

# DESIGN AND IMPLEMENTATION OF A SMART ROBOTIC SHARK WITH MULTI-SENSORS

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Smart intelligent robotic fish has shown promising advantage in underwater searching. This paper addresses the smart robotic shark design and control issues with multi-sensors. In particular, we propose a new design of a two-link mechanism robotic shark equipped with gyroscope, pressure sensor, infrared sensor, and light sensor. Then three-dimensional motion control, depth control, autonomous obstacle avoidance, and light navigation are developed. In particular, a bio-inspired Central Pattern Generator (CPG) based control method is adopted to smoothly control the robotic shark's locomotion in all the above realization. All motion control methods are implemented in real time with a hybrid control system based on embedded microprocessor (STMicroelectronics STM32F407). Latest aquatic experiments demonstrate a fairly good result in improving the robotic shark's intelligence. The developed scheme affords an alternative to smart robotic fish design in complex underwater environments.

**Key Words:** Robotic shark, CPG, Multi-Sensors, Motion control

## 1. Introduction

Underwater vehicles are well recognized in various applications, such as exploration of marine resources, underwater target search, as well as military purposes. Among a variety of underwater vehicles [1], bio-inspired swimming robot [2] has shown superior performance in efficient propulsion and high maneuverability compared with conventional underwater vehicles propelled by rotary propellers [3].

Smart robotic fish plays an important role in underwater exploration, especially in cave search for its limited space. The existing studies almost have been focused on theoretical aspect and development of large robotic fish whose

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body length is up to 50 cm or longer. Among those with the propulsive mechanism of multi-linkage [4], the number of joints is almost larger than three. There have been few or limited studies on the robotic fish with two joints or only one. With the propulsive configuration of two links, how to achieve similar fishlike motions like forward swimming, turning, diving, and surfacing remains challenging.

This paper, on the basis of our previous research on fishlike swimming, aims at designing and implementing a two-link smart robotic shark with multi-sensors [5]. Specifically, a robotic shark with two tail joints and a pair of pectoral fins is designed to validate the functionality of the two-link mechanism. In the meantime, multiple sensors are used to improve its intelligence. A bio-inspired central pattern generator (CPG) controller [6-9] is then adopted to achieve stable 3D underwater movements. Finally, aquatic tests on the real robot verify the effectiveness of the proposed mechanism and control methods.

The rest of this paper is organized as follows. The overall mechatronic design of the smart robotic shark with multi-sensors is overviewed in Section 2. Section 3 gives a brief introduction of motion controller combining sensor information and the CPG controller for stable fishlike swimming. Experimental results are provided in Section 4. Finally, Section 5 concludes the paper with an outline of future work.

## 2. Prototype of the Robotic Fish

### 2.1. Mechatronic Design

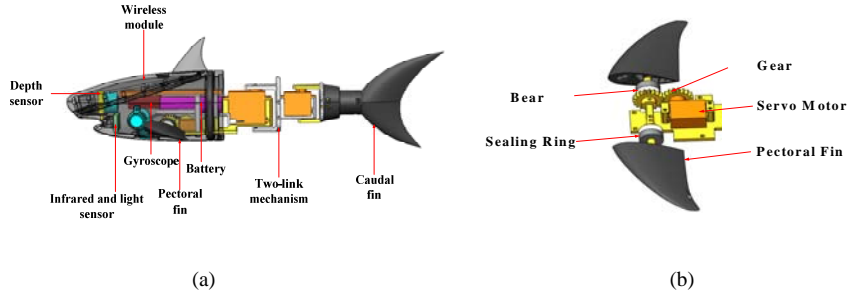


Figure 1: (a) Mechanical configuration of the robotic shark. (b) Mechanical design of pectoral fin propulsion.

Figure 1(a) shows a schematic diagram of the developed robotic fish prototype. As can be seen, the robotic fish has multiple fins including a caudal fin, a pair of pectoral fins. Mechanically, the robotic shark consists of a rigid head housing

multi-sensor, control circuits, and lithium battery pack, a flexible body with two joints, and a caudal fin. Each joint is actuated by one servo motor, whose control signal is produced by the fine-tuned CPG controller. Coordinated multiple joints allow the robotic fish to swim forwards/backwards, submerge, surface, and turn. The detailed technical parameters of the robotic shark are shown in Table 1.

Table 1: Technical parameters of the robotic shark.

| Parameter            | Description   |
|----------------------|---|
| Size (L×W×H)         | 350 × 61 × 83 mm <sup>3</sup>                               |
| Weight               | 970 g   |
| Joint drive          | HS-5565MH and HS-82MG                                       |
| Sensor type          | Infrared sensor, pressure sensor<br>light sensor, gyroscope |
| Controller           | Stm32f407   |
| Operating conditions | 7.4 V   |

Due to the limited size of the robotic shark, there is not enough space to mount two servo motors to drive each pectoral fin. Thus a servo motor along with a pair gears is adopted. As shown in Figure 1(b), the servo motor drives the two pectoral fins through the pair of gears. They will be rotated to the same angular position simultaneously.

## 2.2. Hardware Development

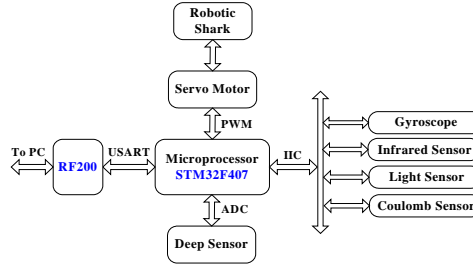


Figure 2: Hardware design of the online swimming control.

At the level of hardware design, as shown in Figure 2, STMicroelectronics STM32F407 microcontroller is selected as the main control chip. A bidirectional RF module RF200 that can transfer message between the embedded system and the PC is chosen. Multi-sensors are selected to improve the intelligence of the robotic shark including gyroscope, depth sensor, infrared sensor, light sensor, and coulomb sensor. Particularly, A MPU9150 is chosen as the gyroscope part. In addition, the BH1750FVI is adopted as the light sensor for its large measurement range. A micro-pressure sensor is used as the depth

sensor with a range of 0 to 2 m. Three infrared sensors are installed on each side of the robotic shark to detect block area. Moreover, a MAX17044 is designed to monitor the capacity of the Li-Po battery. The main control circuit board and infrared sensor board are shown in Figure 3.

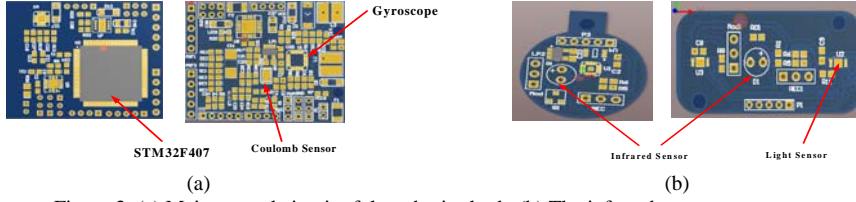


Figure 3: (a) Main control circuit of the robotic shark. (b) The infrared sensor.

### 3. Motion Controller Combining Sensory Information and the CPG Controller

#### 3.1. Three-Dimensional Motion Control Based on Gyroscope Compensation

In general, to achieve three-dimensional (3-D) locomotion aided by the pectoral fin, the robotic fish should maintain a certain forward speed. Particularly, this speed is related to the length of the multi-link mechanism. In order to explore propulsive mechanism and performance of the two-link robotic fish, we propose a 3-D motion control method based on gyroscope compensation.

Particularly to achieve up and down swimming, a pair of pectoral fins is used to realize this. When the robotic shark wants to swim downside, we should set the angle of the pectoral fins as shown Figure 4(a). In that case when the robotic shark swim forward, the water will generate a downward force to the pectoral fins that will make the robotic shark swim downside. Otherwise if it is set as shown in Figure 4(b), the robotic shark will get an upward force that drive it to swim upside. Moreover, if we want to swim forward as fast as we can, we should make the pectoral fins be parallel to the water surface as parallel as we can, for it will get little drag force from the water.

Given that there are tough issues such as the interference of water, output signal error of CPG [10-14], servo motor rotate error, the robotic shark can hardly swim in strictly straight direction in water. Thus an output compensation based on gyroscope feedback is proposed in this paper to reduce the swimming error. Particularly upon the start of forward swimming, we obtain the direction angle it will swim to by sampling the output of the gyroscope. Then we start forward swimming and calculate the current direction angle in real time. Due to its locomotion property, the output direction angle will oscillate around a certain

value. If the robotic shark swim as strictly straight as it is mean to, the value should be the start direction angle. Assume that the compensate period is  $T$ , in the sample period, we average the sampled direction angle and compare it with the destination direction angle, if it is on the left of the destination, then the robotic fish will turn right and vice versa. Then keep turning until the current direction angle is equal to the destination and then continue to swim forward. With the method above, the final direction error is reduced in real time swimming. As a result, the robotic shark will finally achieve 3-D locomotion.

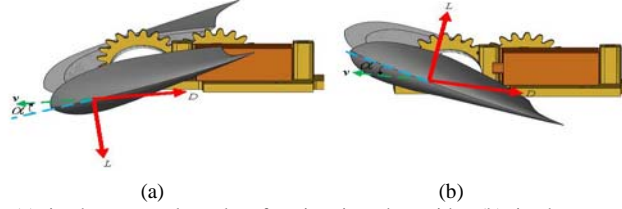


Figure 4: (a) is the pectoral angle of swimming downside. (b) is the pectoral angle of swimming upside.

### 3.2. Depth Control of Robotic Shark Based on Pressure Sensor Feedback

For precise three-dimensional locomotion, depth control is fundamental and significant to the robotic shark. With the pressure sensor equipped in the designed robotic shark, the depth of the robotic shark can be acquired and used as a feedback signal for depth control [15, 16].

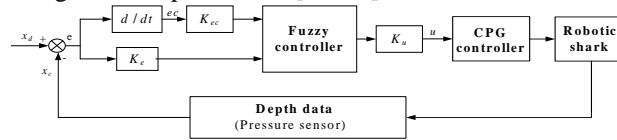


Figure 5: Depth control framework combining the fuzzy logic controller and the CPG controller.

In this paper, a fuzzy logic controller is developed to obtain the input of CPG controller. The control framework that combines the fuzzy logic controller and the CPG model is described in Figure 5.  $e(k)$  denotes the input error, while  $ec(k)$  represents the derivative of the input error.  $d_d$  is a predetermined depth position that the robotic shark finally will reach.  $d_c(k)$  is the real-time depth of the robotic shark. With the fuzzy controller above, the robotic shark can finally reach a predetermined depth after a series of up-and-down movements.

### 3.3. Autonomous Obstacle Avoidance Motion Control Based on Infrared Sensor Feedback

Due to uncertainty of water environment, it is necessary for the robotic shark to have ability to detect the information of the environment, especially obstacle avoidance in autonomous navigation. In this paper, three infrared sensors are installed on the right, front and left side of the robotic shark to detect obstacles underwater. If there are obstacles on the left of the robotic fish, it will turn right, vice versa. If there are obstacles in the front of the robotic fish, it will turn back. If there is no obstacle, the robotic fish will swim forward. An output table is designed based on the status of the infrared sensors. Let 1 be obstacle detected and 0 be none. The status of the three infrared sensors is from 000 to 111 while first bit represents the status of the left infrared sensor, middle bit is front one and third bit is the right one. The detailed description is tabulated in Table 2.

Table 2: Output offset value based on status of infrared sensors.

| Status | Direction              |
|--------|------------------------|
| 000    | Forward                |
| 001    | Turn Left              |
| 010    | Turn Back              |
| 011    | Turn Left and Forward  |
| 100    | Turn Right             |
| 101    | Forward                |
| 110    | Turn Right and Forward |
| 111    | Backward               |

### 3.4. Autonomous Navigation Based on Light Intensity Sensor Detection

Light navigation is very useful in real-world applications, especially when we want to swim out a dark area, such as a pipe or cave.

In this paper, we installed two light detect sensor in the front of the robotic shark, and by sampling the light intensity data of the two sensor, the robotic fish can swimming ahead automatically. If the light intensity of the left is strong than that of the right, the robotic shark should turn left and swimming forward, otherwise it should turn right and swim forward. If the two is almost the same, the robotic shark should swim forward directly. By the rule stated above, the robotic shark will finally be autonomously navigated with the help of light sensors.

## 4. Experimental Results

To verify the feasibility of the designed robotic shark and proposed control method, we have carried out some aquatic experiments in the swim pool. In a pool with the size  $500 \times 400 \times 150 \text{ cm}^3$ , we conduct some experiments including forward swimming, up-and-down swimming, automatic obstacle

avoidance, light navigation and depth control. A sequence of autonomous navigation based on all the sensors is demonstrated in Figure 6, where the robotic shark can successfully perform free-swimming in the pool without remote control. In the experiments, the speed of the robotic shark has 9 levels from 0.25 BL/s to 2.5 BL/s and with the battery capacity of 3400 mAh, the robotic shark can keep about 40 minutes for continuous free-swimming. Particularly the two-link mechanism is really enough for three dimensional free-swimming.

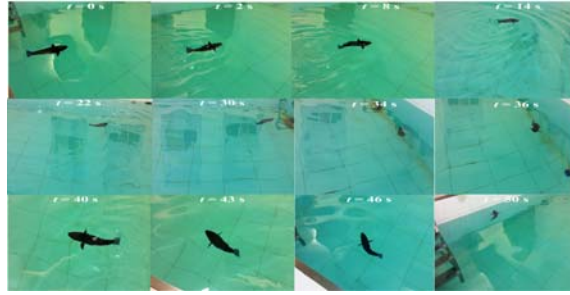


Figure 6: Snapshot sequence of the robotic shark navigation

## 5. Conclusion and Future Work

In this paper, we have designed a smart robotic shark with multi-sensors using a two-link mechanism. Specifically, a hybrid control system framework combining one microprocessor and multi-sensor is firstly built. Then a three-dimensional motion control method based on CPG mode and gyroscope compensation is adopted. In addition, depth control with pressure sensor feedback, autonomous obstacle avoidance with infrared sensor, light navigation is performed to improve the intelligence of the robotic shark. Finally, autonomous navigation swimming control experiments have been carried out to demonstrate the effectiveness of the proposed control framework and methods.

The ongoing and future work will focus on the intelligence improving and energy optimization of the robotic shark, including adding embedded vision and improving CPG model with energy optimization so that the robotic fish can adapt to more complicated underwater environments.

## References

1. Paull L, Saeedi S, Seto M, AUV navigation and localization: A review, *IEEE Journal of Oceanic Engineering*, 39(1), 131–149, 2014.
2. Bogue R, Underwater robots: a review of technologies and applications. *Industrial Robot: An International Journal*, 42(3), 2015.
3. Asare V A, Shende R S, Mechatronics and Motionability of an Underwater Robot: A Review, *Mechatronics*, 2(3), 2014.

4. Faudzi A A M, Razif M R M, Nordin N A M, A Review on Development of Robotic Fish, *Journal of Transport System Engineering*, 1: 12-22, 2014.
5. M. Wang. Locomotion Modeling and Control of Biomimetic Robotic Fish Based on Central Pattern Generators [PhD Thesis]: Institute of Automation, Chinese Academy of Sciences, 2010.
6. J. Yu, M. Tan, S. Wang, and E. Chen, Development of a biomimetic robotic fish and its control algorithm, *IEEE Transactions on Systems, Man, and Cybernetics*, Part B: Cybernetics, vol. 34, no. 4, pp. 1798–1810, 2004.
7. J. Yu, M. Tan, and J. Zhang, Fish-inspired swimming simulation and robotic implementation, in *Proc. 41st International Symposium on Robotics (ISR) and 2010 6th German Conference on Robotics (ROBOTIK)*, Munich, Germany, June 2010, pp. 1158–1163.
8. J. Yu, M. Wang, Z. Su, M. Tan, and J. Zhang, Dynamic modeling and its application for a CPG-coupled robotic fish, in *Proc. IEEE Int. Conf. Robot. Autom.*, Shanghai, China, May 2011, pp. 159–164.
9. Z. Wu, J. Yu, and M. Tan, CPG parameter search for a biomimetic robotic fish based on particle swarm optimization, in *Proc. IEEE Int. Conf. Robot. Biomim.*, Guangzhou, China, Dec. 2012, pp. 563–568.
10. J. Duysens and H. W. A. A. Van De Crommert, “Neural control of locomotion; Part 1: The central pattern generator from cats to humans,” *Gait and Posture*, 1998, 7(2): 131–141.
11. G. Wang, D. Zhang D, L. Lin, H. Xie, T. Hu, and L. Shen, CPGs control method using a new oscillator in robotic fish, *Science China Technological Sciences*, 2010, 53(11): 2914–2919.
12. C. Zhou and K. H. Low, Kinematic modeling framework for Biomimetic undulatory fin motion based on coupled nonlinear oscillators, in *Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst.*, Taipei, Taiwan, Oct. 2010, pp. 934–939.
13. Yu J, Tan M, Chen J, and Zhang J, A survey on CPG-inspired control models and system implementation, *Neural Networks and Learning Systems, IEEE Transactions on*, 25(3), 441–456, 2014.
14. Wang M, Yu J, Tan M. CPG-based Sensory Feedback Control for Bio-inspired Multimodal Swimming, *International Journal of Advanced Robotic Systems*, 11, 2014.
15. K. H. Low, “Locomotion consideration and implementation of robotic fish with modular undulating fins: analysis and experimental study,” in *Proc. Int. Conf. Intelligent Robots and Systems*, 2006, pp. 2424–2429.
16. P. J. Lee, C. H. Yen, C. L. Chan, M. S. Lee, and R. C. Wang, Implementation of a fuzzy control based intelligent robot fish, *International Journal of Fuzzy Systems*, vol. 11, 2009, pp. 287–297.