A Practical Path Tracking Method for Autonomous Underwater Gilders using Iterative Algorithm

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***Abstract*—This paper proposes a path tracking method to solve the engineering problem that how to keep gliders travelling along predetermined routes automatically without using ocean current information. The path tracking method is low cost in computational and without additional sensors on gliders. In the first half year of 2015, two sea trials of glides with different purposes were implemented, in which the path tracking is in use to reduce the cost of manual observation. The final trajectory of gliders and other related results show that the path tracking method is practical and effective.**

Keywords—underwater glider; path tracking; regional ocean observation

I. INTRODUCTION

Autonomous Underwater Gliders, which are driven by buoyancy, are a group of unmanned underwater vehicles (UUVs). Since underwater gliders are suitable for long-term ocean observation, some gliders have achieved commercial such as the Slocum [1], the Spray [2] and the Seaglider [3], while other gliders are on the stage of engineering application such as SeaWing gliders developed by Shenyang Institute of Automation (SIA), Chinese Academy of Sciences. In ocean observation missions, path planning for gliders is a popular research topic which has been well study by using the ocean model with developed algorithms for path planning [4-6].

Different from general path planning, path tracking is a practical engineering problem in applications that gliders are requested to traveling along a predetermined route in an effective and economic way. In an ideal condition to track a path, the heading angle of an underwater glider on the path is the vector direction of the path from the starting point to the point of termination. However, in practical application, there are two factors cause that underwater gliders cannot simply follow the heading angle settings mentioned above: a) the influence from ocean currents, b) the influence from the glider's flaws, such as flexibility of the glider's wings, asymmetry of the glider's installation, and the heading deviation of electronic compass.

Manual adjustment of glider's course is a very direct method to eliminate the influences from ocean currents and glider's flaws to path tracking. However, the frequent interferences of human are bound to increase manual workload, which is difficult to bear in long-term missions.

It can be another theoretical feasible solution that automatic adjustment of the heading angle using satellite remote sensing data to provide a priori knowledge of current information for the glider. But it depends on the accuracy of the satellite data, and requires a lot of computing resources. In addition, the influence to path tracking caused by the glider itself is not considered in this method.

In this work, a "generalized current" concept is defined and used in order to considering and eliminating the both influences to glider's course: it is assumed that the influence of glider's flaws is another kind of current influence, which varies with the movement direction of the glider. This "generalized current" is a superposition of the ocean current and the virtual current about the glider's influence, which can be obtained by the glider's historic trajectory in the mission without an additional payload of current sensors.

II. BASIC STRATEGY

When diving and climbing in the sea, the heading angle of a glider can be kept using a heading closed-loop controller. However, lack of sensors for dead reckoning and thanks to the influences from ocean currents and the glider's installation flaws, the glider's actual horizontal track in a yo-yo profile must be distorted and difficult to be predicted by kinematic model simulation. In this work, the deviation between the theoretical track and the actual track is assumed to be caused only by the "current". In other word, glider's installation flaws is considered as another component of current to affect glider's horizontal track just like the original ocean current. This current based on hypothesis is defined as the generalized current (Figure1).

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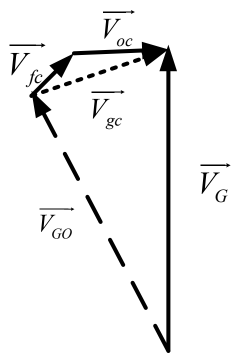

Fig. 1: Definition of the generalized current: $\overrightarrow{V_{GO}}$ is the theoretical horizontal velocity of glider, and $\overrightarrow{V_G}$ is actual horizontal velocity of glider. In this paragraph, $\overrightarrow{V_{gc}}$ is defined as the velocity of generalized current, which has two component: velocity of ocean current $\overrightarrow{V_{oc}}$, and velocity of the visual current about the glider's installation flaws $\overrightarrow{V_{fc}}$.

After each yo-yo profile is finished, the glider obtains its own location information on the surface of sea which is used to calculate the actual horizontal track in the last profile of the glider, while the theoretical track can be calculated using the kinetic model[7]. Since the time cost to the last profile is recorded, the generalized current velocity can be calculation directly by its definition.

The forecast information of generalized currents in next profile is a tricky part in this work, which is discussed in III based on an iterative algorithm to continuously improve the forecast of the generalized currents.

According to the kinematic characteristics of the glider and the forecast information of generalized current, the movement range of the next yo-yo profile can be predicted. Affected by the generalized current, the range of the glider's movement is usually an eccentric circle relative to the present position of the glider. Using the geometry relationship between the eccentric circle and the predetermined path, an optimal heading direction can be designed to make the glider move along the path effectively.

A block diagram of the basic strategy of the path tracking method is shown as Figure 2.

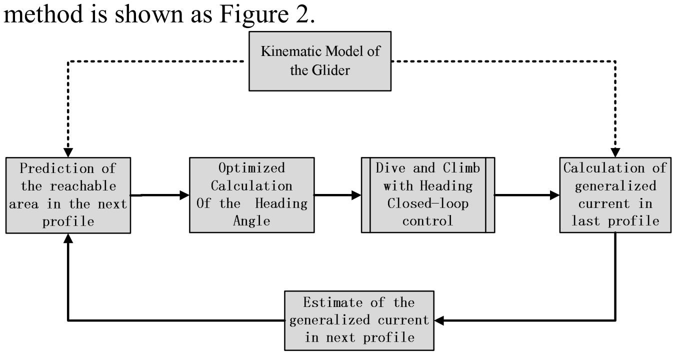

Fig. 2: A block diagram of the basic strategy of the path tracking method.

III. Estimate of the Generalized Current

It is assuming that the glider has just finished the *k*th yo-yo profile with settings: pitch angle θ_k , heading angle δ_k . The glider dived to the depth h_k , and had the actual horizontal track vector $\overrightarrow{D_k}$ in the *k*th profile. The attack angle of the glider α_k can be obtained from calculating of the kinematic model. Therefore, the vector deviation $\overline{\Delta d_k}$ between the actual trajectory and the theoretical trajectory in the *k*th profile of can be calculated by using the equation (1).

$$\overline{\Delta d_k} = \overrightarrow{D_k} - 2\bullet\tan(\theta_k + \alpha_k)\bullet h_k \angle \delta_k \tag{1}$$

Therefore, the generalized current velocity in the *k*th profile is

$$\overline{v_{gck}} = \frac{\overline{\Delta d_k}}{t_k} \tag{2}$$

When the glider is approaching to the *k+1*th profile, the generalized current $\overline{v_{gc(k+1)}}$ in the *k+1*th profile should be estimated before the glider dives.

Since the generalized current has two components: deep average oceans current and visual current about glider's installation flaws, both of which can be assumed nearly stable or changing slowly with time, the estimate of the generalized current $\overline{v_{gck+1}}$ in the of the *k+1*th profile can be described using the historical generalized current velocity, as equation (3)

$$\overline{v_{gc(k+1)}} = f(\overline{v_{gck}}, \overline{v_{gc(k-1)}}, \overline{v_{gc(k-2)}}, \overline{v_{gc(k-3)}}, \ldots) \tag{3}$$

In this work, we choose a weighted average expression with window *w* to set up an iterative algorithm briefly described below to calculate $\overline{v_{gc(k+1)}}$.

$$\overline{v_{gc(k+1)}} = \frac{\sum_{i=0}^{w} a_i \bullet \overline{v_{gc(k-i)}}}{\sum_{i=0}^{w} a_i} \tag{4}$$

The window *w* is a positive integer, which suggest that only several recent profiles' generalized current velocities act on the next profile's estimate and make the iterative algorithm work on improving the effect of estimates. The window *w* can be programmed on-line when the glider is in the mission

The weights a_i , where all of which are decimals between 0 and 1, can also be programmed on-line. The weights a_i imply the degrees of generalized currents in each historical profile to impact the generalized current estimate of the next glider's profile, and the inequality (5) should be followed to make the generalized current of the latest profile dominant in the estimate.

$$a_i > \sum_{j=i}^{w} a_j \text{ , where } i= 0,1,...w\text{-}1 \quad (5)$$

The choice of w and a_i should consider the rate of ocean currents' changing in the specific sea area and the time cost in each profile of the glider.

IV. OPTIMIZED CALCULATION OF THE HEADING ANGLE

The goal of estimating the generalized currents is to calculate the heading angle to make sure that the glider travels along the routes or returns to the routes effectively.

Let $\overrightarrow{P_1P_2}$ be a predetermined route that a glider needs to track, and the glider is on the spot P_0 after the *k*th profile. From kinematic model of the glider, the time cost t_{k+1} and the theoretical horizontal velocity $\overrightarrow{v_{0(k+1)}}$ in the *k+1*th profile can obtained by using kinematic characters of the glider and profile settings such as pitch angle, depth to dive, and volume of net buoyancy to drive.

Considering with the generalized current estimated velocity $\overrightarrow{v_{gc(k+1)}}$ in the of the *k+1*th profile, the glider's reachable area is an eccentric circle L_1 relative to the spot P_0 (Figure 3), and the center P_0' and the radius R of the circle L_1 satisfies the equation (6) and the equation (7) .

$$\overrightarrow{P_0P_0'} = \overrightarrow{v_{gc(k+1)}} \bullet t_{k+1} \quad (6)$$

$$R = \overrightarrow{v_{0(k+1)}} \bullet t_{k+1} \quad (7)$$

Let H be the distance between the spot P_0' and the route $\overrightarrow{P_1P_2}$.

If $H < R$, then L_1 has two intersections with $\overrightarrow{P_1P_2}$ represented by P_3 and P_4 while $|P_3P_2| < |P_4P_2|$. The direction angle $\angle\overrightarrow{P_0'P_3}$ will be the heading angle of the glider in the *k+1*th profile (Figure 3).

If $H \geq R$, then L_1 has only one or no intersection with $\overrightarrow{P_1P_2}$. In this condition, the heading angle should be set vertical to $\overrightarrow{P_1P_2}$ directly.

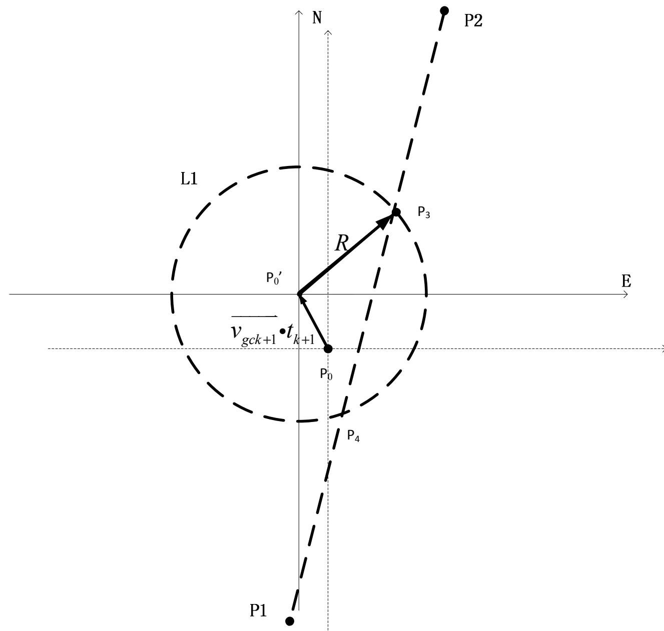

Fig. 3: Optimized calculation of the heading angle considering with the generalized current estimated velocity.

V. SEA TRIAL RESUALTS

In the first half of 2015, two sea trials for different purposes have been implemented using the SeaWing gliders (as Figure 4). In both of the sea trials, gliders traveled along predetermined routes automatically using the path tracking method mentioned above.

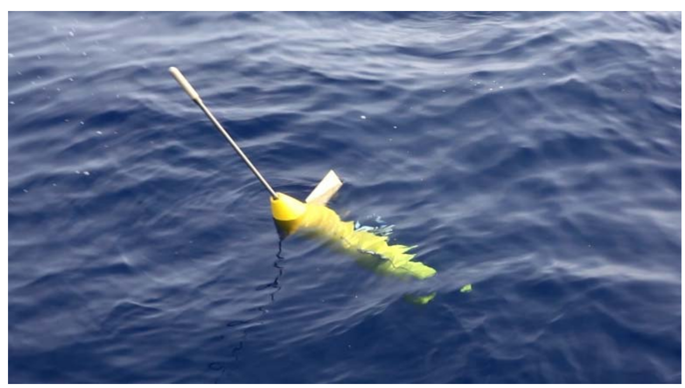

Fig. 4: A SeaWing Glider (1000m-class) which was developed by Shenyang Institute of Automation (SIA), Chinese Academy of Sciences.

A. The sea trial for regional ocean observation

In March 2015, a glider was launched in a regional ocean observation mission, in which the glider was required to get near-real-time data about the western boundary current of China South Sea.

During this 25 days mission, the practical automatic path tracking method was used to ensure that the glider traveled along the predetermined routes (as Figure 5).

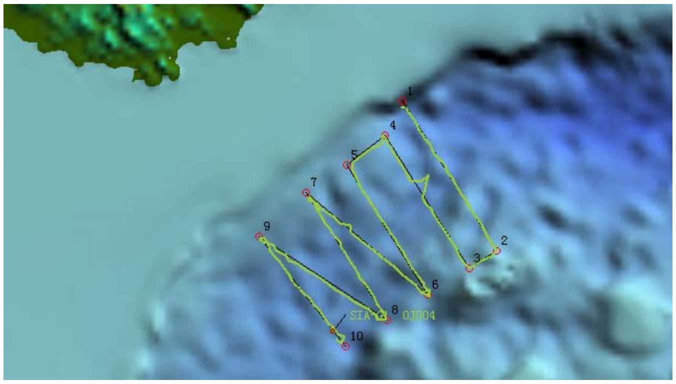

Fig.5. The final trajectory of the SeaWing glider in the mission of continuous regional ocean observation in March 2015 (25 days, 742 km).

Figure 6 shows the distance between the glider's location and the predetermined path when each profile finished. It infers that at most time the glider was within 1 kilometer from the routes among the 170 yo-yo profiles.

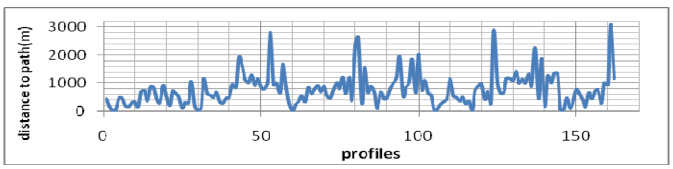

Fig.6. The distance between the glider's location and the predetermined path when each profile is finished.

Since the vector of generalized current of every glider's profile is automatically calculated and recorded, the vector map for the generalized current along the whole trajectory can be gotten as Figure 7.

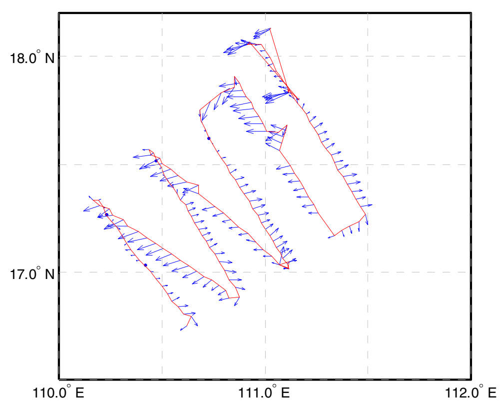

Fig.7. The vector map of the generalized current extracted from each profile in the regional ocean observation mission.

A distinct phenomenon is the vector map of the generalized current is that the direction of generalized current is always perpendicular and left-pointing to the direction of the glider, which is quite different from the pattern of deep average ocean current. The reason of this phenomenon was that the glider's flaws, especially asymmetry of the glider's installation, are the main factor affecting the glider's course deviation. Figure 8 shows the roll angle's change of the glider in a typical profile from the mission. Since SeaWing is a rudder-controlled glider, the asymmetry of the glider's installation makes a fixed and significant roll angle which cannot be adjusted to zero when glider diving or climbing under water. The roll angle produces a rotational torque which affects the deviation of glider's course and the calculation of the generalized current.

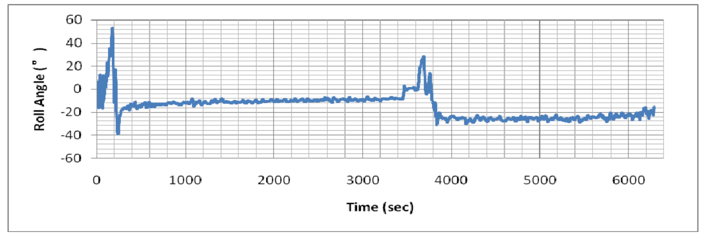

Fig.8. the roll angle change of the glider in a typical profile from the mission: the significant roll angle made a rotational torque which affect the deviation of glider's course and the calculation of the generalized current

B. The sea trial for long range travelling

From April to June in 2015, four gliders were launched in the long range travelling mission to test the performance and autonomy of SeaWing gliders.

During this 47 days mission, the four gliders made 617 yo-yo profiles in total, and the longest duration of one single glider was 35 days, 205 profiles.

In this mission, the gliders were required to travel along the routes between several check points automatically. Figure 9 shows the final trajectory of one glider (Serial No: SIA-G1000J005) from the four, and the trajectory coincided with the routes very well.

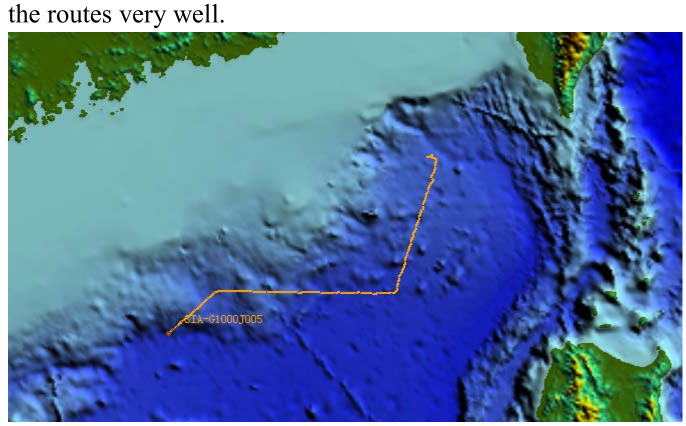

Fig.9. The final trajectory of the glider SIA-G1000J005 in the mission of long range travelling from April to May, 2015 (20 days, 645.7 km), and the other gliders tracked the routes as well.

In this mission, the glider's installation had been improved and made a better performance in heading control. Figure 10 shows that the roll angle was approaching with zero, and the vector map for the generalized current along the whole trajectory is similar to the pattern of deep average ocean current(Figure 11).

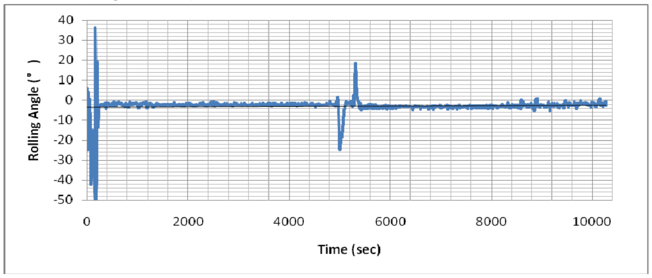

Fig.10. the roll angle change of the glider SIA-G1000J005 in a typical profile from the mission.

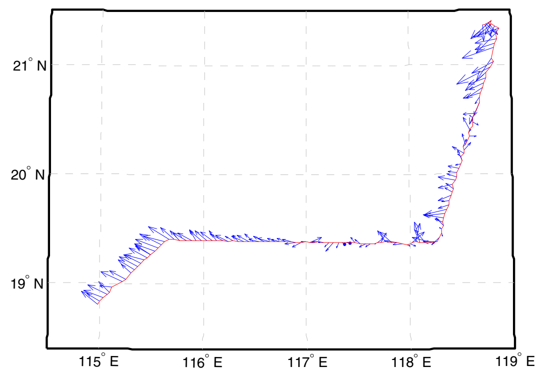

Fig.11. The vector map of the generalized current extracted from each profile of the glider SIA-G1000J005 in the long range travel mission.

VI. CONCLUSIONS AND FURURE WORK

Table 1 shows the means and variances of The distance between the gliders and the routes when each profile is finished in the long range travelling mission, which infers that the path tracking method is practical and effective.

TABLE I. MEANS AND VARIANCES THE DISTANCE BETWEEN GLIDER'S LOCATION AND THE PREDETERMINED ROUTES

Glider Serial No.	Means(meter)	Variances(meter）
1000J002	590.4	815.7
1000J005	534.28	761.7
1000J006	987.6	1282.5
1000J003	740.2	988.5

Although the path tracking method successfully used in the sea trials, there is still some work to do to improve the method, such as:

- Extension of the method to the applications that ocean currents change rapidly.
- Real-time update of weight parameters and the window parameter in equation (4) to make the algorithm more adaptively.
- Modeling the glider kinematic more accurately and filter generalize current with a novel algorithm to make the calculation of the generalize current more valuable to get the information of the ocean current field.

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REFERENCES

[1] D.C.Webb, P.J.Simonetti, and C.P.Jones, "SLOCUM, an underwater glider propelled by environmental energy", IEEE Journal of Oceanic Engineering, vol. 26, 2001, pp. 447-452.

[2] J.Sherman, R.E.Davis, W.B.Owens, and J. Valdes, "The autonomous underwater glider "Spray"," IEEE Journal of Oceanic Engineering, vol. 26, 2001, pp. 437-446.

[3] C.C.Eriksen, T.J.Osse, R.D.Light, T.Wen, T.W.Lehman, P.L.Sabin, J.W.Ballard, and A.M.Chiodi, "Seaglider: A long range autonomousunderwater vehicle for oceanographic research", IEEE Journal of Oceanic Engineering, vol. 26, 2001, pp. 424-436.

[4] Dushyant Rao, Stefan B. Williams, Large-scale path planning for Underwater Gliders in ocean currents, Australasian Conference on Robotics and Automation (ACRA), 2009.

[5] Josep Isern-Gonz´alez, Daniel Hern´andez-Sosa, Enrique Fern´andez-Perdomo, Jorge Cabrera-G´amez, Antonio C. Dom´ınguez-Brito and V´ıctor Prieto-Mara˜n´on, Path planning for underwater gliders using iterative optimization, IEEE International Conference on Robotics and Automation, 2011, pp. 1538-1543.

[6] Ryan N. Smith, Jonathan Kelly and Gaurav S. Sukhatme, Towards Improving Mission Execution for Autonomous Gliders with an Ocean Model and Kalman Filter, IEEE International Conference on Robotics and Automation, 2012, pp. 4870-4877.

[7] Shaowei Zhang, Jiancheng Yu, Aiqun Zhang, and Fumin Zhang, " Steady three dimensional gliding motion of an underwater glider", IEEE International Conference on Robotics and Automation, 2011, pp. 2392-2397.