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A Review on Development of Robotic Fish

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Abstract

In this paper, types of fish swimming propulsion and the mechanics of fish locomotion are reviewed. Body and/or caudal fin (BCF) locomotion and median and/or paired fin (MPF) locomotion are two main categories of fish swimming propulsion. The swimming and characteristics of each propulsion mode are discussed for the development of fish robotics. Development of robotic fish propulsion involves several aspects such as shape of the robot, pattern of movement, hydro-dynamics, control system, location on the machine, mechanical properties and material properties. Various structures and materials used in existing fish robots and significance of selection are reviewed. Several actuators including conventional actuators have been considered. Ionic Polymer-Metal Composite (IPMC), piezoceramic materials, shape memory alloy (SMA) wires and pneumatic soft actuator have been recently attempted and their unique characteristics, advantages and limitations are discussed. Appropriate control system needs to be designed for proper propulsion of fish robots, hence various control system used in the past are presented. Finally, improvements and alternative technique for maneuvering the vessel are proposed.

Keywords: Swimming locomotion, thrust generation, effective maneuvering

1. INTRODUCTION

Engineers and biologists have long been interested in how aquatic organisms are able to propel themselves through water with high efficiency. With the advances in mechanical and mechatronics research since the last few decades, bio-mimetic and biomechanics have become an active research area [1-4]. Many bio-mimetic technologies have been developed to help humans; for example "Thunniform Swimmers" to generate thrust to help tailed boat, "Humpback whales flexible fins" to produce high maneuvering and "Penguin's hand" to create two-fin kayak for power assistance. Fish in particular, have served as model organisms for understanding locomotive patterns underwater.

Fish are able to move efficiently due to their body shape, fin form and kinematic [5]. The aerodynamic shape of fish body reduces drag and turbulent flow while kinematic produces thrust for movement. Different species of fishes have different advantages. For example, dolphins swim steadily at constant speed with little amount of thrust, which can also be related with ships travelling long distances. However, such natural mechanism cannot be applied precisely to marine vessels to produce good practical results. Nevertheless, natural mechanisms of fish locomotion are an inspiration for the development of marine vessels propulsion system. It is not exaggerating to consider that marine vessels have not yet reached a level of efficiency with regard to propulsion mechanisms of marine animals [6-7]. There is always a space for improvement in propulsion system of marine vessels, hence is an aim of this study, with regard to studies on fish swimming propulsion, followed by structures and materials, actuators and controllers used in the past. Improvements and an alternative technique in maneuvering the vessel are also proposed.

2. FISH SWIMMING PROPULSION

There are two categories of fish swimming propulsion, which are body and/or caudal fin (BCF) locomotion, and median and/or paired fin (MPF) locomotion. BCF and MPF swimmers differ from the parts used in swimming. BCF swimmers bend their bodies backward and move propulsive waves that extend to their caudal fin, whereas MPF swimmers use their median and pectoral fins [8]. Both BCF and MPF swimmers are further differentiated by two different movement characteristics; undulatory motion and oscillatory motion. The undulatory motion involves the passage of a wave along the propulsive structure, whereas the oscillatory motion involves a part of propulsive structure, which swings back and forth on its base without producing a wave formation, as shown in Figure 1. Fish are mostly BCF swimmers since almost 85% of fish families are BCF swimmers [8-9].

The locomotion of BCF swimmers can be categorized into several modes, which are distinguished by the thrust generated, wavelength and amplitude, and envelope of the propulsive wave. Five modes have been identified which are Anguilliform, Subcarangiform, Carangiform, Thunniform and Ostraciiform, as shown in Figure 2.

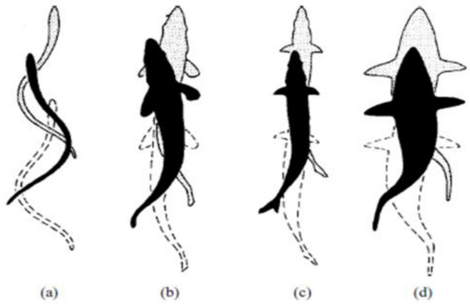


Figure 2. BCF swimming mode; (a) Anguilliform (b) Subcarangiform (c) Carangiform (d) Thunniform [8]

In Anguilliform mode, large amplitude undulations are produced by the whole body, and at least one complete wavelength of the propulsive wave appears along the body. Anguilliform swimmers can swim forward or backward by changing the direction of propulsive wave propagation, which is a unique characteristic [10]. Subcarangiform is similar to Anguilliform, but its undulation is limited anteriorly and is increased in half of the posterior body. Carangiform swimming mode is even faster

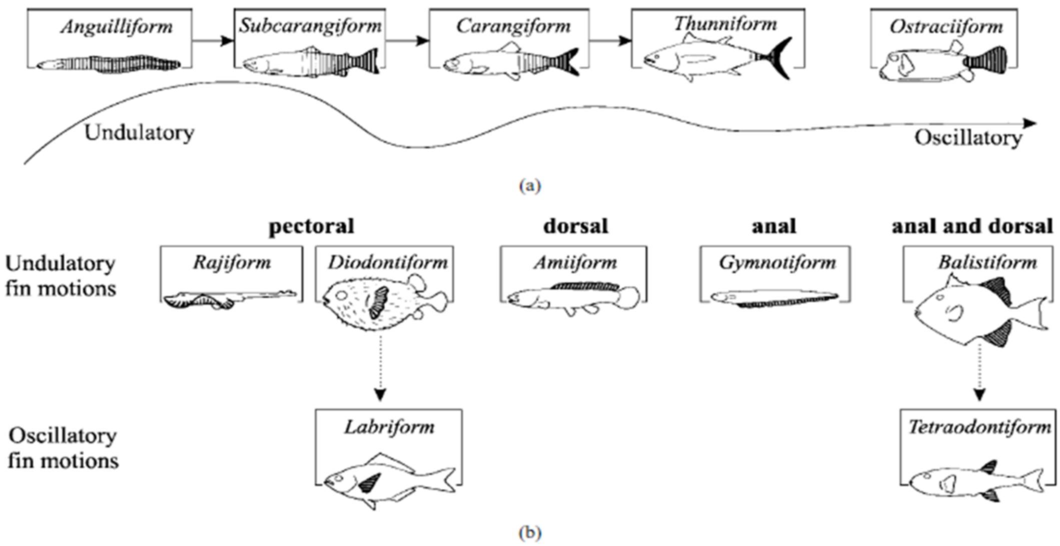


Figure 1. Swimming mode characteristic; (a) Body and/or caudal fin (BCF) locomotion (b) Median and/or paired fin (MPF) locomotion. Shaded areas represent thrust generation [8]

than those of Anguilliform and Subcarangiform, as it restricts its undulation to the third last of the body length, but it compromises turning and acceleration due to the rigidity of the body. The locomotion with the highest speed among BCF swimmers is the Thunniform mode, where the lift-based method is used to produce thrust; but this locomotion mode is not efficient at low speed, or during turning and rapid acceleration. The Ostraciiform locomotion is the pure oscillatory mode, where the caudal of Ostraciiform moves like pendulum while the body remains almost rigid.

In MPF swimming locomotion, median fin and/or paired fins require a set of muscles to control the fin rays and their movement and rotation. MPF locomotion is divided into seven modes based on the fin used during swimming, in which five of them are undulatory locomotions and the remaining two are oscillatory locomotions. Its five modes of undulatory locomotions are Rajiform, Diodontiform, Amiiform, Gymnotiform and Balistiform and the other two modes of oscillatory are Labriform and Tetraodontiform, as shown in Figure 1. Rajiform swimmers have a special, very large, triangular shaped and flexible pectoral fin. This locomotion is either by flapping the fin up and down or manipulating the undulations amplitude along the anterior to posterior fin. Propulsion by Diondontiform is not much different from that of Rajiform, and the undulating propulsion passes down the broad pectoral fin. Both Amiiform and Gymnotiform swimmers have a special long fin, but differ by position of the fin. Amiiform swimmers use dorsal fin, whereas Gymnotiform use anal fin, but both of their bodies are almost rigid during the swimming. The Labriform swimmers basically use only their pectoral fins, whereas Tetraodontiform swimmers use their dorsal and anal fins to perform the swimming.

3. STRUCTURES AND MATERIALS

Development of robotic fish propulsion should consider several aspects such as the shape of the robot, pattern of movement, hydro-dynamics, control system, location of the machine, mechanical properties and material properties [9, 11]. Most existing fish robots are inspired by the real fish locomotion. Robotuna, the world’s first fish robot, was inspired by the bluefin tuna [12, 13], while Vorticity Control Unmanned Undersea Vehicle was inspired by yellowfin tuna [14, 15]. The Robotic Eel was inspired by characteristics of eel [16], Manta Robot was developed with reference to stingray [17, 18], and Nanyang Knifefish [19, 20] and Robotic Knifefish [21-24] were developed by studying black ghost knifefish. The black ghost knifefish is a tropical fish easily found in South America, and it has an ability to maneuver in multi-directions at low speed by undulating the wave along its fin [23, 25].

Tuna is known to have the best propulsion technique because of its high performance in cruising [26]. A 49 inch robotic tuna was constructed by Triantafyllou *et al.* [12], where they used eight links for the body and six brushless motors for the actuation. The body of the fish was made from aluminum and the skin was made from reticulated foam and conformal lycra, which minimized unwanted turbulences and helped the robot to flex smoothly.

Low *et al.* [16] developed a robotic eel by combining six cranks driven by servo motors. The motion of this robot is similar to anguilliform motion, which is one of the undulatory types of fish locomotion. This robot configuration can also be applied for developing stingray, cuttlefish and knifefish.

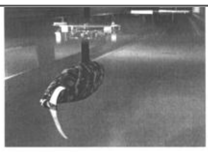
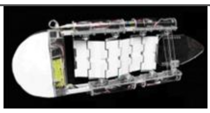
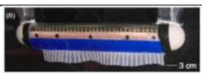
Stingray, or manta ray, is a special fish with two triangular pectoral fins and a short tail. Its special locomotion ability to move forward/backward, turning and gliding has encouraged many researchers to study its flapping fins [18]. Suzumori *et al.* [17] developed a manta robot made from silicone rubber, with its flapping fins driven by pneumatic rubber actuators, which was able to reach swimming speed of 100 mm/s.

The first version of Nanyang Knifefish (2006) contained a buoyancy tank and a fin that contained several rays made from acrylic, which was controlled independently by sinusoidal waves [11]. However, it had many problems, like insufficient water proofing, unsuitable material and electronic component used in control box and other technical problems [19]. The robot was then upgraded to the second version to avoid both hardware and software problems.

Robotic knifefish was another robot inspired by black ghost knifefish, which started being developed in early 2000 by discussing the behavior of the fish, its propulsion and movement in the water and the sensory system used by the fish [23, 25, 27, 28]. Several models of ribbon fins were then developed by varying the number of actuation rays, but all models used latex as replacement for membrane connecting rays [22, 23, 29]. The thrust produced by ribbon fin was studied by varying the propulsive wave frequency, amplitude and wavelength. The total number of rays used in the robotic fin was then increased to thirty-two, in which each ray was controlled by one motor. Several experiments were conducted, and it was found that there are optimal surge and heave force regions for each fin parameter, covering the frequency, amplitude and number of waves [21, 24].

A summary of robotic fishes details are shown in Table 1. Thunniform and Gymnotiform mode show

Table 1. Summary of robotic fishes

Name	Figure	Imitating Fish	Swimming mode	Features
Robotuna [12,13]		Blue fin tuna	Thunniform	Driven by DC servo motor. The length is 1.2 m and the swimming speed is 2 m/s.
Vorticity Control Unmanned Undersea Vehicle [14,15]		Yellow fin tuna	Thunniform	Driven by hydraulic cylinder. The length is 2.4 m and the swimming speed is 1.2 m/s.
Robotic Eel [16]		Eel	Anguilliform	Driven by servo motor attached to six cranks. The fin length is 0.3 m.
Manta Robot [17]		Stingray	Rajiform	Driven by pneumatic rubber actuator. The width is 170 mm and the length is 150 mm. Swimming speed is 100 mm/s.
Nanyang Knifefish [19,20]		Black ghost knifefish	Gymnotiform	Driven by servo motor and the length is 70 cm. The fin is made from acrylic and controlled in sinusoidal pattern.
Robotic Knifefish [21-24]		Black ghost knifefish	Gymnotiform	Driven by 32 motors and the length is 32.60 cm.

high potential to be the references for fish robot models. Both are able to produce high thrust and high maneuvering while keeping the large body area rigid. Thus, the integration of both of their abilities is expected to enhance the propulsion system of marine vessels. The Manta or Stingray robot fish requires large space for the fin compared to the body, which is not efficient for boat design.

4. ACTUATORS USED IN ROBOTIC FISH

Researchers used various kinds of actuators for studying underwater robot locomotion and maneuvering. Electrical motor has been used for actuation system for many decades [1, 2, 11, 30-41]. These types of actuator were simple in design, able to operate at high speeds, and known able to extend or retract identically. However, due to less flexibility, large in size, heavy weight, noisy and complicated control system, they had to be replaced by other new actuation systems [42]. Some of other actuators used are Ionic Polymer-Metal Composite (IPMC), piezoceramic materials, shape memory alloy (SMA) wires and pneumatic soft actuator.

IPMC is an actuator composed of polymer and electrodes. When electric is supplied to IPMC, a change in chemical structure occurs, thus causing mechanical deformation. Since corrosion of electrodes easily occurs during propulsion in the water, Chen *et al.* [43] covered their electrodes using gold-coated copper electrode and further with passive plastic fin to enhance robot propulsion. Ye *et al.* [44] used IPMC actuator to increase the capability of their robotic fish by adding obstacle avoidance function and easy maneuver in low speed and limited space. IPMC also has other advantages such as silent operation [45] and low power consumption compared to conventional motor propeller. It was proven that IPMC actuator can move the robotic fish farther with the same battery capacity [44].

Piezoelectric is a better actuator as it is able to respond faster and produce large actuation force. Thin-layer composite unimorph ferroelectric driver or THUNDER was one of the first PZT-based unimorph actuators. The manufacturing process involves binding a thin sheet of piezoelectric ceramic under hydrostatic pressure between a metal substrate and an aluminum electrode at 320 °C. Nguyen *et al.* [46-48] made lightweight piezocomposite curved actuator (LIPCA) by replacing the metal used in THUNDER with multiple composite layers to improve its performance and making it very light. LIPCA had five layers in which, three of them were made from low modulus and high coefficient of thermal expansion (CTE) glass/epoxy. Another two layers were from carbon/epoxy with high modulus and low CTE and PZT ceramic wafer, which acted as the actuation element. The construction of LIPCA is shown in Figure 3.

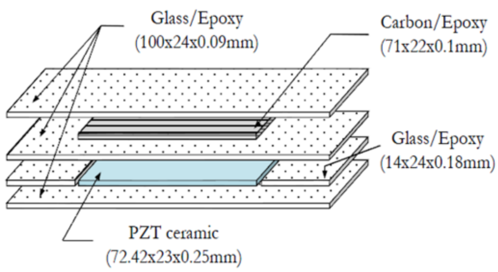


Figure 3. Geometry and Layers in a LIPCA [46]

SMA is an alloy that has the ability to return into its original figure after pre-deformed shape when heated. SMA actuators are mostly used in robotic technologies for various reasons such as low current and voltage consumption, cheaper and commercial availability [49]. Le *et al.* [50] claims that SMA wires are the best choice for producing high actuation force and displacement compared to THUNDER and LIPCA. SMA wires are used for underwater robot actuation due to its high ability to be cooled down when the wires touch water and thus increasing the actuation frequency; but have a weakness that they consume more power.

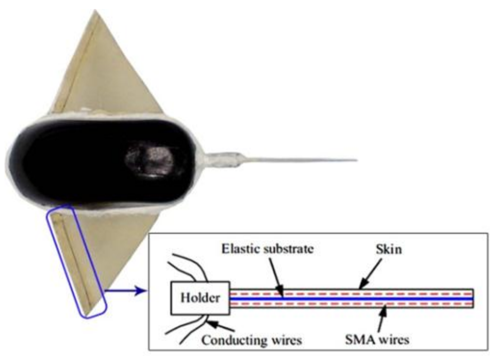


Figure 4. The micro robot manta ray and the structure of biomimetic fin [50]

Wang *et al.* [51] had proven that SMA wires are a possible actuator to be used in developing micro biomimetic Manta ray robot. An SMA wire was integrated into the actuating unit, called biomimetic fin and was attached to two surfaces of elastic substrate. The skin was used to cover SMA and elastic substrates, as shown in Figure 4. The robot was able to reach maximum swimming speed of 57 mm/s and maximum amplitude of 40 mm.

Soft actuator is a newer technology that can be used as an alternative for rays of the fin. Soft actuator consists of a single internal chamber or multiple chambers of rubber structure, which is often reinforced with fibers. Soft actuator can produce unidirectional motion if only one chamber is used, and is able to produce bidirectional motion if two chambers are used. Applying a high pneumatic pressure to the chamber(s) causes elastic deformations of the rubber structure, and it works as an actuator by extending and contracting the rubber structure [52, 53]. The actuator is expected to provide better results in hydrodynamics and vessel maneuvering due to the soft movement produced by the actuator. Suzumori *et al.* [17] used the soft actuator with two chambers; upper chamber and lower chamber, to bend the wings of manta robot, as shown in Figure 5. The wings bend to the upper direction by applying pressure into the lower chamber which is opposite to the bending motion. It could bend to the lower direction if pressure is applied into the upper chamber.

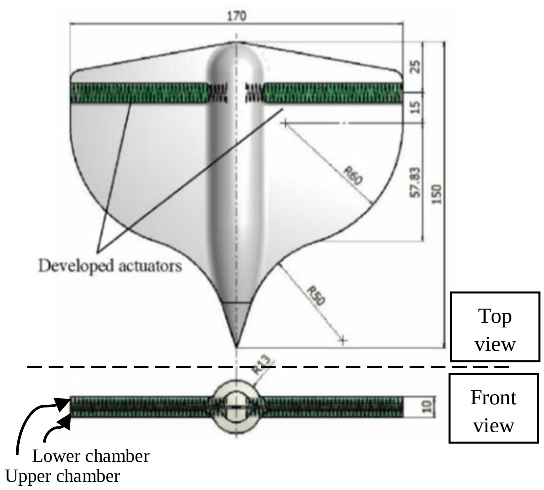


Figure 5. Manta robot and the soft actuator wings [17]

As explained in the literatures above, researchers actually have many options to select any actuator for their design. The most important parameter to be considered is the actuation power, whether it could be produced with less power consumption. The soft actuators have potential to be used as fins in fish robots because of their simple construction, smooth motion and water resistance.

5. CONTROLLERS USED IN ROBOTIC FISH

Controller is an important component to control, actuate and maneuver the movement of the fish robot. The controller usually requires sensors or transducers to provide a feedback data. Salumae *et al.* [54] used Braitenberg controller for robot fish to perform rheotaxis behavior by keeping the robot's angular deviation close to the direction of incoming flow. The controller used two pressure sensors to measure the pressure difference, which were both positioned symmetrically on the nose of the fish robot. The performance of robot with Braitenberg controller was also studied in two different cases: no offset control, in which only holding the station controller active, and offset control using feedback from the overhead camera, in which a PID controller was used to maintain the orientation of the robot. Table 2 shows the mean and standard deviation of heading and lateral positions of controllers. There was not much difference in the mean after 50 seconds, but there was a significant decrease in standard deviation in Braitenberg and Camera feedback controllers compared to No offset controller. It was concluded that the rheotaxis behavior could be successfully achieved using a feedback controller driven by local flow information.

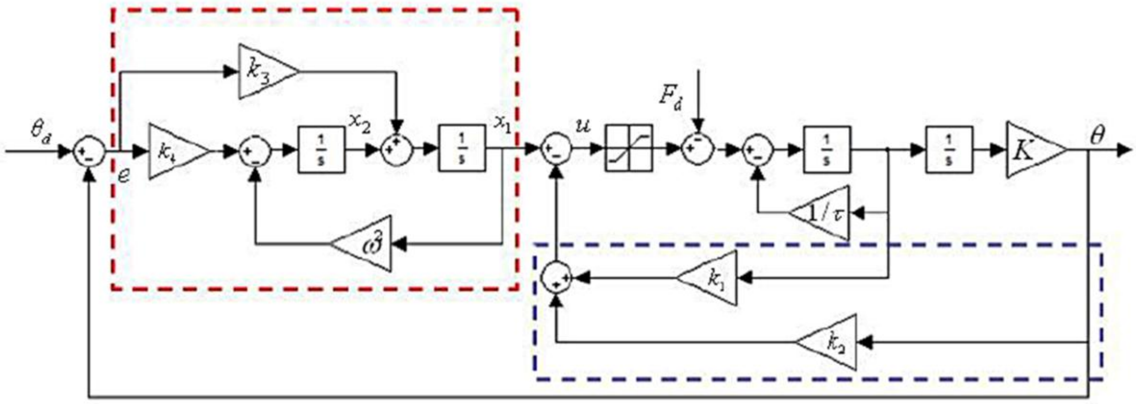
Table 2. Comparison of three controllers for mean and standard deviation of the heading and lateral position [54]

	No offset	Braitenberg	Camera feedback
Mean, *y*	237.7 mm	250.3 mm	253.5 mm
Mean, *θ*	-2.8 deg	-2.9 deg	-2.7 deg
Standard deviation, *y*	146.3 mm	59.2 mm	26.7 mm
Standard deviation, *θ*	11.3 deg	2.9 deg	2.7 deg

Barbera *et al.* [55] focused more on attitude control of the pectoral fin of fish robot. They constructed a fish model based on the box fish and controlled by PD controller. They assumed it as a linear system with transfer function of desired set point, as in Equation 1.

$$G(s) = \frac{21.001}{s(s+1.923)} \qquad (1)$$

Zhou *et al.* [56] also used a PD controller to perform steady swimming of Carangiform robot, and then revised it with mathematical disturbance in order to overcome the issues occurring with frequency and amplitude change. This robust controller model had three loops; two are inner loops and the other one is the outer loop, as shown in Figure 6. The inner loops acted as full order feedback loop of the plant and fed forward the controller loop, whereas the outer loop acted as output feedback loop.



$$\frac{\theta(s)}{\theta_d(s)} = \frac{k_3 K (s + k_4/k_3)}{s^4 + (k_1 + 1/\tau)s^3 + (k_2 K + \omega^2)s^2 + [\omega^2(k_1 + 1/\tau) + k_3 K]s + K(\omega^2 k_2 + k_4)}$$

Figure 6. Closed-loop system with robust controller [56]

Equation 2 represents the overall robust tracking system, in which *E(s)* and *Y(s)* refer to error and output, respectively.

$$U(s) = \frac{k_3 s + k_4}{s^2 + \omega^2} E(s) + \left(k_2 + \frac{k_1}{K} s\right) Y(s) \qquad (2)$$

Ariyanto *et al.* [57] proposed two degrees of freedom PID controller in order to change the swimming direction, which improved the steering performance.

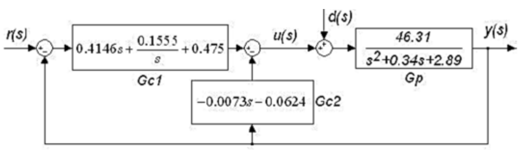
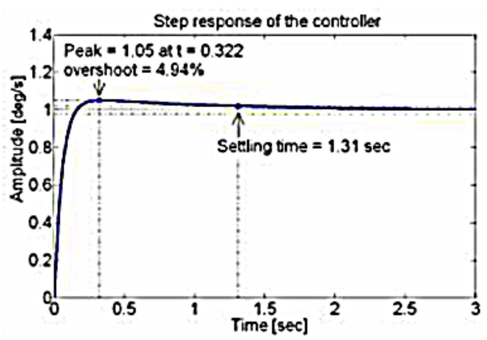
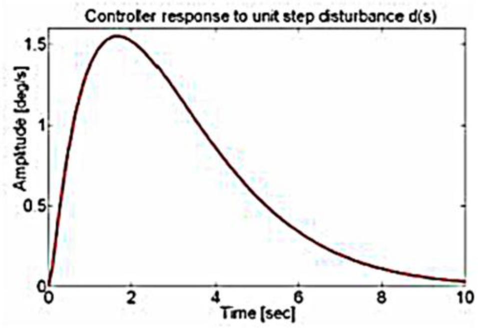


Figure 7. Two degrees of freedom PID controller [57]

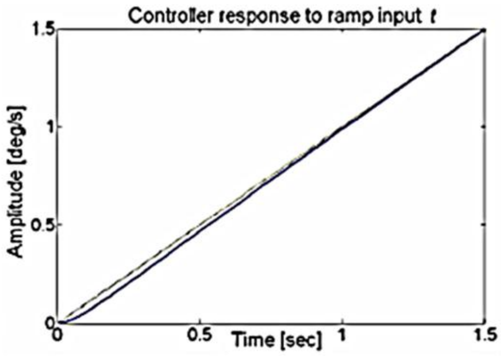
The duration of output overshoot within the range of 5-10% was less than 1.5 seconds and the controller was able to suppress external disturbances. The controller used zero steady-state error and ramp input. Figure 7 and Figure 8 show the controller design and its output.



(a)



(b)



(c)

Figure 8. The simulation results; (a) step response of the controller, (b) controller response to unit step disturbance, (c) controller response to ramp input [57]

Instead of using PD and PID controller for fish robots, Ming *et al.* [58] used the Central Pattern Generator (CPG) controller to control a three-link robotic fish. The data generated by CPG controller was then fed into a Back-Propagation Neural Network (BPNN) for optimization. Hu *et al.* [59] used iterative learning control to improve the stability of a fish robot. The controller was then embedded with filter to reduce noise and curve fitting component to keep the necessary difference between two adjacent rays. Li *et al.* [60] used fuzzy logic vortices controller based on 2-D oscillating foil mechanism to ensure maneuverable swimming in straight line with efficient thrust.

The above discussions show that each controller has particular benefits in their application. Still, for new robotic design, it is suggested to start with PID controller as it is vital to calculate terms proportional to the error (P), the integral of the error (I) and the derivative of the error (D) beforehand. The new control algorithms can also be attempted depending on the accuracy required.

6. CONCLUSIONS

The development of fish robotics is one of the challenging research areas. The propulsion me mechanism of fish robot should mimic natural movement of the real fish fin, in addition to the shapes and materials to be used. Selection of actuator and controller is another factor in determining the generation of thrust and effective maneuvering. This paper is organized to give readers comprehensive information on propulsion mechanism, actuator and controller. It is understood from the literature that the material of the fin and actuator must be flexible for efficient high thrust and high maneuvering.

7. ACKNOWLEDGEMENT

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