## Miniature Underwater Glider: Design and Experimental Results

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Miniature Underwater Glider: Design and Experimental Results

Feitian Zhang, Student Member, IEEE, John Thon, Cody Thon and Xiaobo Tan, Senior Member, IEEE

Abstract—The concept of gliding robotic fish combines gliding and fin-actuation mechanisms to realize energy-efficient locomotion and high maneuverability. Such robots hold strong promise for mobile sensing in versatile aquatic environments. In this paper we present the design and implementation of a miniature glider, a key enabling component for gliding robotic fish. The steady-state glide equation is first presented and then solved numerically for given net-buoyancy and movable mass displacement. Scaling analysis is conducted to understand the trade-off between the glide performance and energy cost. Comprehensive design for the glider is provided. Experimentation and modeling analysis are further conducted to investigate the impacts of movable mass displacement, net buoyancy, and wing size on the gliding performance.

Index Terms—Miniature underwater glider, gliding robotic fish, underwater robotics, modeling.

I. INTRODUCTION

There is a growing interest in monitoring aquatic environments with autonomous underwater robots. Application examples include patrolling seaports, tracking oil spills, and monitoring harmful algal blooms. The robots need to be highly energy-efficient to maintain sustained field operation, and at the same time be highly maneuverable to negotiate versatile environments [1]. Underwater seagliders are known for their great energy-efficiency and long-duration operation in oceanographic applications [2]. An underwater glider utilizes its buoyancy and gravity to enable motion without any additional propulsion, and adjusts its center of gravity to achieve certain attitude. Energy is needed only for the adjustment of buoyancy and center-of-gravity when switching the glide profile, which makes underwater gliders very energy-efficient, as proven by the great success of the Seaglider [3], Spray [4] and Slocum [5]. The maneuverability of underwater gliders, however, is quite limited. The large size (1–2 m long), heavy weight (50 kg and above), and high cost [2] of these vehicles also impede their adoption in non-ocean environments such as ponds, rivers, and inland lakes. On the other hand, over the past two decades, there has been significant interest in developing robots that mimic live fish. Often called robotic fish, they accomplish swimming by deforming the body and fin-like appendages [6–12]. While robotic fish typically have high maneuverability (e.g., small turning radius), they require constant actuation for swimming and cannot work for extended periods of time without battery recharge.

The concept of gliding robotic fish [1] combines the desirable features of both an underwater glider and a robotic fish. Such a robot would realize most of its locomotion through gliding and thus be energy-efficient. On the other hand, it would be much smaller than a traditional underwater glider, and use actively controlled fins to achieve high maneuverability. Given that fin-actuated robotic fish have been demonstrated by a number of researchers, the key challenge in developing gliding robotic fish is to realize a miniature underwater glider that can be readily integrated with fin-actuation mechanisms.

In this paper, we present the design of a miniature underwater glider, and report, to our best knowledge, the smallest untethered glider that has been demonstrated in the literature. While the general concept of the presented miniature glider is similar to ocean gliders, its size constraint introduces new challenges in performance analysis, design, and hardware implementation. Addressing these challenges is the goal and contribution of this paper. The steady glide model is used to design the robot that meets the speed specifications while accommodating size and weight constraints. In particular, we introduce a metric, horizontal travel distance per unit energy consumption, that captures the trade-off between gliding performance and energy consumption, and analyze how this metric and the speed scale with dimensions for a given glider profile.

We have successfully developed a prototype of miniature underwater glider featuring changeable wings. Measuring only 50 cm long and weighing 4.2 kg, the glider has demonstrated desired glide profile and speed performance. For example, with a net buoyancy of 20 g only, it achieves a total glide speed of about 20 cm/s and a horizontal speed of 14 cm/s. The volume and net buoyancy of this glider are less than 10% and 5%, respectively, of those of underwater gliders reported in the literature. We have conducted extensive experimentation along with modeling analysis to characterize and understand the dependence of gliding angle and speed on the movable mass displacement, net buoyancy, and wing size.

II. MATHEMATICAL MODEL OF AN UNDERWATER GLIDER

A. The Model in the Sagittal Plane

We model the miniature underwater glider as a rigid-body system, which has an external force and a moment exerted by an internal movable mass. The focus of this paper is the gliding motion in the sagittal plane, since maneuvers involving
other planes will be enabled by fin-actuation, which is outside the scope of this paper.

The body-fixed reference frame, denoted as $O_{xy}$, and shown in Fig. 1, has its origin $O$ at the geometric center, so the origin will be the point of application for the buoyancy force. The $O_x$ axis is along the body’s longitudinal axis pointing to the head; the $O_z$ axis is perpendicular to $O_x$, axis in the sagittal plane of the miniature glider pointing downwards. The pitch angle $\theta$ is defined as the angle between $O_x$ and the horizontal plane with nose up as positive. $v_b = [v_1, 0, v_3]$ stands for the translational velocity of the glider, expressed in the body-fixed reference frame.

We define the velocity reference frame $O_{x_1y_1z_1}$, where $O_{x_1}$ axis is along the direction of velocity, and $O_{z_1}$ lies in the sagittal plane perpendicular to $O_{x_1}$. The angle of attack $\alpha = \arctan (v_2/v_1)$ is defined as the angle between the velocity direction ($O_{x_1}$ axis) and the $O_{x_0}$ axis. The hydrodynamic forces include the lift force $L$ along the negative $O_{z_1}$ axis and the drag force $D$ along the negative $O_{x_1}$ axis; the hydrodynamic moment includes the pitch moment $M$ in $O_{z_1}$ axis. The gliding path angle $\theta_g = \theta - \alpha$ is defined as the angle between velocity direction and the horizontal plane with gliding up as positive.

In our design, we follow the idea of Slocum, changing the center of gravity by translating a mass (e.g., the battery) inside the glider and changing the net buoyancy through pumping water in and out of an internal tank [5]. During steady glide, the angular velocity is zero, while the velocity stays unchanged. Based on the glider’s full dynamics from literature [13], [14] and our previous work [15], the steady-state glide equations in the sagittal plane can be derived and expressed as

$$0 = -m_0 g \sin \theta + L \sin \alpha - D \cos \alpha,$$  
$$0 = m_0 g \cos \theta - L \cos \alpha - D \sin \alpha,$$  
$$0 = M + (m_3 - m_1) v_1 v_3 - m g r_{m0} \sin \theta$$  
$$- m_0 g (r_{m0} \cos \theta + r_{m0} \sin \theta) - m g r_p \cos \theta.$$  

Here, $m_1$ and $m_3$ are the sums of the body mass and the added mass in the $O_{x_0}$ and $O_{z_0}$ directions, respectively. $m_0$ is the mass of fluid that the glider body displaces; $m_0$ is the excess mass or the negative net buoyancy, presenting the difference between $m$ and the glider total mass, with displacement $r_{m0} = [r_{m0x}, r_{m0y}, r_{m0z}]$ relative to the origin $O$; $m$ is the movable mass, with displacement of $r_m$ along $O_{x_0}$ axis; $r_{cg}$ is the displacement of glider’s center of gravity along $O_{z_0}$ axis; $g$ represents the acceleration of gravity.

In the steady-state gliding motion, the control variables $r_p$ and $m_0$ are constant (fixed control inputs), meaning that the position of the movable mass is fixed and the pumping rate is zero. The solution to the above equations gives us the steady gliding path.

B. Hydrodynamic Model

The hydrodynamic model is similar to what has been used for airfoils and discussed in [14]. The hydrodynamic forces and moment are generally dependent on the angle of attack $\alpha$ and the velocity magnitude $V$ [16]:

$$D = \frac{1}{2} \rho V^2 S D_0(\alpha) = \frac{1}{2} \rho V^2 (C_D 0 + C_D^\alpha \alpha^2),$$  
$$L = \frac{1}{2} \rho V^2 S L_0(\alpha) = \frac{1}{2} \rho V^2 (C_L 0 + C_L^\alpha \alpha),$$  
$$M = \frac{1}{2} \rho V^2 S M_0(\alpha) = \frac{1}{2} \rho V^2 (C_M 0 + C_M^\alpha \alpha).$$

where $\rho$ is the density of water and $S$ is the characteristic area of the glider. Here $C_D 0$, $C_L 0$, and $C_M 0$ are the drag, lift, and pitch moment coefficients, respectively, with constant parameters $C_D 0$, $C_L 0$, $C_M 0$ and $C_M^\alpha$.

III. DESIGN OF A MINIATURE UNDERWATER GLIDER

A. Computation of Steady Gliding Path

We consider a glider geometry with a streamlined, fish-like profile (Fig. 2(a)), in the interest of facilitating realization of future gliding robotic fish. As a comparative trial, another set of wings is used with the same wingspan but doubled aspect ratio (i.e., chord length is half), while the glider body is left unchanged (Fig. 2(b)). CFD-based water-tunnel simulation can be used to obtain the hydrodynamic coefficients for a given glider body geometry [17], as we did in [15].

The steady gliding equations (1)–(3) are highly nonlinear due to the terms involving trigonometric functions and inverse trigonometric functions in the state. We numerically solve steady gliding equations for given control inputs, under different conditions for the location of glider center of gravity.

Table I shows scan results of steady gliding paths for both wing designs illustrated in Fig. 2. From the results, we can see that the larger wings result in shallower gliding paths (longer horizontal travel) but slower total speed compared to the smaller wings, given the same set of control inputs. On the other hand, the results in the table show that, for a fixed wing design, the pitch angle is affected mainly by the pair $(r_p, r_{cg})$. Therefore, the center of gravity plays an important role in determining the steady gliding attitude. In particular, with
TABLE I

**COMPUTED STEADY GLIDING PATH UNDER DIFFERENT VALUES OF THE CENTER OF GRAVITY \( r_{cg} \), THE MOVABLE MASS DISPLACEMENT \( r_p \), AND THE EXCESS MASS \( m_0 \), FOR THE TWO MODELS SHOWN IN FIG. 2. (a) LARGER WINGS; (b) SMALLER WINGS.**

<table>
<thead>
<tr>
<th>( r_{cg} ) (cm)</th>
<th>( r_p ) (cm)</th>
<th>( m_0 ) (g)</th>
<th>((V_0, \alpha, \theta_0)) (m/s, (^{\circ}), (^{\circ}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.3</td>
<td>10</td>
<td>(0.1129 3.0470 -29.5523)</td>
</tr>
<tr>
<td>0.1</td>
<td>0.7</td>
<td>10</td>
<td>(0.1485 1.9396 -52.7389)</td>
</tr>
<tr>
<td>0.1</td>
<td>0.7</td>
<td>30</td>
<td>(0.1766 3.9483 -25.0827)</td>
</tr>
<tr>
<td>0.1</td>
<td>0.7</td>
<td>30</td>
<td>(0.2495 1.3300 -48.7594)</td>
</tr>
<tr>
<td>0.2</td>
<td>0.3</td>
<td>10</td>
<td>(0.0856 5.8988 -20.2069)</td>
</tr>
<tr>
<td>0.063</td>
<td>0.3</td>
<td>30</td>
<td>(0.1486 1.7575 -56.4820)</td>
</tr>
<tr>
<td>0.112</td>
<td>0.3</td>
<td>30</td>
<td>(0.2260 3.2732 -41.9002)</td>
</tr>
<tr>
<td>0.094</td>
<td>0.3</td>
<td>30</td>
<td>(0.2598 1.6385 -58.0061)</td>
</tr>
<tr>
<td>0.094</td>
<td>0.3</td>
<td>30</td>
<td>(0.1129 3.0470 -29.5523)</td>
</tr>
</tbody>
</table>

other parameters fixed, a smaller \( r_{cg} \) results in higher speed and larger glide angle. This observation has been used in our design – by making \( r_{cg} \) small, we can achieve desired glide angle with very small displacement of the movable mass.

**B. Scaling Analysis**

We study the larger-wing glider model (Fig. 2(a)) at different scales and introduce a new cost performance index, which reflects the horizontal travel distance per unit energy consumption. For one dive (descent and ascent), the horizontal travel distance \( D_d \) is approximated as

\[
D_d = V_h t_d = 2 V_h h / V_v,
\]

where \( V_h \) and \( V_v \) are the steady-state horizontal speed and vertical speed, respectively, \( t_d \) is the travel time for one dive, and \( h \) is the vertical travel depth. The energy consumption in one dive comes from two sources, the pump actuation and the movable mass actuation, while the energy consumed for the latter is negligible compared to that for pumping since the pump needs to overcome large pressure when the glider switches to ascent from descent. So the energy consumption per dive \( E_d \) can be approximated as

\[
E_d = \rho g h_0 S_p l_p + \rho g (h_0 + h) S_p l_p.
\]

Here, \( \rho \) is the water density, \( h_0 \) is the equivalent water depth of the atmosphere pressure, \( S_p \) is the cross-section area of the pump tank inlet (and outlet) and \( l_p \) represents the length of the water column if the water pumped in each cycle is placed in a cylindrical container with cross-section area \( S_p \). Noting the net buoyancy \( m_0 = \frac{1}{g} S_p l_p \), we further simplify the energy consumption per dive to

\[
E_d = 2 m_0 g (h_0 + h).
\]

Then we have the horizontal travel distance per unit energy consumption

\[
D_d / E_d = V_h / V_v m_0 1 / (2 h_0 / h).
\]

For a specific task, the depth is fixed and we have

\[
D_d / E_d \propto V_h / V_v m_0,
\]

which we define as the cost performance index \( \tau \).

**TABLE II**

**COMPUTED STEADY GLIDING PATH FOR THE SCALLED MODELS OF THE LARGER WING PROTOTYPE. IN COMPUTATION, \( r_p = 5\text{mm} \) IS USED FOR THE ORIGINAL SCALE MODEL (1:1) WHILE THE VALUE IS SCALLED LINEARLY WITH DIMENSION FOR OTHER MODELS.**

<table>
<thead>
<tr>
<th>scale</th>
<th>mass (kg)</th>
<th>( m_0 ) (kg)</th>
<th>( V_h ) (m/s)</th>
<th>( V_v ) (m/s)</th>
<th>( \frac{V_h}{V_v m_0} ) (kg)</th>
<th>glide ratio</th>
</tr>
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<tbody>
<tr>
<td>0.25:1</td>
<td>1</td>
<td>0.0075</td>
<td>0.063</td>
<td>0.018</td>
<td>488.35</td>
<td>3.2</td>
</tr>
<tr>
<td>0.5:1</td>
<td>2</td>
<td>0.015</td>
<td>0.11</td>
<td>0.039</td>
<td>203.25</td>
<td>2.6</td>
</tr>
<tr>
<td>1:1</td>
<td>4</td>
<td>0.031</td>
<td>0.19</td>
<td>0.094</td>
<td>74.55</td>
<td>2.4</td>
</tr>
<tr>
<td>2:1</td>
<td>8</td>
<td>0.06</td>
<td>0.28</td>
<td>0.207</td>
<td>28.30</td>
<td>1.33</td>
</tr>
<tr>
<td>4:1</td>
<td>16</td>
<td>0.12</td>
<td>0.39</td>
<td>0.377</td>
<td>12.01</td>
<td>1.03</td>
</tr>
<tr>
<td>8:1</td>
<td>32</td>
<td>0.24</td>
<td>0.54</td>
<td>0.574</td>
<td>5.72</td>
<td>0.94</td>
</tr>
</tbody>
</table>

![Fig. 3. The glider performance index with respect to the model scale.](image1)

![Fig. 4. The horizontal velocity with respect to the model scale.](image2)
earlier, pumping is considered to be the main source of energy expenditure for large-depth glides. However, a larger-scale glider is able to achieve faster horizontal speed as shown in Fig. 4. There is a trade-off between the achieved horizontal speed and the horizontal distance coverage per unit energy cost, when selecting the optimal scale for the glider. Other factors, like the dimension and the mass of the sensors and actuation devices, should be also taken into account in the design process.

C. Implementation of Glider Prototype

The final weight and size for our glider are 4.2 kg and 50 cm, respectively. These values and the shape of the robot are based on the above scaling analysis, expected payload (environmental sensors) requirements, and limitations on existing actuators. The glider needs to have a (total) glide speed of about 20 cm/s, to counteract the currents typically seen in a pond or lake environment. The glider takes a fish-like shape profile, but it is not modeled after any species.

As the dimensions shrink, the design difficulty increases. Fig. 5 shows the internal configuration of the glider. The battery pack is moved back and forth along a guide track system using a linear actuator (Firgelli L16-140-63-12-P) with accuracy of 0.4 mm. The pump (Flight Works Model 300C) is connected to an internal cylindrical tank system. A microcontroller (Microchip dsPIC30f6014A) is used to control the actuators and interface with sensors. The charging port and circuit switch are packaged in the tail part. The sealing for the assembly is achieved through matching O-rings and screws. There are several ballast tanks inside, used to balance the glider. The voltage regulators and heat sinks are mounted at the wing base, to dissipate heat quickly. A pressure sensor (Honeywell 40PC100G2A) is soldered on the PCB board, with its pressure port connected to the rear bottom of the glider body, where the pumping port is also located. The outer shell is made of carbon fiber. The wings are made of aluminum and can be easily switched for different sizes and shapes. For the results reported in this paper, the first set of wings used has trapezoidal shapes with wingspan of 16 cm (one side) and aspect ratio of 1.45, while the second set of wings for comparative trial has the same wingspan and aspect ratio of 2.9 (refer to Fig. 2).

IV. EXPERIMENT

A. Experimental Setup

Underwater gliding experiments have been conducted in a large indoor water tank that measures 5 m long, 3.3 m wide, and 1.3 m deep to validate the model. We set the initial net buoyancy (negatively buoyant) and the linear actuator position to desired values. Then the glider is released from the water surface and dives down into steady glide motion. After it reaches the programmed depth the glider pumps water out and resets its attitude to glide up. We focus on the gliding-down section as the gliding-up motion is observed as similar to and approximately symmetrical to the gliding-down motion. We record the whole gliding process with an underwater video camera fixed inside the water tank, pointing directly to the glide motion plane (Fig. 6). We conduct video post-processing to extract the steady gliding data, including the operating depth, horizontal travel distance, and the time spent. Considering image distortion, we have made a grid board for calibration, which measures 2.5 m by 1.5 m with grid cell size of 10 cm by 10 cm. The image of the grid board, taken at the same distance as the glider, is superimposed into the video to help reduce the measurement error.

B. Experimental Results

Fig. 7 and Fig. 8 show the comparison between model predictions and experimental results when we vary the movable mass position while holding the net buoyancy fixed, and Fig. 9 and Fig. 10 show the results when the net buoyancy...
is changing while the movable mass location is fixed. For each fixed control setup, experiments are repeated 10 times to calculate the average and standard deviation.

Parameters for model prediction are identified based on the prototype used in the experiment. The added masses are calculated using slender body theory. The displacement of excess mass is modeled as \( r_{m_0} = (k_1 m_0, 0, k_2) \) where \( k_1 \) and \( k_2 \) are constant. This equation shows the dependence of the displacement of excess mass on the value of the mass itself. The center of gravity \( r_{cg} \) is measured by hanging the glider up at different points on the glider with strings and then taking the intersection of different hanging strings.

The comparison results show that the velocity and glide angle calculated from the model match the experimental data reasonably well. In particular, the model has predicted well the trends that the glider speed increases with increase of the net buoyancy or the movable mass displacement while the glide angle increases with decrease of the net buoyancy or increase of the movable mass displacement. We note that there are some nonnegligible factors contributing to the discrepancies between the model predictions and experimental measurements. Those factors include model parameter identification errors, nonideal experimental processes, and environmental disturbances. In particular, the hanging method for determining the center of gravity and the CFD simulation for obtaining hydrodynamic coefficients can introduce parameter errors. In experiments, due to the finite tank size, the influence from the accelerating period of the miniature glider after the initial release from water surface cannot be diminished to none. Due to the limited depth of the tank, the glider cannot fully reach the steady state within the measurement period. The flow disturbances in the tank and the wall effect also contribute to the differences between experimental results and model predictions. So with these uncertainties, we consider the match between our experimental results and the model predictions in Figs. 7–10 satisfactory.

We have further compared the experimental result with model prediction when the glider is equipped with the smaller wings. Fig. 11 and Fig. 12 show the glide angle and the glide speed, respectively, as the movable mass displacement is varied while the net buoyancy is held fixed at \(-20\) g. From the results, we can see that model predictions and experimental measurement match well with smaller wings just like with the larger wings. Furthermore, comparing the gliding performance at the same control configuration (Figs. 7, 11, and Figs. 8, 12), we find that the glider with smaller wings tends to have a deeper glide profile and higher speed than with larger wings, which renders the robot less affected by the flow disturbances, leading to better match than with larger wings. These results further validate our derived model, and prove the effectiveness of our design method in Section III. The results also indicate that we can realize various gliding performance and meet different mission requirements by replacing the wings, which are designed to be easy to change.
of the robot. While the presented model in this work describes the robot behavior under open-loop control inputs, in reality the robot is subject to ambient flow disturbances and it is thus important to stabilize a desired glide path through feedback control. Therefore, we will also instrument the glider with accelerometers and gyros, and investigate feedback control strategies that accommodate the highly nonlinear dynamics of the robot and environmental uncertainties. With the gliding element in place, we will further study the design, development, and control of a gliding robotic fish, where an actively caudal fin will be integrated with the miniature underwater glider to enable both swimming and gliding.

### V. Conclusion and Future Work

In this paper we presented the design of a miniaturized underwater glider as a key element for realizing gliding robotic fish. The design was carried out systematically with a steady-state model for the glider, and a prototype was successfully demonstrated. We validated the steady glide model via extensive underwater gliding experiments, and also explained the causes for observed discrepancies between the experimental results and the model predictions.

For future work, we will study the side wing influence on the gliding dynamics exploiting the changeable wing feature of the robot.