MECHANICAL DESIGN OF A TWO-JOINT ROBOTIC FISH*

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In this paper, we present the mechanical design of a novel robotic fish capable of fast swimming and yet with less joints. Prior to designing, the principle and goals for design are analyzed, in which the size, central pattern generator (CPG) model, and oscillatory frequency of robotic fish play an important role. Then, the mechanical structure of the two-joint robotic fish is designed. The first joint of the robotic fish is driven by a gear motor. The gear motor is linked to an eccentric wheel which rotates in a free slide. The second joint is driven by a connecting rod to make the two joints form an angle between them, allowing free direction adjustment and flexibility. After that, the mechatronic design and CPG-based control are described. Underwater tests are performed on the robotic fish, validating the effectiveness of the proposed design scheme. Particularly, the robotic fish reached a maximum speed of 0.7 body lengths per second, which is expected to be much faster after improvement.

1. Introduction

After long time evolution, fish has developed great ability of fast swimming, moving flexibly, and performing complicated movements, which attracts many researchers to investigate the characteristics of fast swimming and high maneuverability of fish. After coming into the 21th century, the development of oceanic engineering and related enabling technologies like robotics and automation empowers human beings to harness marine resources and to protect the marine environment. Robotic fish does not have a propeller and thereby creates less noise. Often powered by electric energy, the robotic fish cause minimal disturbance to the environment. More importantly, robotic fish share the characteristics of fast-swimming and high maneuverability[1].

As for the applications of robotic fish, it can detect the water pollution[2]. It is also of great help in oceanic exploration and archaeology. Besides, as robotic fish looks and acts like real fish, it can get close to real fishes and will not scary them away, which can aid in biological research.

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The mechanical parts have a great influence on the performance of the robotic fish. In principle, different propulsive mechanisms, sizes, and morphologies will result in different performance, corresponding to different levels of task execution. In this paper, we aim to develop a new robotic fish capable of fast swimming and yet with less joints.

2. Goals and Principle for Design of Robotic Fish

One of the most important factors for designing robotic fish is the speed. Although there are many reasons that influence the speed of robotic fish, the following three requirements are the most significant.

1. CPG control model for generating fishlike swimming.
2. Oscillation frequency of the tail of robotic fish.
3. Power of the motor and mass of the robotic fish.

As for Requirement 1, there are many researches on CPG model. The CPG model for robotic fish is like the sinusoidal curve, or like part of it. For example, Wu's[3] and Wang's[4] robotic fish which are governed by CPG models reach good swimming performance.

Concerning Requirement 2, SPC-II has a maximum frequency of about 6 Hz in the air[5]. This robotic fish achieved a relatively high swimming speed by means of both well-built CPG model and high frequency[6]. Theoretically, the robotic fish which uses servo motors to provide the propulsive force cannot reach high frequency because the fastest rotating speed is about 0.09 s/60° for servo motors. That is, ω = 60°/0.09≈667°/s. If the oscillation amplitude of the tail is 60°, servo motor will rotate 60°×4 = 240° in one oscillation period. Thus, the oscillation period becomes T=240°/667°≈0.36 s. The oscillation frequency of the tail corresponds to f=1/T=1/0.36≈2.78 Hz. The realistic frequency will be lower while moving through the water, maximally around 2–2.5 Hz. Note that even the faster servo motor will not reach 4 Hz in the water. Therefore, the speed is much limited. In such a situation, we decide to design the robotic fish using gear motor instead of servo motor.

With regard to Requirement 3, the power of the motor is larger and the mass of the robotic fish is lighter (i.e., the size is smaller), robotic fish will swim faster.

3. Mechanical Design of the Robotic Fish

The mechanical structure of the robotic fish is shown in Figure 1, the total length of the robotic fish is about 310 mm to make sure the fish is small and light enough. The motor rotates in one direction. The motor drives an eccentric wheel to make the two joints and the fish tail oscillate back and forth to produce sufficient propulsive forces.

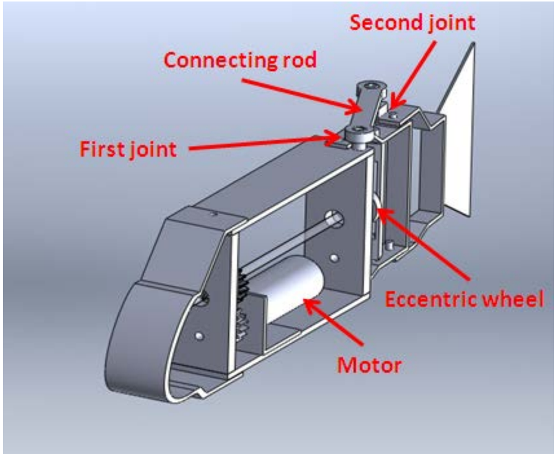


Figure 1. Mechanical structure of the two-joint robotic fish.

3.1. *Mechanical Design of the First Joint*

As shown in Figure 2, the first joint adopts the eccentric wheel structure. When the eccentric wheel rotates in one direction, the first joint of the robotic fish will reach an angle. Besides, the eccentric wheel still has two other holes on it to make the robotic fish have many choices to change the oscillation amplitude. As shown in Figure 3, the slide for the eccentric wheel to rotate along is designed as a free one, allowing rotation around the axis itself, which reduces much resistance of the transmission mechanism.

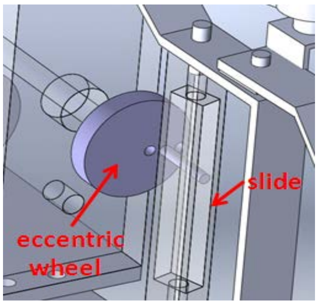


Figure 2. Mechanical structure of the first joint.

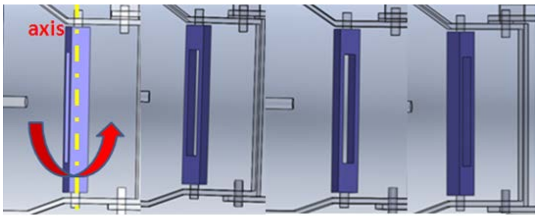
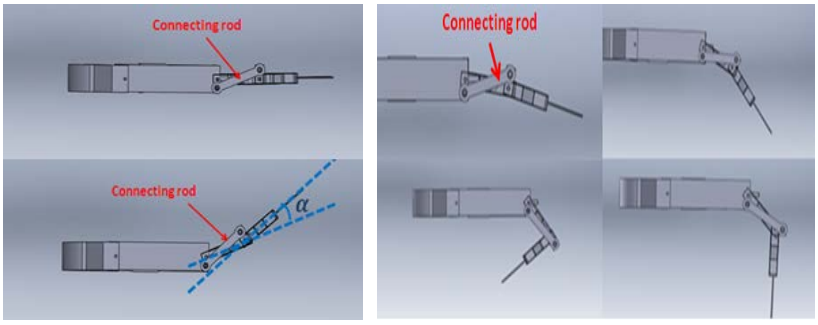


Figure 3. Mechanical structure of the free slide.

3.2. *Mechanical Design of the Second Joint*

The second joint is driven by a connecting rod. The angle between two joints is varied as the connecting rod moves to a different position. The moment when the connecting rod moves to a definite position is shown in Figures 4 (a), where the angle between the two joints is defined as α.



(a) (b)

Figure 4. Mechanical structure of the second joint moving to an angle.

By adjusting the diameter of the eccentric wheel, with the aid of the connecting rod, the angle between two joints will change, which endows the the ability of maneuverability as shown in Figure 4 (b).

4. Swimming Mode and CPG Design

4.1. *State of Straight Swimming*

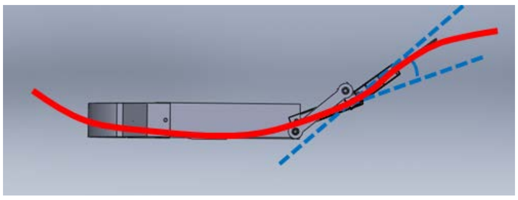


Figure 5. CPG model on robotic fish

The robotic fish tail follows the CPG model as a sinusoidal curve. As shown in Figure 5, the two-joint fish tail theoretically tracks the red line. Note that, for real fish, the amplitude of the head is less than that of the tail.

Mathematically, one sinusoid corresponds to only one intrinsic amplitude. To determine a proper CPG model, we need a combination of different sinusoidal curves which have different amplitudes. Therefore, we determine the CPG model as the following formula:

$$CPG = \sum_{j=1}^{m} a_i \sin(b_i x + c_i) \quad (1)$$

where m is the number of joints, a_i, b_i, and c_i are constants. As the number of the joints for the developed robotic fish is two, the CPG module is designed as:

$$CPG = a_1 \sin(b_1 x + c_1) + a_2 \sin(b_2 x + c_2) \quad (2)$$

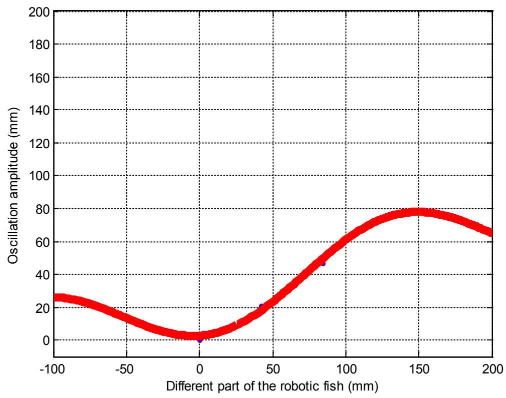


Figure 6. Simulation of CPG model.

After simulation according to the real size of the robotic fish, the result is shown in Figure 6.

The simulation formula is derived as follows:

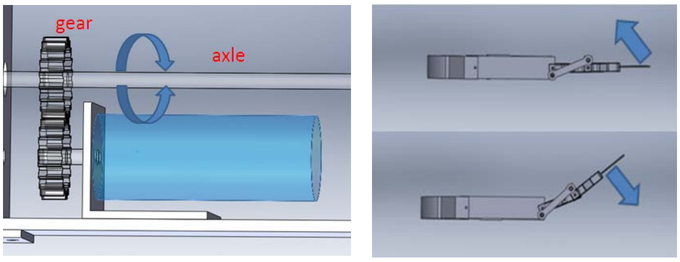
$$CPG = 278.1\sin(0.0007544x + 0.09097) + 23.22\sin(0.02517x - 1.825) \quad (3)$$

Then, we can use this simulation result to predict the swimming patterns and postures of the robotic fish.

4.2. *State of Performing a Turn*

Then, we design the control method to make a turn. The basic turning idea for our robotic fish is that the driving motor in the tail rotates in one direction for a short period of time and then rotates in the opposite direction for a short period of time. As demonstrated in Figure 7 (a), when the motor rotates, the gears will rotate which drive the axle rotating. The axle is linked to the eccentric wheel, which drives the robotic joint. The axle rotates in one direction for a short period of time and reverse for the same time, which helps the robotic fish make a turn. When to repeat this process, the tail of the robotic fish can repeat the process in Figure 7 (b).

In detail, as shown in Figure 7 (b), the tail firstly stays in the horizontal position. Then the motor rotates in one direction, and the tail moves to an angle. After that, the motor rotates in the opposite direction and the tail returns to the horizontal position. Apparently, when the motor rotates fast, the oscillation frequency of the tail increases. Repeating this process for a couple of times, the robotic fish can achieve a turn.



(a) (b)

Figure 7. Schematic diagram of achieving a turn.

5. Design of Hardware System

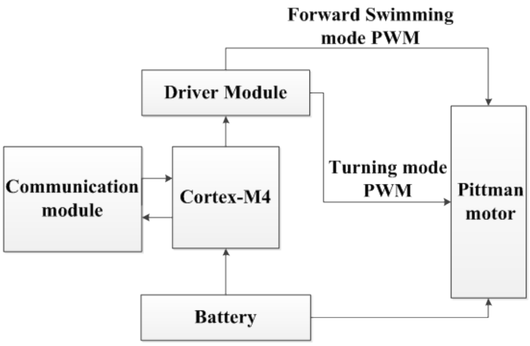


Figure 8. Block diagram of the electric system for the robotic fish.

The electric system of the robotic fish includes battery (11.1 V lithium battery), the board of controller (Cortex-M4), the board of driver module

(L298N), the communication module (RF200), and the gear motor. The whole electric system is illustrated in Figure 8.

After completion of the mechatronic design, the robotic fish is constructed and tested. The characteristic parameters of the robotic prototype are shown in Table 1.

Table 1. Technical parameters of the robotic fish.

Size	310×77.5×28 mm^3
Weight	863 g
Number of joints	2
Duration time	1.5 h
Microcontroller	Cortex-M4
Battery	11.1 V Lithium battery
Communication module	RF200
Driver module	L298N
Gear motor	Pittman motor

6. Underwater Tests

To validate the proposed design scheme, underwater tests are performed on the developed robotic fish with waterproofing treatment. When the oscillation frequency rises, the swimming speed of the robotic fish increases. Remarkably, the robotic fish reached a maximum speed of 0.22 m/s, corresponding to 0.7 body lengths per second (BL/s). A snapshot of steady swimming over a period is shown in Figure 9.

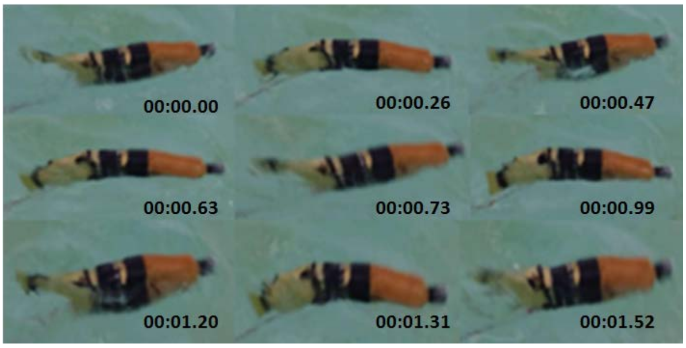


Figure 9. Snapshot of underwater tests on the robotic fish.

7. Conclusion

In this paper, we have proposed a new robotic fish capable of fast swimming and yet with only one motor. Specifically, a two-joint mechanical configuration is adopted based on an eccentric wheel to drive the first joint, while the second joint is driven by the connection rod. The simplified CPG model is proposed and implemented to yield relatively flexible and stable swimming. Underwater tests on the real robot verify the effectiveness of the proposed design scheme. In particular, the robotic fish achieved a maximum speed of 0.7 BL/s. However, the power of the gear motor still needs improvement. If the power of the gear motor increases, the rotating speed and torque will also improve much. In future work, the propulsive speed and maneuverability of the single motor driven robotic fish are expected to be greatly enhanced after improvement on hydrodynamic optimization and motor configuration.

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