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Design and Analysis of the Robotic Devil Fish

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Abstract: *Based on bionics, we design a robotic devil fish based on the MPF movement pattern. Through trigonometric modeling and bionic analysis, we design the three-layer structure of the model and 3D-print it with ABS plastic. Through the circuit board waterproof test, the servo control program test and the servo waterproof test, we conclude that it has good stability and waterproofness, which can be widely used in education, underwater transportation and entertainment. This study further explores the realization of the devil fish's movement pattern, offering a practical direction for future research.*

Keywords: *Bionic devil fish, Trigonometric function, 3D printing*

1. Introduction

Imitation of nature is an old idea, and for centuries, many inventors have tried to understand how things work in nature by imitating animals. Bionics uses models of living systems to find new ideas for useful artificial machines and systems. For example, people invented radars with the inspiration from the bat, manufactured submarines according to the body shape and skin structure of the dolphin, and designed helicopters based on the flight principle of the dragonfly. As a type of bionic robot, bionic fish imitates the shape and movement ability of a living fish, whose inspiration comes from the excellent swimming innateness of fish. They have various applications like water quality detection, underwater archaeology, underwater operations, etc. Since MIT first published research on robotic fish in 1989, hundreds of researchers have devoted themselves to this field. In the last decades, a great deal of research has been conducted on bionic fish including models for path planning and optimization, dynamics modeling and motion control.

This study designs a robotic devil fish according to the real devil fish movement through mathematical modeling. It applies a program-embedded steering gear to imitate the movement of the devil fish, and the float to ensure the adequate buoyancy of the machine. With the application of 3D modeling, the appearance of this robotic devil fish is presented for detailed analysis. This robotic fish restores the motion principle and trajectory of the devil fish with mathematical functions, vividly presenting the swimming movement, which can be applied into the education of related subjects. Besides, the devil fish has a streamlined flat body, which is not only conducive to swimming propulsion, but also to diving and gliding. Therefore, analyzing the movement model of the devil fish can be helpful to promote the development of biomimetic research of efficient underwater thrusters.

In this paper, we firstly analyze the theoretical bases of the robotic devil fish from the perspectives of biomimetics and swimming mode. Then, we construct a trigonometric model to imitate the movement of the devil fish and use 3D printing to realize the physical object. Finally, we conduct the simulation analysis and find the most effective movement mode for the robotic devil fish.

2. Theoretical Basis

2.1 Biomimetics

Biomimetics is the emulation of the models, systems, and elements of nature to solve complex human problems [1]. From the 16 century, studies of birds appeared to enable human flight, which is one of the early examples of biomimetics. The Wright Brothers, who succeeded in flying the first heavier-than-air aircraft in 1903, allegedly derived inspiration from observations of pigeons in flight [1]. The core idea of biomimetics is that inhabitants in nature including animals, plants, and microbes have the most experience in solving problems and have already found the most appropriate ways to last on the Earth [2]. Through imitating, human beings can also find an environmentally friendly and sustainable way to live.

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Biomimetics could in principle be applied in many fields. Because of the biodiversity, the number of features that might be imitated is large. Up till the present day, numerous bio-inspired technologies have been invented to facilitate people's lives. Here are some typical and successful examples.

The first is biomimetic architecture. Researchers studied the termite's ability to maintain virtually constant temperature and humidity in their termite mounds in Africa despite outside temperatures that vary from 1.5 °C to 40 °C. Therefore, by imitating the architectural structure of the termite mound, The Eastgate Centre, a mid-rise office complex in Zimbabwe, is built, with a passive cooling architecture to stay cool and low consumption. The second is biomimetic flying robots. Examples of bat-inspired BFRs include Bat Bot [3] and the DALER [4]. Bird-inspired BFRs can take inspiration from raptors, gulls, and everything in between. And insect-inspired BFRs typically take inspiration from beetles or dragonflies. Thirdly, some new structural materials are inspired by creatures in nature, which are lightweight but offer exceptional combinations of stiffness, strength, and toughness. The material structure of spider silk is used for parachute lines, suspension bridge cables, artificial ligaments for medicine, and other purposes. In this study, underwater biomimetics is explored, which can offer inspiration for future inventions.

2.2 Fish Swimming Modes

Based on fish propulsion mechanism, swimming pattern and body shape, SFAKIOTAKIS et al classified the propulsion modes as body and/or caudal fin (BCF) propulsion mode and median and/or paired fin (MPF) propulsion mode [5].

2.2.1 BCF Swimming Mode

In nature, the majority of fish use BCF swimming mode with their body and caudal fins as the main propellers. They control the body to swing left and right to strike the water and use the reaction force to propel themselves move forward. The body oscillates from side to side and strikes the water, using its reaction force to propel the fish forward. The body and caudal fins are used as the main propellers. Besides, when the BCF propulsion mode fish swim, jets will form at the tail of the fish body, which play a very important role in generating thrust. Tuna, sailfish, and shark species are this type. When they swim, their bodies mainly swing in the tail, with high propulsion efficiency and fast speed. Because fish with BCF swimming mode can generally swim fast with a little effort, the mechanism of these fish attracts numerous researchers to explore. For example, Zhu et al. designed a high-frequency experimental platform as well as tuna robotics based on yellowfin tuna and Atlantic mackerel, laying the foundation to explore a fish-like performance space for bio-inspired underwater vehicles [6].

2.2.2 MPF Swimming Mode

Compared with BCF swimming mode, MPF swimming mode is less common. Only 15% of the fish subjects utilize median and paired fin for propulsion according to statistics [7]. Fish like black basses, sunfishes, knife fishes as well as devil fish all adopt this swimming type. Unlike the left and right swings of the caudal fin, these fish use median and/or paired fin at the center of their body to generate force and propel themselves to move forward. MPF propulsion in fish consists of undulatory fin motion and oscillatory fin motion, which respectively represent drag-based and lift-based mechanisms of thrust production.

Although fish with MPF swimming mode have slower speeds, their moving behaviors have precise maneuverability and stability, which seems to be advantageous in complex habitats such as coral reefs [8]. Fish such as swordfish, butterflyfish and other fish use the MPF swimming mode combines high propulsion efficiency, excellent maneuverability, and stability in one. It not only is beneficial to ocean navigation, but also has the characteristics of flexible maneuvering at low speeds and strong anti-disturbance ability, which is suitable to be adapted to offshore complex environments. Therefore, this type of swimming mode can be further applied to practical vehicles and tools through bionics research.

3. Our Work

After several demonstrations, we find that the fins of the devil fish are composed of a large skeleton in the front and a small skeleton in the back, and the amplitude of the swing of the size of the skeleton is MPF mode, which can be roughly presented as a trigonometric function. Therefore, in this paper, we use simple trigonometric functions to model the way a devil fish's fins swing in motion.

We analyze the conditions required by fish movement and the available efficient and lightweight materials, and decide to use 3D printing to construct the model. We present a robotic devil fish, with

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steering gear, float and battery compartments, which can change the speed of movement and the ability to rise and fall.

The ocean covers 70 percent of the earth, and the exploration never ends. Due to various factors such as the environment, humans can only explore some areas through machines. Even with such advanced technology, there is still a lot of room for bionics to explore, such as MPF's type of motion. To better know the movement of marine creatures, this study has a certain meaning. The model we made this time is used for education and entertainment, which offers a new perspective for the MPF swimming mode application.

4. Bionic Devil Fish Model

Based on the mathematical model and the needs of practical applications, we construct a model of a bionic devil fish and use 3D printing technology to produce the real thing. The whole modeling process is shown below.

4.1 Overall Structural Design

We take the devil fish as our bionic object, which is oval in the middle with the pectoral fin composed of numerous fins from long to short and has two smaller ventral fins at the tail of the devilfish. Besides, the thickness of the body of the devil fish is elliptical, with a thin head and tail and a thick body. The devil fish swims through wavy pectoral fins, which are supported and dominated by the skeleton of the body, and the motion of the entire fin is achieved by the inertia of the skeleton. Therefore, we can divide the devil fish's motion into three axes, and observe that its thrust and lift have obvious trigonometric periodic changes.

After model construction, we use the 3D printing technique to make the physical object, which is mainly composed of three layers for different functions, which is shown in Figure 1.

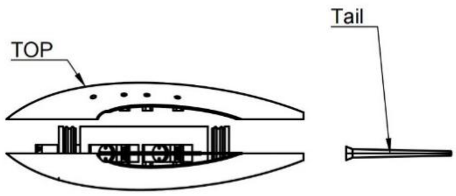

Figure 1: Three layers of the model

The first layer is the electrical equipment compartment, which provides lift for the model and keeps it balanced. The second layer contains six servos, the first two having a smaller torque and rotation range, to mimic the opening and closing lips of the devil fish. Because the devil fish relies on the swinging of its pectoral fins for locomotion, offering enough thrust and lift by swinging its pectoral fins up and down. We used the other four servos of the same size and torque to make sure the model had enough thrust, which is shown in Figure 2.

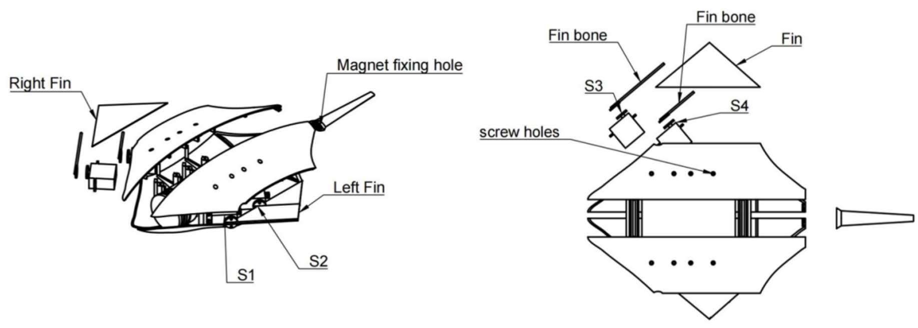

Figure 2: Servos of the model

The length of the backbone glued to the steering gear is different for realistically imitate of the shape of the devil fish. The third layer stores the battery cabin, which can control the rotation of the four servos through the battery, and can also control the speed of the model movement by changing the power. In

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Figure 3, the whole structure and the combination way are presented.

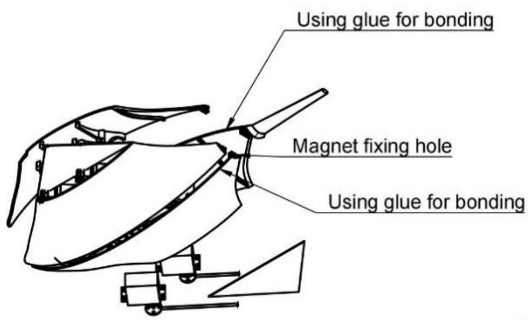

Figure 3: The whole structure

4.2 Key Function Design

To achieve the effect of mimicking the real movement of the devil fish, we divide the robotic devil fish into several parts: the skeleton for supporting and connecting, the plastic film wrapped on the skeleton for imitating the real motion state of the fin in the water, the waterproof servos for providing thrust and lift, and the motion function design for the model. In this section, these functions are introduced respectively.

4.2.1 Motion Function and Design of fins

The swinging of fins provides sufficient lift and thrust for the fish. Through observation and experiment, we find that the movement mode of the devil fish is MPF (the thrust is obtained after the superposition of forces in the same direction of movement). Because of the up and down swing of the fin and the vertical and horizontal motion of the fin during swimming, we express the motion path of the fin through mathematical modeling, and find that the motion of the fin has trigonometric characteristics. Because this robotic devil fish has four waterproof servos, the angle of servos S1 to S4 can be expressed as

$$S_n = 90 + A \times \sin(\omega \times \mathrm{t} + (\mathrm{n}-1) \times 90^{\circ}) \ (\mathrm{n}=1,2,3,4) \tag{1}$$

When the PWM signal of S1-S4 equals 90 degrees, the skeleton controlled by S1-S4 is extended horizontally and recorded as a neutral position. Besides, in formula 1, A represents the amplitude of servos, ω represents the movement cycle, t cycles between 0 to 395 as circumferential motion, and n represents the servo number.

According to the formula, we can get the trigonometric motion curve shown in Figure 4.

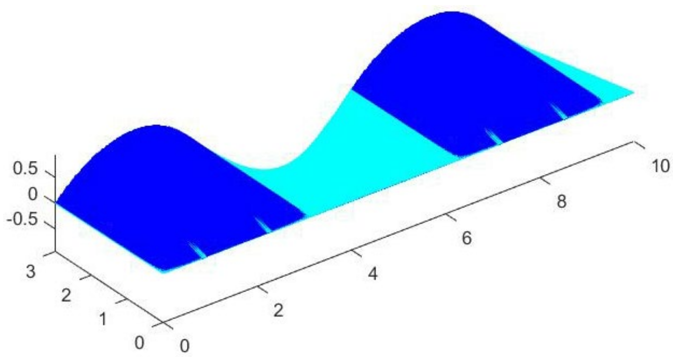

Figure 4: Trigonometric motion curve

Since the movement of the front and back fins of the devil fish is coherent, we believe that having two backbones with different movement cycles and modes, but different lengths can better reflect its characteristics. To ensure that the model can resist certain environmental effects, we choose to use ABS (Acrylonitrile Butadiene Styrene) plastic, which is a thermoplastic and can be printed by a 3D printer. It has much better mechanical properties than PLA polylactic acid, with good resistance and toughness, which is a very common engineering plastic.

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4.2.2 Waterproof Servo

To give the model enough thrust to make it move, and the corresponding angle of the servo, we choose the servo with the working voltage of about 4.8v-7.4v, the model range of 900 to 2100uSec, and the size of $40.4 \times 20 \times 40.3\ mm^3$. Its lightweight and waterproof features make us have more choices among other parts of the model. Two smaller waterproof servos are placed in the middle tier to connect to the battery compartment at the bottom.

4.2.3 Skeleton (thin fin)

The skeleton is connected to one side of the waterproof steering gear. To make the model more realistic, we put the longer skeleton in the front and the shorter skeleton in the back. The skeleton is made of $3 \times 1\text{mm}$ carbon fiber sheet, which makes it have lighter weight, better resistance and more freedom in the structure design. The plastic film wrapped in the skeleton is made of translucent polyurethane rubber beef fabric, which makes it have a better extension and can better imitate the real movement mode of the devil fish.

4.2.4 Battery compartment

Due to the stability requirements of suspended objects in the water, we placed the lithium battery in the lowest cabin of the model after waterproof treatment. Based on safety requirements, the main control (Arduino) / 5v dc-dc buck module/circuit connection PCB was placed in the middle waterproof cabin. The battery compartment uses pc material because pc polycarbonate has high strength, good elastic performance, good compression and impact resistance performance, and good insulation performance in wet underwater environments. At the same time, because the transparency is very high, it is particularly suitable for all kinds of equipment that needs to be waterproof and to observe the internal work.

5. Analysis of the Simulation Results

5.1 Assembling Structure

According to the above introduction, we divide the whole model into three layers along the horizontal plane. The first layer places the float, which is directly connected to the battery bin of the third layer by wires through the small holes between the layers. Afterward, we fixed the parts with waterproof glue. In the second layer, four servos and a backbone are placed, which are fixed through 502 adhesives to ensure certain stability. The wires linking the servo to the battery compartment are also connected through small holes. To achieve the control function, we use a receiver and arduino to realize the control circuit, which is shown in Figure 5.

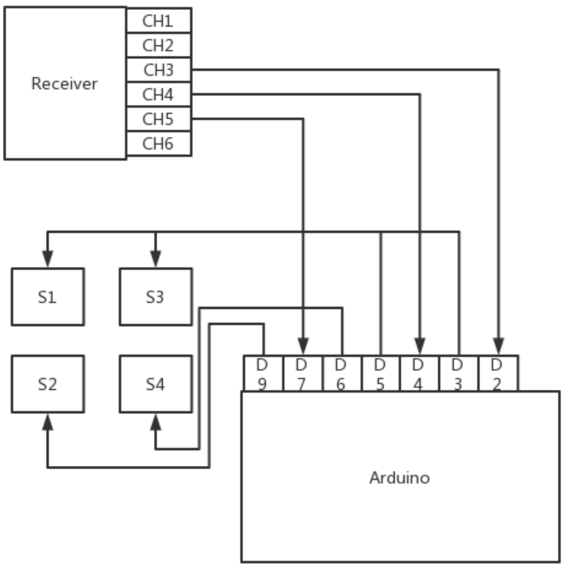

Figure 5: The control circuit

As is shown, in the receiver, ch3 is a throttle, ch4 is a rudder, and ch5 is a three-stage switch for changing the control mode of the project. According to the formula, to change the motion of the model, we can adjust the amplitude A or the angular velocity ω. Besides, we need to make the model capable

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of 2 degrees of motion. Therefore, we assume that this model has the following control modes which are shown in Table 1.

Table 1: Three control modes

	Amplitude A	Angular Velocity ω	Moving forward	Changing direction
Mode 1	Constant	Pulse width mapping with ch3 and ch4	The vibration speed of left and right fins	The difference in vibration speed between left and right fins
Mode 2	Pulse width mapping with ch4	Pulse width mapping with ch3	The vibration speed of left and right fins	The difference in variation amplitude of left and right fins
Mode 3	Pulse width mapping with ch3 and ch4	Constant	The vibration amplitude of left and right fins	The difference in variation amplitude of left and right fins

Afterward, we print each layer separately for better modification. After printing, we first place the electronic components (battery compartment, steering gear and float) in order, and then connect the wires needed for each part and make them waterproof.

5.2 Simulation Analysis and Results

After several experiments, the following behavior descriptions of the control principle of different modes are obtained, which is shown in Table 2.

Table 2: The behaviors of three modes

	Amplitude A	Angular Velocity ω	Behavior description
Mode 1	Constant	Pulse width mapping with ch3 and ch4	Mainly relies on the difference in vibration speed difference between the left and right fins to control, with poor stability.
Mode 2	Pulse width mapping with ch4	Pulse width mapping with ch3	Be able to balance maneuverability and stability relatively well.
Mode 3	Pulse width mapping with ch3 and ch4	Constant	Does not move when the amplitude is very small when only depending on the amplitude.

From the above table, we can summarize the following conclusions:

(1) Due to inertia and other reasons, the vibration periods where the left and right fins of the robot are located should preferably be synchronized, i.e., the robot should preferably turn without relying on adjusting the vibration periods of its left and right fins.

(2) The robot generates effective propulsive force, which mainly relies on the effective angle of the fin membrane driven by the skeleton in the vertical direction. Therefore, one of the prerequisites for generating effective propulsive force should be that the fin membrane has a suitable size of amplitude.

(3) During the operation, we observe that the fin movements do not present the sinusoidal function waveform perfectly. Therefore, the efficiency of the system can be improved by adding more rudders and skeletons.

6. Conclusion

Since ancient times, humans have tried to build useful artificial machines and systems by observing and mimicking the behavior of animals. Bionic fish provide a lot of conveniences for humans to use machines instead of humans to understand and protect the environment, such as water quality detection, underwater archaeology, and underwater operations. In this paper, a robotic devil fish is designed with the 3D printing technique by using the basic trigonometric function model. After placing the model underwater at a depth of 0.5 meters for 72 hours, the model still functioned well, reflecting its sound waterproofness and stability. Besides, among the three control modes, mode 3 presents the best performance. For application, the robotic devil fish can be used for education, underwater transportation and entertainment.

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In addition to the devil fish, there are other fish with unique movement modes can also be bionic, such as the shaver angler fish walking by the fin and the three-legged fish deep fur seal mother. In the future, we can also probe deeper into the movements of these kinds of fish.

The essence of human imitation of animal movement and life characteristics is to provide a better, more efficient and more convenient way of life for human beings. Besides, the development of bionics can help us better understand and protect nature and understand the importance of biodiversity.

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