Modeling and Simulation of Motion of an Underwater Robot Glider for Shallow-water Ocean Applications

Chen Wang, and Amir Anvar

***Abstract*—**This paper describes the modeling and simulation of an underwater robot glider used in the shallow-water environment. We followed the Equations of motion derived by [2] and simplified dynamic Equations of motion of an underwater glider according to our underwater glider. A simulation code is built and operated in the MATLAB Simulink environment so that we can make improvements to our testing glider design. It may be also used to validate a robot glider design.

***Keywords*—**AUV, underwater glider, robot, modeling, simulation.

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I. Introduction

An underwater glider is a type of autonomous underwater vehicles (AUVs) that glides by changing its net buoyancy using internal actuators. It is able to collect oceanographic data and transmit information over the course of weeks or months at a time. This was firstly described by Henry Stommel in his published article "The Slocum" in 1989 [1]. About 20 years later, Stommel's anticipation became a reality. Hundred of gliders operate all over the world. Among them, three test-proven electric-powered gliders, Seaglider, Spray and Slocum were successfully launched. However, these designed gliders are slightly different from Stommel's concept. An underwater glider usually consists of several systems including a ballast system, a sliding mass, a control system and external components. As it consumes low power, operates over long duration, and has a low expense many countries are designing their own underwater gliders for different purposes.

Mathematical model and control theory have been studied to develop the underwater glider. The study of an underwater glider has a short history compared with that of conventional AUVs with propellers. This refers to the dynamic behavior of the underwater glider needs to be studied and examined.

Generally, its motion is divided into motion in horizontal and vertical planes. Its vertical motion involves many variables including buoyancy changes and movable mass system. Compared with motion in vertical plane, horizontal motion involves more variables regarding to the currents. The Equations of motion and its linearization about the steady diving state are described in detail in "Model-Based Feedback Control of Autonomous Underwater Gliders" written by Leonard and [5].

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II. Design of the Glider

This section is a brief introduction of our testing Glider manufactured in 2011, which is the base of the modeling and simulation. The glider consists of a control system, a navigation system, a communication system, a sensor package and external components.

The control system is the most crucial element of an underwater glider. It controls the glider's motion including buoyancy, pitch, yaw and heading. Then, the navigation system contains a fast-fix Navman GPS and a 6-DOFs IMU which is capable of estimating underwater motion. A radio frequency (RF) is responsible for sending and receiving collected data and transmitting navigation coordinates. In terms of sensor package, the system is able to measure pressure and temperature due to budget restraints. The system diagram is shown in Fig. 1 to illustrate the automation .structure. All the processes are controlled by an Arduino Mega microcontroller.

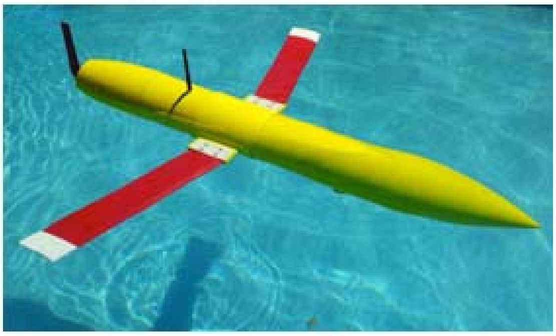

Fig. 1 The Glider during testing [4]

Underwater gliders have a similar shape which improves performance controllability and maneuverability with the help of hydrodynamics. The glider's external components, as shown in Fig. 2, included a nose cone, a central hull, a tail cone and wing assembly. The designers accounted that the concept of the nose cone has a low stagnation pressure and associated pressure distribution [4]. Also, the wing assembly was designed not to

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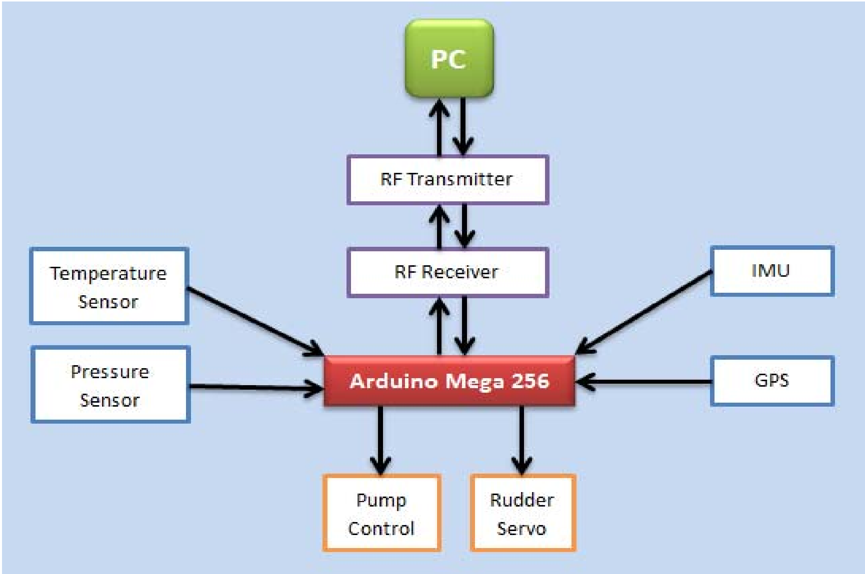

Fig. 2 Automation Control Flow Diagram

be tangent with the central hull face. They believed this would be helpful for working out whether there is a threat to underwater cables and other sea bed infrastructure.

TABLE I
DESIGN SPECIFICATION

Hull Length	1.1 m
Wing Span	1.1 m
Wing Chord	100 mm
Maximum Hull Diameter	161 mm
Microcontroller	Arduino Mega 256
Dead Reckoning	Atomic 6-dof IMU
Surface Navigation	Navman OEM GPS
Communications	UM-12 RF 433 MHz
Pressure Sensor	10 bar absolute pressure sensor
Temperature Sensor	LM35 sensor
Power Source	Sealed lead acid battery
Buoyancy System	2 pumps

Table I summarizes the detail design, both internal and external components of the glider.

III. MODELING OF THE GLIDER

It is essential to simulate dynamic behaviour of the glider so as to assure its performance and avoid unstable motion. As the glide process is difficult to investigate experimentally, it requires a computer simulation to predict its dynamic behavior. The computer analysis consists of a Matlab SIMULINK code and associated computational fluid dynamic (CFD) analysis. The results from the Matlab code are used to study the motion, while the CFD is implemented to study its hydrodynamic behavior. It is noted that the horizontal motion involves variables which are unpredictable, so we investigate the motion in the vertical plane. This section is broken down into: i) Equations of motion in the vertical plane; ii) simulation of dynamic in the vertical plane.

A. Equations of Motion in the Vertical Plane

Our glider hull is symmetrical with wings and tail attached so that the center of buoyancy (CB) is at the center of the vehicle. Then, we assign a coordinate frame according to right-handed rule. The coordinate is fixed on the vehicle body to have its origin at the CB and its axes aligned with the principle axes of the hull. We let body axis 1 lie along the long axis of the vehicle, let body axis 3 point in the direction orthogonal to the wings as shown in Fig. 3 [3].

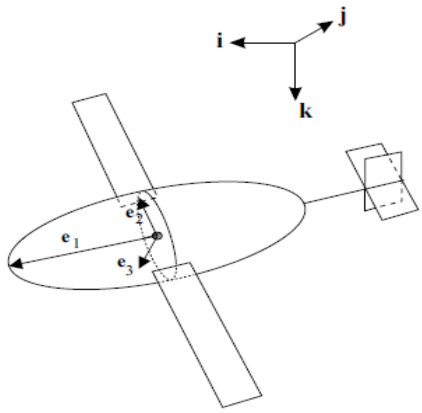

Fig. 3 Body Frame Assignment

The total stationary mass of glider contains several parts: the hull, the wings, the movable weight and the ballast system. It can be represented as $m_s = m_h + m_w + m_b$. The mass of ballast, m_b varies over time according the rate of pumps. Thus, the total mass of the vehicle, m_v, refers to the sum of the stationary mass and the movable mass, $\overline{m}$. We denote m as the mass of the displaced fluid. Then, the net buoyancy is

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defined as $m_0 = m_v - m$. Therefore, the vehicle is positively buoyant if m_0 is negative.

Here we simplified the vertical plane equilibrium Equations according to our glider. Since the glider is designed to be symmetric. We specialize the model to the vertical plane. Thus, the state can be denoted as

$$R = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix}, \quad b = \begin{pmatrix} x \\ 0 \\ z \end{pmatrix}, \quad v = \begin{pmatrix} v1 \\ 0 \\ v3 \end{pmatrix}, \quad \Omega = \begin{pmatrix} 0 \\ \Omega_2 \\ 0 \end{pmatrix}$$

$$r_p = \begin{pmatrix} r_{p1} \\ 0 \\ r_{p2} \end{pmatrix}, \quad P_p = \begin{pmatrix} P_{p1} \\ 0 \\ P_{p2} \end{pmatrix}, \quad \bar{u} = \begin{pmatrix} u_1 \\ 0 \\ u_2 \end{pmatrix}$$

where θ is pitch angle.

We adopt the Equation of motion for the oceanic glider derived by [2]. As shown in Equation 2, the Equation of

$$D\cos\alpha - u_1) \quad (5)$$

$$\dot{v}_3 = \frac{1}{m_3}(m_1 v_1 \Omega_2 - P_{P1}\Omega_2 - m_0 g\cos\theta - L\cos\alpha -$$

$$D\sin\alpha - u_3) \quad (6)$$

$$r'_{p1} = \frac{1}{m}P_{p1} - v_1 - r_{p3}\Omega_2 \quad (7)$$

$$r'_{p3} = 0 \quad (8)$$

$$P'_{p1} = u_1 \quad (9)$$

$$P'_{p3} = u_3 \quad (10)$$

$$\dot{m}_b = u_4 \quad (11)$$

Here, α is the angle of attack, D, L and M_{DL} are drag, lift and the viscous moment respectively. We can obtain these values through the Equation 3. As the sliding weight can only move along the e_1 direction, we obtain $r'_{p3} = 0$.

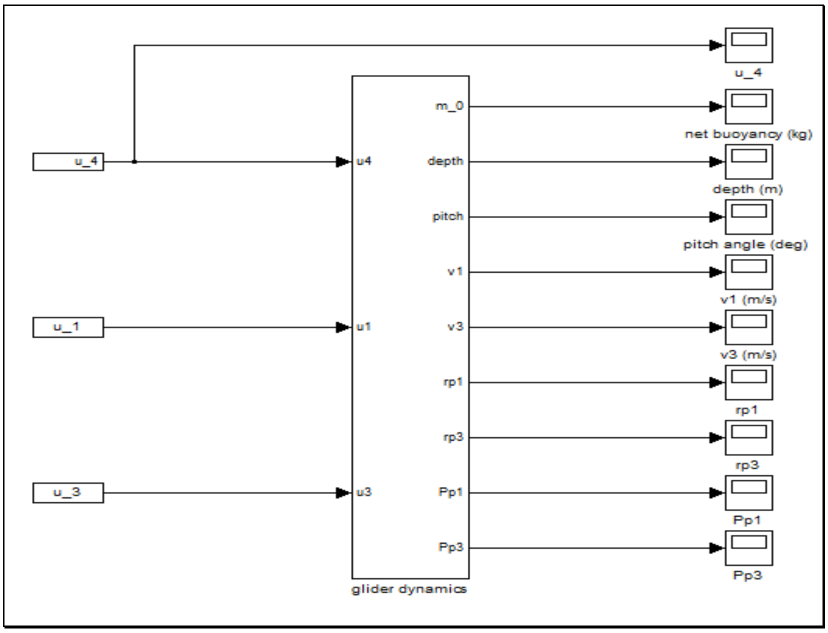

Fig. 4 System of Modeling Diagram

motion is utilized to generate the simulation code and solved by numerical method. Also, the hydrodynamic forces and momentum in the Equations obtained from the CFD model.

$$\dot{x} = v_1\cos\theta + v_2\sin\theta \quad (1)$$

$$\dot{z} = -v_1\sin\theta + v_3\cos\theta \quad (2)$$

$$\dot{\theta} = \Omega_2 \quad (3)$$

$$\dot{\Omega}_2 = \frac{1}{h}((m_3 - m_1)v_1 v_3 - (r_{p1}P_{p1} + r_{p2}P_{p2})\Omega_2 -$$

$$\bar{m}g\,(r_{p1}\cos\theta + r_{p3}\sin\theta) + M_{DL} - r_{p3}u_1 + r_{p1}u_3) \quad (4)$$

$$\dot{v}_1 = \frac{1}{m_1}(-m_3 v_3 \Omega_2 - P_{P3}\Omega_2 - m_0 g\sin\theta + L\sin\alpha -$$

$$D = \frac{1}{2}\rho C_D(\alpha)AV^2 \approx (K_{DO} + K_D\alpha^2)(V_1^2 + V_3^2) \quad (12)$$

$$L = \frac{1}{2}\rho C_L(\alpha)AV^2 \approx (K_{LO} + K_L\alpha\ )(V_1^2 + V_3^2) \quad (13)$$

$$M_{DL} = \frac{1}{2}\rho C_M(\alpha)AV^2 \approx (K_{MO} + K_M\alpha\ )(V_1^2 + V_3^2) \quad (14)$$

Here, C_D , C_L and C_M are the coefficients of drag, lift and moment respectively. Usually, we are able to obtain these values from experiments. However, we utilize the CFD simulation (shown in Fig. 4) and obtain these values.

B. Simulation of Dynamic in the Vertical Plane

The simulation program is built and operates in MATLAB

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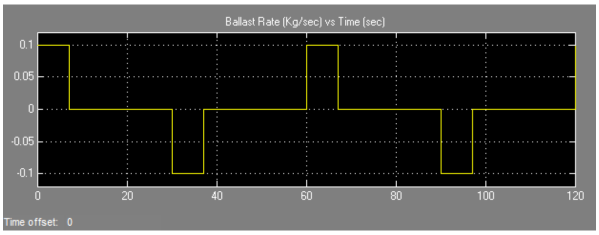

Fig. 5 The ballast rate against time

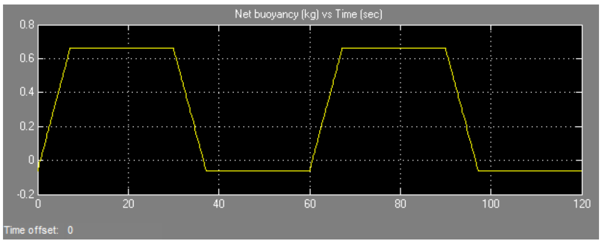

Fig. 6 Net buoyancy against time

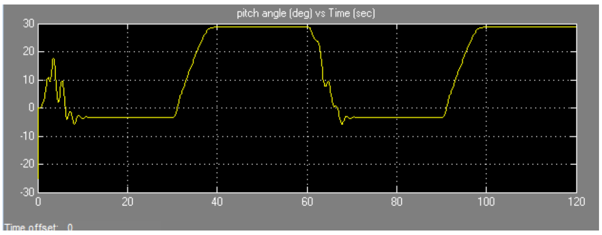

Fig. 7 Pitching angle against time

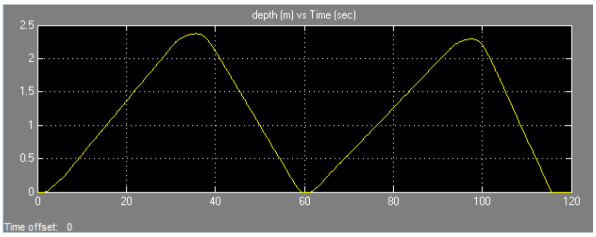

Fig. 8 Depth against time

Simulink environment which uses GUI to have the program visual.

As shown in Fig. 4, we set u_1 , u_3 and u_4 as inputs of the dynamic, and outputs include net buoyancy, pitching angle and depth. Here, u_4 is presented as a composite signal of both a positive pulse and a negative pulse (see Fig. 5). The positive one refers to command the ballast to pump water into the bladder; reversely, the negative one refers to command the ballast to pump water out of the bladder. This results into the periodic changes of the glider mass. Additionally, the mass of displacement water which only relates with the volume of the glider is constant. Therefore, this makes the glider's motion looks like a sawtooth in the vertical plane. In general, u_4 affects not only the mass of the ballast system, but also the excess mass. Thus, it is crucial factor in the simulation model.

We simulate our glider and gain within Fig. 6 to Fig. 8 which illustrate the dynamic motion of the glider in the terms of its net buoyancy, pitching angle and depth. We set the initial input values: $u_1 = 0$ and $u_2 = 0$. The bladder of the glider is empty at the beginning. In terms of other data, we follow the data used to model SLOCUM according to Graver [2].

It is notable that these are some shakes in the beginning of the pitching curve. This means the glider is unstable. In case of the net buoyancy, the maximum value is far different from its minimum value.

IV. Conclusion

The results from the simulations were successful with considering that our glider test-bed requires a partial improvement and modifications particularly on the structural layout of the vehicle. To improve the layout of mass distribution, we may add some small quantity of mass to make the average of the net buoyancy around zero.

Meanwhile, due to the complexity of the process there are possibilities of some errors that may occur during the simulation process, which may affect our results. In terms of its hydrodynamic performance, we acquire hydrodynamic coefficients from CFD which are very close to the data that SLOCUM used. Our aim is to minimize the errors. However, as our glider use different geometry and mass distribution designs similar to SLOCUM, we cannot estimate errors unless carry out more laboratory experiments to observe the results and after a series of calculation we may be able to obtain the actual coefficients. In terms of the mass distribution, our data can be achieved via either hand calculations or electronic scales. In particular, there are always possibilities of having some errors via the hand calculations data such as the mass of displacement water. The other possibilities could be some minor mistakes in the geometrical parameters.

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