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Swaying Wire-driven Robot Fish Design and Prototyping

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ABSTRACT

In this paper, a newly designed robot fish adopting bio-inspired wire-driven mechanism is presented. It can twist its caudal fin to give sway motion, just like most of the fish do when cursing. First, sway motion analysis and computer simulation are conducted. Next, a prototype is built and experiments are carried out to validate the simulation results. It is noted that the robot fish may roll side to side during swimming. To optimize the design, we study the fish with small pectoral fin and mimic its bone structure. The new design adopts a gradual decreasing eyelet spacing along the spine. This helps the swaying concentrated at the rear part of caudal fin. Based on the computer simulation, the new design results in an improved performance.

Keywords: biomimetic, wire-driven mechanism, robot fish

1. INTRODUCTION

Through millions of years of natural selection, the caudal fin propulsion of fish is a wonder of nature. It has excellent maneuverability, very low noise, and most importantly very high propulsion efficiency [3]. In recent years, many researchers try to build fish-like robots. According to literatures, the first robot fish, RoboTuna, was built in 1994 in MIT [5]. Subsequently, many robot fishes were built. Based on the method of actuation, these robot fishes can be divided into four categories: (a) Single joint design, (b) Multiple joint design [1,10,11], (c) Smart materials design[2,7,8,9], and (d) Wire-driven design. In comparison, the wire-driven design is the best in mimicking fish swimming and has a number of advantages including simple, easy to control and most importantly, highly efficient [6, 15]. The wire-driven robot fish may be further grouped by its backbone (either continuum or serpentine), number of segments (from 1 to n), wire arrangement (parallel, inclined, or spiral) and joints (planar or spherical). In the past few years, our team has built a number of different wire-driven robots [4, 6, 15].

A careful examination of fish swimming reveals that many fish species sway their caudal fin when cursing. The swaying motion helps the fish to stabilize its body and adjust swimming direction. It also helps the fish swimming up and down. This motivates us to design and build a new wire-driven robot fish whose caudal fin can sway just like a fish. The rest of the paper is organized as follows: Section 2 presents the design of the new robot fish. Section 3 presents the experiment results. Section 4 contains conclusions and future work.

2. SWAYING WIRE-DRIVEN ROBOT FISH

As shown in Fig. 1, the new robot is composed of two parts: the head and wire-driven caudal fin propeller. The water-proof head contains all the electronic parts, including a set 4 AA size batteries, 2 servomotors and a control board. It has an ellipse cross section and the maximum dimension is 120 mm in height and 100 mm in width. It also has a weight block to balance the buoyancy of the fish.

The wire-driven caudal fin propeller is an under-actuated mechanism driven by the two pairs of wires. As shown in Fig. 2, it consists of 8 equally-spaced eyelets connected through a continuum backbone (a piece of plastics with two carbon fiber enhancement strips), and two pairs of wires (one near the top and the other near the bottom). The eyelet is symmetric. The two pairs of wires are powered by the two servomotors mentioned above. The last piece eyelet holds a fin plate with the height of 170 mm and the length of 50 mm. Also, each wire is attached to a spring to ensure the wire always in tension.

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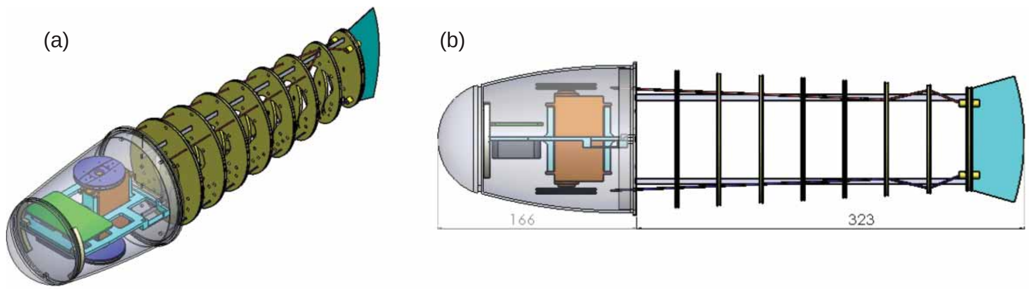
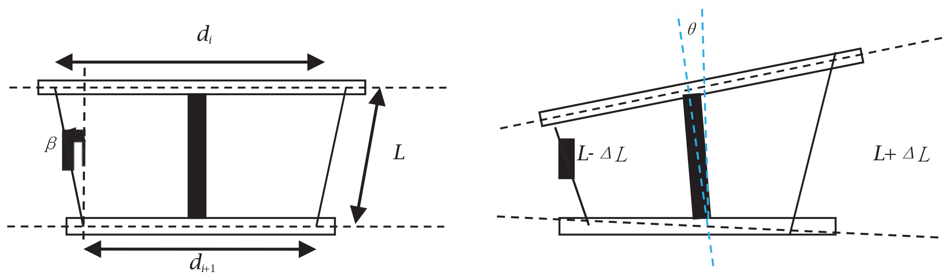


The 3D view

The side view (dimensioning in mm)

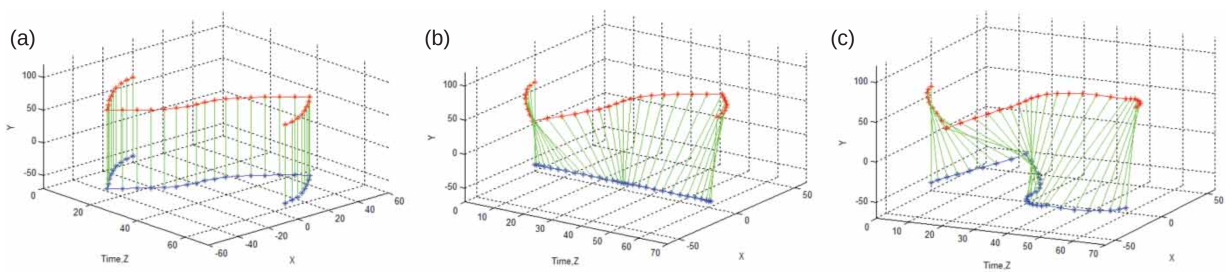
Fig. 1: The CAD model of the wire-driven swaying robot fish.



At rest

Bending

Fig. 2: Wire-driven mechanism between two eyelets.



Case 1

Case 2

Case 3

Fig. 3: Simulation of the swaying swim.

The bending of the caudal fin is illustrated in Fig. 3. The thickness of eyelet is assumed negligible. L is the distance between the two eyelets, d is the distance between the wiring holes, β is the incline angle, and θ is the angle between the two eyelets. When bending, one side becomes $L - \Delta L$ while the other side becomes $L + \Delta L$. At the rest position, the dimensions are shown in Table 1.

The swaying motion is simulated using MATLAB®. Figure 3 shows the trajectories of the tail fin (the upper tip is in red and the lower tip is in blue) in three cases: In Case 1, both the upper wire and the lower wire move in the same manner. In Case 2, the upper wire moves while the lower wire keeps steady. In Case 3, the upper wire moves in one direction while the lower wire moves in the opposite direction. Case 1 is the normal caudal fin swim and its thrust force and propulsion efficiency can be well predicted by the Lighthill's model [12,13,14]. Though, there is no model that can predict the thrust force and propulsion efficiency of swaying swim in Case 2 and 3.

Eyelet number i	d_i (mm)	L (mm)
1	55	35
2	50	35
3	45	35
4	40	35
5	35	35
6	30	35
7	25	35
8	22	35

Tab. 1: Parameters of eyelets.

Examining the skeleton of a fish, such as the one shown in Fig. 4, it is seen that joints are not equally spaced, instead, the rear part of caudal fin are typically smaller.

Fig. 4: The skeleton of cod shown by dyeing.

How does this affect the flapping? We designed another swaying robot fish as shown in Fig. 5. As shown in the figure, the design is more streamlined. The head, the main weight, occupies 45% of the body length to ensure the center of gravity lies in the head. The caudal fin is divided into 3 sections: In the first section, the 3 eyelets are with 45 mm apart; in the second section, the two eyelets are 35 mm apart; and in the last section, the 3 eyelets are 25 mm apart.

Figure 7 shows a comparison between the two designs when the $\Delta L = 1$ mm. In the figure, the green line represents the first design while the black line represents the second design. It is seen that the first design has a flap angle about 26.95°; while the second design has a flapping angle about 25.09°. More important, in the second design, the flapping is more concentrated at the end. Moreover, Fig. 6 shows the swaying curves in 3D of the two designs, in which the red-blue curve corresponds to the first design while the purple-black curve corresponds to the second design. From the figure, it is seen that the second design is smoother.

3. EXPERIMENT RESULT

A prototype of swaying robot fish is built as shown in Fig. 8. Its eyelets are fabricated by 3D printing. The backbone is made of a 0.5 mm thick PVC plastic plate with two 0.5×5 mm carbon fiber plate for enforcement. The wires are plastic wires of 1 mm in diameter. 4 AA batteries are used to drive the motors and an Arduino UNO board. Control commands are sent to the Arduino board via Bluetooth.

The swimming tests are conducted in a small pool measuring $1.6 \times 1.0 \times 0.5$ m. Tests are carried out as shown in Table 2 and Figure 9. In the table, ΔL is the change of distance between each pair of eyelets, A is the flapping amplitude, Φ is the phase difference between the upper and lower wire, f is the flapping frequency, and V_a is the average swimming velocity.

Examining Table 2, it is seen that swaying slows down the swimming speed. Also, complete swaying

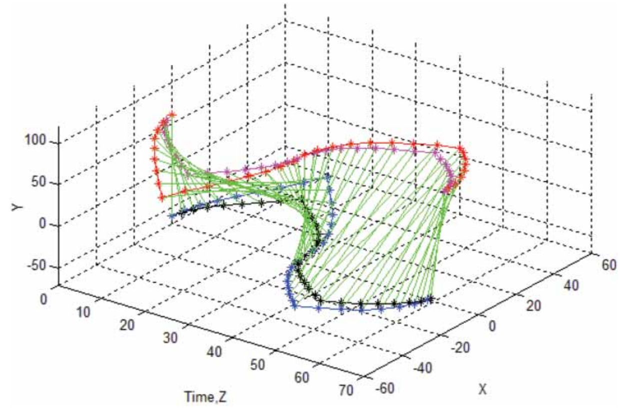


Fig. 6: A comparison of the flapping curve in 3D of the two designs.

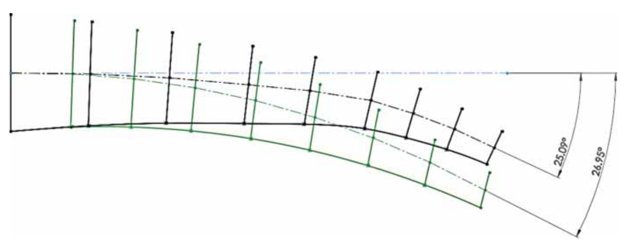


Fig. 7: A comparison of flapping patterns of the two designs.

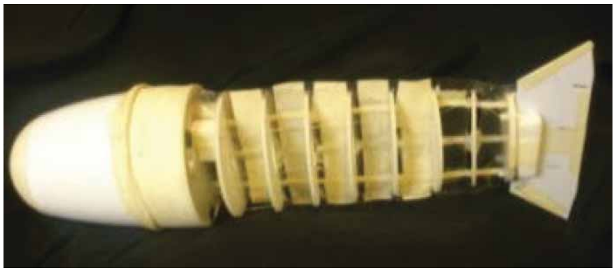
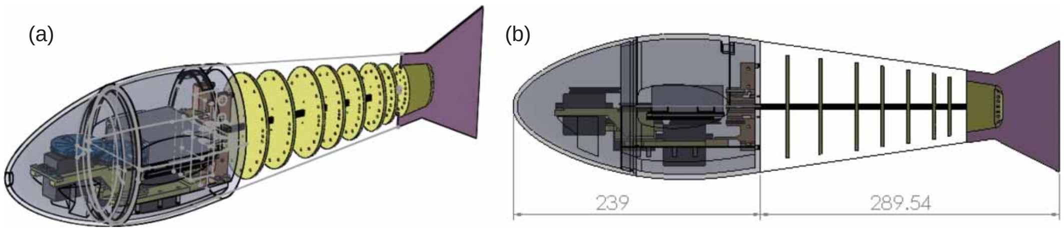


Fig. 8: A photo of the swaying robot fish prototype.



The 3D view

The side view (dimensioning in mm)

Fig. 5: The CAD model of the wire-driven swaying robot fish.

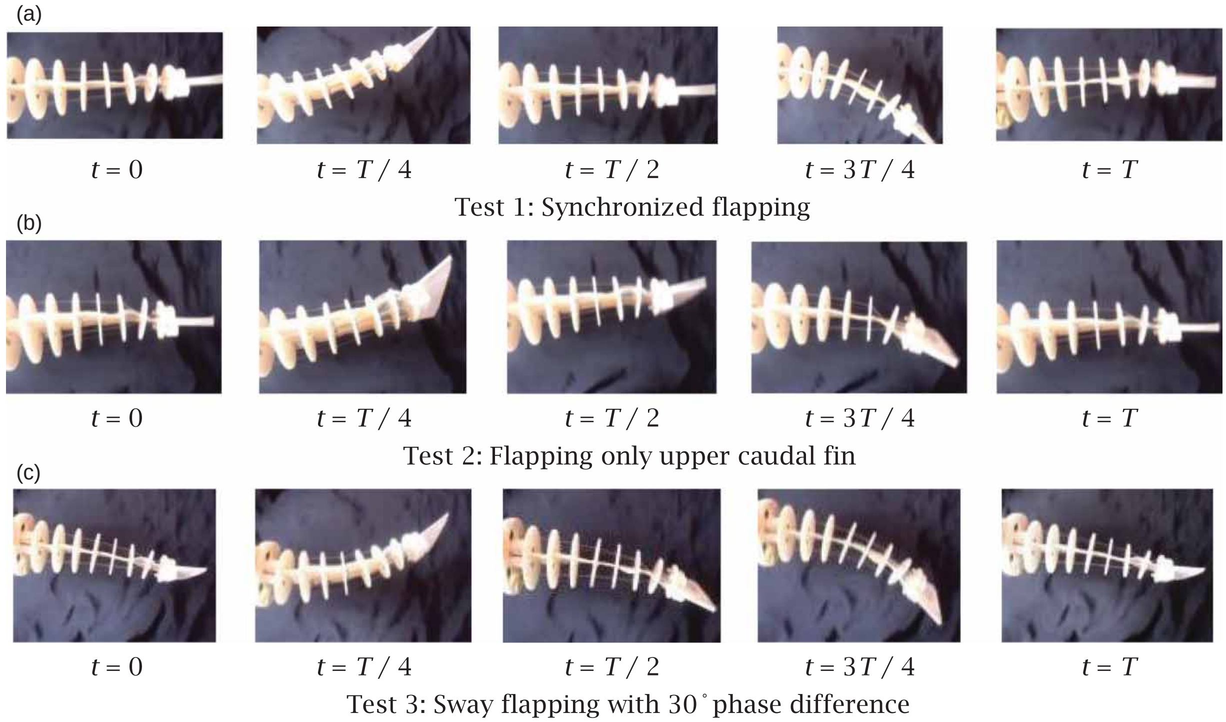


Fig. 9: The photos in different swimming tests.

Test	$\triangle L_{upper}$ (mm)	$\triangle L_{bottom}$ (mm)	A (mm)	Φ (°)	F (Hz)	V_a (mm/s)
1	± 1.5	± 1.5	± 100	0°	0.74	80
2	± 1.5	0	± 100	-	0.80	69.6
3	± 1.5	± 1.5	± 100	30°	0.72	72.6

Tab. 2: Parameters and results of different flapping modes.

is better than partial swaying. A careful examination indicates that reduced speed is mainly due to the rolling of the robot fish. The rolling may be attributed to a couple of reasons: First, the center of gravity of the robot fish lies in the caudal fin. As the caudal fin sways, the center of gravity rolls as well, causing the rolling of the robot fish. Secondly, the robot fish do not have pectoral fins and hence, its swimming is a bit unstable.

To further study the sway motion, two additional tests are carried out. In both tests, there is a 30^o phase difference between the upper wire and the lower wire. Test 3 is designed to study the effect of the flapping frequency. As shown in Table 3, the higher the flapping amplitude, the faster the robot fish swim. Test 4 is designed to study the effect of the flapping amplitude and the flapping frequency. As shown in Table 4, the flapping frequency has a bigger effect than that of the flapping amplitude. This is perhaps why that fish never over-sways.

	$\triangle L$ (mm)	A (mm)	f(Hz)	V_a (mm/s)
1	± 1.5	± 100	1.11	134.0
2	± 1.5	± 100	0.56	72.0
3	± 1.5	± 100	0.37	54.5
4	± 1.5	± 100	0.28	39.8
5	± 1.5	± 100	0.22	39.7

Tab. 3: The effect of the flapping frequency.

	$\triangle L$ (mm)	A (mm)	F (Hz)	V_a (mm/s)
1	± 1.5	± 100	0.56	72.0
2	± 1.5	± 120	0.43	63.2
3	± 1.5	± 140	0.34	61.3
4	± 1.5	± 160	0.29	53.1

Tab. 4: The effect of the flapping amplitude and the flapping frequency.

4. CONCLUSIONS AND FUTURE WORK

This paper presents a new swaying robot fish. Based on the discussions above, following conclusions can be drawn: First, the swaying robot fish swims fine. Second, swaying may reduce the swimming speed. This is because swaying may cause the robot fish rolling when swimming. Third, sway flapping amplitude is less important than the sway flapping frequency. This is perhaps why fish never over-swaying.

It should be pointed out that the research on swaying robot fish is still in its infancy. The future work includes (a) Modeling and analyzing its thrust force and propulsion efficiency; (b) Optimizing the design for minimal rolling and yawing; (c) Building an improved prototype; and (d) Conducting experiments systematically covering wider range of swimming conditions.

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