Path Planning Method of Underwater Glider Based on Energy Consumption Model in Current Environment

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Abstract. It is generally considered that the speed of underwater glider is the function of buoyancy and gliding angle. However, the buoyancy and gliding angle are adjustable, which makes the speed of underwater glider within an adjustable range, however, it is usually taken as a constant in current documentations. Considering the path planning in ocean currents, if the maximum speed of a glider can find a path that connects the start point and the target point, then it can decrease its consumption by adjusting its speed in current field of some regions to fit the favorable currents and overcome the influence of adverse currents. Based on the above facts, the paper presents a new path planning method of adjustable speed glider in currents, and the simulation result is shown. According to the result: compared with the path planning method in constant speed, the adjustable speed glider can utilize the current in a better way and save the consumption of energy in a further way.

Keywords: optimal energy consumption, adjustable speed, iteration, underwater glider, path planning.

1 Introduction

Underwater gliders are a class of Autonomous Underwater Vehicles (AUVs) that are buoyancy-driven, deploying with lower operating cost and long duration in the ocean deployments. They go especially well with marine observation and have been used extensively in oceanography of late[1][2][3]. Their speeds are typically lower than motor-driven AUVs, reaching a maximum speed of around 1knot.Due to the low surge speed, they are susceptible to ocean currents.

Path planning of AUVs have been discussed in many literatures. At the beginning, the only consideration was the obstacles in ocean environment without currents [4][5][6].Till 2005,Garau et al. [7] transformed obstacles of A* graph search algorithm into unreachable grid points in ocean currents, then the path planning in currents field had been widely researched. Based on[7],the author of [8]built Rapidly-Exploring Random Trees(RRTs) that connect the start point and the target point, then utilized A* algorithm to search a path with lower energy consumption, but the

X. Zhang et al. (Eds.): ICIRA 2014, Part I, LNAI 8917, pp. 142–152, 2014.

energy-consuming model they used was extremely simplified. Constraining the vehicle to move in an 8-connected grid also means that optimality is compromised in the graph discretisation alone, a continuous technique is desirable. Continuous planning techniques have been explored for both AUVs and gliders alike in[8][10][11]and[12] .Without the constraining of 8-connective,the problem had been considered further in [9]and[13]. The gliding motion control of underwater gliders can be described by considering a typical diving and surfacing cycle, but we can only control the glider at the surfacing cycle for the unavailable underwater communication. Meanwhile, in a typical cycle, compared with diving ,the time of surfacing can be neglected. Based on the above mentioned facts, authors of [9]and[13] proposed methods to determine optimal paths that account for the influence from ocean currents .

In the above literatures, speeds of AUVs are considered to be constant generally. For a underwater glider, once the structure is fixed, the water-referenced speed of underwater glider is the function of buoyancy and gliding angle[14][15][16],and we can adjust the water-referenced speed in a certain range by controlling the driven-buoyancy or pitching angle. Compared with vehicle of constant speed, the vehicle of adjustable speed can utilize currents far more efficient.

Based on a high efficiency path planning searching algorithm in ocean currents field, this paper describes and evaluates a new algorithm for glider path planning, which contains a precise energy consumption model. Once the path exists, the proposed scheme would choose the most appropriate speed of glider automatically to fit the currents, which actualized by a iterative optimization process, and it can save energy consumption further.

2 The Description of Current Field of Adjustable Speed Glider Path Planning

The information of ocean currents can usually be obtained from marine environment numerical prediction. And it can assume that local currents remain unchanged over a period of time. Once given the start point and the target point, if the maximum speed of glider can find a path that connects the start point and the target point, the optimization of energy consumption of the glider can be considered further. Assuming that the glider moving to a certain domain, if currents of the area are beneficial for the glider to drive to its target, the speed of glider can be considered to decrease to save the energy consumption. On the contrary, if the currents are unfavorable, glider is supposed to increase speed properly to overcome the influence of the currents. In that case, it can across the unfavorable region as soon as possible.

Assuming a domain D , global currents of the environment V_c, setting a start point p_1 and a target point p_N , the glider begin to perform its deployment from the start point. According to reference [17], the water-referenced speed of gliders has the following description in horizontal direction

$$v_{glider} = \cos\gamma\sqrt{\frac{B\cos\gamma}{K_{L0} + K_L\alpha(\gamma)}} \tag{1}$$

$$\alpha(\gamma) = \frac{K_L}{2K_D}\tan\gamma(-1 + \sqrt{1 - 4\frac{K_D}{K_L^2}\cot\gamma(K_{D0}\cot\gamma + K_{L0})}) \tag{2}$$

The K_{L0}, K_L, K_{D0}, K_D are lift and drag coefficients.By equation (1), v_{glider} is a function of the net buoyancy B and gliding angle γ .In this paper, the gliding angle is fixed as $\gamma = 20^\circ$, so v_{glider} is only the function of the buoyancy B . Setting the range of the net buoyancy B into $[B_{\min} \quad B_{\max}]$ and substituting into equation (1), the adjustable speed range of glider satisfied $v_{glider} \in [v_{r\min} \quad v_{r\max}]$

The goal of the path planning is to find a path with least energy consumption from the start point to the target point. The path of the glider is consist of gliding cycles one by one, but it can only be controlled when raising to the surface. Owing to this, there is no guarantee that the glider can arrive the target point precisely, so we set a target domain with center p_N . When the glider surfacing at a point located in the target domain, we regard the glider as to approach the target point. Therefore, all the way-points and the trajectory under the influence of currents between the each pair way-points composed a path $P = \{\mathrm{p}_1, \cdots \mathrm{p}_i, \mathrm{p}_{i+1} \cdots \mathrm{p}_N'\}$

Glider can be controlled at the location of way-points. The speed of glider is controlled by adjusting the net buoyancy of the glider. The bearing of the glider is controlled by adjusting the heading. Each pair of two adjacent way-points meet the relationship

$$\mathrm{p}_{i+1} = \mathrm{p}_i + \int_{T(i)}^{T(i)+t_s(i)} \mathrm{v}(\mathrm{x})dt \tag{3}$$

$t_s(i)$ is a gliding cycle time cost ,is the function of diving depth h, gliding angle γ and speed v_{glider}

$$t_s(i) = \frac{2h}{v_{glider,i}\tan\gamma}, v_{glider,i} \in [v_{r\min} \quad v_{r\max}] \tag{4}$$

Where v(x) is the glider speed referenced to ground, it is the vector sum of the current speed and water-referenced speed of the glider.

$$\mathrm{v(x)} = \mathrm{v}_{c}(\mathrm{x}) + \mathrm{v}_{glider}(\mathrm{x}) \tag{5}$$

The segment $\mathrm{p}_i\,\mathrm{p}_{i+1}$ corresponds energy consumption $E_{i,i+1}$. According to the reference [18]. The energy consumption of the underwater glider a gliding cycle can be divided into two parts: one is related to time, which is the power consumption of sensor and control unit, and the other part is the power consumption of buoyancy device and the position device, which has nothing to do with the time. Addressed as follow.

$$E_{(i,i+1)t} = P_t \frac{2h}{\tan\gamma} \frac{1}{v_{glider,i}} \tag{6}$$

$$E_{(i,i+1)c} = \frac{2}{\rho g}(P_c + \frac{kh}{q_p})\left|K_{L0} + K_L\alpha(\gamma)\right|{v_{glider,i}}^2 \cos\gamma + K\tan\gamma \tag{7}$$

Among (7)

$$K = \frac{4P_m M\Delta h}{mv_m} \tag{8}$$

Therefore, the total energy consumption of a complete gliding cycle is

$$E_{i,i+1} = E_{(i,i+1)t} + E_{(i,i+1)c} \tag{9}$$

The problem of glider path planning in the current environment can be described as below:

Given: The global information current field V_c The adjustable range of glider net buoyancy is $B \in [B_{\min}\ B_{\max}]$, The glider dynamic model, the start point p_1 , the target point p_N .

Required: path $P = \{\mathrm{p}_1, \cdots \mathrm{p}_i, \mathrm{p}_{i+1} \cdots \mathrm{p}_N'\}$,the corresponding energy consumption , time consumption and the glider control law of every way-point in the path $\mathrm{p}_i \to (v_{glider,i}, \theta_i), i = 1, 2 \cdots N$

Planning objectives and constraint conditions are as follows:

$$\min E=\sum_{i=1}^{i=N}E_{i,i+1}=P_t\frac{2h\cos\gamma}{\sin\gamma}\sum_{i=1}^{i=N}\frac{1}{v_{glider,i}}+\frac{2}{\rho g}(P_c+\frac{kh}{q_p})\left|\frac{K_{L0}+K_L\alpha(\gamma)}{\cos^3\gamma}\right|\sum_{i=1}^{i=N}v^2{}_{glider,i}$$
$$+nK\tan\gamma$$
$$s.t. \tag{10}$$
$$v_{glider}=\cos\gamma\sqrt{\frac{B\cos\gamma}{K_{L0}+K_L\alpha(\gamma)}}$$
$$B\in[B_{\min}\ B_{\max}],\theta\in[0\ 2\pi)$$
$$\left|\mathrm{p}_N-\mathrm{p}_N^{'}\right|\le C$$

3 Path Planner Introduction

There exist plenty of constant speed AUVs path planning algorithms in ocean currents. The method CTS-A* is a variant of the classic A* where the time between two consecutive surfacings is kept constant. This method discretizes the bearings that can be commanded on each surface. Since it is a high efficiency path planning method for underwater gliders, this paper adopt this method and improve it slightly. A glider energy consumption model and a novel heuristic function are integrated in CTS-A*,and then iterative optimization process is implemented. Ultimately, we gain a minimum energy consumption path.

CTS-A* includes a notable modification to the original A* algorithm. The main difference between the two is the process of generating successors:

1)For the glider at node p_i ,the water-referenced speed is $v_{gliderC}$,which is kept constant. We select K sample bearings in $0\sim360^\circ$ to represent all bearings .While we neglect the vertical currents, the time of a gliding cycle can be calculated as $t_s=\dfrac{2h}{v_{gliderC}\tan\gamma}$. For each bearing θ_k we integrate the glider trajectory for the surfacing time t_s .i.e. we compute the trajectory followed by a glider that keeps a bearing θ_k under the influence of instantaneous ocean currents, which is described in(3).

2) The final location p_{i+1} of each trajectory is stored in the Nearest Neighbor node, which is shown is Fig.1. The Nearest Neighbor nodes are regarded as the generating successors in CTS-A*, rather than node p_{i+1} .

3) If two locations fall into the same node, we take the one with lower cost. If both have the same cost, we take the closest to the node.

4) Although the Nearest Neighbor node has been stored, node p_{i+1} should be selected as the current node in the next turn of generating successors (from p_{i+1} to p_{i+2}),rather than the Nearest Neighbor node.

For classic A* and variants of the classic A*, choosing a appropriate heuristic function may cause a significant influence of the algorithm efficiency. It is generally believed that if the cost of heuristic function is less than the real cost, then the optimal solution can be got. Corresponding with the energy consumption mode, we can divide the cost of heuristic function into two parts, one part of which is associated with time, and the other part has no relationship with time. The time in the first part should be minimized. Since the time is the product of distance and the reciprocal of resultant speed, we should maximize the resultant speed and minimize the distance from current node to the goal. The distance from p_i to p_N can be described as below:

$$d = |p_i - p_N| \tag{11}$$

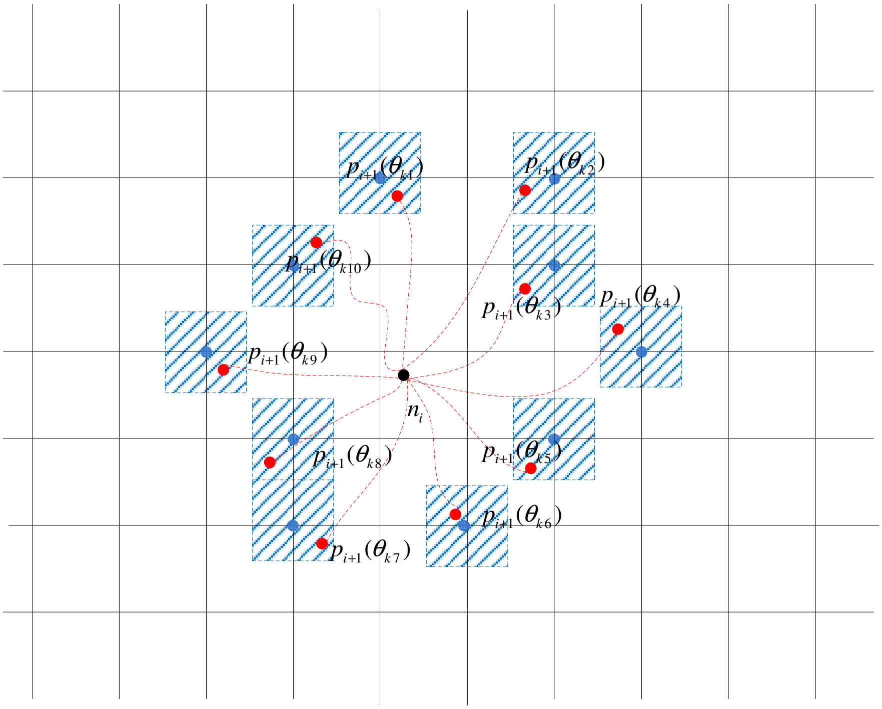

Fig. 1. Schematic diagram of the successors generated in CTS-A*

While the resultant speed should be maximized, considering the constant glider speed, we choose the maximum current speed in the domain as the estimated current speed, then add their absolute value together as the resultant speed. In that case, the time t_p can be expressed as follows:

$$t_p = \frac{d}{\left|v_{gliderC}\right| + \left|v_{c\max}\right|} \tag{12}$$

When considering the term that has no association with time, we found that the number of gliding cycles is the only factor that should be taken into account. In calm water, the horizontal distance is fixed with $2D_h = \frac{2h}{\tan\gamma}$,so the minimum number of total cycles is $\left\lceil \frac{d}{2D_h} \right\rceil = \left\lceil \frac{d\tan\gamma}{2h} \right\rceil$,in which, the symbol $\lceil \bullet \rceil$ means ceiling. Adding the two energy consumption terms ,it is obviously that the heuristic function can be written as below:

$$h(\mathrm{x}) = P_t t_p + E_{(i,i+1)c}\left\lceil \frac{d}{2D_h} \right\rceil \tag{13}$$

Substituting(7) and(12)to(13), we obtain the energy consumption heuristic function as

$$\begin{aligned} h(\mathrm{x}) = {} & P_t \frac{d}{\left|v_{gliderC}\right| + \left|v_{c\max}\right|} \\ & + \left\lceil \frac{d\tan\gamma}{2h} \right\rceil \left(\frac{2}{\rho g}\left|(P_c + \frac{kh}{q_p})(K_{L0} + K_L\alpha(\gamma))\cos\gamma\right| v_{gliderC}{}^2 + K.\tan\gamma\right) \end{aligned} \tag{14}$$

This paper uses CTS-A* with heuristic function (14) as the basic search algorithm, then repeat the iteration with different water-referenced speeds, to realize the further energy consumption optimization between the two adjacent way-points. The final goal is to make sure the less consumption globally compared with the constant velocity situation. In section 2, we obtain the range of glider speed $v_{glider} \in [v_{r\min} \quad v_{r\max}]$ within the range B allowed, then we select n samples of it to represent all values, so $v_{glider} \in \{v_{r1}, v_{r2} \cdots v_{rn}\}$.

In currents environment, given start point p_1 and target point p_N ,we utilize CTS-A* to search path by different v_{glider} ,if the path exist, then the optimal energy consumption can be got. Assuming that the global energy consumption is E_1 and the corresponding constant speed $v1 \in \{v_{r1}, v_{r2} \cdots v_{rn}\}$,the path can be written as $P_1 = \{\mathrm{p}_1, \mathrm{x}_{1,1}, \cdots \mathrm{x}_{1,n}, \mathrm{x}_{1,n+1} \cdots \mathrm{p}_{N1}\}$. E_1 can be divided into two parts: one part is the energy cost from p_1 to $\mathrm{x}_{1,1}$,and the other part is the energy consumption from $\mathrm{x}_{1,1}$ to p_{N1} .

$$E_1 = E_{p_1,\mathrm{x}_{1,1}} + E_{\mathrm{x}_{1,1},\mathrm{p}_{N1}} \tag{15}$$

Saving the first way-point p_1 ,second way-point $\mathrm{x}_{1,1}$ and the corresponding energy consumption $E_{p_1,\mathrm{x}_{1,1}}$ between the two adjacent way-points of path P_1 , $\mathrm{x}_{1,1}$ is regarded as the new start point and target point is kept the same. If we reuse CTS-A* to search paths from $x_{1,1}$ to p_N, the path $\{x_{1,1},\cdots x_{1,n},x_{1,n+1}\cdots p_{N1}\}$ would be found, and the corresponding energy cost is $E_{x_{1,1},p_{d1}}$. Generally, it may found less energy consumption path $P_2=\{x_{1,1},x_{2,1}\cdots x_{2,n},x_{2,n+1}\cdots p_{N2}\}$, which corresponding energy cost $E_{x_{1,1},p_{N2}}$,and $E_{x_{1,1},p_{N2}}\le E_{x_{1,1},p_{N1}}$,then we save the first way-point $x_{1,1}$,second way-point $x_{2,1}$ and the corresponding energy consumption $E_{x_{1,1},x_{2,1}}$ .Repeating the iterative process until we get path $P_k=\{x_{k-1,1},p_{Nk}\}$,at this time, p_{Nk} is just located in the domain of target point p_N .We found all the saved way-points constitute a new path $P=\{p_1,x_{1,1},x_{2,1},x_{3,1},\cdots x_{k-1,1},p_{Nk}\}$ .If we let $x_{i,1}=p_{i+1},p_{dk}=p_N^{'}$,the path can be written as $P=\{p_1,\cdots p_i,p_{i+1}\cdots p_N^{'}\}$,and the total energy consumption of P is the sum of each segment.

$$E=E_{p_1,x_{1,1}}+E_{x_{1,1},x_{2,1}}+\cdots E_{x_{k-1,1},p_{Nk}} \tag{16}$$

From above mentioned, apparently, the inequation $E\le E_1$ could be satisfied.

4 Simulation and Analysis

With hydrodynamic parameters testing, the hydrodynamic parameters of glider model it the part 2 can be listed as follows:

$$K_{L0}=-0.421, K_L=488.7837, K_{D0}=6.7143, K_D=435.052$$

$$P_t=3W, P_{p0}=20.618W, k=0.0459W/m, P_v=12W$$

$$q_p=4.0\times10^{-3}L/s, q_v=2.6\times10^{-3}L/s, M=65kg$$

$$m=11.278kg, Pm=16W, v_m=3.5\times10^{-3}m/s, \rho=1.025kg/L$$

$$\Delta h=0.05m$$

In addition, we set the gravitational acceleration $g=9.8m/s^2$, and fixed the maximum depth of glider every cycle as $h=200m$ within $100km\times100km$ domain.The environment is divided into squares $1km\times1km$. Assume that the underwater glider net buoyancy $B\in[0\ \ 8]N$, we select five samples to represent all values of B, $B=[0.2465\quad 0.9861\quad 2.2187\quad 3.9443\quad 6.1630]N$, which corresponds to $v_{glider}=[0.1\quad 0.2\quad 0.3\quad 0.4\quad 0.5]m/s$,it is convenient to calculate. In CTS-A*,we set 20 glider bearings in every generating successors process, and the 20 glider bearings distributed uniformly in $[0\quad 360^\circ)$. As the underwater glider can only be controlled when surfacing, this paper argues that the glider diving into the target domain（1.1kilometer, one horizontal distance of a gliding cycle in calm water approximately） can be regarded as the target is arrived. Maximum depth of every diving cycle is fixed $h = 200m$ .gliding fixed angle is $\gamma = 20^\circ$,the horizontal speed of the glider is only associated with buoyancy B . The start point is（15.1 ,40.2） ,the target point is (70,70). The current field is described as a moment of hyperbolic currents. Hyperbolic currents and the parameters are defined as follows:

$$x = \frac{xx}{100}, y = \frac{yy}{100}, \quad xx = 1:100, yy = 1:100$$

$$u = -\pi A \sin(\pi f(x)) \cos(\pi y)$$

$$v = \pi A \cos(\pi f(x)) \sin(\pi y) \frac{df}{dx}$$

Among then $f(x,t) = a(t)x^2 + b(t)x, a(t) = \varepsilon \sin(\omega t), b(t) = 1 - 2\varepsilon \sin(\omega t)$, A 、 ε are related to the amplitude of the current field. ω represents frequency. Setting $A = 0.4, \varepsilon = 0.25, \omega = 0.2\pi$,and setting t=6s, Fig.2. shows the simulation result. Given in table 1, speed of 0.3 m/s under the constant velocity of CTS-A *algorithm and adjustable speed obtained respectively under the iterative solution of energy consumption and time .Fig. 3. shows the iterative algorithm to get the path to the specific control scheme.

Table 1. hyperbolic currents, constant CTS - A * (0.3 m/s) and get the path of the energy consumption under variable iteration time list

The speed of the glider	CTS-A*(0.3m/s)	Variable iteration
Time consumption	20.5749h	21.1164 h
Energy consumption	3.1728×10^5J	2.5787×10^5J
Corresponding color	green	black

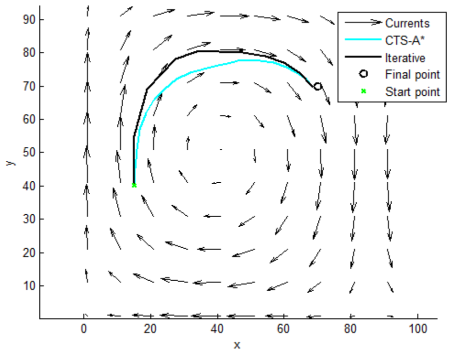

Fig. 2. The simulation results of the hyperbolic currents

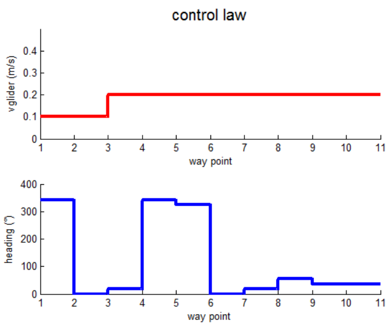

Fig. 3. The specific control scheme

Analyzing of simulation results can be found that within a given speed range, using variable iteration scheme, we get a path of energy consumption is only 81.3% of the energy consumption under constant speed, saving nearly 20% of the energy consumption, and time consuming only spent 2.63% more than constant speed situation. We can conclude that using the proposed iterative scheme can obtain a better energy consumption path, and from the point of view of time, it is still acceptable.

5 Conclusion and Future Works

This paper presents a novel CTS-A* based iterative path planning algorithm to address underwater gliders with variable speeds, which avoids the deficiency of constant speed path planning. It can maximize the usage of the favorable currents, while overcome the adverse currents as well. Once a path obtained under the maximum speed, the proposed scheme can be implemented. A accurate energy consumption model and a novel heuristic function are included in the path planner, which make the path planning problem far more close to the real situation. From the simulation of hyperbolic currents field, it can be easily found that our novel variable speed scheme can get a path with lesser energy cost compared with constant speed scheme, while the increasing of time is not obvious, and the control law was demonstrated as well, which illustrates the scheme can be actualized not so hard.

In future work we will generalize the scheme into three-dimensional current field and time-varying current field.

Acknowledgments. The authors would graciously acknowledge the support for this work provided by the glider research teams of Underwater Research Center, Shenyang Institute of Automation.

References

1. Blidberg, D.R.: The Development of Autonomous Underwater Vehicles (AUV): A brief summary. In: IEEE International Conference on Robotics and Automation (2001)
2. Eriksen, C.C., et al.: Seaglider: a long-range autonomous underwater vehicle for oceanographic research. IEEE Journal of Oceanic Engineering 26, 424–436 (2001)
3. Sherman, J., Davis, R.E., Owens, W.B., Valdes, J.: The autonomous underwater glider 'Spray'. IEEE Journal of Oceanic Engineering 26, 437–446 (2001)
4. Carroll, K.P., Mc Claran, S.R., Nelson, E.L., Barnett, D.M., Friesen, D.K., William, G.N.: AUV path planning: an A* approach to path planning with consideration of variable vehicle speeds and multiple, overlapping, time-dependent exclusion zones. In: Proceedings of the 1992 Symposium on Autonomous Underwater Vehicle Technology, pp. 79–84 (1992)
5. Tan, C.S., Sutton, R.: J, Chudley. Anincremental stochastic motion planning technique for autonomous underwater vehicles. In: Proceedings of IFAC Control Applications in Marine Systems Conference, pp. 483–488 (2004)

6. Petres, C., Pailhas, Y., Petillot, Y., Lane, D.: Underwater path planning using fast marching algorithms. In: Oceans 2005-Europe, vol. 2, pp. 814–819 (2005)
7. Garau, B., ´ Alvarez, A., Oliver, G.: Path Planning of Autonomous UnderwaterVehicles in Current Fields with Complex Spatial Variability: an A* Approach. In: Proc. 2005 IEEE International Conference on Robotics and Automation, pp. 194–198 (2005)
8. Rao, D., Williams, S.B.: Large-scale path planning forUnderwater Gliders in ocean currents. In: Australasian Conference on Robotics and Automation (ACRA), Sydney, December 2-4 (2009)
9. Fernandez-Perdomo, E., Cabrera-Gamez, J., Hernandez-Sosa, D., Isern-Gonzalez, J., Dominguez-Brito, A.C., Redondo, A., et al.: Path planning for gliders using Regional OceanModels: Application of Pinzón path planner with the ESEOAT model and the RU27 trans-Atlantic flight data. In: OCEANS 2010 IEEE - Sydney, pp. 1–10 (2010)
10. Soulignac, M., Taillibert, P., Rueher, M.: Adapting the wavefront expansion in presence of strong currents. In: Proceedings of the 2008 IEEE International Conference on Robotics and Automation, pp. 1352–1358 (2008)
11. Soulignac, M.: Feasible and Optimal Path Planning in Strong Current Fields. IEEE Trans. Robot. 27(1), 89–98 (2011)
12. Soulignac, M., Taillibert, P., Rueher, M.: Time-minimal Path Planning in Dynamic Current Fields. In: Proceedings of the 2009 IEEE International Conference on Robotics and Automation (2009)
13. Isern-Gonzalez, J., Hernandez-Sosa, D., Fernandez-Perdomo, E., Cabrera-Gamez, J., Dominguez-Brito, A.C., Prieto-Maranon, V.: Path planning for underwater gliders using iterative optimization. In: 2011 IEEE International Conference on Robotics and Automation (ICRA), May 9-13, pp. 1538–1543 (2011)
14. Leonard, N.E., Graver, J.G.: Model-based feedback control of autonomous underwater gliders. IEEE J. Ocean. Eng. 26(4), 633–645 (2001)
15. Graver, J.G.: Underwater glider s: Dynamics, control, and design.Ph.D. dissertation, Dept. Mech. Aerosp. Eng. Princeton Univ., Princeton, NJ (2005)
16. Mahmoudian, N., Woolsey, C.: Underwater glider motion control. In: Proc. 47th IEEE Conf. Decision Control, Cancun, Mexico, December 9-11, pp. 552–557 (2008)
17. Yu, J., Zhang, F., Zhang, A., Jin, W., Tian, Y.: Motion parameter optimization and sensor scheduling for the sea-wing underwater glider. IEEE Journal of Oceanic Engineering, 243–254 (2013)
18. Zhu, X., Yu, J., Wang, X.: Sampling path planning of underwater glider for energy consumption. Robot 33(3), 360–365 (2011)