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Research on Autonomous Underwater Robot Propelled by Bionic Octopus Tentacle Propulsors

Li Jian, Guo Yanling and Wang Wei

College of Electromechanical Engineering, Northeast Forestry University
lijian499@163.com

Abstract

In this paper, a common marine life - octopus is imitated. Based on the research of its tentacles hydrostatic skeletal muscle structure, the propulsive function of the tentacles is strengthened, and a bionic tentacles propulsor driven by shape memory alloy wires is developed. The action experiments show that the propulsor has a simple structure, large flexible deformation and silent action. Using LAEBT to compute tentacle's average propulsion force, the outcome shows that the tentacle can provide sufficient power. Based on this, a multiple-bionic tentacle propulsor underwater robot is developed. The robot is 230 mm in length, 110 mm in diameter and 590 g in weight. Having discussed the strategy of its motion, a proper one is selected and has been tested. The result of research shows that the robot has reliable structure and seal. It is well friendly to the environment and good at motility. The peak speed is about 115 mm/s while linearly swimming and it can turn at speed of18 ° /s. This prototype provides a new view on underwater robot developing.

Keywords*: bionic underwater robot, octopus, multi-tentacles propulsion, autonomous robot, shape memory alloy*

1. Introduction

The ocean area, which occupies 71% of the earth's surface containing a plenty of resources. The prospecting, development and utilizing the ocean resources have become a significant issue of human renewable development . But limited by some problems needed to be solved such as marine equipment, several technical problems on structure, control and correspondence, *etc.* Nowadays, underwater robot plays an important role in many aspects, including submarine mineral and biological resource exploration, marine environmental monitoring, submarine cable laying, *etc*. And traditional underwater robot is divided into two types:ROV(Remote Operated Vehicle) and AUV(Autonomous Underwater Vehicle). Generally, both of them using the rigid shell to sustain high pressure and propling several screw propeller which driven by the rich functional and mature development's electromotor. However, at the some time , there are some obvious defects existing, such as, sealing and miniaturization difficulty, low efficiency and maneuverability, uncontrolled cost, much noise and poorly friendly to environment[1].

Scientists in this field focus on those creatures living in the water because of the nature provides almost perfect solution on the many issues. Having been evolving for countless years, marine life acquired their various capacities to swim. Inspired by this, technicians invented many kinds of bionic underwater robot to meet different requirements and to get over the imperfection of traditional ones. Newly invented robot includes robotic fish[2], biomimetic robot[3], flapping foil AUV[4], *etc*. The research on bionic underwater robot is just on the beginning stage. In case of constitute forms, the majority of robot is still driven by electromotor which leads to complicated structure and much noise. What's more, the turning of joint lacks of

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smoothness. No matter physical structure or swimming level of the robot, it is far from paralleled with real creature. But in recent ten years, smart material has been used for producing artificial musculature, which can be applied on bionic machines. The new kind of robotic fish driven by smart material such as SMA(shape memory alloy)[5], IPMC(Ion-Exchange Polymer Metal Composite)[6], piezoceramics[7], and polypyvrole[8] become greatly more flexible, miniaturized and less complicated. All these will improve robot's propulsion capability.

Octopus is a kind of common marine life what has several tentacles and quick in action and able to provide thrust when it swimming. At home and abroad, study of biomimetic tentacle has been engaged. Figure 1 shows three kinds of underwater robot propelled by bionic tentacle. They are as follows. Robot in Figure 1.a is developed by professor Guo Shuxiang. It firstly use the SMA and IPMC as driving material and processes some degree of water jet propulsion[9,10]. Inspired by jellyfish's phugoid motion, Festo ltd manufactured Aquajelly. It's primarily consist of s sealed cabin sinteried by laser and eight tentacles propulsor. Each propulsor is able to bend back and forth driven by electromotor to supply thrust[11]. The third one is from South Korean Intelligence System Design and Control Laboratory. They built polymer actuator and based on it came up with their own bionic underwater robot[12].

Figure 1. Diagram of Three Kinds of Bionic Tentacle Propulsor Underwater Robot

This paper is based on the research of octopus' tentacle hydrostatic skeletal muscle structure. And a bionic tentacle propulsor driven by SMA wire is developed. Assembled with six propulsors and control system, this underwater robot can achieve autonomous swimming and works well.

2. Analysis of Octopus' Tentacle Skeletal Muscle and Design of Bionic Tentacle Propulsor

Octopus has eight tentacles which serve itself to prey and keep moving smoothly and balancedly. The tentacles are usually placed side by side to form a flexible plane while swimming. This plane gently deflects to one side when octopus needs to change its direction. Its basic state is a two dimensional bending posture. It shows the octopus's gesture when crawling and swimming in Figure 2.

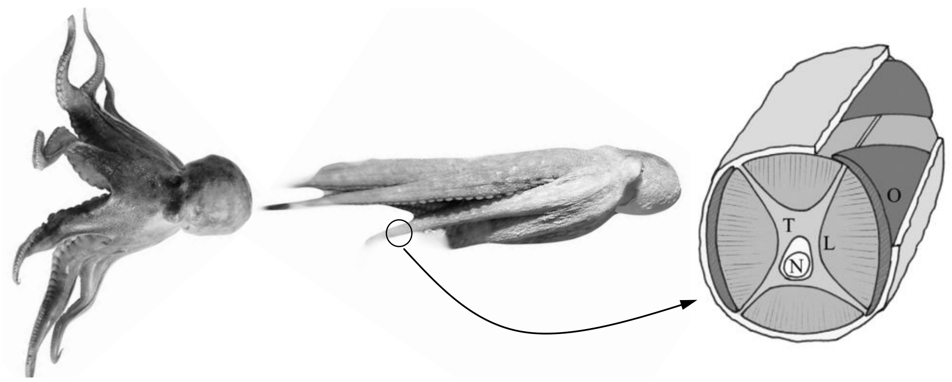


Figure 2. Diagram of Octopus' Appearance and Tentacle Muscle Structure

For musculature, it's a typical hydrostatic skeletal muscle structure of tentacle. As Figure 2 shows, it contains three kinds of muscle, the longitudinal which parallels tentacle(L), the transverse which is perpendicular to tentacle(T) and the oblique which covers on the longitudinal(O). They weave firmly on three dimensions. Hydrostatic skeletal muscle has a large range of deformation when elongating, bending and shortening. And via this motion, the muscle provides thrust within the volume remaining unchanged. One side of longitudinal muscle shortens while bending. The off-centered longitudinal makes the whole tentacle motivated. The bending stores energy in the transverse and the central elastomer, which can be used for regaining its original gesture.

The concept of bionics demands that the design is from biont and above biont. And at the same time, there must be some simplification in imitation. Leaded by this thought, both turning and propulsion is required when designing the bionic tentacles by imitating the real ones. But it is too hard to copy the vector motion of the real tentacle completely. In this circumstance, the acquirable scheme that propulsor only bends on two dimensions approximately is selected. Based on it, the bionic tentacle propulsor driven by SMA wire is developed.

The structure of propulsor is the very way to reproduce the motion of the real tentacle. To make it more flexible and simple, SMA wire is chosen as the drive material. The propulsor is consist of elastomer(PVC), SMA wire, skin(704 Silicone Rubber), support and control wire. One SMA is attached to each side of elastomer and shaped into "U". The both end of SMA is placed on the support and electrified by control wire. And the bottom of the "U" is placed on the edge of the elastomer opposite to the support. The skin covers on SMA to insulate from outside. For enlarging propulsion capability, the soft fin-shape chips are fixed on the rear of the propulsor. The principle for propulsor's motion is as follow. SMA wire is pre-elongated before electrified. After electrified and heated, SMA wire shortens via martensite transformation. Some degree of stress remains existing during shortening. Because of the off-centered placement of SMA, the stress produces the flexible bending on the whole tentacle. The poor thickness of elastomer, skin and the SMA leads a large range of swing with energy stored synchronously. Then, with the power cut off, the temperature goes down sharply in the water. And energy in skin and elastomer released which is used for elongating SMA again. Electrify SMA on both side of elastomer alternately and propulsor swings rapidly.

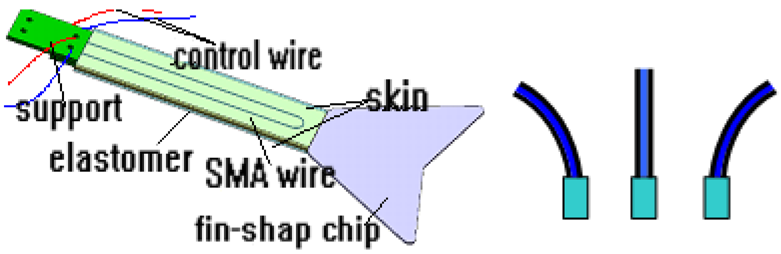
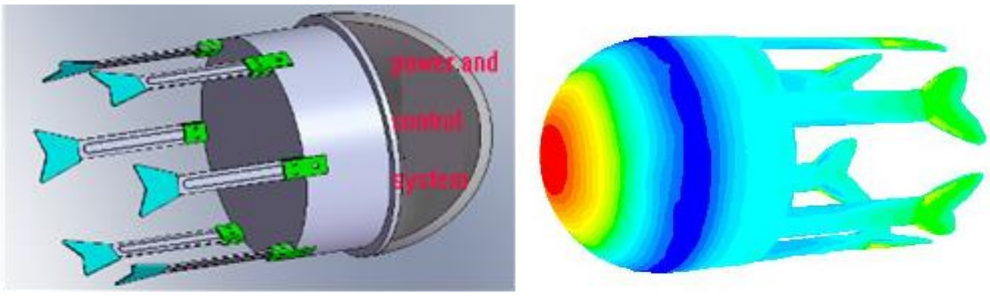


Figure 3. Diagram Of Bionic Tentacle Propulsor's Structure And Motion

3. Design of Multiple Tentacles Underwater Robot

3.1. Design on Structure and CFD Simulation

Based on bionic tentacle propulsor mentioned above, a prototype of six-tentacle robot is developed. The main body is a chamber and a half-ball like head. It embeds power source, correspondence and control system. The six tentacles are separated evenly at the rear of chamber. Different propulsion mode motivates different moving order of the tentacles. Apart from propulsion, the speed of the robot is also effected by its outline's resistance reduction. So, in order to find out how resistance influences, three dimentions model is built to be tested on FLUENT. The model is set as 230 mm in total length including 110 mm for its propulsor, and 110 mm in diameter. Set the model in a fluid field three times large as model's size. And fluid speed is regarded as the resistance force which robot meets in the water. When simulating, the entrance border is set as the beginning of the speed, the flowing speed is about 0.1~1 m/s, and the exit border is set as the edge of the pressure. This simulation is like a experiment of robot swimming in a water hole.



(a)3D model of the robot (b)Scattergram of static pressure

Figure 4. Diagram of 3D Model and Pressure Scattergram

Using the first-order separation implicit unsteady solution solves the control equations of fluid in FLUENT. According to the condition of speed border and size of the model, its Reynolds number is about 5000. This indicates a phase between laminar flow and turbulent flow. Thus, the laminar flow viscidity model is applied when computed. The surrounding field in water whose density ρ_w is 998.2 kg/m^3 and kinematic viscosity is 1.0×10^{-6}m^2/s. Figure 4.b shows how robot's body sustains pressure while moving. As we can see, the pressure covers evenly on most area. The exception is minority which includes head part with high pressure and chamber with back pressure. And these exceptions is why resistance of differential pressure exist. So focusing on these imperfection, there are two rational solution. One is to improve its shape. To streamline the robot is a promising choice. The other is building it with low-resistance material.

Besides, in simulation, it also shows how fluid resistance force changes with speed of the robot. Figure 5 shows the curve chart. As we all see, with the speed increasing, the resistance goes up exponentially. The speed reaches peak when propulsion force is equal with resistance force. And meanwhile, a non-tentacle robot model is simulated as well. From curve chart, we can get that the tentacle robot suffers less resistance than the non-tentacle one. And this indicates that the tentacle propulsor can retard the separation of the fluid. And, that's to say, it reduces the resistance.

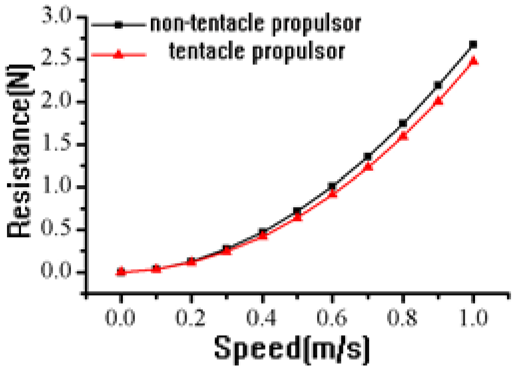


Figure 5. Curves of Resistances of the Biomimetic Underwater Robot

3.2. Structure and Control system

The bionic octopus robot and its control system is shown in Figure 6. It's 230 mm in length ,590 g in weight and with a diameter of 110 mm. Main parts of the robot are chamber, end cap, six tentacle propulsors, battery, circuit board, and balance weight, which three is placed inner the chamber. And the chamber made from polyethylene is attached to acrylic end cap via screw and sealed by O-ring. The propulsors are embedded on the outer surface of the chamber. And propulsors' wire reaches to the inside via little holes on the stick spot, sealed for no more displacement.

Six-tentacle propulsors are divided into three groups with every two propulsors in the same group side by side. In each group, the SMA wires on the same side of two propulsors is paralleled and connected to MOSFET. The MOSFET is controlled by PIC16F877A on circuit board. And via MOSFET, PIC16F877A commands SMA wire electrified differentially, pulsingly and open-looply. Three 3.7V, 1500 mA rechargable battery cascade to power SMA. The remote control module on circuit board contributes to the correspondence between PIC and controller. PT2262 and SC2272 works as wireless sending and receiving module. They can guarantee six corresponding signals. This module is small in size and easy to test, but limited by the number of signals and the range of correspondence.

The SMA wire in propulsor is 0.2 mm in diameter of section and is made from Ni-Ti. Its transformation temperatures under no strength are as follow, M_f=43.4 ℃, M_s=52.2 ℃, A_s=51.4 ℃, A_f=58.8 ℃. The maximum stress of SMA and elastomer are 26.69 GPa and 2.796 GPa. So the shorten of SMA is able to overcome elastomer's bending stress. As for size, tentacle propulsor is 90 mm in length, 10 mm in width and 0.4 mm in thickness. Thus, by computing, the bending angle can reach to 191° while the strain of SMA is only 2%.

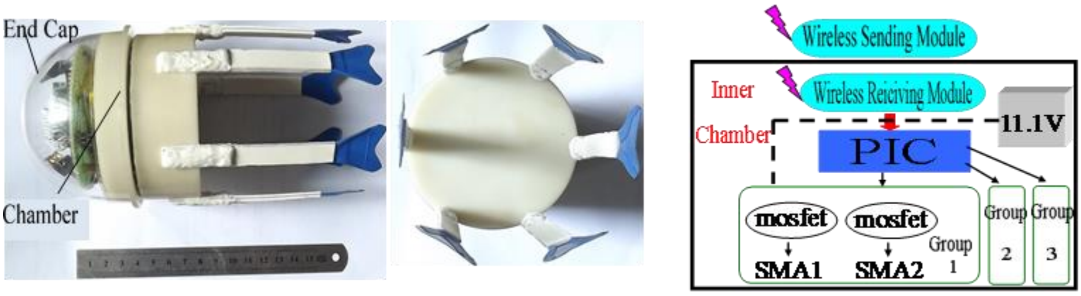


Figure 6. Diagram of Multiple Tentacle Robot and Schematic Drawing of Control System

4. Action Experiments

4.1. Testing Experiment on Tentacle Propulsor's Motion

To test the function of the bionic tentacle propulsor, the underwater motion experiment is conducted. In the experiment, the water temperature is 22℃. Electrify SMA on two sides of elastomer with the way demonstrated on Figure 7. In diagram, t_{on}, t_{off} and t_{int} stand for time for electrifying(drive pulse width), time for cooling(drive pulse separation) and time for separation of electrification between SMA wires on two sides of elastomer. And Figure 8 shows the result of the experiment on the condition that energizing voltage is 7.4 V and t_{on}, t_{off} are 60 ms,150 ms. The result indicates that the bending of propulsor is flexible, smooth, reliable and reachable in a large range.

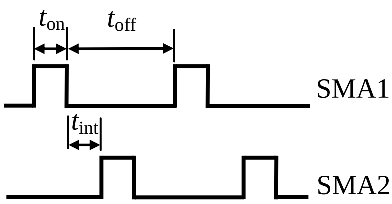


Figure 7 Diagram Of Pulses' Parameter

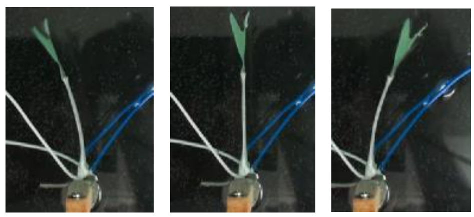


Figure 8 Diagram Of Bionic Tentacle Propulsor's Motion

4.2 Linar swimming experiment

A linar swimming experiment is also conducted. Under the same pulse order, the whole six tentacles are electrified on the condition that and are 80 ms and 200 ms. Figure 9 is demonstrated how the propulsors swim. The swing provides force to move forward. From the curve of distance and speed over time, we can see that speed goes up as well as the distance increasing. The peak average speed is about 115 mm/s on which propulsion force is balanced with resistance force. In tiny time segment, the speed is not stable as propulsion force is not a constant value, either. So the speed curve consists of many sharp pulses.

Figure 9. Diagram of Robot's Motion While Linar Swimming

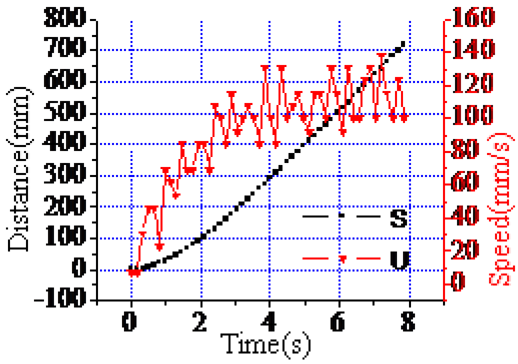


Figure 10. Curve Chart of Speed and Distance Overtime

4.3 Turning Experiment

At last, a turning experiment is conducted as well. In this experiment, only one side propulsor of the robot is motivated. The electrifying condition is still with t_{on} 80 ms and t_{off} 200 ms. Figure 11 shows how it turns. As we can get, propulsor on the only side provides a off-centered force and gives the robot a torque making the body turn in arrow's direction. The speed of turning can make it to 18 °/s.

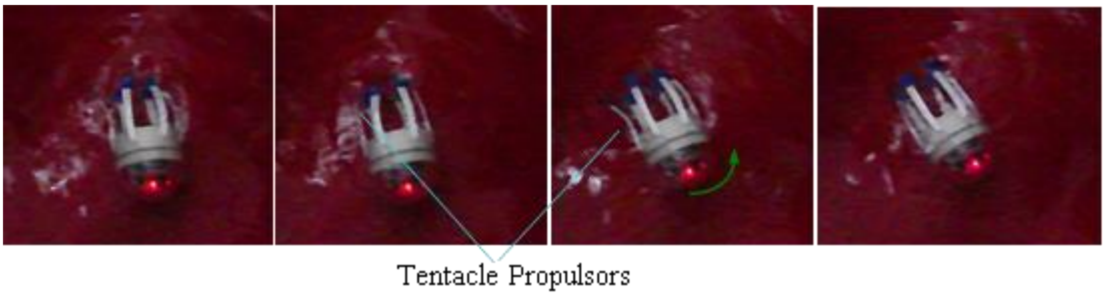


Figure 11. Diagram of Robot's Motion While Turning

5. Conclusion

Based on the research of hydrostatic skeletal muscle structure of octopus tentacles, the prototype of six-tentacle underwater robot is developed. Driven by artificial musculature-SMA wire, it gets simple structure and multiple propulsors. The robot is needless to apply motive seal and able to move silently. Fluid simulation proves that it has a good outline feature. And the experiments indicate that it possesses quite good level of linar swimming and turning and all of these are under a reliable control. However, the machine are also remaining something unsolved . The consistency and coordination of propulsors still remain to improve. The power is not strong enough. What's more, the work on accurate control of

SMA and cooperative motion of propulsor will be conducted in the next step of development.

Acknowledgements

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