Design and Preliminary Evaluation of A Biomimetic Underwater Robot with Undulating Fin Propulsion

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Abstract. Biomimetic undulating fin propulsion systems have the advantages for enhancing the maneuverability and efficiency of underwater robot when compared with conventional driving forms. However, there are still some defects existing in this approach, such as low speed and difficulty in depth control. This paper presents the mechanical design, control system design and experimental evaluation of a biomimetic underwater robot with undulating fin propulsion. First, a 3D model of the robot was established in CATIA. According to the kinematic model of the fins, the design of undulating fin propulsion system have been optimized and the phase control method has been proposed to fit with the design. Next, a control system with hybrid structure switching between autonomous mode and remote mode has been implemented to address the problem that the robot is out of control in underwater environment due to the attenuation of radio signals. Finally, the underwater locomotion performance of the robot has been validated in a swimming pool. The result indicates that the robot can achieve multiple degree of freedoms (DOFs) motions by controlling the kinematic parameters of the fin and was able to swim as fast as 31.6 cm/s (nearly 0.8 body length per second).

Keywords: Undulating fin propulsion; Biomimetic robot; Underwater robot.

1. Introduction

Currently, underwater vehicles typically adopt propellers or water pumps as their propulsion systems, which cannot meet the growing demand of underwater applications. On the contrary, the biomimetic robots outperform the conventional underwater robots in aspects of low noise, long duration and high maneuverability, which not only draw attentions of researchers but also widely used in the underwater applications, such as close-up exploration of underwater life [1], spatially explicit water column sampling [2] and water quality monitoring [3].

Fish are endowed with ideal shape and driving structure to swim under water agilely and efficiently. Imitation of the fish swimming patterns is an effective method to develop biomimetic underwater robot. According to the different parts of fish body utilized for propulsion, the swimming modes of fish consist of two main categories: Body and/or Caudal Fin (BCF) propulsion, and Median and/or Paired Fin (MPF) propulsion [4]. Undulating fin propulsion is a typical MPF mode, which is inspired by stingrays or knight fish, and often equipped with the characteristics of good maneuverability, environmental protection and high swimming efficiency at low speed. Therefore, a number of studies

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have been devoted to the modelling [5], computational fluid dynamics (CFD) simulation [6], hydrodynamic analysis [7] and control methods [8] of the undulating fin propulsion. Unlike BCF propulsion, the body of undulating fin robots can maintain its stability, which allows robots to be embedded with some sensors or modules (such as gyro sensor or camera) to obtain data or images without the interference of vibration. But undulating fin robots usually operate at lower speed due to their lower utilization of the body than that of BCF mode. Yangwei Wang et al. designed a freshwater stingray robot, and the maximum velocity was 4.3 cm/s (about 0.18 body lengths per second (BL/s)) [9]. Izaak D Neveln et al. tested a physical model of knife fish using a biomimetic ribbon fin which has 32 independent fin rays. The robot achieved a maximum swimming speed of 26 cm/s when the frequency was 3 Hz and the number of undulations was 2 [10]. Hyung et al. designed a soft morphing ray propulsor using shape memory alloy (SMA) for actuation [11]. The maximum speed of this robot is 0.26 BL/s. Michael Sfakiotakis et al. designed SQUIDBOT-mini robot[12]. The robot can restoring torque on the elastic membrane, the swimming speed could reach 23 cm/s (about 1 BL/s). The robots mentioned above are slower than most BCF mode robots except for SQUIDBOT-mini. Robots of BCF mode commonly reach the speed around 0.5 BL/s or even higher. SQUIDBOT-mini has only 3 fin rays on its both sides, so the number of waves along the fin is far less than one cycle, which results in the instability of pitch angle on the body and reduces the efficiency. Moreover, the length of the robot is relatively short when compared with its width, which is another reason for the instability.

Vertical movement ability of underwater vehicles is necessary for underwater work, but most robots cannot use undulating fin propulsors to achieve vertical motion, which limits the application field of them. Thus, these robots tend to assemble buoyancy control unit [12] or gravity location module [7], but these devices often consist of linear actuators, ball-screw/gear mechanisms, which are complicate and heavy. The motivation for this paper is to design a biomimetic underwater robot to overcome these defects. The principles of the design are as follows:

- High efficiency;
- Low noise;
- Untethered control;
- A comparable speed to BCF mode robots;
- Achieve vertical motion with only undulating fin propulsors.

Based on the above principles, a rajiform-type underwater robot was developed, as shown in Figure 1. The design of this robot combines requirements of mechanical structure design and control system design, such as shape design, gravity distribution and control method of multiple degree of freedoms (DOFs) motions. The performance of the robot was evaluated through underwater experiments.

**Figure 1.** The prototype of the undulating fin robot.

The rest of this paper is as follows. Section II describes the detailed mechanical structure. Section III gives the architecture of control circuit and motion control strategies. To evaluate the performance of this robot and the influence of kinematic parameters, underwater experiments were carried out in a swimming pool, and this part will be introduced in section IV. Section V presents the discussion, conclusion, and future work direction.
2. Mechanical Design

2.1. Mechanical structure

The mechanical structure of the biomimetic undulating fin robot is shown in Figure 2. This overall prototype is 407 mm long, 340 mm width, 64 mm high, weighing 2.82 kg in air, and is comprised of two major parts: a 3-D printed resin body and an undulating fin propulsion system. The body can be further divided into the upper cover and the lower cabinet. These two parts are fixed by screws. Two holes on the cover are utilized for battery charging and program downloading, sealed with nylon cap and O-ring. One hole on the front of cabinet is reserved for switch. Since the main movements of this robot are forward swimming and turning, the front and two sides of the body are designed to be streamlined to reduce the fluid drag. The propulsion system is equipped with a pair of undulating fins symmetrically on both sides and each undulating fin consists of 7 waterproof servo motors, 7 fin rays and a membrane made of 2 mm thickness rubber. The servo motors, fin rays and membranes were all mounted by screws.

The buoyancy and the weight of the robot have roughly calculated, and made it neutrally buoyant, which is important for vertical motion. The robot is bottom-heavy, so as to achieve self-adjusted balance.

![Figure 2. Mechanical structure.](image)

2.2. Undulating fin propulsor

The undulating fin propulsor comprises fin rays, flexible membranes and driving devices. The fin rays are actuated by waterproof servo motors (i.e., the driving devices), and are interconnected by membrane. By the oscillation of the fin rays, the membrane will produce a traveling wave on its surface to generate propulsion force. The oscillation of fin rays can be given as:

$$\theta_i(t) = A \sin(2\pi f t - (i-1)\phi_0) + \phi_i, i = 1, 2, ..., n$$

Where $A$, $f$ are the maximum angular amplitude and undulating frequency. $\phi_0$ is the phase shift between the adjacent fin rays. $\phi_i$ is the deflection angle between the fin rays and the horizontal plane. Each fin ray is actuated individually. The number of waves $w$ is given as:

$$w = \left\lfloor \frac{n-1}{2\pi} \phi_0 \right\rfloor$$

When $w = 1$, the moment of robot on pitch angle is balance. Considering $|\phi_0|$ is around $\pi/3$, 7 fin rays were employed on each side (i.e., $n = 7$). Compared with normal fin rays in undulating fin propulsor, the fin rays of this designed are relatively short. Given that the membrane can bend through its elastic stress, there is no need to employ long fin rays. It can also reduce the deformation caused by the stress. Since the membrane cannot be stretched, the oscillation difference of adjacent fin rays is noteworthy, which can be given as:

$$\theta_i(t) - \theta_{i+1}(t) = \text{sign}(-\phi_0) \cos(2\pi f t + \frac{\phi_0}{2} - i\phi_0)$$
where

\[ \Theta = A \sqrt{2(1 - \cos\phi_0)} \]  

According to (3) and (4), the maximum oscillation difference of adjacent fin rays is \( \Theta \). With regard to a certain morphology of membrane, there exists a corresponding certain value of \( \Theta \), so \( A \) and \( \phi_0 \) should simultaneously change to make \( \Theta \) constant. In this case, the membrane will not bend excessively or stretched.

3. Control System Design

3.1. Control circuit design

The architecture of electrical circuit is shown in Figure 3. The control circuit is based on Arduino Mega 2560. The master controller receives commands from a wireless receiver through serial port, which are sent from a transmitter, so the robot can be controlled with a remote controller. The attitude and acceleration data are collected by an Attitude and Heading Reference System (AHRS) through Serial Peripheral Interface (SPI), and the depth data are collected by depth sensor MS5837-30BA. The data of the two sensors will be used to the closed-loop control of depth and attitude. Since there are 14 waterproof servo motors in this circuit, a servomotor driver has been adopted to integrate management. The driver receives data from the main processor through I2C bus, which reduces data wires and increases the data transmission efficiency. The servo motor driver sends PWM signals to the servomotors (Hitec-HS-5086WP) of undulating fin propulsors. All the components, including servo motors, sensors, driver and controller are powered by a lithium battery with the capacity of 18.5 V, 5300 mA•h.

![Figure 3. Architecture of electrical circuit. (The black arrows indicate the control signal directions, and the white arrows indicate the drive current directions.)](image)

3.2. Motion control method

The locomotion of the robot is controlled by adjusting the parameters including amplitude \( A \), frequency \( f \), phase shift \( \phi_0 \) and deflection angle \( \phi_\ell \) of the two undulating fins, which have been defined in section II. \( A \) and \( f \) are related to the force generated by the undulating fins, and \( \phi_\ell \) is related to the direction of the force. Despite that the undulating fins also generate the force in the vertical direction and lateral direction, these forces do not contribute to the locomotion of the robot, so only the force along the direction of propagation of the wave has been taken into account. When \( \phi_0 > 0 \), the undulation propagates towards the last fin rays, generating forward thrust. Conversely, when \( \phi_0 < 0 \) generating backward thrust. Note that \( A \) should be adjusted as well with \( \phi_0 \) to satisfy (4). Figure 4 illustrates the basic motion control method for the robot. When the forces produced by the two fins
have the same magnitude and direction, the robot will move along the straight line in the direction opposite to the fin’s undulation (Figure 4a). When the thrust of two forces are equal but in opposite directions, in-place rotation is instigated (Figure 4b). Any asymmetry of the thrust will cause the robot to turn (Figure 4c). The vertical motion is achieved by adjusting the deflection angle $\phi$. When $\phi > 0$ or $\phi < 0$, the propulsive force is correspondingly lower or higher than the center of gravity, causing rising or diving motion (Figure 4d and f).

![Figure 4. Motion control method. (The blue arrows indicate the directions of the thrust, and the lengths indicate the magnitude. The dotted arrows indicate the motion directions.)](image)

### 3.3. Software design

In order to meet the requirements of practical applications, the robot is designed to be an untethered underwater robot, it also causes the problem that the robot is out of control in underwater environment due to the attenuation of radio signals. To address the problem, a hybrid control method combined remote control mode with autonomous control mode has been proposed.

The flow chart of software of the robot is shown in Figure 5. The control unit will initialize system at first, and then, the depth sensor sends depth data to master controller to determine which control mode will be adopted. If the depth is greater than zero, which denotes the robot is on the surface of water, remote control mode will be triggered. Once the depth is less than zero, the robot will be converted into autonomous control mode since the robot is under water. The two control modes can be switched fast enough and in real time. At remote control mode, all the commands are sent by human operations via a remote controller, and at autonomous control mode, the robot will follow the set target. The target contains the time and space settings, i.e., the initial depth, attitude angle and velocity. The data calculated by depth sensor and AHRS will be used to control the kinematic parameters through a PD controller.

This hybrid control method combines the control methods of ROV (Remote Operated Vehicle) and AUV (Autonomous Underwater Vehicle), avoids using large sonar communication equipment, it provides a simple and practical solution to the control problem of underwater robot.
4. Experiments

The underwater experiments were carried out in an outdoor swimming pool (dimension: 4 × 1.5 × 0.6 m) to evaluate the locomotion performance of the robot and verify the feasibility of the motion control method proposed in section III.

As the one of the purposes in this paper is to address the speed issue of undulating fin propulsor, the experiments were devoted to focusing on the robot speed and the influence of the kinematic parameters. A series of forward locomotion speed tests were carried out in the pool. There were two parallel measuring rods with colored marks for each 10 cm at the bottom of the pool for measurement. The total length of the markers is 2 m. The measurement method is by taking a snapshot of the moving robot at each 2 s, as shown in Figure 6a, which the kinematic parameters of undulating fins were set to $f = 1$ Hz, $\phi_0 = 60^\circ$, $\phi_b = 0^\circ$. The speed was calculated by recording the time that the robot took to go through the total length of the markers. Note that the robot did not move from the starting point of the measuring rod. The acceleration process has been completed before the starting point, so the robot is assumed to swim at a constant speed. The relationship between the speed and the frequency is displayed in Figure 6b. It’s obvious that the moving speed of the robot increases linearly with the frequencies. The robot can swim up to 31.6 cm/s when $f = 1.4$ Hz, nearly 0.8 BL/s. In Figure 6c, the speed reaches its maximum when $\phi_0 = 60^\circ$, and decreases rapidly when $\phi_b$ increases or decreases. Theoretically, as the phase shift decreases, the amplitude, the swept area and the generating force of the undulating fins will increase accordingly. But when $\phi_0 < 60^\circ$, the number of wave $\nu$ is not a positive integer, causing the robot pitches and energy consumption. The same situation occurs when $\phi_b > 60^\circ$. 

![Figure 6. Forward motion test.](image)
Figure 7 illustrates the yaw motion test of the robot. The left fin were set to \( f = 0.8 \) Hz, \( \phi_0 = 60^\circ \), \( \phi_b = 0^\circ \), while the right fin were set to \( f = 0.8 \) Hz, \( \phi_0 = -60^\circ \), \( \phi_b = 0^\circ \). The in-place rotation is instigated with the speed of 0.91 rad/s.

![Figure 7. Yaw motion test.](image1.jpg)

The diving experimental result is shown in Figure 8. The parameters were set to \( f = 1 \) Hz, \( \phi_0 = 60^\circ \), \( \phi_b = 30^\circ \). It took about 2 s to accelerate. At the time of 3 s, the robot began to dive into the water, and switched to autonomous control mode. A pitch angle of the robot inclined downward from the time of 3 s to 5 s.

![Figure 8. Diving motion test.](image2.jpg)

The endurance test of the robot was conducted to evaluate the efficiency. By setting the frequency under 1 Hz, the robot can swim freely for 5 hours, and has the features of low noise and high maneuverability.

5. Conclusion

In this paper, a prototype of the biomimetic underwater robot with undulating fin propulsors have been developed. According to the kinematic model of the fins, the design of undulating fin propulsion system was optimized, and the phase control method has been proposed to fit with the design. The results indicate that the robot can achieve multi-DOFs motions in underwater environment. The speed of the robot can reach 0.8BL/s, which is comparable to many other BCF propulsion mode robots [13, 14]. The robot also achieved vertical motion with only undulating fin propulsors, which makes the structure of the robot is relatively simple and easy to implement compared with other undulating fin robots [1, 7, 12]. With these characteristics, i.e., high speed, long duration, low noise and high maneuverability, this robot is especially suitable for long-term work in expansive underwater area, such as underwater reconnaissance and water quality monitoring.

This paper proves that it is feasible to develop a high-speed MPF mode underwater robot, and proposes a new control scheme to solve the problem of underwater robot. It has also been verified in this work that the vertical motion of undulating fin robot can be controlled by adjusting the deflection angle. The further work will be concentrated on the underwater reconnaissance and water quality monitoring by installing cameras or sensors on the robot.

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