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Development of Robot Fish, ROFI 1.1

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Abstract

This study introduces the development of robot fish ROFI 1.1. Today, robot fish is one of strong candidates for next-generation UUV. The present paper describes the design, manufacturing, and operation tests of the robot fish developed at Seoul National University. The very first robot fish in Korea, ROFI 1.1 is operated by a wireless remote controller. Its overall length is 680mm, and weight is 8.8kg. The fore body contains main mechanical and electrical systems and is covered by a FRP skin. The aft body has a mechanical bone system that mimics fish bones, and its skin is made of flexible silicon sponge to allow elastic motion for propulsion. It is found that this mechanical system creates effective and realistic fish-like swimming mode. It is observed that the normal and maximum advancing speeds of ROFI 1.1 are about 1 and 2 m/sec, and the turning radius is between 0.7~2.5m, depending on the turning mechanism.

Keywords: robot fish, biomimetics, fish propulsion

1 Introduction

The evolution of fisheries goes back to 160 million years ago. To survive and adapt in watery environment, they have been evolved to the optimum shapes with the maximized efficiencies of propulsion and maneuvering. Some tunas of less than 1m length can create explosive swimming speed up to 100km/hr, and sharks can turn 90 degrees in a second during their fast cruise. Yet, any machinery invented by human cannot mimic such population efficiency and quick turning motion.

Based on the biomechanical point of view, Lindsey (1978) and Webb (1984) introduced useful physical description about fish motion, and Sfakiotakis et al. (1999) provided a good summary. The physical mechanism involved in fish motion has been of interest to engineers, as well as zoologists. Lighthill (1969) introduced a wing theory to explain fish propulsion, but the very first mechanical product mimicking the shape and motion of fish was introduced by Barrett (1996). A robot tuna, named to Charlie I, was developed at MIT which introduced later more robot fish, Robot Tuna II and Robot Pike. MIT's Towing Tank Laboratory has led both theoretical (e.g. Wolfgang et al. 1999) and experimental studies (e.g. Triantafyllow et al. 2003) in this field. Afterward, other researches were introduced, for instance, Robot Lobster (Northeastern Univ., Ayers et al. 2000) and Calibot (U.C. Berkeley 2003). Particularly Draper Laboratory developed the Draper Tuna (Anderson and Kerrebrok 2002) which can swim and collect information for three hours in aquatic environment. The study on robot fish also has been continued in Japan. For instance, a robot named to Coelacanth (1999) was built by Mitsubishi Heavy Industry, and Hirata (2001) built various educational robot fishes.

This paper introduces the development of ROFI (Robot FIsh) 1.1, the first robot fish in Korea. ROFI 1.1 has a fish-like outfit, and equips internal machines to generate fish propulsion. It is operated by wireless controller, and a new system similar to real fish bone is adopted for fish-like locomotion by generating undulatory motion of the aft body. Its turning mechanism is designed to mimic the fish motion which continues tail motion in one side and/or keeps a bending posture. The propulsion and turning motions are observed in water tank, and it is found that the designed mechanism is very effective to simulate the fish motions. In this paper, the fundamentals of fish motion are briefly described at first. Then the design, fabrication, and tests of ROFI 1.1 are introduced.

2 Fundamentals of fish motion

Figure 1 shows the main parts of fish body related to swimming. Fish use their fins and tails for propulsion and/or maneuvering, and many fish couple the motion of whole body with fin action. In addition, some fish use unique fins or parts.

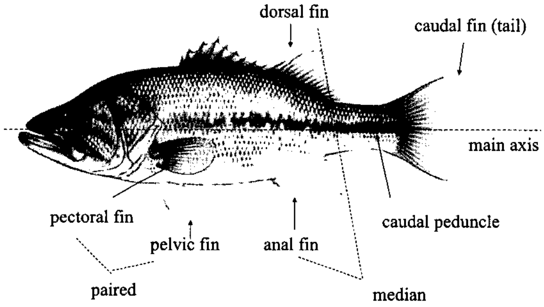


Figure 1: Fish Fins

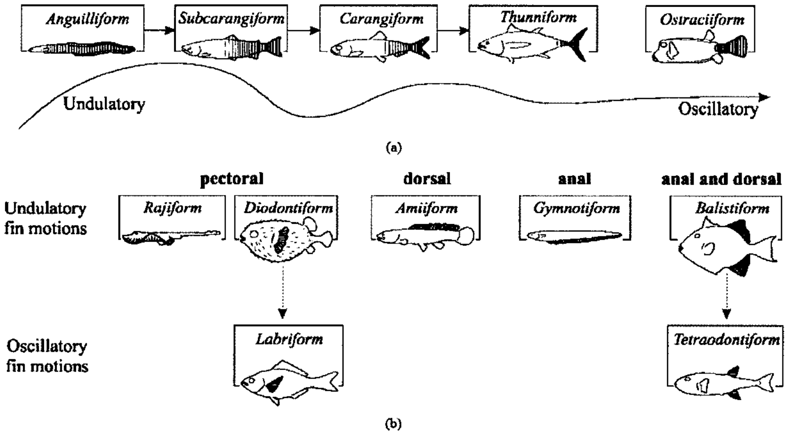
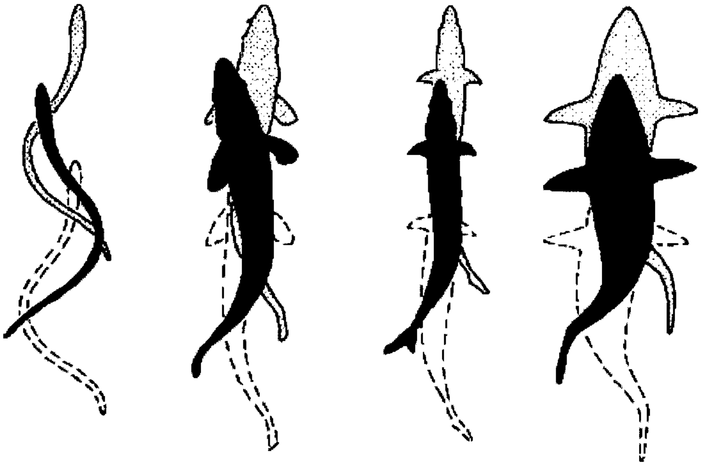


Figure 2: Category of swimming modes associated with (a) BCF and (b) MPF propulsions. Shaded parts provide the primary contribution to thrust generation. (Lindsey 1978)

In a large sense, the fish motion can be categorized into two mechanisms: body and/or caudal fin (BCF) locomotion, and median and/or paired fin (MPF) locomotion. The former mechanism generates propulsion force by bending fish bodies into a backward-moving propulsive wave that extends to its caudal fin, while the latter uses median fins (see Figure 1). Most fish employ the BCF locomotion, and only 15% of fish families use non-BCF modes (Sfakiotakis et al. 1999) Based on propulsion types, Breder (1926) categorized the three types of fish: Anguilliform, Carangiform, and Ostraciiform. Lindsey (1978) introduced a more detailed classification that covers the three types. Figure 2 shows a category of swimming modes associated with BCF and MPF propulsion.

Figure 3 shows the swimming modes of BCF propulsion. Angulliform fish have the undulatory movement of whole body to push water. To get propulsion force, the speed of undulatory motion should be faster than that forward speed, and the motion amplitude of aft body should be greater than that of fore body. Angulliform swimming is effective in small or narrow domain, but the body motion should be very smooth and the body should consist of many joint hinges. Moreover, maneuverability is not efficient. Carangiform swimming mode has the significant movement of 1/3 aft body. Fore-body movement is combined to induce more positive and negative pressure gradients around the body, but the major propulsion force comes from the aft body. Fish of Carangiform swimming has generally faster speed than Angulliform fish. Subcarangiform swimming model is in between Angulliform and Carangiform. Tunniform is the most effective swimming style in water. This style generates powerful propulsion by combining the aft-body motion and tail motion. Two motions have a phase difference (90-deg in general) to maximize propulsion and reduce the energy. Well-streamlined bodies such as shark and tuna belong to this group. Ostraciiform depends on the oscillation of tail. Due to simple stiff oscillation of tail to push water, the propulsion efficiency is poor. However, a simple swim mechanism is enough. Figure 4 summarizes the relation between the propulsors on fish body and their swimming functions, proposed by Webb (1984).



(a) Anguilliform (b)Subcarangiform (c) Carangiform (d) Ostraciiform

Figure 3: BCF swimming modes (Lindsey 1978)

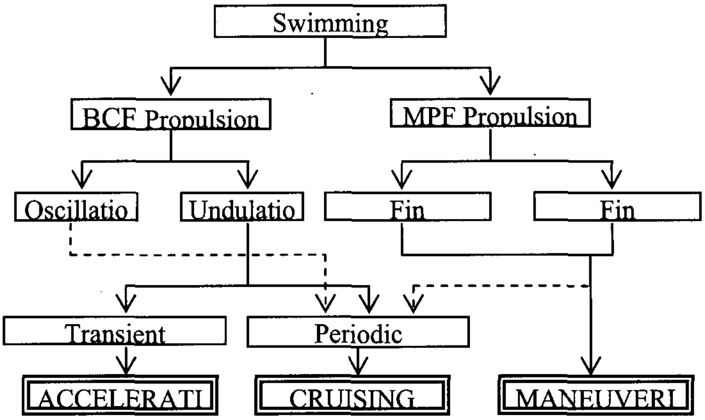


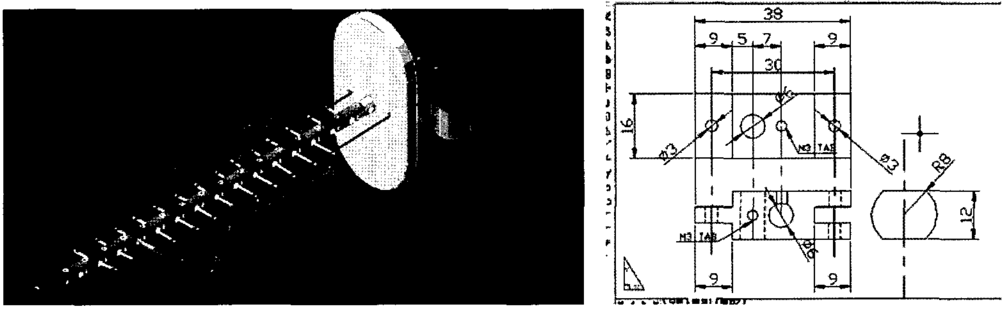
Figure 4: Relation between swimming propulsors and swimming functions (Webb 1984)

3 Design and manufacturing

Two models were considered in the design stage: a RC model and an autonomous model. The RC model, ROFI 1.1, was designed to be operated by a wireless remote controller, while the autonomous model, ROFI 1.3, was designed to equip sonar sensors and internal control devices for distance detection and collision avoidance. In the present paper, the concentration is given to the RC model.

3.1 Concept design

ROFI 1.1 was designed to imitate the Carangiform or Subcarangiform swimming. Plane motion near free surface was of primary interest and the control of submergence depth was not considered in this study. Most of previous robot fishes adopted two or three nodes in their whole or after bodies, which consisted of separated motors and mechanical systems. For instance, Charlie I (Barrett 1996) and Robot Pike had adopted two or three nodes in their aft bodies for tail propulsion, and each node was operated by an individual motor. In the case of Draper Tuna (2002), the body has four degree-of-freedom robot linkage to create the fish-like motion. In the present study, we designed a single system for the aft body to accomplish more natural fish-like motion and also to reduce labor effort for manufacturing. To this end, a mechanical bone system similar to fish bone was invented (Figure 5). This system consists of small pieces similar to the backbone pieces of fish. These pieces were designed to be connected by vertical joints to allow transverse motion.



(a) Concept design of motion control (b) Drawing of bone piece

Figure 5: Design of mechanical bone system in aft body

It was designed that the motion of the mechanical bone is controlled by two motors. A DC motor activates a crank that controls the tension of two steel wires connected with bone pieces. A strong rod penetrates transversely each piece of bone, and its both ends are connected with steel wires. The DC motor repeats the tension and release of wire through a gear system which has a function of controllable speed. The tension and release of wire generate the transverse motion of the mechanical bone system. Obviously the amplitude of motion becomes larger as distance from the motor increases. This mechanism was designed to create the propulsion force. The other servo motor was planned to control the motion of the base plate that the DC motor lays. A small rotation of the base plat of the DC motor provides more tension of one wire and more release of the other wire. When this is the case, the main axis of the mechanical bone system keeps a bending posture. The DC motor can be activated at this condition, either. This design makes the robot fish to turn with and without propulsion.

There are some advantages of this mechanical bone system. Above all, this is a natural mimic of fish propulsion. Fish use their body muscles to repeat the tension in one side and release in the other side. Our design is to reproduce the physical mechanism of fish muscle by a mechanical system. Therefore, this system is expected to generate smooth and natural fish motion. Furthermore, this mechanism is easy to manufacture. The arrangement of multiple motors and units in aft body is not necessary, therefore the manufacturing effort and cost are less than other robots. However, there is doubt that this system is adequate for a very large fish robot.

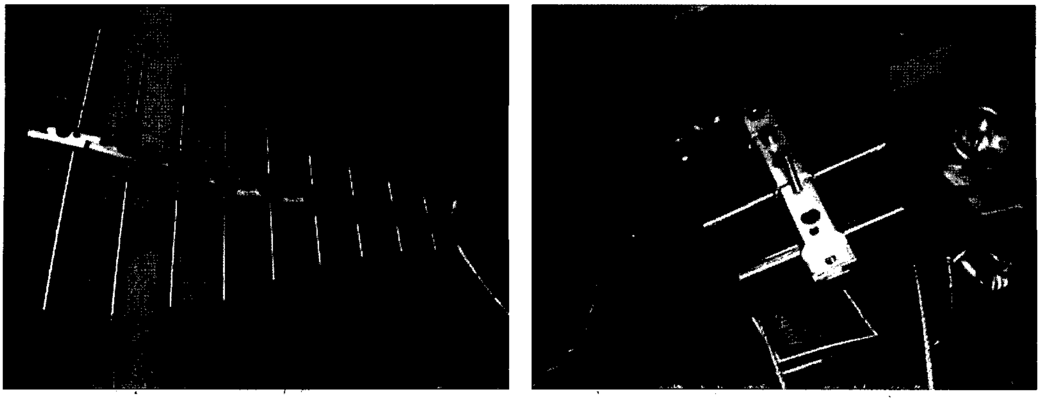
A bulkhead was arranged to divide the fore and aft bodies. The fore body was designed to equip all the mechanical and electric systems, e.g. motors, cranks, gears, electric boards, chips, and batteries, except for the bone system. It was planned that base plates for mechanical and electric systems are eventually assembled with the bulkhead, and two small holes through the bulkhead were designed for connecting the steel wires and the DC motor. Then, the skin of the fore body should be solid to protect the internal machines.

A choice of proper material is essential in the design of aft body, since the propulsion efficiency is strongly dependent on the elasticity of the material. Fabric materials or flexible silicon had been selected to cover the aft body of other robot fishes, and silicon sponge was selected in the present design. Silicon sponge is a flexible material, but requires a certain thickness to resist deformation due to water pressure. This implies that propulsion efficiency may not be high. However, this is acceptable since any structure to support skin is not designed in the aft body.

All the designed parts were divided into two groups: ready-made and self-made parts. To reduce manufacturing cost, the mechanical, electric parts and pieces were designed to use ready-made products as many as possible. The detailed drawings were prepared for all the custom-order parts, as shown in Figure 5(b).

3.2 Manufacture and assembly

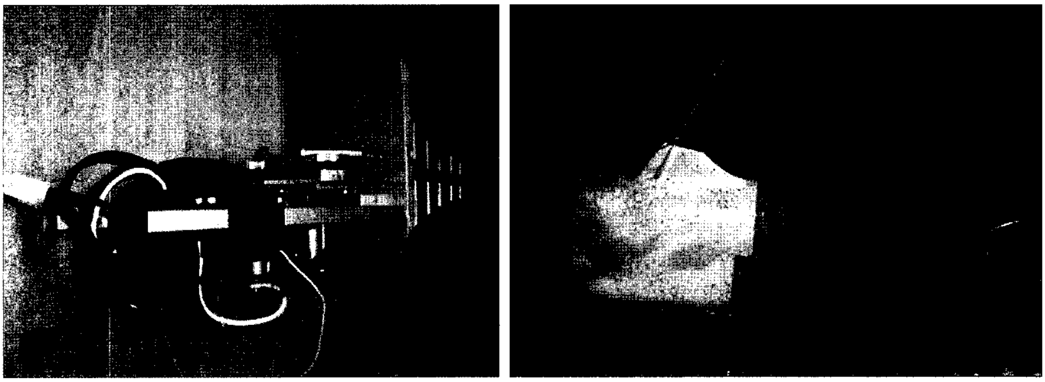
Most mechanical parts including base, bone pieces, and bulkhead were made of aluminum. Precise cutting machines were used to manufacture the self-made parts, as designed. Figure 6 shows the assembled bone in the aft body. 10 bone pieces were manufactured and assembled to have 30mm distance between joints. To make skin of the aft body, the silicon-sponge sheets of 30mm thickness were put together and glued, then carved to imitate fish shape. To allow the motion of mechanical bone system and increase the elasticity, some internal part of the silicon sponge was hollowed out.



(a) Assembled bone pieces with wires and tail (b) Internal structure of the aft body

Figure 6: Bones and internal structure of the after body

The hull of the fore body was made of FRP. The hull protects all the machines and parts in the fore body, and was assembled with a bulkhead and the aft body. Water-tight was successfully done by screwing down the hull and bulkhead, and applying water-tight silicon to the surface connecting the fore and aft bodies. A fish-like tail was manufactured by cutting aluminum plat and attached to the last bone piece. An Athena for wireless control and power switch were stretched out of the hull. To keep a designed submergence depth, a heavy weight made of lead was attached on the bottom of the fore body. Figure 7 shows the assembled major parts of the robot fish (a) and the fully assembled shape of ROFI 1.1 (b). Table 1 summarizes the main particulars of ROFI 1.1.



(a) Assembly of major parts (b) ROFI 1.1 after full assembly

Figure 7: Assemblies of ROFI 1.1

Table 1: Particulars of ROFI 1.1

Item	Particulars	
Weight	8.80 Kg	
Lengths	680 X 118 X 218 mm (L X B X D)	
Block Coefficient	0.502	
Design Speed	1 m/s (2knots)	
Maximum Speed	Higher than 2 m/s (4knots)	
Tactical Diameter	Propulsion with Bending Posture: about 2.5 m	
	Bending Posture after Propulsion: about 0.7m	
Materials	Mechanical Parts	Aluminum, Hard Steel 45C, Brass
	Skin of Fore Body	FRP
	Skin of Aft Body	Silicon Sponge
Power	7.2V Ni-MH Battery	
Controller	Transmitter-receiver	2CH RC PROPO
	Speed Control	DC Motor with Digital Transmission
	Direction Control	Servo Motor

4 Propulsion and turning tests

The first run ROFI 1.1 was carried out in the towing tank at Seoul National University (SNU), and more tests were done in SNU swimming pool. In the tests, propulsion and turning capabilities were observed. Mechanical and electrical problems were detected during the tests, and all the problems were fixed. During the process of tests and feedback, all the designed functions were properly worked. Figure 8 shows the test operations at the SNU towing tank and swimming pool.

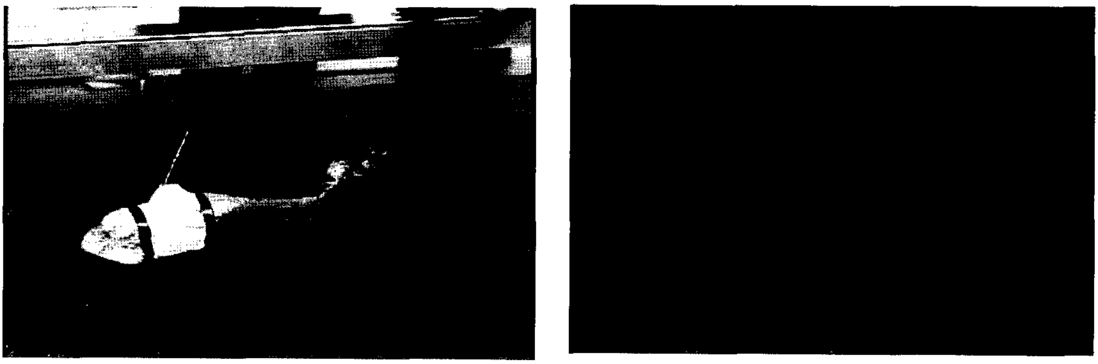


Figure 8: Test operations in SNU towing tank and swimming pool

In the tests, it was found that ROFI 1.1 mimics very realistic fish-like swimming. In particular, Carangiform swimming style was well realized by the designed bone system. Figure 9 shows the motions of the aft body during propulsion. Some phase difference between the tail and body motions was observed, like Thunniform mode. In general, this phase difference contributes to increasing propulsion efficiency. It was observed that the longitudinal location of mass center is important in fish motion. That is, the distribution of weight is important in mimicking the fish-like swimming.

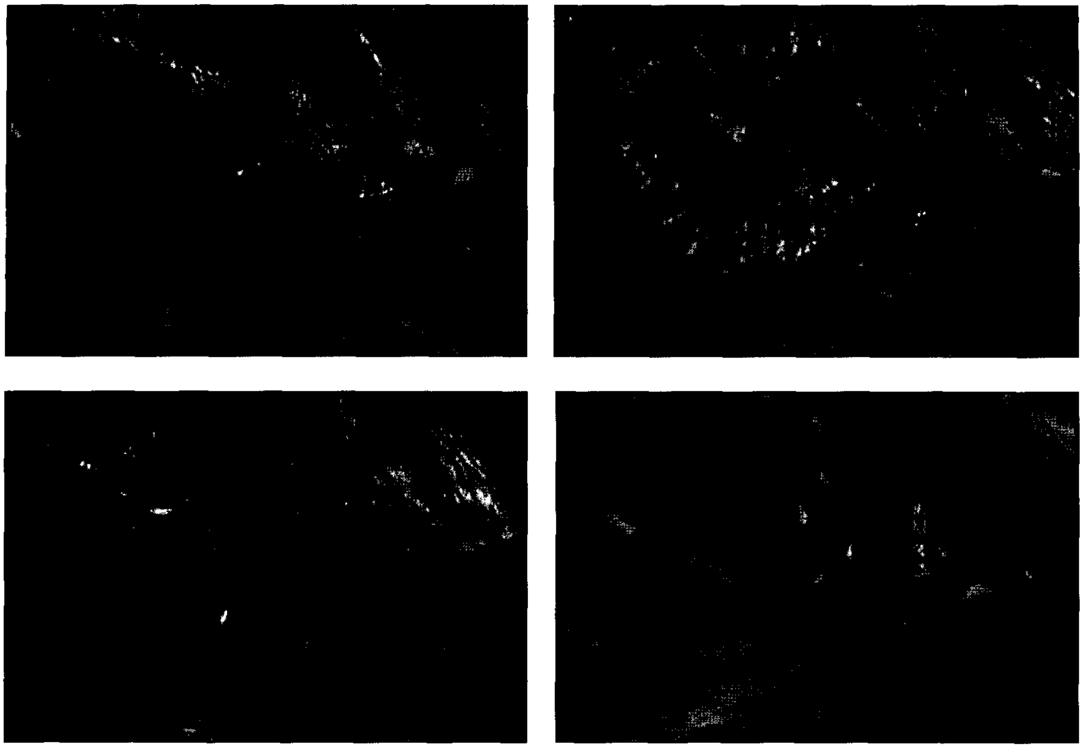


Figure 9: Carangiform swimming of the aft body

It was observed that the propulsion efficiency of ROFI 1.1 is not high as much as propeller propulsion at the same power. This may owe to high energy loss in mechanical operation for thick silicon sponge. Power requirement is much more demanding in aquatic condition than in air. We experienced mechanical damage during the preliminary test in air, due to overload in the mechanical parts designed for operation in water. Later on, ROFI was always powered on in water.

(a) Turning by bent body after propulsion

(b) Turning by propulsion with bent body

Figure 10: Two turning modes of ROFI 1.1

Most BCF swimmers use bending posture combined with caudal fin (tail) for their maneuvering. Figure 9 shows two mechanisms of ROFI 1.1 for turning motion. In the case of Figure 10(a), propulsion is continued at a bent-body posture. Due to the bent body axis, the propulsion contributes to turning motion. The second method, as shown in Figure 10(b), is to keep the bending posture without propulsive motion. In this case, to get turning motion, forward speed should be achieved before the body bends. These two methods are typical turning mechanisms of BCF swimmers. In the tests, it was observed that the tactical diameter of the second mechanism is much shorter than that of the first method.

5 Conclusions

In the present study, the very first robot fish in Korea, ROFI 1.1, has been developed. ROFI 1.1 operated by a wireless RC has been designed to mimic the BFC propulsion, particularly Carangiform swimming mode. To this end, a new mechanical bone system was adopted. Small bone pieces were assembled by joints and connected by two steel wires, and the transverse motion was controlled by two motors: one for propulsion and one for turning. This mechanism realized smooth fish-like propulsion and turning motion. The developed robot fish has been operated in the SNU towing tank and swimming pool, showing that all the functions are properly working. This study is expected to contribute to the development of more mechanically-evolved robot fish.

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