Mechatronic Design and Implementation of
a Novel Gliding Robotic Dolphin
Zhengxing Wu, Junzhi Yu, Jun Yuan, Min Tan, and Jianwei Zhang

Abstract—This paper provides an innovative design for a gliding robotic dolphin. In order to realize high maneuverability and long endurance, the robotic dolphin combines the advantages of both robotic dolphins and underwater gliders. It can not only realize fast and flexible dolphin-like swimming depending on the powerful propulsive posterior body and fluke, but also implement gently and durable gliding motion due to the buoyancy-driven system. More importantly, the controllable pectoral fins and horizontal fluke can effectively complete the attitude adjustment, so traditional internal movable masses could be removed for saving a considerable space. Besides, the hydrodynamic analysis in the steady gliding motion is executed and hydrodynamic coefficients including lift, drag, and pitching moment are also obtained through Computational Fluid Dynamics (CFD) method. Finally, extensive experiments including dolphin-like swimming, spiraling motion and gently gliding motion illustrate the great locomotion ability of the developed gliding robotic dolphin.

I. INTRODUCTION

Natural selection endows dolphins with striking swimming skills in characteristics of high speed, high maneuverability and adaptability [1]. As typical cetaceans, dolphins smartly utilize their strong and agile posterior bodies with flattened flukes to perform astonishing motions. They could easily reach a maximum swimming speed over 11 m/s, and complete a fast turn with a high speed (561.6°/s) and a small radius (0.20 body lengths, BL) [2], [3]. Moreover, dolphins could flexibly realize elegant acrobatic stunts, e.g., easily leaping up to several meters and then deftly making a turn in the air.

Since natural dolphins have such surprised swimming skills, the researchers focus on the dolphin-like swimming to explore a practical, effective and flexible propulsive mechanism. Thus, robotic dolphins, as necessary auxiliaries, have been increasingly developed in last two decades [4]–[6]. Generally, the present researches in the robotic dolphin mainly concentrate on the bio-inspired mechanism development, hydrodynamic analysis and the motion control. Nakashima et al. developed two generations of two-joint robotic dolphins to realize 3-D maneuverability [4]; Dogangil et al. presented a control algorithm for a pneumatically driven four-link robotic dolphin [7]; Yu et al. provided a closed-loop robotic dolphin control strategy based on the intrinsic oscillatory property to realize excellent acrobatic maneuvers such as frontflip and backflip (360° rotation in the vertical plane) [6]. With considerate mechanical designs and effective control strategies, these robotic dolphins always perform excellent capability for the dolphin-like swimming, especially high-maneuverability motions. However, due to their limited electric energy, they always have a poor endurance which extremely reduces their practical applications in oceans. Therefore, in this paper, we attempt to improve the capability of long endurance for a robotic dolphin and switch our attention to the gliding motion well known for extended duration.

Gliding motion was first inspired by Stommel in 1989 [8] and recently has caught much attention due to their long distance and extended duration [9]. Up to now, various underwater gliders have been developed and successfully applied in scientific research and ocean observatory, like three great successful commodities—Slocum [10], Seaglider [11] and Spray [12]. Generally, the underwater glider obtains vertical propulsive thrust through changing its buoyancy or weight which only needs a little energy. Then, the vertical motion could be converted into a sawtooth glide with the help from a pair of fixed wings and internal moveable masses. Therefore, the underwater glider could glide for a long distance with limited energy, e.g., the updated Slocum G2 could be able to last up to nearly 360 days and dive into over 1000 m depth [13].

The main purpose of this paper is to offer an innovative design for a gliding robotic dolphin to implement both high maneuverability and long endurance. As a combination of robotic dolphins and underwater gliders, the gliding robotic dolphin could not only realize a fast and flexible dolphin-like swimming, but also glide for a long distance due to the buoyancy-driven system. Compared with traditional underwater gliders and biomimetic ones [14], the gliding robotic dolphin has several special characteristics as follows:

1) Flapping posterior body. By means of the dolphin-like swimming mechanism, the gliding robotic dolphin could easily perform a much faster and more flexible motion than traditional underwater gliders.

2) Controllable pectoral fins. Traditional underwater gliders with fixed wings often utilize an internal moveable mass to adjust their attitude in gliding motion that may bring a slow response and also require a sufficient large space. Instead, the robotic dolphin adopts controllable pectoral fins to adjust the gliding attitude. Moreover,
the pectoral fins can also provide enough thrust for multimodal locomotion such as forward swimming, turning, descending, and ascending.

3) Flatten and horizontal fluke. It could not only produce a high propulsive speed in dolphin-like motion, but also provide considerable pitching torques due to the relative larger force arm.

These fascinating features make the gliding robotic dolphin can perform three kinds of motions including gliding motion, dolphin-like swimming with two-joint flapping, and stable pectoral propulsive motion. To the best of our knowledge, this is the first time that three hybrid motions have been successfully performed on the same robotic platform. Furthermore, the robot could adaptively choose appropriate motion mode relying on the mission and underwater environments.

The rest of this paper is organized as follows. The overall description of the mechanical design for the new gliding robotic dolphin is provided in Section II. Section III gives the detailed analysis in the steady gliding motion in the vertical plane. Experiments on the actual robot as well as analyses are further offered in Section IV. Finally, concluding remarks are given in Section V.

II. MECHANICAL DESIGN

For simplified mechanical design and easy installation, the gliding robotic dolphin adopts distinctive modularity concept. As shown in Fig. 1, the gliding robotic dolphin consists of six principal cabinets according to their own function: Head cabinet, Pectoral cabinet, Mission cabinet, Control cabinet, Waist cabinet, and Caudal cabinet. These cabinets adopt wired electrical connection and wireless command connection which can effectively improve the waterproof capability. Generally, the robotic dolphin is 1.13 m long and weighs 18.20 kg. Table I tabulates the basic technical parameters of the prototype. In order to improve the space utilization rate and lift-drag ratio, the robotic dolphin adopts a well-streamlined body shape modeled after killer whale. Meanwhile, a low-speed airfoil, NACA0018, is also employed to design the pectoral fins and flattened fluke for a better hydrodynamic performance.

To realize an excellent dolphin-like swimming, an effective and powerful propulsive unit is designed. The propulsive unit employs two pitching joints respectively called waist and cauda to execute symmetrical sinusoidal dorsoventral oscillations for enough propulsive thrusts. Two powerful DC motor (Maxon EC-4pole) with fast turn speed and strong torque are utilized to drive the posterior body up-and-down locomotion. Besides, the robotic dolphin also employs a yawing joint in Waist cabinet to achieve planar turning maneuvers. Alternatively, the turning maneuvers can also be realized through the pectoral fins in a high propulsive speed. In order to change the turning direction from roll to pitch, three group of reducing bevel gear set are employed by the body joints. These bevel gear sets are all made of titanium alloy which can not only reduce the weight but also avoid getting rusty. Notice that the adopted DC motors should be powered off to save energy when they need not work such as in a steady gliding motion. In this case, a brake system is utilized to keep the body locked.

On the other hand, a practical buoyancy-driven system which changing the buoyancy through draining off and pumping the water is developed to realize the gliding motion. As shown in Fig. 2, the buoyancy-driven system consists of a DC motor, transmission gear set, a guide screw with a brake, a push rod and an emulsion bag in a protective shell. When changing the buoyancy of the robotic dolphin, the DC motor turns to drive the guide screw to move back and forth through the transmission gear set. Simultaneously, the push rod begins to push and pull the emulsion bag in the protective shell. With the moving of the emulsion bag, the water is pumped and drained off to change the buoyancy of

![Fig. 1. Mechanical design of the gliding robotic dolphin.](image1)

![Fig. 2. Mechanical design of the buoyancy-driven system.](image2)

<table>
<thead>
<tr>
<th>Items</th>
<th>Characteristics</th>
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<tbody>
<tr>
<td>Size ($L \times W \times H$)</td>
<td>$\sim 1.125 \times 0.189 \times 0.208 \text{ m}^3$</td>
</tr>
<tr>
<td>Total mass</td>
<td>$\sim 18.2 \text{ kg}$</td>
</tr>
<tr>
<td>Number of the body joints</td>
<td>3 (Pitch: 2; Yaw: 1)</td>
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<tr>
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<td>DC motors, Digital Servomotor</td>
</tr>
<tr>
<td>On-board sensors</td>
<td>Attitude transducer, Depth sensor</td>
</tr>
<tr>
<td>Controller</td>
<td>ARM Cortex-M4</td>
</tr>
<tr>
<td>Power</td>
<td>NCR 18650B</td>
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</table>

TABLE I

**TECHNICAL SPECIFICATION OF THE DEVELOPED GLIDING ROBOTIC DOLPHIN**

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the robotic dolphin. Specially, a limit switch fixed on the top of the guide screw is utilized to keep the running range of the guide screw. Similar to the propulsive unit, the buoyancy-driven system is only powered on when needing to work. In order to gain additional pitching torques, the buoyancy-driven system is fixed in the head of the pectoral cabinet. So the changing volume of emulsion bag could provide pitching torques for attitude adjustment. Thus, an internal moveable mass which is necessary for traditional underwater gliders can be removed, and the robotic dolphin can effectively regulate its attitude with the pitching torques from the buoyancy-driven system and the controllable pectoral fins and horizontal fluke.

III. ANALYSIS OF THE STEADY GLIDING MOTION

In this section, we will develop a hydrodynamic analysis for the robotic dolphin during a steady gliding motion. In previous work about underwater gliders, Graver et al. derived a general hydrodynamic model and provided the planar equilibrium equations for a traditional underwater glider [15], [16]. Here we adopt the similar analysis. For the gliding robotic dolphin, the main difference is that we should separately analyze the hydrodynamic forces on the dolphin body, pectoral fins and flattened fluke because they could be controlled for a better gliding motion.

A. Determination of Coordinate Systems

To clearly describe the gliding motion of the robotic dolphin, coordinate frames including an inertial frame and a body reference frame are first defined, as shown in Fig. 3. The inertial frame $E_{XYZ}$ is considered to be earth-fixed and non-rotating, where the horizontal axes of $X$ and $Y$ are perpendicular to the gravity, and the $Z$ axis is along the positive gravity direction. The body reference frame $O_{XYZ}$ is fixed in the center of buoyancy (CB) of the robotic dolphin, where the $x$ axis is along the longitudinal axis of the robotic dolphin from fluke to head, and the $y$ axis is located in the plane of the pectoral shafts and $z$ axis follows the right-hand rule. Define $R$ as the rotation matrix from the body frame to the inertial frame. Let $b$ denote the vector from the origin of the inertial frame to the origin of the body frame.

B. Mass Distribution

Suppose that the pectoral shafts pass through the center of the mass (CM) of the pectoral fins, and the fluke shaft also passes through the CM of the horizontal fluke. Therefore, the position for the CM of the gliding robotic dolphin remains still even the pectoral fins and fluke turning. For the robotic dolphin, the whole masses consist of three parts: $m_b$ is a fixed mass including the mass of pectoral fins and horizontal fluke that is uniformly distributed throughout the body of the robotic dolphin; $m_r$ is also a fixed point mass which may be offset $r_b$ from CB of the robotic dolphin; $m_v$ is the variable ballast point mass, also offset $r_b$ from the CB. So the total mass of the robotic dolphin can be defined by $m_a = m_b + m_r + m_v$.

The mass of the displaced fluid is denoted as $m$. So the net buoyancy $m_0$ can be defined by $m_0 = m_a - m$. Therefore, the robotic dolphin is negatively (positively) buoyant if $m_0$ is positive (negative).

C. Hydrodynamic Analysis

Generally, the unsteady hydrodynamic of the robotic dolphin gliding in a fluid are extremely complex. These hydrodynamic forces and moments are from both viscous and in viscous effects. Because of the controllable pectoral fins and flattened fluke, the hydrodynamic forces and moments on dolphin body, pectoral fins and flattened fluke should be separately modelled as follows:

$$
\begin{align*}
L_i & = \rho C_{L_i}(\alpha_i) S_i n^2 \quad (i = body, lpec, rpec, fluke) \\
D_i & = \rho C_{D_i}(\alpha_i) S_i n^2 \quad (i = body, lpec, rpec, fluke) \\
M_i & = \rho C_{M_i}(\alpha_i) S_i n^2 \quad (i = body, lpec, rpec, fluke)
\end{align*}
$$

where $i$ = body, lpec, rpec and fluke denotes the related variable about the dolphin body, left pectoral fin, right pectoral fin and flattened fluke, $\alpha_i$ indicates the angle of attack of the robotic dolphin. $\alpha_i$ (i = lpec, repc and fluke) can be obtained through $\alpha_{body}$ and turn angles of pectoral fins and fluke. $C_{L_i}, C_{D_i}, C_{M_i}$ are the standard aerodynamic lift, drag and moment coefficients by cross sectional area for dolphin body, pectoral fins and fluke. $S_i$ denotes the maximum cross sectional area. $\rho$ indicates the fluid density. $n$ denotes the relative velocity of the robotic dolphin respect to the fluid.

Hydrodynamic force coefficients including $C_{L_i}, C_{D_i}, C_{M_i}$ could be determined using a variety of methods including airfoil theory, Computational Fluid Dynamics (CFD) methods, and flight tests. Here, CFD methods are employed to analyze the gliding performance of the robotic dolphin. Because the pectoral fins and flattened fluke can be controlled, we need separately compute the hydrodynamic coefficients about the dolphin body, pectoral fins and flattened fluke. For an accurate and convenient CFD simulation result, the commercial software ANSYS 15.0 including ICEM CFD and Fluent is employed [17].

In the pre-processing meshing work, an unstructured tetrahedron mesh is formed to describe the flow domain for great adaptability and high quality, as shown in Fig. 4. Meanwhile, seven prismatic layers are stacked onto the surface mesh for accurate simulation results. The whole computational domain
of the dolphin body is surrounded by the following boundaries: 1) Inlet boundary: 2.5 body lengths from the nose and set as velocity-inlet with \( v = 0.3 \) m/s; 2) Outlet boundary: 2.5 body lengths from the fluke and set as outflow; 3) Top and Bottom boundaries: set as velocity-inlet with \( v = 0.3 \) m/s in order to avoid reflected effect; 4) Farfield boundary: set as no-flip walls; 5) Surface boundary: set as no-slip moving walls. The CFD computational domain for the pectoral fins and flattened fluke adopt the similar boundary conditions. In Fluent simulation, suppose the fluid is incompressible and steady, and \( k-\omega \) SST (Shear-Stress-Transport) turbulence model with low-Re corrections is employed.

Generally, the hydrodynamic force coefficients are decided by various factors such as the angle of attack, sideslip angle, Reynolds number of the flow and so on. When modeling the steady gliding motion in the vertical plane, the hydrodynamic coefficients could be simplified as a function about the angle of attack, e.g., quadratic polynomial for a drag coefficient and monomial for lift coefficient according to previous results [16]. As for the dolphin body, we adopt the quartic polynomial to fit the curves of the hydrodynamic coefficients of the dolphin body for more accuracy results and the quadratic polynomial and monomial for the pectoral fins and flattened fluke. The hydrodynamic coefficients about the dolphin body, pectoral fins and flattened fluke are fitted as follows:

\[
\begin{align*}
C_{\text{body}}(\alpha) &= 4.749\alpha^4 - 0.111\alpha^3 + 0.556\alpha^2 - 0.007\alpha + 0.148 \\
C_{\text{body}}(\alpha) &= -1.833\alpha^4 + 4.997\alpha^3 - 0.072\alpha^2 + 0.485\alpha - 0.006 \\
C_{m\text{body}}(\alpha) &= 0.220\alpha^4 + 1.407\alpha^3 - 0.050\alpha^2 - 0.097\alpha + 0.005 \\
C_{\text{pec}}(\alpha) &= 1.555\alpha^2 - 0.003\alpha + 0.034 \\
C_{\text{pec}}(\alpha) &= 1.725\alpha \\
C_{m\text{pec}}(\alpha) &= -0.314\alpha \\
C_{\text{fluke}}(\alpha) &= 1.920\alpha^2 - 0.003\alpha + 0.069 \\
C_{\text{fluke}}(\alpha) &= 2.260\alpha \\
C_{m\text{fluke}}(\alpha) &= 1.424\alpha
\end{align*}
\]

D. Steady Gliding Motion in the Vertical Plane

When steady gliding in the vertical plane, the robotic dolphin gets the hydrodynamic equilibrium and the accelerated velocity and angular accelerated velocity are both zero. So it is easy to get the vertical plane equilibrium equations as follows [15]:

\[
\begin{align*}
\dot{x} &= v_x \cos \theta + v_z \sin \theta \\
\dot{z} &= -v_x \sin \theta + v_z \cos \theta \\
0 &= (m_z - m_x)v_v - mg(r_{h\text{h}} \cos \theta + r_{h\text{v}} \sin \theta) - m_w(r_{w\text{h}} \cos \theta + r_{w\text{v}} \sin \theta) + M_{D\text{total}} \\
0 &= -mg \cos \theta + L_{\text{Total}} + D_{\text{Total}} \\
0 &= mg \cos \theta + L_{\text{Total}} + D_{\text{Total}}
\end{align*}
\]

where \( v_x \) and \( v_z \) are respectively the components of the gliding velocity in the \( x \) and \( z \) directions. \( \theta \) denotes the pitch angle of the robotic dolphin. \( m_z \) and \( m_x \) are respectively the added mass terms corresponding to the \( x \) and \( z \) directions. \( L_{\text{Total}}, D_{\text{Total}}, M_{D\text{total}} \) respectively denote the sum of the hydrodynamic forces on the body, pectoral fins and fluke, as shown in the following equations.

\[
\begin{align*}
L_{\text{Total}} &= (L_{\text{body}} + L_{\text{pec}} + L_{\text{fluke}}) \sin \theta_{\text{body}} \\
D_{\text{Total}} &= -(L_{\text{body}} + L_{\text{pec}} + L_{\text{fluke}}) \cos \theta_{\text{body}} \\
M_{D\text{Total}} &= -(D_{\text{body}} + D_{\text{pec}} + D_{\text{fluke}}) \cos \theta_{\text{body}}
\end{align*}
\]

where \( I = \text{body}, \text{pec}, \text{repe} \) and fluke denotes the related variable about the dolphin body, left pectoral fin, right pectoral fin and flattened fluke. \( L_i, D_i \) respectively denote the hydrodynamic lift and drag on the body, left pectoral fin, right pectoral fin and flattened fluke, which can be obtained by (1) above.

According to the equilibrium equations, we can easily obtain the relationship between pitch angle \( \theta \) and the angle of attack \( \alpha_t \) for the robotic dolphin. As shown in (7), the pitch angle \( \theta \) only depends on the angle of attack \( \alpha_t \) and the lift coefficient, drag coefficient of the body, pectoral fins and flattened fluke. Therefore, we can easily control the pitch angle \( \theta \) or the angle of attack of the gliding robotic dolphin for an expected gliding motion through adjusting the turn angle \( \phi_i \) of pectoral fins and flattened fluke. Fig. 5 draws the gliding path angle \( \xi \) and pitch angle \( \theta \) varying with the angle of attack of the body \( \theta_{\text{body}} \) which is changed from \(-15^\circ\) to \(5^\circ\) with \( \phi_i = 0^\circ \). Generally, an excepted path angle \( \xi \) always locates in \([20^\circ, 40^\circ]\) which stands for an excellent gliding motion. According to Fig. 5, we can obtain that the angle of attack of body \( \theta_{\text{body}} \) should be controlled about in \([-10^\circ, -5^\circ]\) for an excellent gliding motion.

\[
\theta = \arctan\left(\frac{-\sum C_{L_i}(\alpha_t) \sin \theta_{\text{body}} - \sum C_{D_i}(\alpha_t) \cos \theta_{\text{body}}}{\sum C_{L_i}(\alpha_t) \cos \theta_{\text{body}} + \sum C_{D_i}(\alpha_t) \sin \theta_{\text{body}}}\right)
\]

We also execute some simulation experiments to explore how the turn angle \( \phi_i \) of pectoral fins and flattened fluke affect the gliding attitude of the robotic dolphin, as shown in Fig. 6. According to the blue and green curves in Fig. 6, we can see that a little adjustment for \( \phi_i \), about \( 5^\circ \), even with \( \phi_{\text{fluke}} = 0^\circ \), could successfully lead to an expected pitch angle near \( 30^\circ \) with a small \( \theta_{\text{body}} \). If we also adjust \( \theta_{\text{fluke}} \) at the same time, more apparent effects can be achieved, see the black...
Fig. 5. The relationship between pitch angle $\theta$ and the angle of attack $\alpha_i$.

Fig. 6. The relationship between pitch angle $\theta$ and the angle of attack $\alpha_i$.

and red curves in Fig. 6. These results illustrate that the controlled pectoral fins and flattened fluke will bring obvious effects for adjusting gliding attitude.

IV. EXPERIMENTS AND RESULTS

In order to evaluate the motion capability of the developed robotic dolphin for the dolphin-like swimming and gliding motion, extensive experiments were carried out in a 6 m depth diving pool.

A. Testing of Dolphin-Like Swimming

The first experiment focuses on the dolphin-like swimming including the body and/or caudal fin (BCF) locomotion and median and/or paired fin (MPF) locomotion. In order to produce efficient and effective dolphin-like swimming, a Central Pattern Generator (CPG) model based on Hopf oscillators was adopted. The details in the control method can be referred to our previous work [18], [19]. In BCF locomotion, the body CPGs are activated to generate the rhythmic signals, while the pectoral CPGs are inactivated to keep the pectoral fins horizontal. Similar to our previous results, the robotic dolphin could successfully realize forward swimming and flexible turn, and the propulsive speed increases directly with the flapping frequent. Moreover, the robotic dolphin could realize a spiraling motion in MPF locomotion. Fig. 7 depicts a slow spiraling motion of the robotic dolphin. In this experiment, the robotic dolphin obtained a left turn torque if the left pectoral fin has $5^\circ$ lower turn angle than the right one. Then, a descending motion can also be realized if both pectoral fins has a positive turning angle, e.g., $30^\circ$ in this experiment. Moreover, the robotic dolphin will reach a better spiraling motion if the buoyancy-driven system joins in to provide descending thrusts and moments.

B. Testing of Gliding Motion

The second experiment focused on the gliding motion. At the beginning, the robotic dolphin got a force balance in the surface of the water. When receiving the descending command, the robotic dolphin began to absorb the water to change its buoyancy and the pectoral fins synchronously turn a positive angle to provide some additional pitch torques. After several seconds, the robotic dolphin adjusted to gliding upwards through pumping the water and turning a negative angle for the pectoral fins, as shown in Fig 8(f). In order to obtain the gliding performance, several experiments were conducted.
executed under the different turn angles of pectoral fins, e.g., 15° and 30°, see Table II. Finally, the robotic dolphin successfully realized the gliding motion with about 0.155 m/s horizontal gliding speed when $\phi_{pec} = 15°$.

<table>
<thead>
<tr>
<th>$\phi_{pec}$ (°)</th>
<th>No.</th>
<th>Horizontal velocity (cm/s)</th>
<th>Vertical velocity (cm/s)</th>
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<td>#1</td>
<td>15.98</td>
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<td></td>
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<td>13.84</td>
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C. Discussion

The dorsoventral propulsive mechanism endows robotic dolphins with excellent swimming skills like high speed and high maneuverability. However, the limited endurance always curbs its practical applications. The gliding robotic dolphin effectively solves this problem by combining the gliding motion with flexible swimming. Through changing the net buoyancy, the gliding robotic dolphin only consumes a little energy to implement a long-distance glide. Coupled with the controllable pectoral fins and horizontal flatten fluke, the robotic dolphin can easily reach an expected path angle through adjusting the turn angles of pectoral fins and flatten fluke. Compared with the movable-mass method in traditional gliders, the robotic dolphin can easily and rapidly change its gliding attitude depending on the controllable pectoral fins and fluke. Moreover, the pectoral fins can successfully be utilized to realize multimodal locomotion, like forward swimming, turning, and spiraling motion. Depending on its high maneuverability capability, the gliding robotic dolphin can be qualified in many tough tasks, especially in a complex underwater environment.

On the other hand, the gliding robotic dolphin also has some difficulties at the present stage. As opposed to the cylinder shape of traditional gliders, the well-streamlined one of dolphins could lead to some difficulties in processing and manufacturing, although it can effectively reduce the hydrodynamic drag. However, with the development of 3D printing, it will become much easier in the future. The second one is the demands for high quality of seal airtight of driving shafts in the limited space. For example, some driving shafts like caudal shaft only has very little installation space and could not employ the traditional seal airtight with a large volume. These problems bring about difficulties in applications in deep oceans.

V. Conclusions and Future Work

In this paper we have developed a novel gliding robotic dolphin to implement both high maneuverability and long endurance. Concerning the dolphin-like swimming, the robotic dolphin could realize high propulsive speed depending on the powerful posterior body and fluke. As for the gliding motion, the robotic dolphin could achieve a steady gliding relying on its buoyancy-driven system. Moreover, the hydrodynamic analysis in the steady gliding motion are also performed to verify the great gliding ability of the robotic dolphin. Finally, aquatic experiments on the actual robot demonstrate hybrid propulsion modes involving gliding motion, dolphin-like swimming with two-joint flapping, and stable pectoral propulsive motion.

The ongoing and future work will focus on the closed-loop control and the motion transition strategy according to the assigned mission and complex underwater environment, since the robotic dolphin could realize three kind of motions including gently gliding for long distance, dolphin-like swimming for high speed, and propulsive motion for smoothness and steadiness.

References