Modelling and Identification of Underwater Glider for Heading Angle Correction

Tri Wahyu O. Putri, Ulinnuha Latifa, Bambang R. Trilaksono, and Egi M. I. Hidayat

Abstract—**Autonomous Underwater Glider (AUG) as a high durability Autonomous Underwater Vehicle (AUV) is typically capable of extremely long missions and may travel thousands of kilometers in the ocean. An ability to track the desired paths is indispensable ability of underwater glider due to its long range paths. Heading control system has the main role in path tracking. This paper presents mathematical modelling of a class of underwater glider in lateral plane in order to design the heading control system. Model identification using N4SID method was used to tune the parameters based on the experiment data. The heading motion model of a class underwater glider was evaluated in simulation with varying inputs. The results showed that the tuned model's responses satisfy the real behavior of underwater glider.**

Index Terms—**Autonomous underwater glider, modelling, identification, heading motion.**

I. INTRODUCTION

The ocean covers 71% of Earth's surface. It is important to observe both physical and biological dynamics of the ocean. The main challenge is collecting data "in a vast, inhospitable, and unforgiving" ocean environment [1]. In recent years, oceanographers have used Autonomous Underwater Vehicle (AUV) as an important tool in gathering oceanographic data, replacing the traditional process [1]. Conventional AUVs use propellers as their main driver and battery as their main power source, which make it cannot be operated for long-term deployment.

Underwater gliders are kind of AUV that propel themselves by modifying the buoyancy and center of mass. It provides the high endurance and long-term operation in ocean research missions. An ability to track the desired paths is indispensable ability of underwater glider. Heading control system has the main role in path tracking. Hence a rudder is an appropriate choice for heading control [2], besides the tunnel thruster that also can be used as heading actuator. Before the rudder and heading control system can be designed and analyzed, the dynamics that describe the motion of a glider in lateral plane must be determined [2]. Derivation of mathematical equations is a prevalent method in modelling. The same modelling method has been used by [3] to their AUG named NPS AUV II. The detail of an AUV's mathematical models has also been

explained by [4] in their book.

This paper presents underwater glider models of a class of underwater glider in the lateral plane in order to design the heading control system, based on the underwater glider that we built, named GaneshBlue Glider. Modelling in the lateral plane was also presented and succesfully applied by [5] to their HUGIN 4500 AUV. It is an undeniable truth that every system, in this case AUV, has different model one to another because of different dimensions, shapes, physical characteristics, and actuators. The models which were presented in many literatures were not suitable if applied in GaneshBlue due to the differences in physical parameters and actuators. Then, it needs to build the right models for it.

The paper is organized as follows. Section 2 gives a system overview of the GaneshBlue Glider and its control systems. Section 3 focuses in modelling. Linearization of dynamic models and parameter determination using analytical methods are described in this section as well. Section 4 describes the identification method. Section 5 shows the simulation result based on the tuned model with doublet input. Section 6 provides concluding remarks and directions for the future works.

II. SYSTEM OVERVIEW

A. GaneshBlue Glider

Fig. 1. GaneshBlue Glider.

GaneshBlue Glider is buoyancy-driven underwater glider which was developed by Institut Teknologi Bandung, Indonesia. This glider is designed for shallow water exploration with maximum depth of 200 meters. As shown in Figure 1, this underwater glider has 2 meter's length, 92.8 kg nominal dry mass, and propels itself by modifying the buoyancy and center of mass. The buoyancy is controlled by a bladder bag which can modify its buoyancy due to volume displacement. The pitch angle is controlled by two ballast tanks inside the hull. The motion in the lateral plane of GaneshBlue Glider is actuated using a rudder and two horizontal tunnel thrusters. This paper is focused in

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underwater glider motion in the lateral plane with a rudder as the heading actuator.

B. Heading Control

The most intuitive means of changing heading is by deflecting a rudder to induce a yawing moment [2] or by using two horizontal thrusters (bow thruster and stern thruster). GaneshBlue Glider has a rudder in the upper vertical wing and two horizontal tunnel thrusters which are located in rear and front. The maximum rudder deflection angle is ± 30 degrees. Controller design of heading control is important part to correct the heading angle in order to keep the glider tracks the desired path.

III. MODEL OF AUG IN LATERAL PLANE

Model of AUG in lateral plane can be developed from its kinematic and dynamic equations. Then, the value of hydrodynamic parameters are determined by hydrodynamic parametrization using analytical methods. After that, the model of a class off AUG in lateral plane have to be validated by comparing its model response with experiment's response.

A. Kinematic Equation

The forces and moments acting on the underwater glider need to be referenced to the same frame [3]. This paper uses standard notation from [4] to describe the 6 DOF (Degree of Freedom) equations of motion. AUG motion in lateral plane neglects any other motions and rotations in longitudinal plane. Then the kinematic equations in lateral plane are as follow (see (1) and (2)), with x is position in x-direction, $\dot{x}$ is linear velocity along x-axis in world coordinate, y is position in y-direction, $\dot{y}$ is linear velocity along y-axis in world coordinate, ψ is yaw angle, u is surge velocity along x-axis in body coordinate, and v sway velocity along x-axis in body coordinate. The x and y axes of AUG which is seen from above is described as in Fig. 2.

$$\dot{x} = u\cos\psi - v\sin\psi \qquad (1)$$
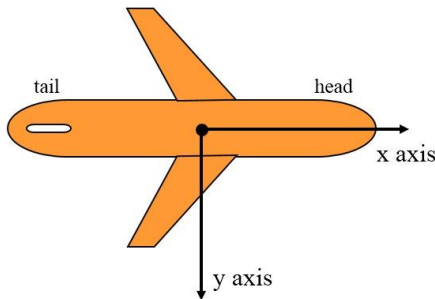
$$\dot{y} = u\sin\psi + v\cos\psi \qquad (2)$$

Fig. 2. x and y axes of AUG.

B. Dynamic Equation

Dynamic equations in the lateral plane are sway force equation (see (3)) and yaw moment equation (see (4)). It is well-known [3]-[5] that speed can be decoupled from sway and yaw dynamics. The dynamics equations in the lateral plane [4]-[6] are shown in equation below.

$$m[\dot{v} + ur + x_G(pq + \dot{r}) - y_G(p^2 + r^2) + x_G(qr + \dot{p})] \qquad (3)$$
$$= Y_H + Y_W + Y_C$$

$$I_z\dot{r} + (I_y - I_x)pq - I_{xy}(p^2 - q^2) + m[x_G(\dot{v} + ur) - y_G(\dot{u} - vr)] \qquad (4)$$
$$= N_H + N_W + N_C$$

where m is AUG mass, x_G is x position of center of gravity, y_G is y position of center of gravity, r is yaw angular velocity, p is roll angular velocity, q is pitch angular velocity, I_z is inertia of vehicle in z axis, I_x is inertia of vehicle in z axis, I_y is inertia of vehicle in y axis, I_{xy} is x-y cross inertia, and the right side of those equations are external forces.

Hydrodynamic force and moment:

$$Y_H = D_4(Y_{\dot{r}}\dot{r} + Y_{qr}qr) + D_3(Y_{\dot{v}}\dot{v} + Y_r ur + Y_{vq}vq + Y_{wr}wr) \qquad (5)$$
$$+ D_2(Y_{uv}uv + Y_{vw}vw)$$

$$N_H = D_5(N_{\dot{r}}\dot{r} + N_{qr}qr) + D_4(N_{\dot{v}}\dot{v} + N_r ur + N_{vq}vq + N_{wr}wr) \qquad (6)$$
$$+ D_3(N_v uv + N_{vw}vw)$$

$Y_{\dot{r}}, Y_{qr}, Y_{\dot{v}}, Y_r, Y_{vq}, Y_{wr}, Y_v, Y_{vw}, N_{\dot{r}}, N_{qr}, N_{\dot{v}}, N_r, N_{vq}, N_{wr}, N_v, N_{vw}$ are hydrodynamic coefficients and $D_n = 0.5\rho L^n$ where ρ is water density, $L=2$ m is the vehicle length.

Hydrostatic forces and moments for motion in the lateral plane are described in Equation 7 and 8, where g is gravity acceleration, V_v is AUG's volume, θ is pitch angle, ϕ is roll angle, x_B is x position of vehicle's center of buoyancy, and y_B is y position of vehicle's center of buoyancy.

$$Y_W = (mg - \rho g V_v)\cos\theta\sin\phi \qquad (7)$$

$$N_W = (x_G mg - x_B \rho g V_v)\cos\theta\sin\phi + (y_G mg - y_B \rho g V_v)\sin\theta \qquad (8)$$

Force and moments due to rudder deflection and tunnel thrusters are described in Equations 9 and 10.

$$Y_C = D_2 u^2 (Y_{\delta r}\delta r) \qquad (9)$$

$$N_C = D_3 u^2 (N_{\delta r}\delta r) + L_{t1}F_{t1} + L_{t2}F_{t2} \qquad (10)$$

where, δ_r is rudder angle deflection, L_{t1} is distance of bow tunnel thruster to center of gravity of underwater glider, F_{t1} is bow tunnel thruster's force, L_{t2} is distance of stern tunnel thruster to center of gravity of underwater glider, F_{t2} is stern tunnel thruster's force.

Assumed that in the lateral motion, roll angle is equal to zero. Then the nonlinear dynamic equations of heading motion are derived from Equation 4 with assumption that the sway force is less significant in heading model.

$$(I_z - D_5 N_{\dot{r}})\dot{r} - my_G\dot{u} = (y_G mg - y_B \rho g V_v)\sin\theta \qquad (11)$$
$$+ (D_4 N_r u - mx_G u)r + D_4 N_{wr}wr - I_{xy}q^2$$
$$+ D_3 u^2 (N_{\delta r}\delta r) + L_{t1}F_{t1} + L_{t2}F_{t2}$$

C. Model Linearization

Model linearization is needed because Equation 11 is a nonlinear dynamic equation, while this paper's objective is to

obtain the linear heading model of a class of underwater glider. Linearization uses Taylor's Series Method is described as follows:

$$\dot{r} = \left\lfloor \frac{\partial f}{\partial r} \right\rfloor_{(r_0, U_0)} r + \left\lfloor \frac{\partial f}{\partial U} \right\rfloor_{(r_0, U_0)} U \tag{12}$$

$$U = (\delta_r, F_{t1}, F_{t2}) \tag{13}$$

$$\dot{r} = \frac{\partial f}{\partial r}\bigg|_{(r_0=0)} r + \left[\frac{\partial f}{\partial \delta_r} \quad \frac{\partial f}{F_{t1}} \quad \frac{\partial f}{F_{t2}} \right]_{(r_0, U_0=0)} \begin{bmatrix} \delta_r \\ F_{t1} \\ F_{t2} \end{bmatrix} \tag{13}$$

Thus the linear dynamics heading model in the lateral plane are described in Equation 14 with assumption sinθ=θ, cosθ=1, $\delta_{r0} = F_{t1_0} = F_{t2_0} = r_0 = y_G = y_B = x_G = x_B = 0$.

$$\begin{bmatrix} \dot{\psi} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & \dfrac{D_4 N_r u}{I_z - D_5 N_{\dot{r}}} \end{bmatrix} \begin{bmatrix} \psi \\ r \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ \dfrac{D_3 N_{\delta_r} u^2}{I_z - D_5 N_{\dot{r}}} & \dfrac{L_{t1}}{I_z - D_5 N_{\dot{r}}} & \dfrac{L_{t2}}{I_z - D_5 N_{\dot{r}}} \end{bmatrix} \begin{bmatrix} \delta_r \\ F_{t1} \\ F_{t2} \end{bmatrix} \tag{14}$$

Physical and system parameters of linear heading model in the lateral plane as described in Equation 14 are shown in Table I.

TABLE I: PHYSICAL AND SYSTEM PARAMETERS OF LINEAR HEADING MODEL

Parameters	Value
m	92.8 Kg
u	0.3 m/s
I_z	26.574 Kg.m^2
L_{t1}	0.917 m
L_{t2}	0.748 m

D. Hydrodynamic Parametrization

Hydrodynamics parametrization using analytical methods based on [7] and [8] gives values for hydrodynamic parameters for heading motion in the lateral plane (see Table II).

TABLE II: HYDRODYNAMIC PARAMETERS FOR HEADING MOTION MODEL

Parameters	Value
$N_{\delta r}$	-0.0158
N_r	-0.0170
$N_{\dot{r}}$	7.275×10^{-4}
D_3	4000
D_4	8000
D_5	16000

E. Model Validation

Using given model and parameters, the response of heading motion model in the lateral plane can be simulated using Matlab as seen in Figure 3. The simulation and validation only used rudder deflection angle as the input. So, the equation (14) can be simplified as single input and single output state space. The input is rudder deflection angle and the output is yaw (heading) angle. Henceforth, this paper focused in heading model with rudder deflection angle as its input.
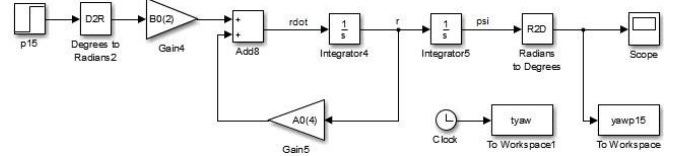

Fig. 3. Model simulation using Simulink Matlab.

The model's response was compared with the experiment data. Experiment data were gotten from pool testing using the real GaneshBlue Glider with various rudder deflection angle. Figure 4 shows the comparison of heading model as validation of model. It can be concluded from the plots that there were big differences between model and real data. Thus, the heading model needed to be tuned by identification method.

IV. IDENTIFICATION

The identification method that was used in this paper is N4SID. N4SID stands for Numerical algorithms for Subspace State Space System Identification. This method is well-known as powerful method for high order multivariable systems. With N4SID algorithms, most of a priori parametrization can be avoided. Only the order of the system is needed and it can be determined through inspection of the dominant singular values of a matrix that is calculated during identification [9].
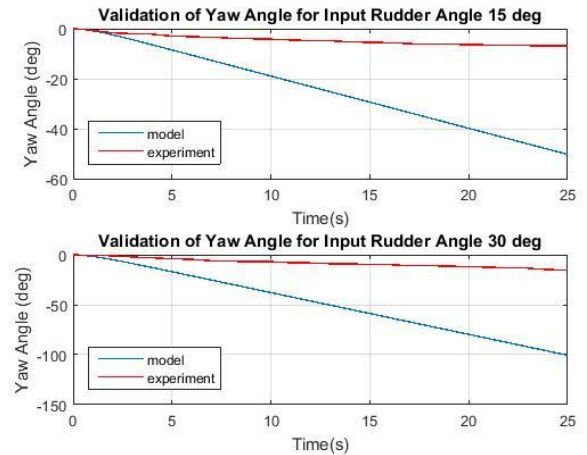

Fig. 4. Validation of model for input rudder angle 15 and 30 degree.

N4SID solves subspace matrix equations by estimating past and future of Kalman filter states. The detail of N4SID algorithm can be seen in [9]-[11].

With the toolbox of Matlab ident, it is possible to identify a model with different types of structures using N4SID method. The *n4sid* syntax in Matlab estimates models in state space form. The identification was done using input and output experiment data from pool testing. The response of raw data needed to be linearized in order to avoid N4SID estimating the model as first order system whose steady state value. The response of heading model is supposed to be ramp. Figure 5 shows the result of linear regression of yaw (heading) angle response with various rudder angle.

The input and output data that were used to estimate is showed in Fig. 6, which the data were input-output data with rudder deflection angle is -15 degree (0.26 radian). The identification using N4SID method gave a fit value of 100%

(see Fig. 7). The cross validation of model estimation with another input-output data shows a fit value of 94.61% (see Fig. 8).
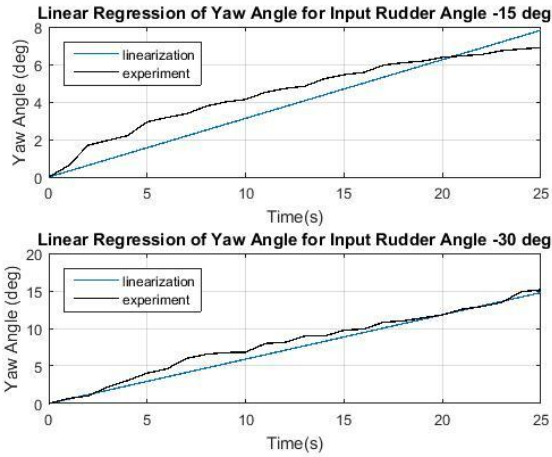

Fig. 5. Linear regression of output data with various rudder angles.
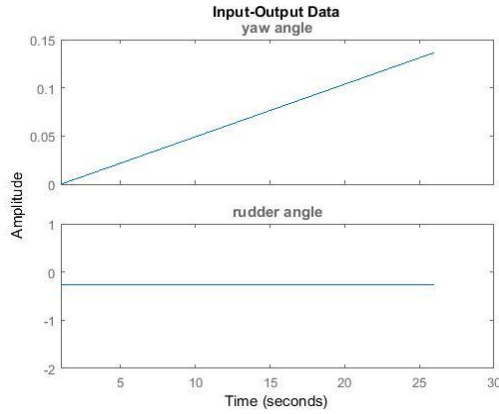
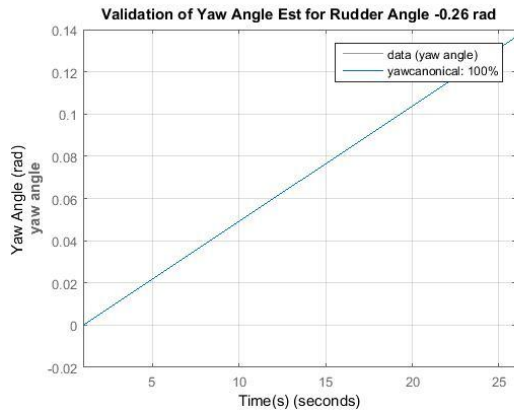

Fig. 6. Input and output data for identification.

Fig. 7. Validation of heading angle estimation and experiment data for input rudder angle -0.26 radian.

New parameters were added to compensate the difference between model estimation and original model. The tuned model with added parameters is described in (15). The values of added parameters are $K_{y1} = 1.866 \times 10^{-8}$; $K_{y2} = 1.75704$; $K_{y3} = -0.02086$; $K_{y4} = -2.8594 \times 10^{-8}$.

$$\begin{bmatrix} \dot{\psi} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ K_{y1} & \dfrac{D_4 N_r u}{I_z - D_5 N_{\dot{r}}} K_{y2} \end{bmatrix} \begin{bmatrix} \psi \\ r \end{bmatrix} + \begin{vmatrix} K_{y3} \\ \dfrac{D_3 N_{\delta r} u^2}{I_z - D_5 N_{\dot{r}}} K_{y4} \end{vmatrix} \delta_r \quad (15)$$
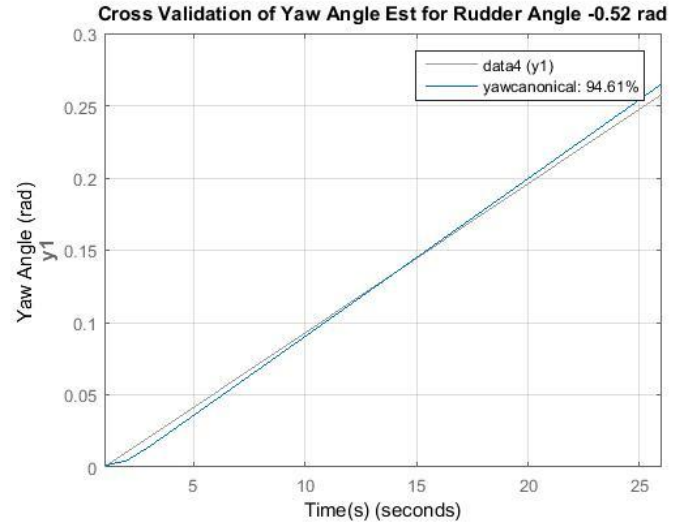

Fig. 8. Cross validation of heading angle estimation and experiment data for input rudder angle -0.56 radian.

V. SIMULATION

The simulation of a class of underwater glider's heading model was built in Matlab to observe the system's response with certain input. Basically, the simulation blocks were almost similar to the simulation blocks in Figure 3 except the addition of parameter compensations. The output of heading angle with doublet signal as an input had been simulated. The result is shown in Fig. 9. The simulation using tuned model were compared with experiment data are shown in Fig. 10 and 11. The simulation shows that the tuned model's responses satisfy the real behavior of underwater glider.
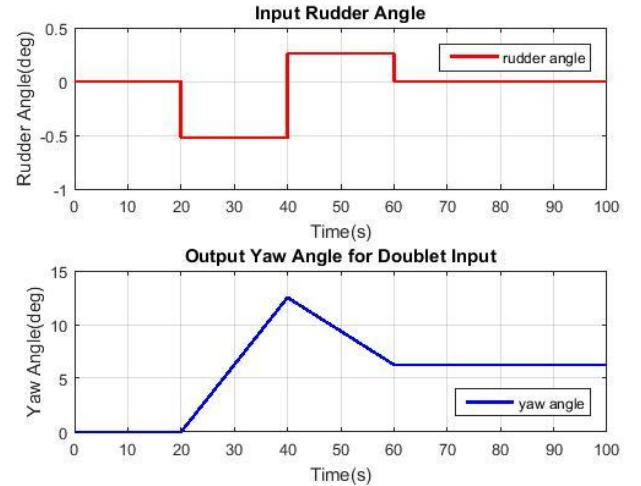

Fig. 9. Input and output of heading (Yaw) angle using Doublet input.

The heading angle correction using the obtained heading model is proposed to keep the AUG tracks the desired trajectory. It is the complex system which consists of guidance system, navigation system, and heading control system. The model is used to design the proper control system and to simulate the overall systems before the deployment in the ocean.
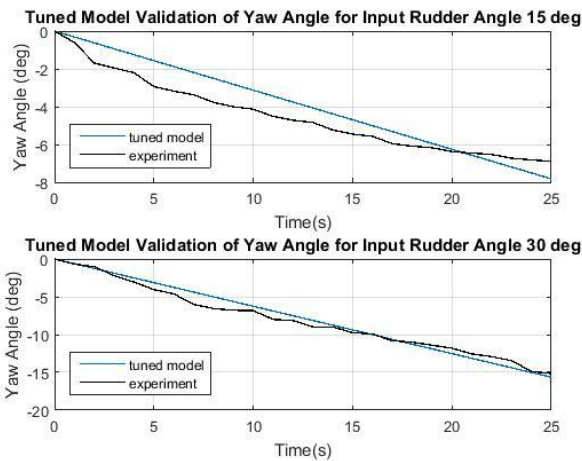
Fig. 10. Tuned model validation of heading model simulation for input rudder angle 15 and 30 degrees.
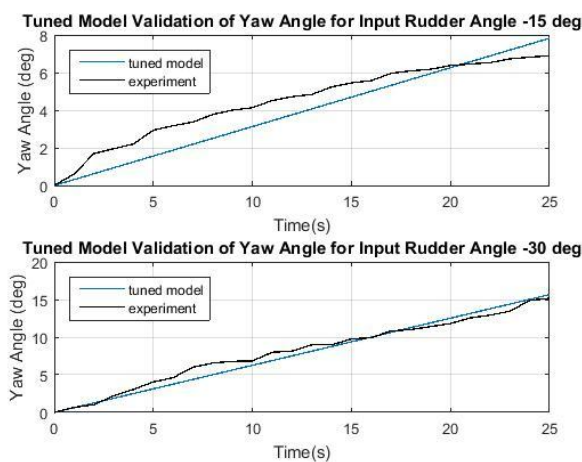

Fig. 11. Tuned model validation of heading model simulation for input rudder angle -15 and -30 degrees.

VI. CONCLUSION

The models of a class of underwater glider in the lateral plane are presented. Mathematical modelling of heading motion has been developed. The hydrodynamic parameters using analytical methods have been calculated. The model simulation showed there was a steady state error compared with the real data. Identification method using N4SID was used to estimate the suitable model to get the value of added parameters. The model with added parameter had a fit value of 100%. Cross validation of the tuned model also gave satisfying result with a fit value of 94.61%. The simulation showed that the tuned model's responses satisfy the real behavior of underwater glider.

The models of a class of underwater glider which have been developed can be used to design the control system. Guidance and navigation visualization systems can be developed based on the models. Simulation that is built by the models of the underwater glider will eliminate the need for a dedicated and costly support ship during the real experiments and deployment. Moreover, simulation can provide the efficient way to develop the control design algorithm and observe underwater glider's performances.

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