Modeling and Identification of An Underwater Glider

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***Abstract*— Underwater gliders are type of autonomous underwater vehicle that glide by controlling their buoyancy and attitude using internal actuators. By changing the vehicle's buoyancy intermittently, vertical motion can be achieved. Characteristic of glider motions include upward and downward in a saw tooth pattern, turning and gliding in a vertical spiral motion glides without using thrusters or propellers. This paper presents the modeling and identification of underwater glider system. Ballast tank subsystem is considered for the identification process since it is the main propulsion of the operated system. By selecting the ballast rate as the input, the net buoyancy is observed as the output signals. The MATLAB System Identification Toolbox is used to obtain a mathematical model of the glider ballast-buoyancy and ballast-depth conditioning system. The best three parametric models that able to estimate the system correctly are chosen and the fit between measured and estimated output are presented. The knowledge and information obtained from modeling and identification approaches will be used to design the future control design of the USM Underwater Glider Prototype, in which, is currently under development at Underwater Robotic Research Group, Universiti Sains Malaysia.**

I. Introduction

An underwater glider glides by controlling their buoyancy using internal tanks and pumps. Existing gliders have fixed external wings and tails, and control their attitude by moving internal masses and using external control surfaces such as rudder [1]. Gliders travel from place to place by concatenating a series of upward and downward glides. Gliding flight is buoyancy driven, and does not use thrusters system. Thus, glider must change depth to glide. They glide downwards and upwards in the ocean by controlling their buoyancy to make themselves negatively and positively buoyant. Gliders may also hold their position by gliding against current. This will make them neutrally buoyant and drift with the current or rest on the bottom. Through their use of buoyancy propulsion system and low power design, gliders are capable of long-range and high-endurance deployments. With careful design, buoyancy-driven gliders are quiet and use little power [2,3,4,5,6,7] .

Underwater gliders can be utilized in remote sensing for physical, chemical and biological oceanography. Other possible applications include used as communications gateways or navigation aids and military application such as tactical oceanography and maritime reconnaissance. Attractive glider characteristic include autonomous operation, high endurance and range, and low cost. Gliders are well suited to extended missions such as collecting sensor data while move along a chosen path or maintaining position. Gliders can operate autonomously individually or in a group and may adaptively adjust their missions according to remote instruction or according sensor information [8].

The development of underwater glider especially to derive a model directly from physical law can be too complicated for engineers due to time constraint in achieving goal for prototyping development process. Therefore, other alternative that is easier, time save and less complicated should be considered. Based on Leonard and Graver [2,3], the equation of motion for underwater glider are derived from the beginning that includes major design elements of underwater gliders, including buoyancy control, wings and external control surfaces and nonlinear coupling between the glider and internal mass actuators. From this development, system identification approach is used to obtain the underwater glider system model. System identification is a well known method of estimating the model characteristics based on experimentation data [9]. This data can be manipulated in order to construct the parameters of the system or the model itself. The assessment of the model quality is typically based on how the models perform when they attempt to reproduce the measured data. Either modelling or system identification, there are two goals that need to be achieved at the end of the procedures.

1) The fit between frequency/impulse responses of the identified model should be close to the measured frequency/impulse response of the system.

2) The poles/zeros can be explained physically.

The information obtained from these procedures will provide with a more transparent overview into the glider system dynamics and properties, in which, will become a useful guides and knowledge for later controller design. As for the underwater glider control system, the control design development are based on the ballast subsystem that's give the forward movement to the vehicle and act as an input of the control system. Since the ballast subsystem is the buoyancy engine that gives the bigger influence of the whole vehicle dynamics performance, so it is suitable to be chosen as the input signal. The output of the system is the net buoyancy or the total mass change of the total vehicle during gliding. Due to this effect the vehicle dynamics can be observed such as the gliding angle, depth, velocity components, the rate of pitching angle and movable mass location. The main purpose of this paper is to investigate and estimate the performance of the ballast subsystem to the vehicle dynamics and this estimated model will be used for the control design of the underwater glider.

In summary, this paper goes as follows. Section 2 discusses on modeling of underwater glider platform. The design criteria and consideration are inclusive of mass distribution, motion in vertical plane and the vehicle specifications for development. The equation of motion of the glider system in vertical plane will be derived and some of the simulations of motion are presented. In Section 3, the system identification for ballast subsystem is considered. Using the ballast rate as the input and net buoyancy as the output variables that represent the system dynamic are observed. The discussion based on the investigation and observation on modeling and identification of the underwater glider system is performed in Section 4. Some design issues and limitations will be addressed. Finally, Section 5 concludes the paper.

II. MODELING OF UNDERWATER GLIDER

The kinematics of the vehicle can be explained based on the Fig. 1 [10]. Consider an inertial frame ***i***, ***j*** and ***k***. Let ***i*** and ***j*** inertial axes lie in the horizontal perpendicular to gravity. The ***k*** axis lies in the direction of the gravity vector and is positive downwards. The inertial value for ***k***=0 coincides with the water surface, in which case ***k*** is depth.

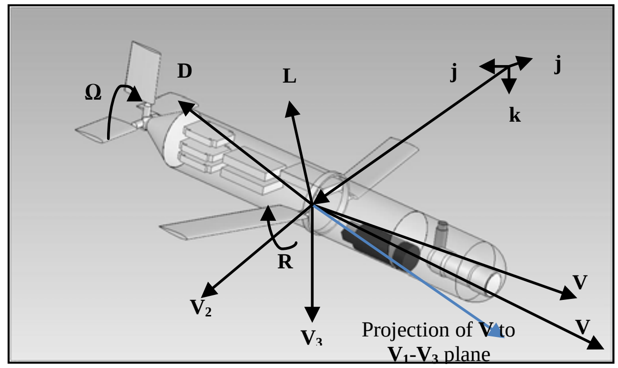

Figure1. Glider Dynamics.

Based on Fig. 1, the center of the origin of the vehicle is the center of buoyancy (CB) and the angle of attack, α is the angle between the components $\mathbf{V_1}$ and projection of **V** (speed in vertical plane) to $\mathbf{V_1}$-$\mathbf{V_3}$ plane while $\mathbf{V_2}$ is the lateral speed component. The sideslip angle β is defined as the angle from projection of **V** to $\mathbf{V_1}$-$\mathbf{V_3}$ plane and **V**. In the standard of aircraft literature [11], the orientation of the wind frame relative to the body frame will be described by two dynamic angle; the angle of attack, α and side slip angle, β. The wind reference frame is defined such as that one axis aligned with the velocity of the body relative to the **V**.

$$\alpha = \tan^{-1}(\mathbf{V_3}/\mathbf{V_1}) \quad \text{and} \quad \beta = \tan^{-1}(\mathbf{V_2}/|\mathbf{V}|) \qquad (1)$$

The orientation of the vehicle is given by the rotation matrix **R** which maps vectors expressed with respect to the body frame into internal body coordinates. Yaw ψ, pitch θ, and roll φ are the three rotation angles from inertial body frame. Yaw ψ is defined as positive right (clockwise) when viewed above, pitch θ is positive nose-up and roll φ is positive right wing down. The position of the vehicle, $\mathbf{b} = (x,y,z)^T$, is the vector from the origin of the vehicle's body. The vehicle moves with translational velocity $\mathbf{V} = (\mathbf{V_1}, \mathbf{V_2}, \mathbf{V_3})^T$ relative with angular velocity $\mathbf{\Omega} = (\Omega_1, \Omega_2, \Omega_3)^T$ as in the Fig. 1.

A. Mass Distribution

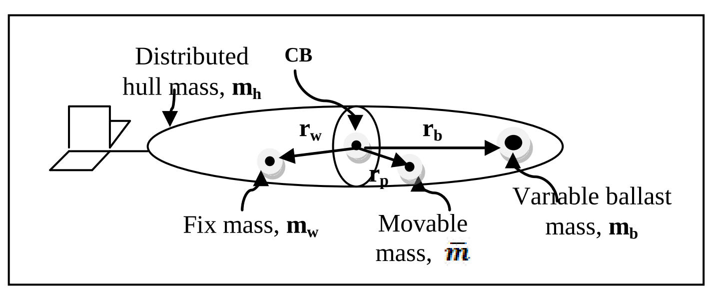

Figure 2: Glider Mass Definitions

Based on the Figure above, the vehicle has buoyancy control and controlled internal moving mass and will manipulate the CB to change the glide angle and speed. The total mass of the vehicle or body mass can be defined by $m_v = m_h + m_w + m_b + \bar{m}$. Point mass m_w and variable ballast mass are given by the vector r_w and r_b from the CB to the respective masses. The vector r_p describes the position of the moving mass $\bar{m}$ in the body fixed frame at time *t*. The static mass parameters mw and r_w can be rearranged to set the balance the pitching and rolling moment on the vehicle from the other point masses. The mass of the fluid displaced by the vehicle is donated by *m*. We define the net buoyancy $m_o = m_v - m$ so that the vehicle is negatively (positive) buoyant if m_o is positive (negative).

B. Motion in the Vertical Plane

The restriction to the vertical plane ignores certain associated dynamics. Experiments using Slocum glider show that the vertical plane steady glides are qualitatively consistent with the result of the model [3,10]. In dynamic equation the vertical plane can be classified by invariant plane. In aircraft dynamic analysis some restriction of longitudinal plane are commonly used. Most of glider design used the separate control algorithm and actuators in controlling the lateral dynamics and vertical plane dynamics. In this paper, the vertical plane dynamics is controlled using movable mass and variable ballast mass in vertical plane dynamics without concerning the lateral dynamics because this dynamics are stabilized using the fix back rudder to glide in a straight motion in a vertical plane. It can be concluded the all the lateral component such as $\mathbf{V_2}$ are equal to zero except for the pitching component $\mathbf{\Omega_2}$. In these reasons, the study for the vertical plane dynamics and representative of actual glider operation are useful.

C. Equation of Motion in the Vertical Plane

Some restriction has to be made to simplify the mass distribution on the vehicle in order to ease the analysis process [2]. The fix mass m_w is eliminated by setting to zero and fix the ballast mass at the center of the vehicle body. The value, $r_b = 0$ to eliminate the inertial coupling due to the offset static point mass m_w and the coupling between the ballast state and the vehicle inertia pitch moment. The model to the vertical plane can be simplified as:

$$R = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix},\quad b = \begin{pmatrix} x \\ 0 \\ z \end{pmatrix},\quad \mathbf{v} = \begin{pmatrix} v_1 \\ 0 \\ v_3 \end{pmatrix},\quad \Omega = \begin{pmatrix} 0 \\ \Omega_2 \\ 0 \end{pmatrix},\quad r_p = \begin{pmatrix} r_{p1} \\ 0 \\ r_{p3} \end{pmatrix},\quad P_p = \begin{pmatrix} P_{p1} \\ 0 \\ P_{p3} \end{pmatrix},\quad \bar{u} = \begin{pmatrix} u_1 \\ 0 \\ u_3 \end{pmatrix}$$

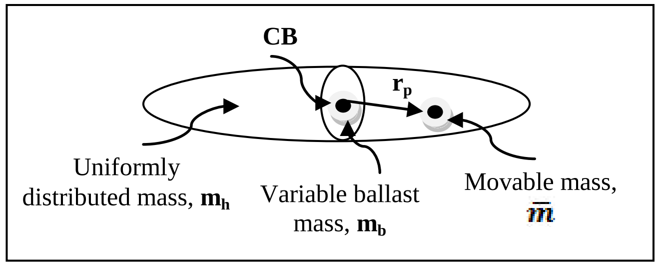

Figure 3: Glider with Simplified Internal Mass

The equation of motion of underwater glider suggested by Leonard and Graver [2,3] is chosen to validate the estimation model during the system identification process. This is important for the selection of the vehicle model order, in which, a comparison can be done during black box identification. The equations are stated as below:

$$\dot{x} = v_1\cos\theta + v_3\sin\theta \qquad (2)$$

$$\dot{z} = -v_1\sin\theta + v_3\cos\theta \qquad (3)$$

$$\dot{\theta} = \Omega_2 \qquad (4)$$

$$\dot{\Omega}_2 = \frac{1}{J_2}\left((m_3 - m_1)v_1v_3 - (rp_1 Pp_1 + rp_3 Pp_3)\Omega_2 - \bar{m}g(rp_1\cos\theta + rp_3\sin\theta) + M_{DL} - rp_3u_1 + rp_1u_3\right) \qquad (5)$$

$$\dot{v}_1 = \frac{1}{m_1}(-m_3v_3\Omega_2 - Pp_3\,\Omega_2 - m_o g\sin\theta + L\sin\alpha - D\cos\alpha - u_1) \qquad (6)$$

$$\dot{v}_3 = \frac{1}{m_3}(m_1v_1\Omega_2 + Pp_1\,\Omega_2 + m_o g\cos\theta - L\cos\alpha - D\sin\alpha - u_3) \qquad (7)$$

$$\dot{rp}_1 = \frac{1}{\bar{m}}(Pp_1 - v_1 - rp_3\,\Omega_2) \qquad (8)$$

$$\dot{rp}_3 = \frac{1}{\bar{m}}(Pp_3 - v_3 - rp_1\,\Omega_2) \qquad (9)$$

$$\dot{Pp}_1 = u_1 \qquad (10)$$

$$\dot{Pp}_3 = u_3 \qquad (11)$$

$$\dot{m}_b = u_4 \qquad (12)$$

Here, α is the angle of attack, D is drag, L is lift, θ is pitching angle, v_1 & v_3 are velocity respect to fixed body cord and M_{DL} is the viscous moment. The forces and moment are modeled as:

$$D = (K_{Do} + K_D\alpha^2)(v_1^2 + v_3^2) \qquad (13)$$

$$L = (K_{L0} + K_L\alpha)(v_1^2 + v_3^2) \qquad (14)$$

$$M_{DL} = (K_{M0} + K_M\alpha)(v_1^2 + v_3^2) \qquad (15)$$

Where *K's* are constant coefficients and glider speed V as:

$$V = \sqrt{(v_1^2 + v_3^2)} \qquad (16)$$

D. Vehicle Design

The platform made for the data acquisition process is based on the USM underwater glider prototype. The USM underwater glider is under development in order to be the first prototype platform to investigate the buoyancy driven mechanism and vehicle dynamic motion. The platform will be operated on shallow sea water not more than 30 meters depth. Upon completion of the prototype, it will be tested for it workability in giving the forward motion. The shape of the underwater glider will be circular cylindrical form based on the proven concept design. This is due to underwater hydrodynamic pressure effect and it is known that this shape capable to resist this effect efficiently [12]. Table 1 gives the general characteristics of the prototype design and Fig. 1 demonstrates the proposed hull shape design of USM underwater glider.

TABLE 1: Specification of USM Underwater Glider

Dimension	0.17 m (Diameter) 1.3 m (Length) 1.0 m (Wing Span)
Operation Depth	30 meters maximum
Operation Time	More than 2 hours
Main Power	Lithium-Ion
Sensors	Eco-Sounder Transducer IMU 5 Degrees of Freedom Depth Sensor Distance Sensor Displacement Sensor

E. Simulation of Equation of Motions

By using the MATLAB [13], simulation of equation of motion was done by selecting the proper initial condition and the simulation cases are studied. This will become a guideline for the real experiment of input and output for the control system [14]. Fig. 4-7 shows some of the glider dynamics. The simulation of motion is done by downward gliding motion in 50 seconds of time.

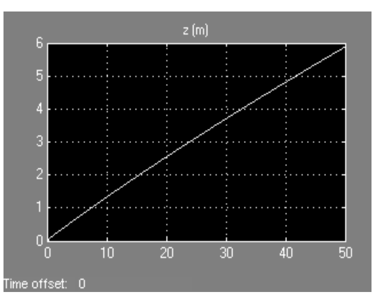

Figure 4: Depth (m)

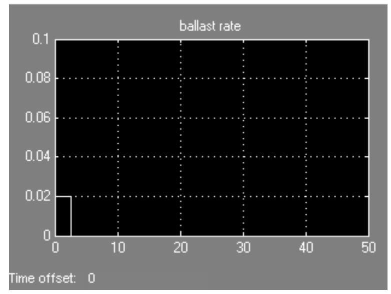

Figure 5: Ballast Rate (kg/sec)

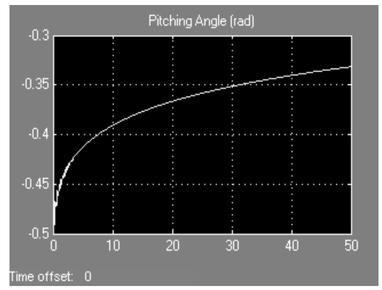

Figure 6: Pitching Angle (radians)

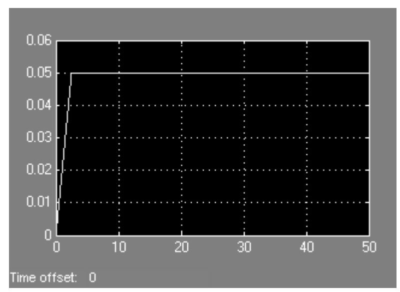

Figure 7: Net Buoyancy (kg)

In downward gliding motion, the initial condition of v_1=0.3 sec, θ=-0.5 radians, m_b=0, r_p=0 and Ω=0. The ballast rate act as the control input for the simulation and three outputs; depth, pitching angle and net buoyancy are observed. Result shows some hydrodynamics changes based on the input signal. Moreover, it is also important to know the control system of the buoyancy system itself. Therefore, the simulation is also done in upward motion and the parameter is changing based on the push and pull of the ballast system.

III. SYSTEM IDENTIFICATION OF UNDERWATER GLIDER

The purpose of conducting a system identification procedure is to investigate the ballast system of the USM underwater glider in order to know the pumping rate as the input of the system and the net buoyancy of the ballast system. In line with that, the mathematical model that relates the system output to system input will be obtained. For this purpose, the input signal are positive and negative pulses to command the ballast to pull and push the water from the ballast tank. This input will manipulate the mass distribution in the vehicle thus the vehicle dynamic can be observed. In this paper, two outputs have be chosen for observations; the net buoyancy and the glider's depth. The net buoyancy effect will make the vehicle to move forward due to angle of attack and velocity components. The wings are designed with the 0012 airfoils geometrical construction similar to aerospace design that will manipulate the lift and drag effect. The positive net buoyancy m_o will change the pitching angle, the angle of attack, lift and drag coefficients so that the overall vehicle dynamics are effected due to this input.

To complete the objective, MATLAB System Identification Toolbox is used. In general, most parametric model structure available in the toolbox is given by:

$$A(q)y(t) = \frac{B(q)}{F(q)}u(t-n_k) + \qquad (17)$$

Where *y* and *u* is the output and input sequences and *e* is the white noise sequence with zero mean value. The polynomials A, B, C, D and F are defined in term of the backward shift operator by:

$$A(q) = 1 + a_1 q^{-1} + \cdots + a_{na} q^{-n} \qquad (18)$$
$$B(q) = b_1 + b_2 q^{-1} + \cdots + b_{nb} q^{-} \qquad (19)$$
$$C(q) = 1 + c_1 q^{-1} + \cdots + c_{nc} q^{-nc} \qquad (20)$$
$$D(q) = 1 + d_1 q^{-1} + \cdots \qquad (21)$$
$$F(q) = 1 + f_1 q^{-1} + \cdots + f_{nf} q^{-nf} \qquad (22)$$

Depends on how these structures combine with the number of parameters, there are several model structures can be chose in the toolbox, for example, the Auto Regressive (AR) model, Auto Regressive with Exogenous Input (ARX) model, Auto Regressive of Moving Average with Exogenous Input (ARMAX) model, Output Error (OE) model, Box-Jenkins (BJ) model and State Space (SS) model. By observing these models performance for estimation, the best three are then chosen for the best fit criteria.

During the data acquisition process, about 100 grams of water was displaced inside and outside of the piston tank. At a sampling interval of 0.5 seconds, the input (ballast rate, kg/sec) and output (net buoyancy, kg) data is recorded. The input and output data were loaded to the System Identification Toolbox as the time domain data, in which, it can be shown as in Fig. 8.

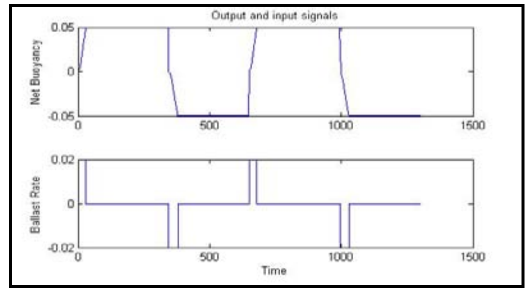

Figure 8: Input (ballast rate, kg/sec) and output (net buoyancy, kg) signal

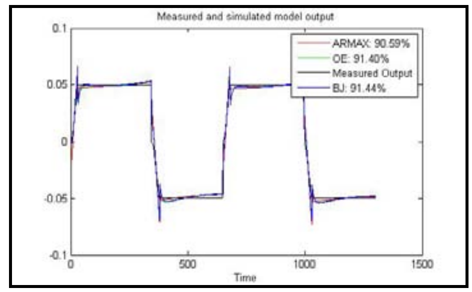

Figure 9: Superimpose of measured and simulated model output

Most of the parametric models available in the System Identification Toolbox are tested to identify the glider system. Among all, the best three parametric models which show good performance in identifying the system are chosen. Result based on the ability of the model to reproduce the output is shown in Fig. 9. Based on Fig. 7, Box-Jenkins with 9th order of the system has demonstrated the best estimation of parametric model that gave 91.94% of fit, follows by Output-Error, 91.4% and ARMAX model of 90.59%. Other models have given the percentage of accuracy below than these three models. According to these results, BJ model structure is chosen as the best model to replicate the output measurement of the ballast system and the parametric polynomial are presented as follows:

$B(q) = 1.593q^{-1} – 1.363q^{-2} - 2.634^{q-3} + 3.209^{q-4} - 0.0711q^{-5}$
$-3.17q^{-6} + 2.536q^{-7} + 1.32q^{-8} – 1.42q^{-9}$ (23)
$C(q) = 1 – 0.933q^{-1} + 0.019q^{-2}$ (24)
$D(q) = 1 – 1.87q^{-1} + 0.871q^{-2}$ (25)
$F(q) = 1 – 0.933q^{-1} – 1.63q^{-2} + 2.195q^{-3} – 0.1715q^{-4}$
$- 2.093q^{-5} + 1.829q^{-6} + 0.74q^{-7} – 1.026q^{-8}$
$+ 0.090q^{-9}$ (26)

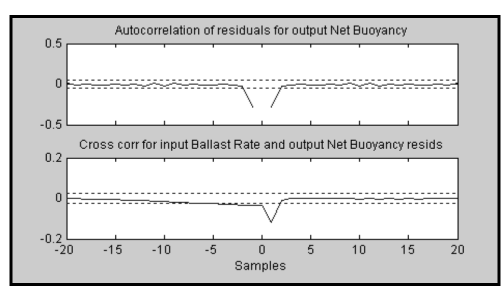

Figure 10: Residual analysis

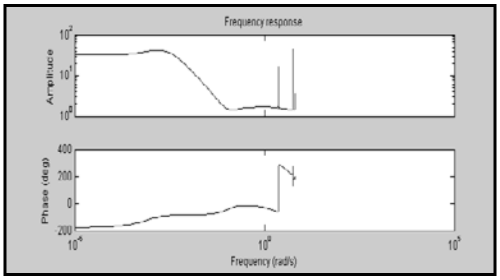

Figure 11: Frequency response

The residual analysis and the frequency response of the observed System 1 using a BJ model are also shown as in Fig. 11 and Fig. 12 respectively.

IV. DISCUSSION

The objective of performing system identification procedure in this USM Underwater Glider platform is to investigate the vehicle parameters input and outputs interaction. There are about ten state variables that need to be observed as to understand the vehicle behavior in order to design the control system. For example, in the Slocum, Sea glider and Spray prototype development [14] the vehicle modeling can be time consuming and much human resource needed to complete the task. Based on the vehicle simulation result as in Fig. 5-7, the vehicle can be analyzed according to the vehicle specifications and the equation of motion establish by Leonard and Graver.

The performance of the gliding motion is totally causes by the water volume intake by ballast tank [1]. Fig. 10 and Fig. 11 demonstrate the residual analysis and the frequency response of the BJ model. It shows that the autocorrelation and cross correlation test give a good performance, in which the model is able to identify the system within the 95% confidence level. The fit for the frequency response also show a good performance. Therefore, the model can be used to replicate the true system based on the vehicle prototype design.

V. CONCLUSION

System identification was conducted to investigate the ballast system of the USM underwater glider in order to know the pumping rate as the input of the system and the net buoyancy of the ballast system. The estimation is done using various models available in the System Identification Toolbox, in which, the BJ model is chosen as the best model to represent the system and obtain the transfer function. The glider's depth is also observed. Currently under development are the pitching angle and altitude of the vehicle during underwater gliding. Based on this information, the vehicle dynamics can be observed from the beginning and the custom controller design can be implemented to the prototype. Besides using the MATLAB System Identification Toolbox, the novel model estimation method is also under development, which later to be used as a comparison with some of the existing modeling methods.

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