dot{x_1} &= x_2 \\ \dot{x_2} &= c_{22}x_2 + c_{23}\theta + d_2\delta_s + C_b \end{aligned} \tag{13}$$

We design elevator deflection as

$$\delta_s = -\frac{1}{d_2}(c_{22}x_2 + c_{23}\theta - \hat{\delta}_{SMC}) \tag{14}$$

This reduces the state equation (13) to:

$$\begin{aligned} \dot{x_1} &= x_2 \\ \dot{x_2} &= \hat{\delta}_{SMC} + C_b \end{aligned} \tag{15}$$

To eliminate the offset term C_b, we define $\hat{\delta}_{SMC} = \int \delta_{SMC} \mathrm{d}\tau$ and the state becomes:

$$\begin{aligned} \dot{x_1} &= x_2 \\ \dot{x_2} &= \int \delta_{SMC} \mathrm{d}\tau + C_b \end{aligned} \tag{16}$$

To eliminate the integral term, we define $x_3 = \dot{x_2}$. By differentiating (16), we get:

$$\begin{aligned} \dot{x_1} &= x_2 \\ \dot{x_2} &= x_3 \\ \dot{x_3} &= \delta_{SMC} \end{aligned} \tag{17}$$

We define a sliding surface

$$s = x_3 + \lambda_2 x_2 + \lambda_1 x_1 \tag{18}$$

and $s = 0$ is the sliding surface. The control parameters λ_1, λ_2 have to be chosen such that the characteristic equation is stable. To ensure the reachability condition, we define the Lyapunov function as:

$$v = \frac{1}{2}s^2 \tag{19}$$

The reachability condition can be ensured by:

$$\dot{v} < 0 \Rightarrow \text{sign}(s) = -\text{sign}(\dot{s}) \tag{20}$$

$$\dot{s} = \delta_{SMC} + \lambda_2 \dot{x_2} + \lambda_1 \dot{x_1} \tag{21}$$

Then, the control law can be chosen as:

$$\delta_{SMC} = -(\lambda_2 \dot{x_2} + \lambda_1 \dot{x_1}) - K\text{sign}(s) \tag{22}$$

To avoid chattering effect due to discrete implementation, we have following modification:

$$K\text{sign}(s) = K_s \dot{s} + \epsilon \text{sign}(s) \tag{23}$$

Hence, the overall control law becomes:

$$\delta_S = -\frac{1}{d_2}\left[c_{22}q + c_{23}\theta + K_s s + \int_0^t \lambda_2 \dot{q} + \lambda_1 q + \epsilon \text{sign}(s) \mathrm{d}\tau\right] \tag{24}$$

V. Proportional Depth Controller with an Adaptive Feedforward Controller

We can rewrite (6) as

$$\dot{z} = -u_0(\theta - \frac{w}{u_0}) \tag{25}$$

Let $\beta = \frac{w}{u_0}$ and β is the pitch angle that AUV need to pitch down during constant depth motion. By designing the pitch set point to have two components, $\theta_{sp} = \theta_d + \theta_\beta$ where θ_d is the desired pitch angle generated by the proportional depth controller, and θ_β is the feedforward pitch angle to compensate for β, we have:

$$\dot{z} = -u_0(\theta_d + \theta_\beta - \beta) \tag{26}$$

If $\theta_\beta \simeq \beta$, then:

$$\dot{z} = -u_0 \theta_d \tag{27}$$

From the proportional depth controller:

$$\theta_d = k_p(z_d - z) = k_p e_{depth} \tag{28}$$

During steady state:

$$\dot{z} = 0 \Rightarrow -u_0(\theta_d + e_\beta) = 0 \tag{29}$$

Let $e_\beta = \theta_\beta - \beta$:

$$\begin{aligned} k_p e_{depth} + e_\beta &= 0 \\ e_{depth} &= -\frac{e_\beta}{k_p} \end{aligned} \tag{30}$$

Let define a normalizing term

$$k_{bb} = \frac{\theta_\beta}{\hat{\theta_\beta}} \tag{31}$$

where $\hat{\theta_\beta} = 5°$ is the typical pitch down angle for STARFISH AUV. However, the exact value changes according to the payload configuration and trimming of the buoyancy. The operating speed also changes to meet mission requirements. So an adaptive algorithm as shown in Fig. 6 has been developed to tune k_{bb} before mission start.

The steady state error is related to θ_β using (30). In other words, we can estimate θ_β from the steady state error during a constant depth run. Thus, we only tune k_{bb} during the steady state. The steady state is characterized by:

1) The different between set point of pitch and pitch angle response is small.
2) The rate of change of pitch is small.

During the steady state, we sum up the e_{depth} for 50 steps (2.5s), then adjust k_{bb} toward the direction that eliminate the steady state error. Fig. 5 shows an experimental result when tuning was turned on for a depth set-point of 1.5m. The k_{bb} was start at 0.6 and was tuned only during steady state (at time 7800s). It converged to 0.9 while the steady state error was reduced during the process. The tuning algorithm was turned off after the steady state error reached a reasonably small value, in this case when it was less than 0.1m.

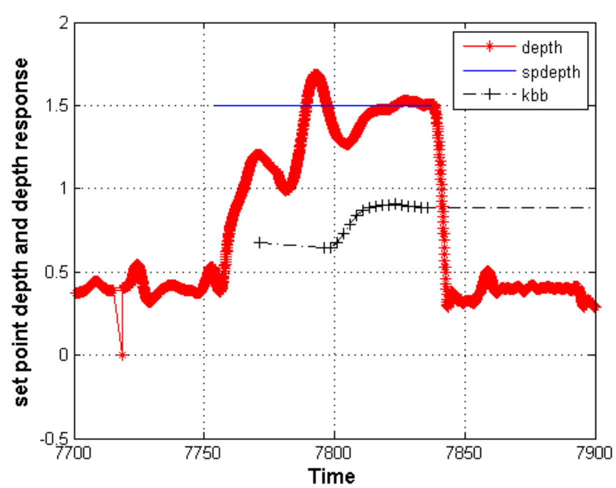

Fig. 5. Experiment result of tuning of kbb

The steady state error could also be reduced by implementing an PI (Proportional + Integrator) depth controller. However, the feedforward method provides few advantages over the integrator. First, the feedforward method does not suffer from the windup problem of the integrator. Second, since we know the AUV should pitch down in order to dive, feeding that value forward in advance gets us a faster response in pitch. When tuning is on, it induces an oscillatory response to depth as k_{bb} value oscillates due to sensor noise. So, we stop the tuning once the average depth error is below a certain threshold. The k_{bb} was tuned during an initial trial run and the tuning was turned off after that. So, the depth response does not suffer oscillatory motion due to integrator effect and the system is more stable.

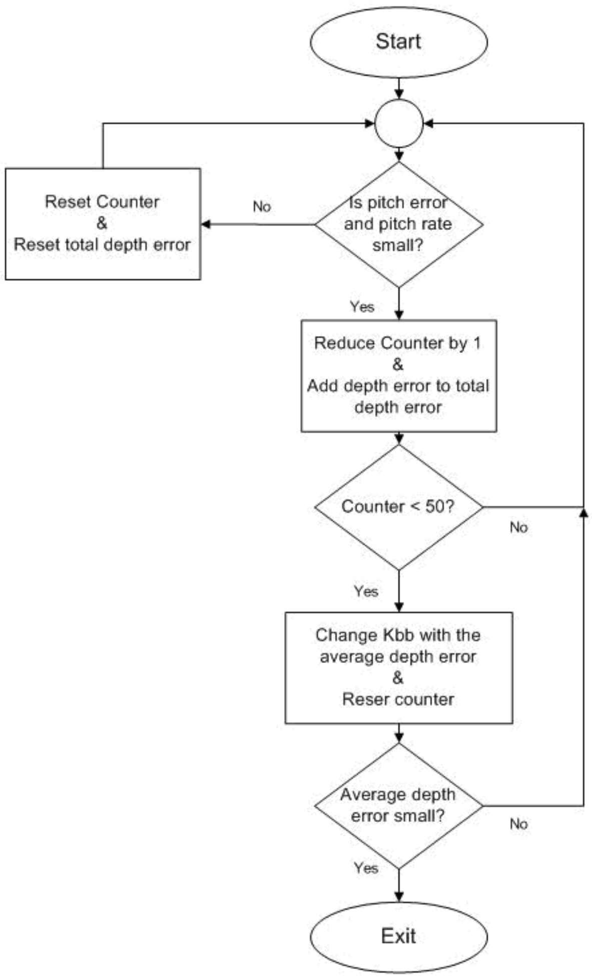

Fig. 6. Adaptive feedforward tuning algorithm

VI. Results

Fig. 7 shows a typical depth response of the STARFISH AUV during a lawn mower mission with depth set point of 2m. The steady state depth error is bound within 0.15m. From the yaw response and x-y position plot in Fig. 8, one can see the AUV makes a numbers of 180°turns during the 600s mission. The plot of pitch response clearly shows that the AUV was pitch down at around 5°in order to maintain the depth at 2m. This observation also corresponds to the fact that the elevator deflection was not zero during the constant depth run.

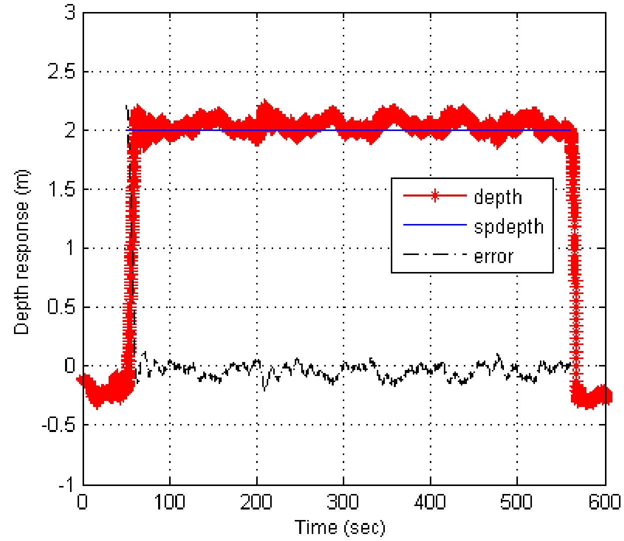

Fig. 7. Depth response during a lawn mower mission

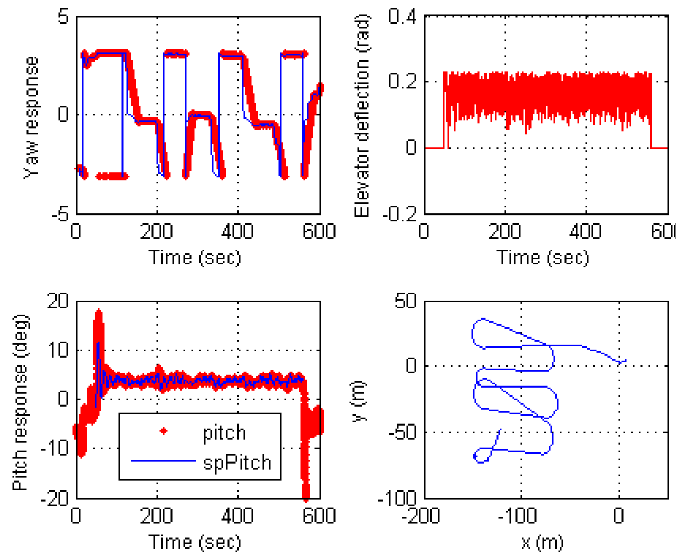

Fig. 8. Yaw, pitch, elevator deflection and x-y position for the lawn mower mission

VII. Conclusion

A dual-loop depth controller design with inner SMC pitch controller and outer proportional controller had been designed and implemented in STARFISH AUV. The effect of positive buoyancy on both pitch and heave dynamics is discussed and handled directly by the proposed controller scheme. Experimental results show that the controller is effective in controlling the depth of the AUV with negligible steady state error.

Acknowledgment

The authors would like to thank the STARFISH project team members, especially Koay T. B. and Tan Yew Teck for their support and involvement in field trials and experiments.

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