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Progress in the Research and Design of Bistable Soft Robots

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Introduction

As the main tool for human to explore the ocean, underwater robot has attracted the attention of more and more researchers. Traditional underwater robots generally use propeller-type propulsion device, which is energy consumption, noise, low efficiency and easy to harm underwater organisms. Compared with propeller, natural fish has high maneuverability, high efficiency, low noise, good concealment and small environmental disturbance during movement. These excellent swimming properties of fish have aroused the research interest of many experts in fields such as bionics in advancing theory and making robot fish models.

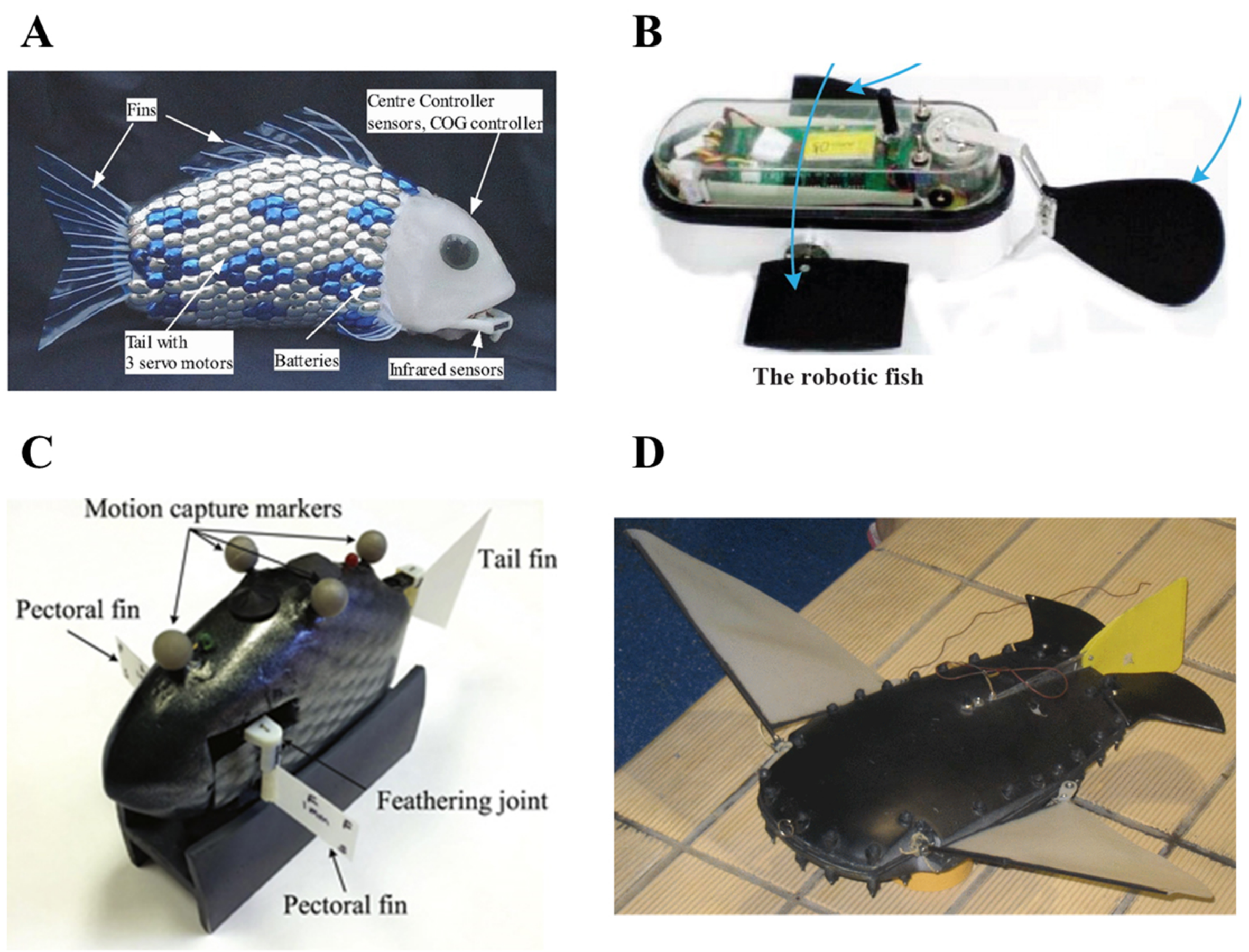

Figure 1. Representative fish-inspired robots are listed in the above figure. A) G9 Fish[1] B) Boxfish-like Robot[2] C) Flexible Pectoral Fin Joint Labriform Robot[3] D) Manta Ray Robot[4]

In this project, the principle of multi-modal beam buckling is used as the drive mode of the robot fish, and a bistable underwater soft robot is designed. This kind of bistable robot has the advantages of rapid mode switching and good swimming performance. Besides, multi-modal robot can be designed according to this principle.

Design & Modeling

In general bistable structures, one-dimensional constrained beams are the most common, which have two stable states as shown in **Fig 2**. The one shown above is the initial stable state with no applied force, while the one shown below is another stable state with buckling after a force is applied to both ends of the beam.

Considering these two steady states from the perspective of energy, stable state 1 and stable state 2 have two different peaks in the energy landscape (**Fig 3**), and the stable state after buckling has higher strain energy. In the process of changing from stable state 2 to stable state 1, the energy of the difference in strain energy is released, and we use this energy to drive the robot. The equation for energy is as follows

$$E_{strain} = E + E_c$$

where E_{strain} is the strain energy of the beam after buckling, E is the strain energy of the beam when no force is applied, and E_c is the kinetic energy released.

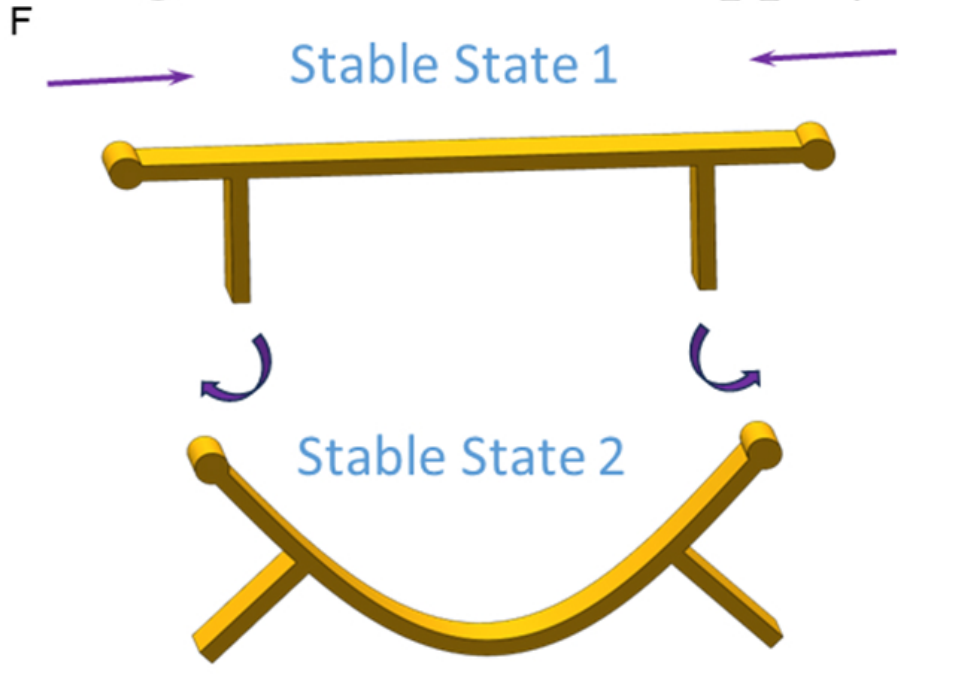

Figure 2. Two stable states of one-dimensional constrained beams

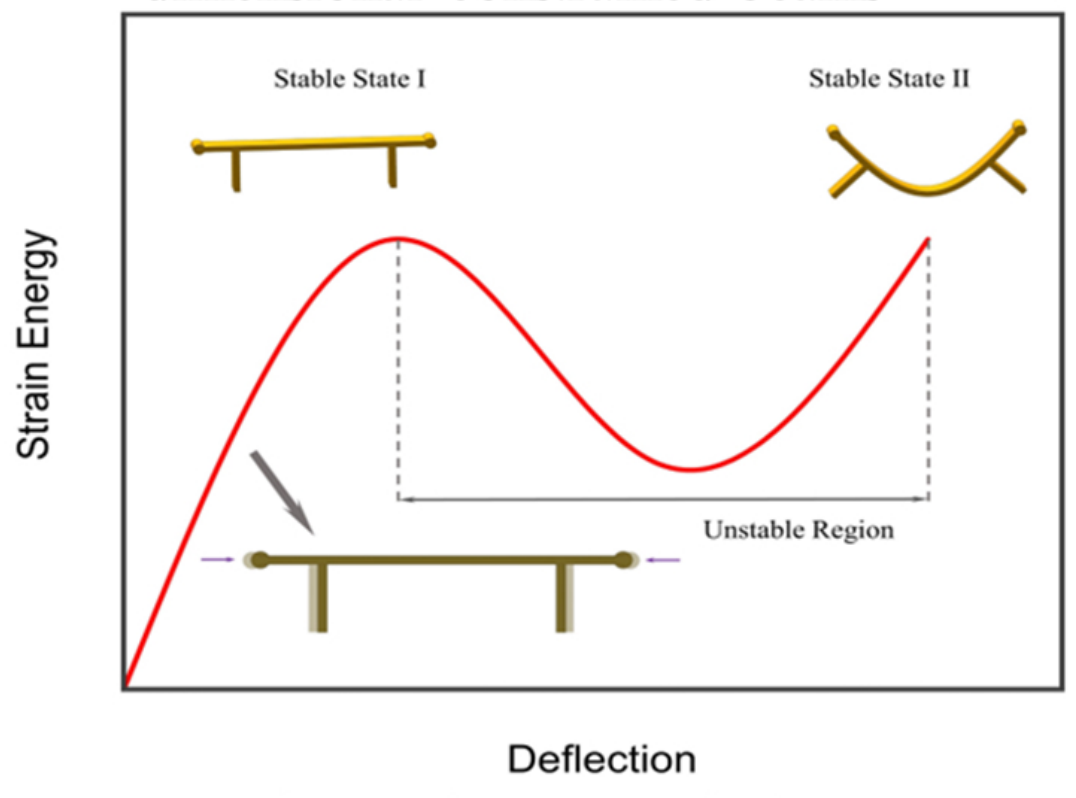

Figure 3. The typical energy landscape of 1D bistable beam

Based on the above principle, we designed a bistable robot, the basic structure of which is shown in **Fig 4**.

Among them, the frame at both ends of the beam are made of nylon, which is a hard material and connected by steel sheets. Its role is to exert a horizontal force on the beam. Coils and magnets are used to drive the robot. The main principle is to attract the magnet through the frequency periodic change of the current in the coil, so as to achieve the effect of applying a periodic force at both ends of the beam. The function of the stop block is to make the robot only deform downward. The legs mounted on the bistable actuator act as a tail similar to a fish, allowing the robot to swim better in the water.

After designing the structure of the bistable robot, we 3D printed and assembled each part to obtain the real object as shown in **Fig 5**.

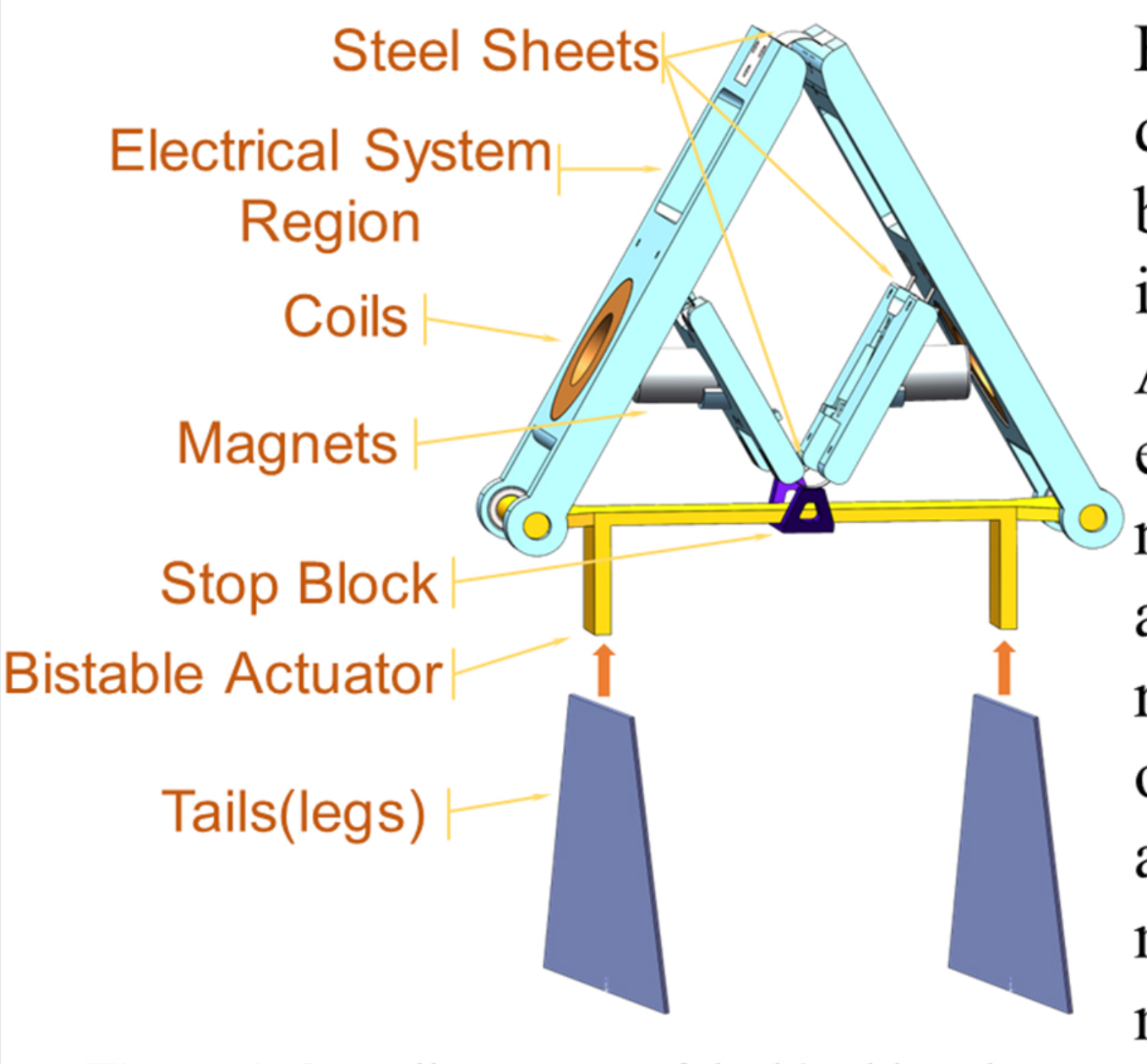

Figure 4. Overall structure of the bistable robot

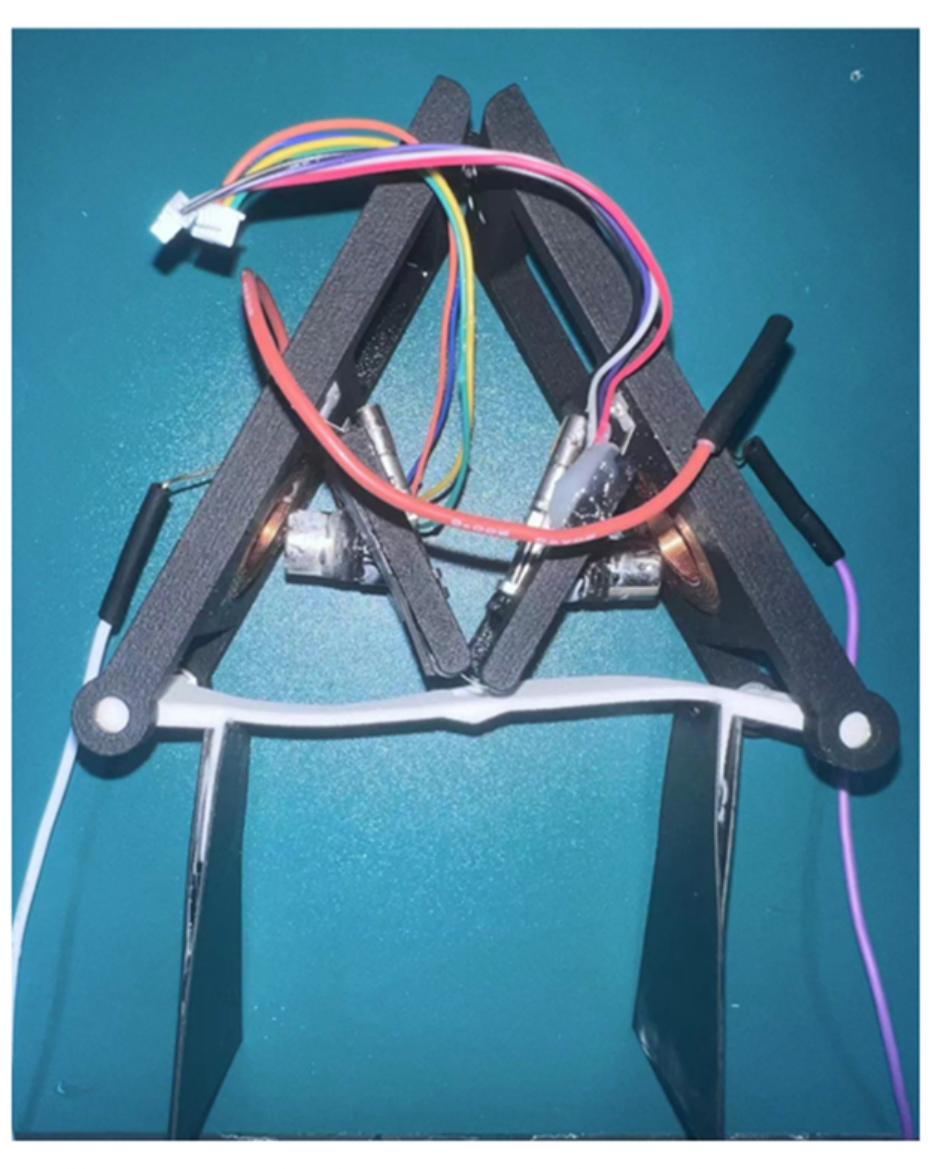

Figure 5. 3D-printed bistable robot

Analysis & Results

After 3D printing the bistable robot, we need to drive the robot with electricity and measure its swimming performance under water. By photographing the robot's swimming posture during one cycle, we found that it was quite similar to that of a frog, and its decomposed posture was compared in **Fig6**.

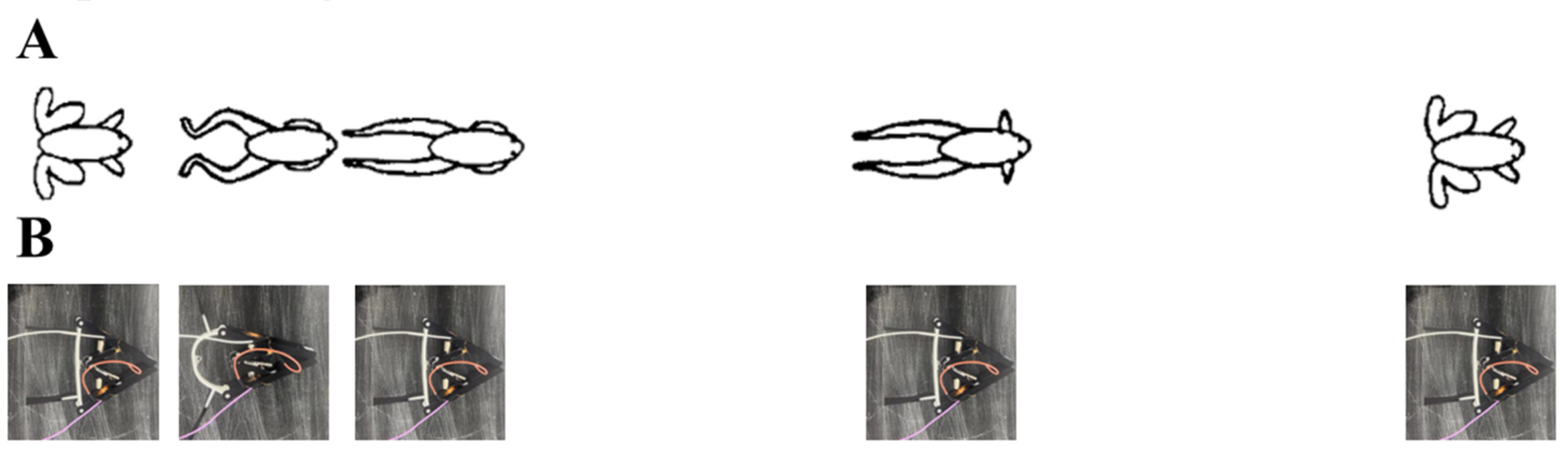

Figure 6. Comparison of swimming posture between frog and bistable robot. A) The swimming posture of a frog during a cycle [5]. B) The swimming posture of a bistable robot during a cycle

Then, after changing the current frequency in the coil and the thickness of the beam, we measured several sets of velocity data respectively and plotted them into the following curves, as shown in **Fig 7**. Through these data statistics, we can analyze the effects of frequency and beam thickness on the robot's swimming performance respectively.

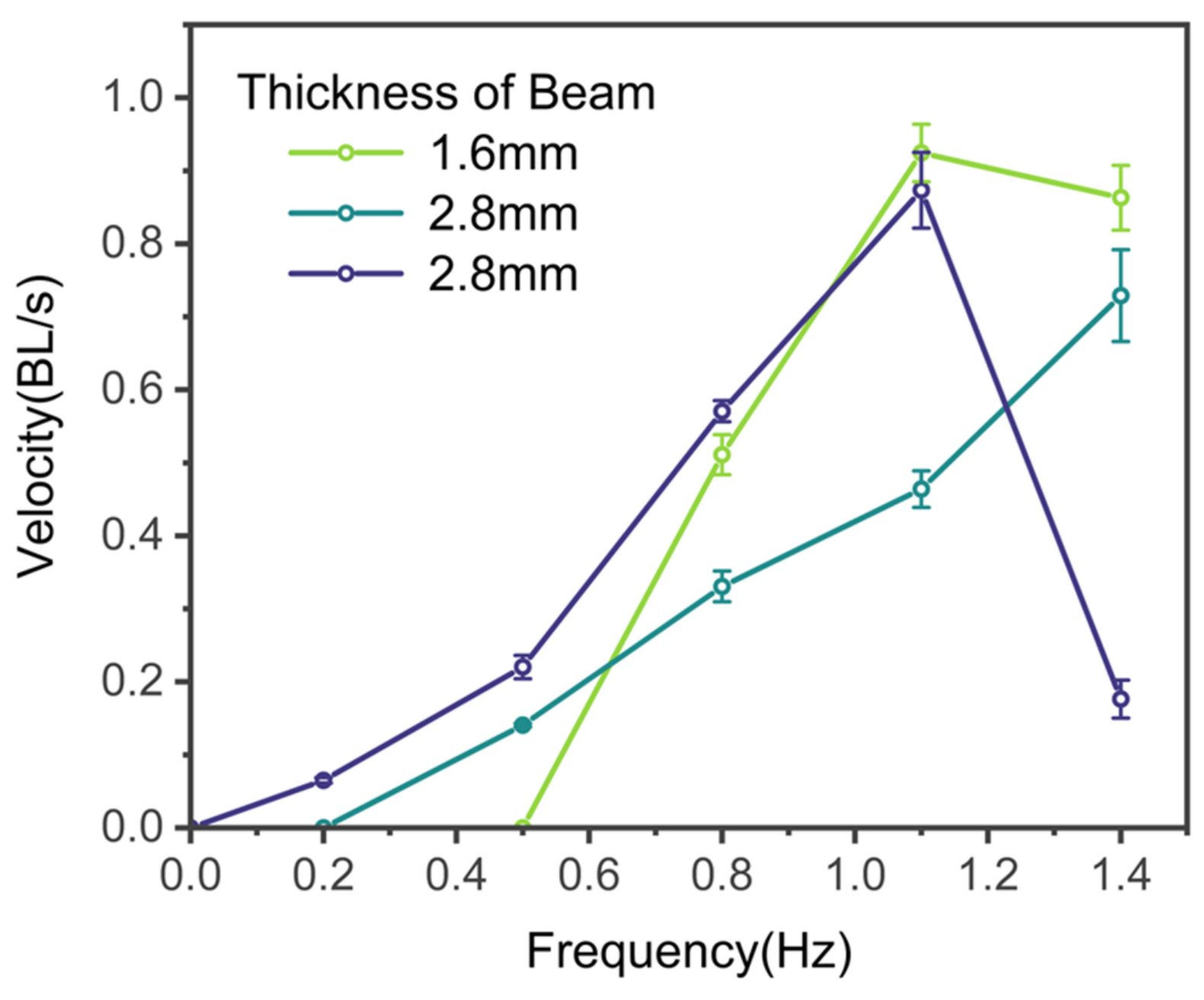

Figure 7. Bistable robot swimming velocity

By analyzing the data of the swimming velocity measured in the experiment, we can study the relationship between the velocity of the bistable robot and the frequency of the driving current under different thicknesses of beam. With the increase of the driving current frequency, the swimming velocity of the robot shows a trend of first increasing and then decreasing, reaching a peak at the frequency of about 1 Hz. We analyze that the possible reason is that when the frequency is too low, the frequency of robot gliding is not enough to make the swimming speed slow, and when the frequency is too high, the robot starts the next cycle before the end of gliding, so that the robot cannot make full use of the speed when gliding. Additionally, the thickness of the beam is also crucial. Choosing a beam with a larger thickness results in a larger driving force, but also makes the robot heavier. Therefore, we conjecture that there is an ideal beam thickness for the robot to achieve the fastest swimming speed. In the experiment, the fastest swimming speed was close to reaching 1 body length per second, which represents the current swimming performance of the robot is quite excellent.

Conclusion & Prospects

To summarize, we designed a bistable soft robot with excellent swimming performance. When it moves underwater, it has the advantages of low noise and high efficiency. The movement of the robot is also similar to that of the frog, realizing the idea of bionic. Based on the existing work, we expect to further improve the swimming speed of the robot. For example, from the design of streamlined shell, to reduce the overall structure weight and determine the optimal beam thickness and drive frequency and so on improvements. This kind of robot will help to explore the ocean in the future.

Moreover, we are also doing research on the second-order buckling mode of the beam, and would like to realize switching between the first and second modes on this robot. This switching between modes helps the robot to transition between different motion postures, so as to carry out more valuable biomimetics, such as the biomimetics of the vampire squid, an ancient deep-sea creature.

References

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