Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Implementing 3-D high maneuvers with a novel biomimetic robotic fish ⋆

Zhengxing Wu, Junzhi Yu, Zongshuai Su, and Min Tan *

* *State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China; e-mail: {zhengxing.wu, junzhi.yu, zongshuai.su, min.tan}@ia.ac.cn*

Abstract: This paper is devoted to the exploration of three-dimensional (3-D) maneuvers using a free-swimming fishlike robot. For the sake of a better maneuverability, an *Esox lucius* robotic fish consisting of a yawing head, two degrees of freedom pectoral mechanism and multilink body joints together with a caudal fin is developed. With full consideration of both mechanical configuration and propulsive principles of the robotic fish, detailed analysis and viable approaches to perform serval high maneuvers involving rotational maneuvers and translational maneuvers are presented. Based on the feedback of turning angles measured by an onboard six-axis gyroscope, the robotic fish achieves various agile and swift motions. Specifically, according to the C-start of *Esox lucius*, a flexible and wide-range yaw turn up to 360° is attained. Under the propulsive forces and moments from pectoral fins with symmetric or asymmetric pitching and heaving attack angles, the robotic fish can agilely flip in a pitch style and roll a 360° rotation around the swimming direction. Moreover, two types of backward swimming separately employing pectoral fins and body undulation are also accomplished. The experimental results verify the remarkable maneuverability of the developed robotic fish and the effectiveness of approaches presented for the maneuver control.

---

1. INTRODUCTION

Nature is a vast and abundant treasure providing inspiration for new design concepts (Lentink [2013]). Over the aeons of evolution, creatures have developed such sophisticated skills to survive in the harsh, competitive environments. As an excellent swimmer, fish is becoming a comparatively ideal subject for improving the current manmade nautical techniques, since it is endowed with astonishing swimming techniques in the characteristics of high-speed, high-efficiency, and high-maneuverability (Yu *et al.* [2013], Esposito *et al.* [2012]).

In order to increase the chance of survival, many fish can instantaneously perform surprised behaviors with flexibility and maneuverability, which means a series of changes in direction and position for a certain purpose, especially in avoiding predators and striking at potential preys (Tytell and Lauder [2008], Domenici [2011]). In simple behaviors like acceleration, fish state changes in a single plane such as surge (back-and-forth), slip (lateral), and heave (a vertical displacement) or around a single rotational axis such as yaw, pitch, and roll (Shadwick and Lauder [2006]). Complex behaviors involve complicated maneuvers combining translational ones and/or rotational ones. In addition, some certain behaviors, such as backward swimming and hovering, are considered to be maneuvers but do not refer to changes of state, because these behaviors always share the same characteristics with other maneuvering behaviors including cooperation and coordination of multiple propulsors, high energy consumption, and so on (Shadwick and Lauder [2006], Webb [2004]).

Since the first biomimetic robotic fish, RoboTuna, was developed at MIT in 1994, more and more prototypes are being developed as an aquatic mobile platform for researches and experiments (MIT [1994], Liang *et al.* [2011]). Many robotic fish were applied to explore the maneuverability in fishlike swimming. Zhou *et al.* [2013] analyzed the backward swimming of european eel and provided a gait planning method for a carangiform robotic fish to realize backward swimming; Lee *et al.* [2012] adopted fuzzy logic method to control a robotic fish obstacle avoidance and target tracking in three-dimensional space; Su *et al.* [2013] proposed a dynamic trajectory tracking-based control strategy to generate relatively flexible and precise C-starts and the robotic fish attained a top turning rate of approximately 670°/s and an upper limit of turning precision of less than 10° in the horizontal plane.

In this paper, we focus on the 3-D maneuvers of a robotic fish. For the purpose of high maneuverability, a novel robotic fish modelled after *Esox lucius* is developed. Specifically, a broad flat head capable of ±50° yaw is designed to strengthen the turning ability. A pair of pectoral fins with two degrees of freedom (DOFs) per a fin is constructed to enhance the 3-D swimming capability. Due to the symmetrical or asymmetrical actions of left and right pectoral fins, the robotic fish is able to perform serval acrobatic maneuvers. In the tests of rotational maneuvers, the robotic fish successfully realized three basic turns in

---

⋆ This work was supported by the National Natural Science Foundation of China (nos. 61375102 and 61333016), the Beijing Natural Science Foundation (nos. 4122084 and 3141002), and the Interdisciplinary Cooperation Project of Beijing Nova Program (no. XXHZ201303).

the form of yaw, pitch, and roll. Due to a yawing head and well-streamlined configuration, the robotic fish yawed beyond 360° in the horizontal plane, better than 213° by Su *et al.* [2013], although it weights 0.92 kg more than the slim robotic fish in Su *et al.* [2013] (2.21 kg vs 1.29 kg). Remarkably, the pitch and roll motions all received wide range, e.g., a 360° flip in a pitch style and a swift 360° roll. As for translational maneuvers, backward swimming is realized in two types of body undulation and pectoral propulsion.

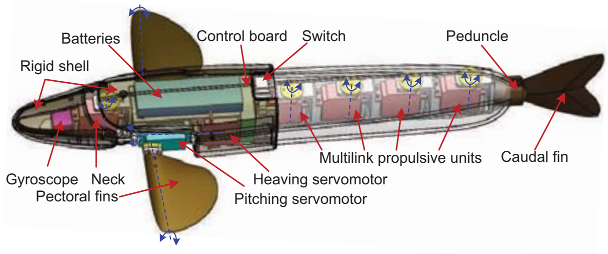
The rest of the paper is organized as follows. Section 2 describes the mechanical design for the innovative robotic fish. In Section 3, the detailed analysis and control approaches for maneuvers in fishlike swimming are provided. Experimental results and discussion are further offered in Section 4. Finally, conclusion and future work are summarized in Section 5.

2. MECHATRONIC DESIGN OF THE ROBOTIC FISH

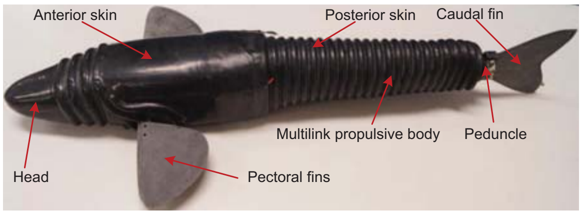
In nature, every fish has its own special characteristics, such as swordfish's excellent propulsive speed up to 96.5 km/h (Kaylor and Learson [1999]), and archer fish's (*Toxotes jaculatrix*'s) outstanding turning rate up to 4500°/s (Wöhl and Schuster [2007]). For the purpose of high maneuverability, our robotic fish is loosely inspired from *Esox lucius*, a fish with surprised flexibility. As a ferocious predator, *Esox lucius* has distinctive swimming acceleration/deceleration and outstanding turning maneuverability, especially its fast-start performance in which the turning rate is easily beyond 2800°/s (Hale [2002]). By adopting a well-streamlined shape like *Esox lucius*, the robotic fish gains relatively little hydrodynamic drag.

In general, as shown in Fig. 1, the robotic fish developed in this work consists of three principal parts: a yawing head, a rigid anterior module with pectoral fins, and a flexible multilink posterior body with an attached caudal fin. Table 1 lists the corresponding technical parameters related to the robotic prototype. To strengthen the turning maneuverability, a particular neck joint allowing the head to yaw in ±50° is introduced to the mechanical design, which is distinct from other robotic fish. The head adopts a broad flat countered shape like *Esox lucius* for reduction of hydrodynamic drag in turning motion and the hollow interior holds a gyroscope and communication units. As a main storehouse for the robotic fish, the anterior part holds other devices and machineries involving batteries, control boards, some balance weight blocks and pectoral mechanisms. For the convenience of installation, the rigid anterior shell made of polypropylene is divided into upper and lower portions and a black skin made of emulsion covers outside the rigid shell to protect the module from water. At the same time, as illustrated in Fig. 1(b), the waterproof skin especially around the neck and pectoral mechanism adopts a wrinkle design to enhance the flexibility and toughness.

Another new feature of this robotic fish is the pectoral mechanism. For the purpose of better flexibility, the pectoral mechanism offers four independent joints separately around the pitch and roll axis. So the robotic fish can easily achieve three pectoral motions in the form of pitching, heaving, and heaving-pitching (a coupled motion of pitching and heaving). Both pitching servomotors and heaving servomotors are all fixed in aluminum stands and then installed in the titanium alloy chassis.



(a) Conceptual design.



(b) Robotic prototype.

Fig. 1. Mechanical design of the innovative robotic fish.

Table 1. Technical specification of the developed robotic fish

Items	Characteristics
Size (L × W × H)	$\sim 614 \times 83 \times 81$ mm^3
Total mass	$\sim$ 2.21 kg
Degrees of freedom	9 (head: 1; pectoral fins: 4; body joints: 4)
Drive mode	DC servomotors
Controller	ARM Cortex-M4
On-board sensors	Gyroscope, depth sensor
Operation voltage	DC 7.4 V

The posterior body adopts a multilink hinge structure as the main propulsive mechanism. Specifically, four flexible links actuated by servomotors are connected in series with aluminum skeletons. A 3-D caudal fin attaches the last link via a slim peduncle made of polyvinyl chloride. A black outer skin also made of emulsion is custom-built to protect the structures from water and to reduce fluid drag.

3. ANALYSIS AND CONTROL OF 3-D MANEUVERS

This section will give detailed analysis and relevant control approaches for some high maneuvers including three simple rotational maneuvers, complex combined maneuvers, and backward swimming.

3.1 Rhythmic Swimming Motions

Before discussing the fishlike maneuvers, we firstly introduce the central pattern generators (CPGs) (Ijspeert [2008], Delcomyn [1980]) based control method for rhythmic swimming motions. Generally speaking, CPGs are often employed in periodic swimming but not in maneuverable swimming (Yu *et al.* [2011], Herrero-Carron *et al.* [2011]). Here CPGs are only employed for the rhythmic undulation of body joints to produce main propulsive forces. Under the action of these propulsive forces, the robotic fish effectively takes advantage of the pectoral fins as a rudder to perform several maneuverable actions like roll motion and pitch motion. Here, a Hopf oscillator based CPGs model is adopted in this paper. With a simple adjacent coupling, the CPGs have much less parameters. Meanwhile, the CPGs have several explicit parameters, which can flexibly adjust the frequency, amplitude, and phase relationship of the output signals.

$$\begin{cases} \dot{x}_i = -\omega_i(y_i - b_i) + x_i(r_i - x_i^2 - (y_i - b_i)^2) \\ \quad +h_1(x_{i-1}\cos\varphi_i + (y_{i-1} - b_{i-1})\sin\varphi_i) \\ \dot{y}_i = \omega_i x_i + (y_i - b_i)(r_i - x_i^2 - (y_i - b_i)^2) \\ \quad +h_2(x_{i+1}\sin\varphi_{i+1} + (y_{i+1} - b_{i+1})\cos\varphi_{i+1}) \end{cases} \tag{1}$$

where x_i, y_i denote the state variables of the ith oscillating neurons. ω_i, r_i stand for the intrinsic oscillation frequency and amplitude. φ_i denotes the phase relationship of the output signals. b_i is the directional bias for state variable y_i. h_1, h_2 are positive constants standing for the coupling strength. For simplicity, the same frequency parameter $\omega_i = \omega$ and phase relationship parameter $\varphi_i = \varphi$ are used for all oscillators.

In order to transform the rhythmic output signals of CPGs to the actuating signals for servomotors, an output amplification function, $f_i(y_i)$ is defined as follows:

$$z_i = f_i(y_i) = \begin{cases} c_i\lambda_i y_{imax} + m_i & y_i \geq y_{imax} \\ c_i\lambda_i y_{imin} + m_i & y_i \leq y_{imin} \\ c_i\lambda_i y_i + m_i & else \end{cases} \tag{2}$$

where z_i denotes the axon output potential of the ith CPG. $f_i(y_i)$ is the output amplification function. y_{imax},y_{imin} are the membrane potential threshold. c_i denotes the amplification coefficient for CPG outputs. λ_i and m_i respectively represent the conversion coefficient and axon output potential bias, which are determined by the adopted servomotor.

3.2 Rotational Maneuvers

Rotational maneuvers are flexible actions for changing swimming directions around the body axis. Three basic rotational maneuvers cover yaw, pitch, and roll. Combining these basic rotational ones will result in complex maneuvers suitable for a certain task.

Yaw Motion Fast-start, a high-acceleration startle behavior, is a typical yaw motion in direction-changed process. For *Esox lucius*, two types of fast-start have been identified kinematically, the S-start and the C-start (Hale [2002], Scheiefer and Hale [2004]). Compared with S-start, C-start, characterized by a 'C' sharp body bend, has much larger turning range. So we chose C-start to design the yaw motion for our robotic fish, for the purpose of wide-range yaw turns.

Firstly, the action rules for the fish head is defined. In the closed-loop control approach, the fish head will adjust its turn angle according to the feedback from an onboard gyroscope. Specifically, if the realtime angle from the gyroscope θ_{gy} is less than a certain threshold like $\beta\theta_{goal}$ (θ_{goal} represents the expected direction, and β is a threshold factor), the fish head will deflect to $\beta\theta_{goal}$ at full speed. Notice that if $\beta\theta_{goal}$ is beyond the θ_{limit} of this head (50°) due to the mechanical constraints, the fish head will only reach θ_{limit} and then keep still. If the realtime angle θ_{gy} is beyond the certain threshold $\beta\theta_{goal}$, the fish head will turn back to the straight position according to θ_{gy}.

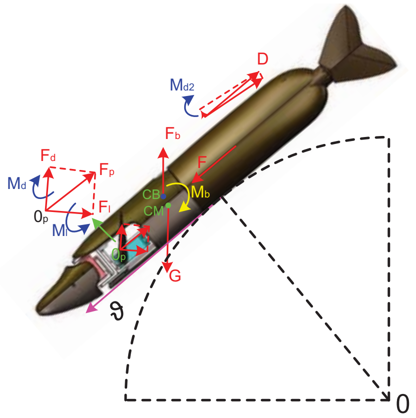


Fig. 2. The analysis of the pitch motion.

In the following, we divide the whole yaw motion into three stages, according to the biological C-start.

1) Bending stage: The robotic fish bends its elongated body into a 'C' sharp. In this stage, the robotic fish deflects its head into the expected direction following the control rules above. Meanwhile, the body joints turn into their identical joint angle limit at their full speeds. By this way, the robotic fish can obtain relative higher turning rate.
2) Retention stage: The robotic fish keeps its 'C' sharp state until arriving at the expected direction. If the turning angle is beyond the threshold, the fish head begins to turn back to the straight state.
3) Unbending stage: The robotic fish unbends its body back to straight state or to periodic swimming. In order to reduce recoil, the active joint unbends following its previous one. The detailed algorithm please refer to our previous work about fast-start Su *et al.* [2013].

Pitch Motion Pitch motion is often employed by most fish to realize surfacing and diving. So it is a very common and important component of fish maneuvers. Many robotic fish have realized surfacing and diving via the pectoral fins or the mechanism for adjusting the center of weight. However, these actions are only limited to a simple and small range. In this paper, we expect to achieve a large-scale diving and surfacing, e.g., a flip in pitch style.

Particularly, a simplified dynamic analysis is conducted to find out the key factors about this motion. We abstract the robotic fish as a moving rigid body with velocity ν. As shown in Fig. 2, the robotic fish suffers three kinds of moments in pitch motion: a thrust moment M_l from the pectoral fins with an attack angle, a resistant moment (M_d, M_{d2}) from the pectoral fins and body, and a moment M_b induced by the difference between the center of mass (CM) and the center of buoyancy (CB). In the front half a cycle of flip motion, the moment M_b plays a role of resistant. In order to realize the flip successfully, one possible approach is to reduce negative function of the moment M_b. So in the design of robotic fish, we try our best to shorten the distance between the CM and the CB

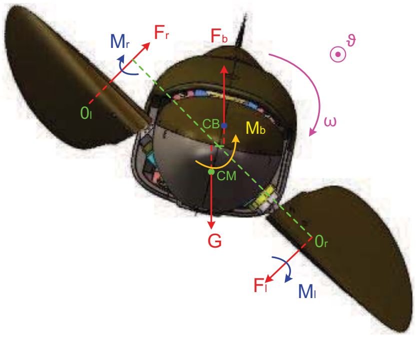


Fig. 3. The analysis of the roll motion.

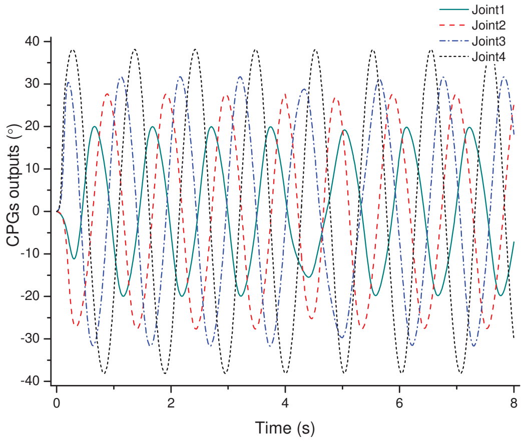


Fig. 4. CPGs output signals for oscillating body joints in both forward and backward swimming ($r_1 = 8.70$, $r_2 = 19.08$, $r_3 = 25.50$, $r_4 = 40.39$, $\omega = 6$, $h_1 = 1.0$, $h_2 = 2.0$, $c_i = 6.0$, $b_i = 0.0$, $\varphi = 90°/-90°$).

to obtain a relative little resistant moment M_b. Another approach is to improve the thrust moment M_p (M_l and M_r) by increasing the swimming speed and enlarging the attack angle of pectoral fins.

Roll motion Roll motion often appears as a component of complex maneuvers. For example, when a fish faces with the end of a narrow blind channel, it may roll onto the side, make a yaw turn, roll upright again, and swim upward to its original path (Shadwick and Lauder [2006], Schrank *et al.* [1999]). In this paper, our robotic fish achieves a wide-range roll motion depending on the 2-DOF pectoral fins. With asymmetric pitching and heaving attack angles of pectoral fins, the robotic fish can obtain effective moments to realize roll motion.

Similarly, as shown in Fig. 3, the moment M_b from the difference between the CM and the CB plays a resistant role in the front half a cycle. So the design for reduction of M_b also serves a positive function in roll motions. Besides, higher swimming speed and appropriate pitching and heaving attack angles can also increase the positive moment M_l and M_r and make it easier for the implementation of roll motion.

3.3 Translational Maneuvers

Translational maneuvers are very common in fish swimming involving acceleration/deceleration during periodic swimming, braking, backward swimming, and so on. Here we focus on backward swimming, an important behavior for fish to adjust posture preparatory to predation and avoiding dangers in narrow spaces.

Most fish produce thrust through bending their body into a backward-moving propulsive wave that extends to its caudal fin. For some anguilliform swimmers, they can reverse the direction of propulsive wave to realize backward swimming (Herrel *et al.* [2011]). Take the lamprey for example. A reversed propulsive wave can be produced in the isolated spinal cord if the caudal part of the spinal cord has higher excitability than rostral segments (Grillner *et al.* [2007]). Based on the CPGs network presented above, we can adjust the phase relationship via the parameter φ_i to generate a forward-moving propulsive wave. Fig. 4 depicts the control signals for body joints in both forward and backward swimming. Specially, forward swimming needs a backward-moving propulsive wave, which means the CPGs outputs for body joints should keep phase lag, corresponding to the time from 0 to 4 s in Fig. 4. At $t = 4$ s, φ_i is varied from 90° to $-90°$. Accordingly, the phase relationship shifts to phase-lead. Thus the robotic fish switches to backward swimming at $t = 4 - 8$ s.

4. EXPERIMENTS AND DISCUSSION

In order to evaluate the presented analysis and the maneuverability of the developed robotic fish, extensive experiments were carried out. The parameters of CPGs adopted for rhythmic body undulation are set as follows: $r_i = \{8.70, 19.08, 25.50, 40.39\}$; $\varphi_i = 70°$; $b_i = 0.0$; $h_1 = 1.0$; $h_2 = 2.0$; $m_i = 1499$; $\lambda = 6.67$; $c_i = 6.0$.

4.1 Testing of Rotational Maneuvers

In the experiments, simple rotational maneuvers involving yaw, pitch, and roll motions were firstly tested. In the yaw test, based on the well-streamlined configuration and a flexible yawing head, we expected to make a breakthrough and tried a wide-range yaw turn. Fig. 5 shows a 360° yawing motion of our robotic fish. In the beginning of the yaw turn, the robotic fish turned its body joints to their identical joint angle limit (all be set to 45° in this experiment) at their full speeds. Meanwhile, the fish head quickly yawed to its angle limit (50°) and then kept still, see Fig. 5(a)–(c). Then the robotic fish kept body bending and turned to the direction quickly. When the turn angle was beyond the head angle threshold (270° in this experiment), the fish head started to turn back and kept straight with the anterior body. Until the reach of the expected direction, the robotic fish fluently unbent its body joints one by one, as shown in Fig. 5(h)–(i). Due to a great weight and large range turn, the robotic fish obtained a relatively lower speed. However, the well-streamlined configuration especially the special head design effectively reduced the hydrodynamic drag, extended turn time, and successfully leaded a 360° yaw turn.

In the pitch experiments, the robotic fish firstly executed a symmetrical body undulation to obtain a propulsive

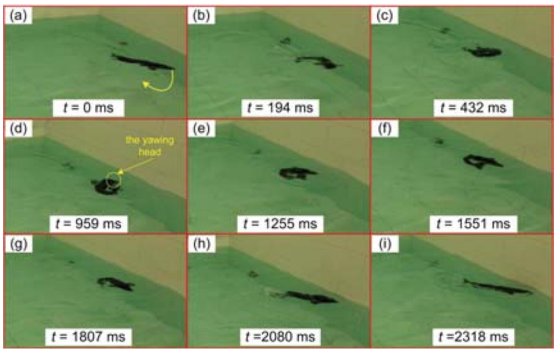


Fig. 5. Snapshot sequence of a 360° yaw motion.

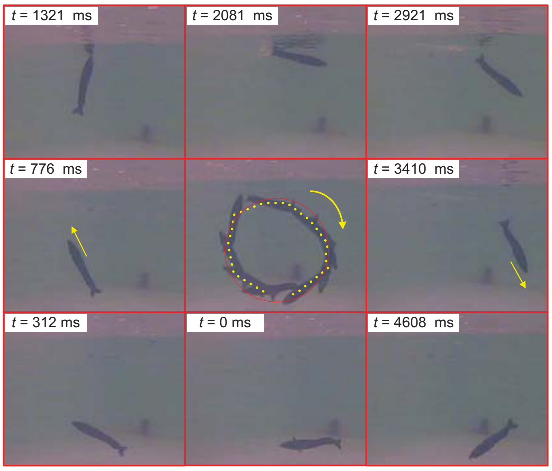


Fig. 6. Snapshot sequence of a flip in pitch style.

Table 2. The angle settings for rolling motion

Items	Left		Right	
	Pitching	Heaving	Pitching	Heaving
Clockwise roll	60°	45°	60°	45°
Anticlockwise roll	$-60°$	$-45°$	$-60°$	$-45°$

speed. Then pitch servomotors in the pectoral mechanism turned a certain angle (35° in this experiment) to provide effective attack angle for pitch moments. According to the previous analysis, the robotic fish can realize continuous pitch turns if the pitch moment M_p can overcome the resistant moment M_d, M_{d2} and the metacentric moment M_b. Notice that M_b only played a negative role in front flip but a positive role later. Fig. 6 shows the whole flip in the pitch style. Actually, the fish mostly flipped in a circle, but not in a standard circle, because of the open loop control. The radius of the flipping circle was determined by the attack angle of pectoral fins and the swimming speed.

Similarly, the roll motion also requires a propulsive speed from the rhythmic body undulation. Asymmetrical pitching and heaving attack angles would be set for generating the roll moments (M_l and M_r). Detailed angle-set information in this test is listed in Table 2. Because of the mechanical mirror installation of left and right pectoral mechanisms, the same values were set for the pectoral fins. Fig. 7 depicts both clockwise and anticlockwise roll motions. The propulsive speed and attack angles were key factors for this roll motion. Relative lower swimming speed or attack angles would lead to a slight roll turn, not a 360° roll motion.

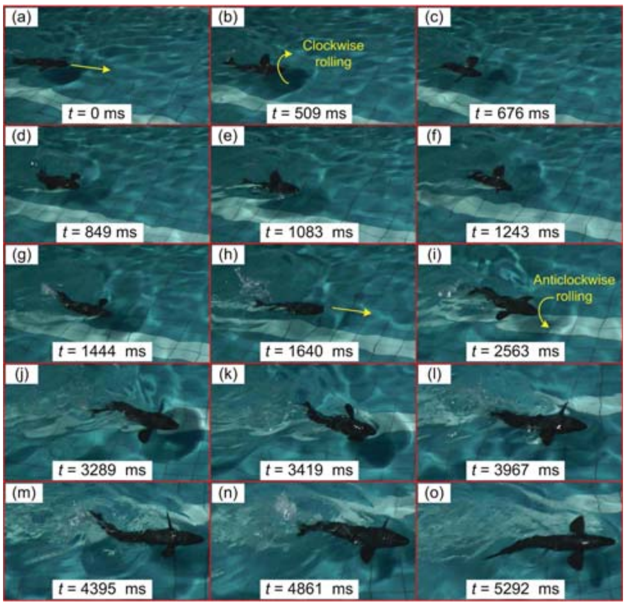


Fig. 7. Snapshot sequence of both clockwise and anticlockwise roll motions.

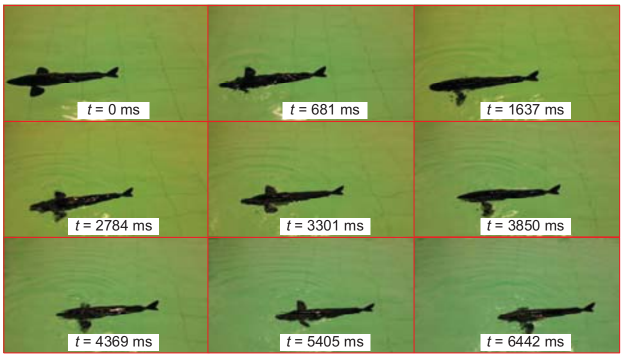


Fig. 8. Snapshot sequence of backward swimming on pectoral fins.

4.2 Testing of Backward Swimming

In the test of backward swimming on body undulation, a reversed propulsive forces were generated via just changing CPGs' phase parameter φ to $-90°$. Because of a symmetric body shape, some anguilliform fishes like *Piosodonophis boro* can realize a fast backward swimming, even faster than forward swimming (Herrel *et al.* [2011]). However, our robotic fish has an obvious asymmetric body. The stiff anterior body can not provide the same propulsive forces as the caudal fin in forward swimming. So the robotic fish swam backward very slowly, only 0.08 m/s at $\omega = 30$, far slower than the speed in forward swimming. In addition, as shown in Fig. 8, applying appropriate coupling motion of heaving and pitching in pectoral fins governed by CPGs, a backward propulsive force would be resulted and the robotic fish effectively swam backward. This backward swimming style is employed by most fish with stiff body in nature.

4.3 Discussion

Pursuing high maneuverability is a critical survival skill for natural fish. In terms of the imitation of achievable maneuvers, the developed robotic fish obtained excellent maneuverability. It partly benefited from the innovative mechanical design. Different from other previous robotic fish, the robotic fish has a flexible yawing head which contributes relative lesser hydrodynamic drag in turn. Besides, the well-streamlined configuration like *Esox lucius* is further to reduce the hydrodynamic drag. As a consequence, the robotic fish makes a breakthrough of yaw turn up to 360° under an effective C-start algorithm. Moreover, flexible multi-DOF pectoral mechanism easily results in effective turning moments. With the symmetric and asymmetric pectoral attack angles, the robotic fish successfully realizes wide-range pitch and roll motions (all up to 360°). Note that reducing the metacentric moment from the different between the center of mass and the center of buoyancy in the design is an effective approach to improve the maneuverability. According to the analysis and experimental results, propulsive speed and pectoral attack angles also have a major impact on the rotational maneuvers.

Another issue to mention is backward swimming. Although having no velocity changed and no direction changed, backward swimming is still considered to be maneuvers by biologists. Two types of backward swimming separately employing pectoral fins and body undulation are realized. Compared with forward swimming, backward swimming achieves a lower speed, especially for the robotic fish with an asymmetric body. However, backward swimming is still a highly effective maneuver for robotic fish to avoid obstacles in narrow spaces.

5. CONCLUSIONS AND FUTURE WORK

In this paper we have presented a detailed analysis and effective implementation of maneuvers for a robotic fish. In order to enhance the maneuverability and reduce the hydrodynamic drag, an innovative robotic fish, modelled after *Esox lucius* is developed. Many rotational maneuvers including a wide-range yaw motion up to 360°, a flip in pitch style and a 360° clockwise and anticlockwise roll, are analyzed and realized. Besides, we also analyze and examine the backward swimming based on both body undulation and pectoral fins. The experimental results demonstrate the high maneuverability of our developed robotic fish.

The ongoing and future work will focus on precise closed-loop control for high maneuverability of a robotic fish in a disturbed aquatic environment.

REFERENCES

D. Lentink. Biomimetics: flying like a fly. *Nature*, 498: 306–307, 2013.

J. Yu, R. Ding, Q. Yang, M. Tan, and J. Zhang. Amphibious pattern design of a robotic fish with wheel-propeller-fin mechanisms. *Journal of Field Robotics*, Article first published online: 1 Jul. 2013, DOI: 10.1002/rob.21470.

C.J. Esposito, J.L. Tangorra, B.E. Flammang, and G.V. Lauder. A robotic fish caudal fin: effects of stiffness and motor program on locomotor performance. *Journal of Experimental Biology*, 215:56–67, 2012.

E.D. Tytell and G.V. Lauder. Hydrodynamics of the escape response in bluegill sunfish, *Lepomis macrochirus*. *The Journal of Experimental Biology*, 211:3359–3369, 2008.

P. Domenici. Webb scales fast-start maneuvers. *The Journal of Experimental Biology*, 214(6):875–877, 2011.

R.E. Shadwick, and G.V. Lauder. Fish Biomechanics. Elsevier Academic Press, San Diego, California, USA and London, UK, 2006.

P.W. Webb. Maneuverability–general issues. *IEEE Journal of Oceanic Engineering*, 29(3):547–555, 2004.

MIT Towing Tank, Available at: http://web.mit.edu/towtank/www/.

J. Liang, T. Wang, and L. Wen. Development of a two-joint robotic fish for real-world exploration. *Journal of Field Robotics*, 28(1):70–79, 2011.

C. Zhou, Z. Cao, Z.Hou, S. Wang, and M. Tan. Backward swimming gaits for a carangiform robotic fish. *Neural Computing and applications*, 23(7–8):2015–2021, 2013.

P. Lee, M. Lee, and R. Wang. A fuzzy control based on robotic fish with multiple actuators. *International Journal of Fuzzy Systems*, 14(1):45–53, 2012.

Z. Su, J. Yu, M. Tan, and J. Zhang. Implementing flexible and fast turning maneuvers of a multijoint robotic fish. *IEEE/ASME Transactions on Mechatronics*, PP(99):1–10, 2013.

J.D. Kaylor, and R.J. Learson. The Seafood Industry. Springer Science and Business Media New York, US, 1999.

S. Wöhl, and S. Schuster. The predictive start of hunting archer fish: a flexible and precise motor pattern performed with the inematics of an excape C-start. *Journal of Experimental Biology*, 210(2):311–324, 2007.

M.E. Hale. S- and C-start escape responses of the muskellunge (*Esox masquinongy*) require alternative neuromotor mechanisms. *The Journal of Experimental Biology*, 205(2):2005–2016, 2002.

A.J. Ijspeert. Central pattern generators for locomotion control in animals and robots: a review. *Neural Networks*, 21(4):642–653, 2008.

F. Delcomyn. Neural basis of rhythmic behavior in animals. *Science*, 210(4469):492–498, 1980.

J. Yu, M. Wang, M. Tan, and J. Zhang. Three-dimensional swimming. *IEEE Robotics and Automation Magazine*, 18(4):47–58, 2011.

F. Herrero-Carron, F.B. Rodriguez, and P. Varona. Bio-inspired design strategies for central pattern generator control in modular robotics. *Bioinspiration and Biomimetics*, 6(1):1–16, 2011.

J.E. Schriefer, and M.E. Hale. Strikes and startles of northern pike (*E*sox lucius): a comparison of muscle activity and kinematics between S-start behaviors. *The Journal of Experimental Biology*, 207:535–544, 2004.

A.J. Schrank, P.W. Webb, and S. Mayberry. How do body and paired-fin positions affect the ability of three teleost fishes to maneuver around bends? *Canadian Journal of Zoology*, 77(2):203–210, 1999.

A. Herrel, H. Choi, N. Schepper, P. Aerts and D. Adriaens. Kinematics of swimming in two burrowing anguilliform fishes. *Zoology*, 114(2):78–84, 2011.

S. Grillner, A. Kozlov, P. Dario, C. Stefanini, A. Menciassi, A. Lansner, and J.H. Kotaleski. Modeling a vertebrate motor system: pattern generation, steering and control of body orientation. *Progress in Brain Research*, 166: 221–234, 2007.