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A Prototypical Multi-Locomotive Robotic Fish Parametric Research and Design

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Abstract—**This paper presents a study and design of a robotic fish that imitates natural aquatic animals' forms of locomotion by focusing on the apparatus of swimming performances. Numbers of animal-liked aquatic robots have been researched in the past; however, very few works involved the study of robot with full behavioral locomotion of these aquatic animals: anguilliform, carangiform, subcarangiform and thunniform. The main focus of the research is to develop an aquatic robot that can perform all the natural motion mechanism of the fish. Not only does the research able to enclose various general aquatic locomotive forms into a single robot, but also able to dynamically change the robotic fish motion behavior according to the environmental condition. The adaptive behavioral selection allows the robotic fish to perform various locomotive forms based on the operational situation. Series of movements are designed to demonstrate the natural fish-liked locomotion: maneuvering, forward, backward, and turning. The collection of robotic movements is operated by designed apparatus including tail peduncle and pectoral fin for propulsion, docking, and maneuvering. The proposed robotic fish has been implemented, and the experiments show a good performance as well as illustrate the robustness of such a robotic framework.**

Index Terms—**Robotics, underwater robot, robot design, swimming locomotion, mobile robots and autonomous systems**

I. Introduction

NATURE has endowed diversity of habitual characteristic and locomotion for particular behavior and environment of creations. Inspired with this wonder of nature, many researchers have invested on stimulation of luring locomotion of living things. For decades, living-thing-imitated robots have been designed for lifelike invention. Splendid aquatic creations are also attractive and various to suit such differences of their own lives. This influences on technological evolution of underwater vehicles and robots. Even numbers of animal-liked aquatic robots have been researched in the past; very few works involved the study of full behavioral movement of these aquatic animals.

Scientists and biologists have been inspired to study how fish swim and maneuver [1] [2] [3]. The very first research of fish maneuvering is presented by Sir James Gray known as Gray's Paradox [4]. He discovered the cause of speedy movements, propulsions, and accelerations which found in the small muscles of dolphin [4]. In 1975, Lighthill [5] modeled the fish movement position from propelling frequency. In 1995, a research team at MIT developed the very first aquatic robot named RoboTuna which mimicked the bluefin tuna. Anderson developed a velocity control unmanned undersea vehicle in 1999 [6]. This robot consisted of a flexible "tuna-f shaped hull" and was propelled by an oscillating fin. In 2002, carangiform-like movement of aquatic animal was adapted to robotic fish by Morgansen to help with trajectory stabilization [7]. Kato conducted a study on apparatus of pectoral fin motion with the robotic fish [8]. Yan et al. presented parametric research of experiments on a carangiform fish robot [9]. Our previous paper [10] employed variety of momentum and angle on each articulation of the robotic fish to control movement and used the pectoral fins that can react to avoid the underwater obstacles. However, very few studies in the realm utilize the differences of each swimmer type of locomotion for appropriation of environmental condition changes. This in-depth research will impact on flexibility of adaptive swimming locomotion. Exploring into the differences of natural aquatic locomotion, the research aims to focus on the further experiment on characteristic of each swimming mode—including subcarangiform, carangiform, and thunniform—to be utilized with the adaptive swimming function of the designed robotic fish that can meet the facing underwater environment with such particular mode.

II. Design Concept

Swimming models of marine animals are various depended on the types and species [11]. In nature, each aquatic swimmer has unique locomotive form that characterizes the maneuvering performance. Furthermore, robotic fish's propulsion is concerned with fluid hydrodynamic and is difficult to establish purely analytical methods. This paper's robotic fish is based on the study of fish natural movement. The robotic fish consists of modulating joints that propel the body by oscillating the tail peduncle and pectoral fins.

A. Locomotion and Movement

The fish locomotion is compounded from various fundamental factors including the hydrodynamic of fluid environment, apparatus of the marine animals packed with collections of their locomotive styles. Fish swimming mechanism affects surrounding water in any movements; while a fish swimming, transformation of momentum between the fish and the surrounding water occurs. The essential of locomotion and movement in fluid environment is the forces acting on the body of the swimming fish as well as the robotic fish. Forces stabilize, propel, and maneuver the fish or robot motion. The concept of fish swimming mechanism is modeled in Fig 1.

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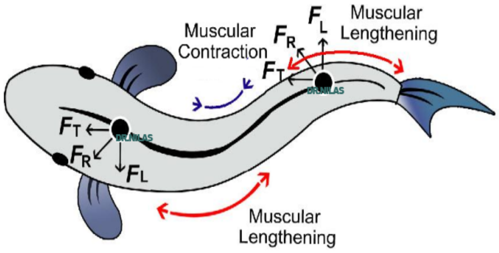

Fig. 1. Fish swimming mechanism

Fish swimming mechanism is created by the reacting force of the motion. The thrust force will increase if the fish could generate larger propulsive wave; thus, the tail peduncle must traverse greater distance (wider swing-angle) with higher oscillation frequency. Fish generates the propulsive wave of water passing backwards along the body segment and propels the fish forwards. The force contributed from its small body segment creates the momentum of passing water that called the reacting force (FR). The reacting force is the propulsion element that could be analyzed into a lateral force (FL) and a thrust force (FT) component. The forward propulsion is produced from the thrust force component (FT) but the lateral force component (FL) produces the tendencies for the anterior part of the body to sideslip and yaws the body along its vertical axis. This lateral force causes significant energy loss in fish motion.

B. General Form of Locomotive Swimmer

In general, aquatic vertebrate's body movements can be explained in four main kinematic [11] [12], shown in Fig. 2.

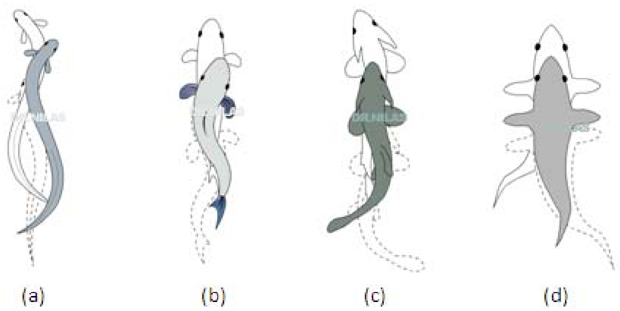

Fig. 2. Four kinematic of locomotive swimmers

-- Anguiliform propels the entire body with at least one complete wavelength along the body. The amplitude of the body movements is relatively large along the entire length of the body. This can found in flexible body structure animal such as eel, tadpole, etc. [Fig. 2. (a)]

--Subcarangiform is similar to anguiliform, but the amplitude of the undulations occurs in posterior half of the body. The body is stiffer, making for higher speed but reduced maneuverability. This can be found in trout, cod, etc. [Fig. 2. (b)]

-- Carangiform has the undulation increase only the last third part of the body length with less than half wavelength along the body. This can found in salmon, mackerel, etc. [Fig. 2. (c)]

-- Thunniform has the oscillation in the anterior aspects of the body, such as the tail and peduncle. It has a distinctive high aspect ratio for high speed and long-distance swimmer. This can found in tuna, and marine mammals. [Fig. 2. (d)]

C. Robotic Fish Skeleton Model

The research methodology of robotic fish skeleton model involves real fish structural analysis. This paper observes the fish natural movement and models the fish body into parts to develop a robotic fish then applies various locomotion forms of swimming to control the robot propulsion and maneuvering. Our proposed study of robotic fish is engaged with adaptive multi-locomotive swimmer models, including subcarangiform, carangiform, and thunniform, resulting in appropriate movement in underwater conditions and environments or means of obstacle avoidance.

Fig. 3 shows each step of the locomotion of the fish swimming by segmenting the fish body into four parts: head, main-body, rear-body, and tail peduncle. Fish bends the body in to a tight 'C' shape to create the momentum of passing water that generates the reacting force (FR) to propel forwards.

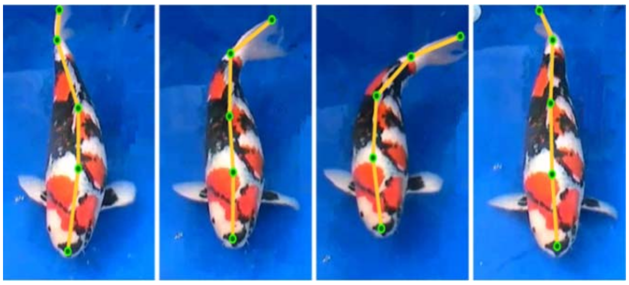

Fig. 3. The crap fish's "C" shape swimming behaviors

This paper analyzes the fish body into three models with five modules: the head, the body part (middle and rear), the pectoral fin, the anal fin, and the peduncle. The anal fin and the peduncle are attached on the tail of the robot. The first model is the subcarangiform that consists of a rigid head, two moving body parts, and an oscillating tail peduncle [Fig. 4 (b)]. The second model, carangiform, has a rigid head, a fix middle-body part, and a moving tail peduncle [Fig. 4 (c)]. The third model is the thuniform that has all rigid body parts but the tail peduncle [Fig. 4 (d)].

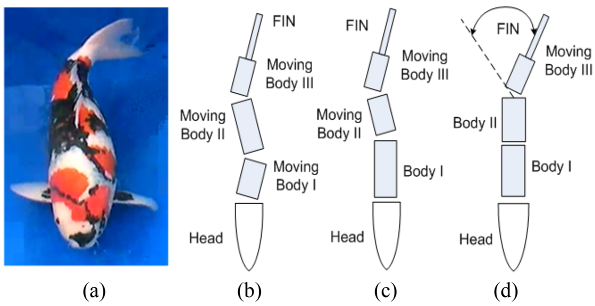

Fig. 4. Robotic fish skeleton models

According to observation of the fish's swimming behavior, the research could establish the behavioral maneuvering and locomotive model. Fish performs the major movement at the very end of the body and tail in order to driving forwards. The Carp fish (KOI) in Fig. 4(a) could be divided into multiple joints of body modules. The larger number of the body segmented modules results in the greater propulsive swimming wave (the greater thrust force (FT)). However, increasing amount of body modules will increase the robot length as well as the lateral force (FL).

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The structure of the designed robotic fish consists of multiple joints of body modules that could be decomposed into multiple joints of body modules. The greater number of the body segmented modules, the greater the propulsive swimming wave (the greater thrust force (FT). However, increasing of the body modules will increase the robot length as well as increase the lateral force (FL). Such the robotic structure supports multi-locomotive swimming modes that react to underwater environments and surrounding obstacles. For example, subcarangiform mode—oscillating with moving body part I, II, and III—is utilized for slow and smooth swimming. Carangiform mode—oscillating with moving body part II and III—is faster than subcarangiform mode but causes inclination to body recoil because of the only-posterior oscillation. Thunniform mode—oscillating with moving body part III—performs the most efficient aquatic locomotion mode with high speed yet long distance and period.

D. Maneuver and Motion Factors

The robotic fish's propulsion depends on the traverse distance and oscillation frequency of the moving parts (fish's rear-body and tail peduncle). The traverse distance represents the magnitude (the angular distance) of the motion. The propelling frequency represents the repeatability of the motion. These two are essential factors contributed to the fish thrust force and the velocity. In addition, the initiative angle of the moving parts and the relative angle of these parts will contribute to the heading direction of the fish motion. If the robotic fish has greater number of initiative angle and relative angle, it will have higher turning angle and smaller turning radius. Moreover, the number of moving joints also affects the robot motion.

E. Mathematical Model

In this paper, we observe fish swimming behavior and develop a simple mathematical model based on the "C" shape motion pattern [Fig.3]. This research adapts Lighthill's swimming model of slender fish [2].

$$Y(t, f)=(C_1X+C_2X^2)sin(2\pi\ X/T+2\pi ft) \tag{1}$$

where $Y(x,t)$ is the transverse displacement of the robotic fish along the x-axis at time t, C_1 and C_2 are the linear coefficient and the quadratic coefficient of the wave amplitude envelope respectively. T is the wave length and f is the propelling frequency.

Using only the linear coefficient and including the turn angle component, the movement of the n_{th} moving part of the robotic fish can be expressed as

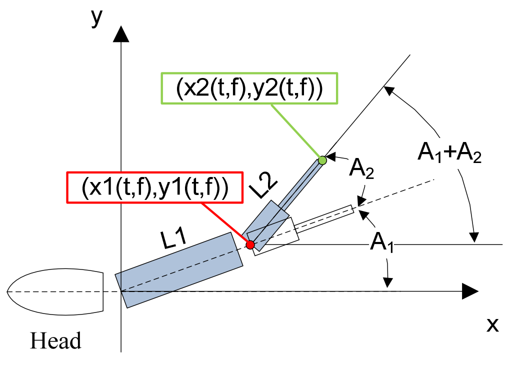

Fig. 5. Robotic fish propelling model

$$X_n(t, f) = X_{n-1}(t, f) + L_n cos(A_n + A_{n-1} + \cdots + A_1) \tag{2}$$

$$Y_n(t, f) = Y_{n-1}(t, f) + L_n cos(A_n + A_{n-1} + \cdots + A_1) \tag{3}$$

where x, y are the position of the moving part according to the propelling frequency f at time t, A_n is the traverse angle of each joint related to the x-axis. In addition, the joint's initial angle will be used as the turning coefficient that directs the propelling force of the robot. Therefore, the traverse angle of the n_{th} moving part can be expressed as

$$A_n = K_a sin(2\pi ft - \beta_{n-1}) + TA \tag{4}$$

$$TA = K_i (A_{max} - A_{actual}) / A_{actual} \tag{5}$$

where K_a is the propelling amplitude coefficient, β is the relational initial angel of to the n_{th} to the $(n-1)_{th}$ moving part. TA is the turning angle that usually is the initiative angle of the joint. This research uses TA in the form of the angle regulation of each joint multiply by turning coefficient K_i. If TA equals to zero, the robotic fish will be in a straight line path. A_{max} is the maximum turning angle and A_{actual} is the actual oscillation angle.

III. Implementation

Developing aquatic robot is quite different from other kinds of robot. This work has been hindered the variability and complexity of the fish natural behaviors as well as mechanical and electrical requirement of water-resistant system for underwater locomotion.

A. Robotic Fish Design

The structure of the robotic fish consists of two primary parts: head module and moving section. This paper designs two similar robotic fishes to study the parametric of the locomotion as well as to mimic the natural fish movement. The first robot is composed of a moving body part, an anal fin, and a tail peduncle [Fig. 6 (a)]. The second robot composed of two section of moving body parts, an anal fin, a tail peduncle, left and right pectoral fins [Fig. 6 (b)].

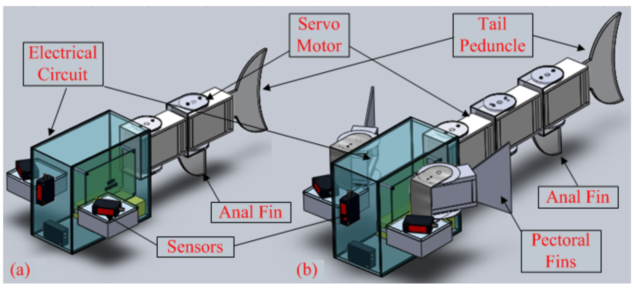

Fig. 6. Robotic fish's mechanical design

The robot body is made from waterproof acrylic case which contains all electrical circuit, control system, battery, sensors, servo motors and counterweight module. There are four infrared sensors installed on the head module. The front, left, and right sensors can notice obstacle horizontally while the underneath sensor senses the bottom surface of the water vertically. The robotic fish's moving parts consist of joints and u-shape strut that supports servo motors for generating the wave motion. The anal fin and pectoral fins assists the robot hydrodynamic stability and direction of movement.

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Four major required electrical circuits of the robotic fish are control system, sensor circuit, servomotor and power supply. This paper uses ARM7 LPC2103 with 32KB ram and multiple serial interfaces. The robot powered by 2 cells 6Ah Li-Po battery with 0.14 sec/60 speed and 3.60 kg/cm torque servomotor.

B. Control Software

The robotic fish utilizes multi-locomotive swimmer models; subcarangiform, carangiform, and thunniform that adaptively selected by the controller. The robotic fish's controller employs an adaptive action selection mechanism, spreading activation network (SAN), from of our previous works [13] to adjust the robotic fish's propulsive angle and maneuvering actuator. The robotic fish swimming is realized with the infrared sensors equipped on the head module; in the case of no obstacles, the robotic fish swims autonomously. When the obstacles are detected, the robotic fish can avoid or round them by taking an appropriate turn with a desired speed using the most suitable locomotion form based on the spreading activation network (SAN). On the robot head installs four infrared sensors for detection obstacles on all sides and also measurement the distance to surrounding objects. The robotic fish is programmed to react to the sensors and deviates travel path as obstacle detected. Fig. 7 shows the simulation and control software. The embedded program in microcontroller onboard the robotic fish receives signal from sensors. The program also gets parameter values from robotic fish to be calculated with the robotic motion equation and sends data to servomotors to control movements.

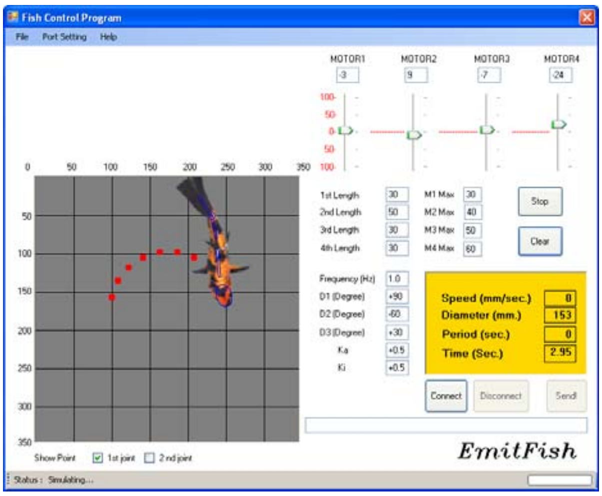

Fig. 7. Robotic fish simulation program

IV. EXPERIMENTS AND PERFORMANCES

A. Relationship between Velocity and Frequency

The robot velocity depends on the frequency in direct relationship of the propelling oscillation frequency *f* of tail peduncle; as mostly seen in thunniform swimming model. The relationship of velocity and frequency of tail peduncle oscillation configuration is shown as Fig. 8.

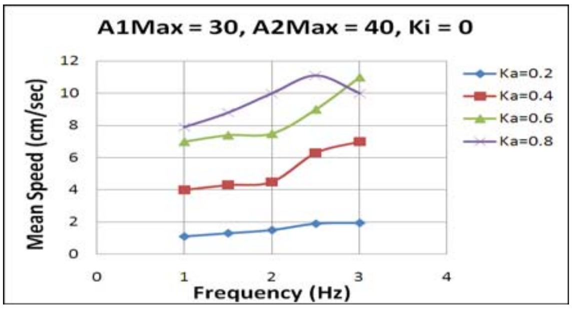

Fig. 8. Velocity and frequency of the tail peduncle oscillation in straight trajectory

B. Relationship between Propelling Amplitude, Velocity, and Turning Angle

In the case that the robotic fish swims forward, Fig. 9 demonstrates the robot performance. The more *f.* is increased, the more velocity (speed) and amplitude rise. Similarly, if Ka increases, the robotic fish speed will be increased. In the case of turning trajectory, if Ka increases, the turning radius will be increased as well as turning velocity and turning period respectively as shown in Fig. 10 and Fig. 11.

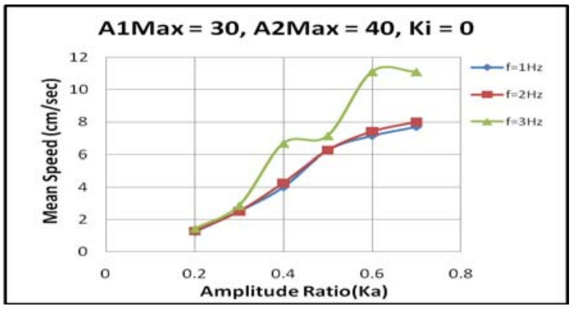

Fig. 9. Velocity and propelling amplitude

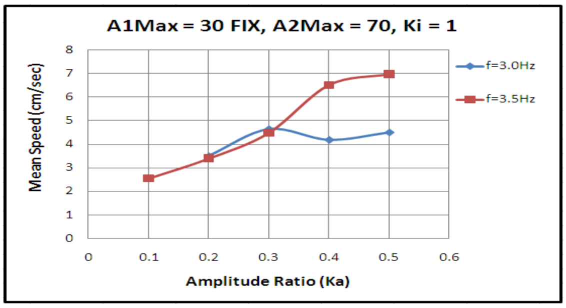

Fig. 10. Turning velocity and Ka at different frequency

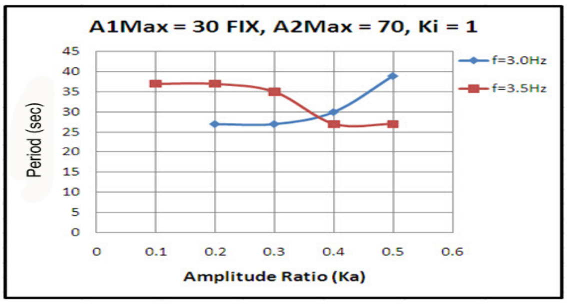

Fig. 11. Turning period and Ka at differnet frequency

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C. *Robotic Fish Propelling Behavior according to Swimming Modes*

The natural swimming pattern is the fundamental factors of the aquatic animal's propelling and maneuvering performances. This research develops an adaptive multi-locomotive selection that employs three most common kinematic of fish propulsion. The experiments demonstrate the essential of each active articulation that propels and turns the robot trajectory. Fig. 12 and Fig. 13 show robotic trajectory that utilizes carangiform-liked and subcaragiform-liked locomotion respectively with oscillating the rear-body part II and III of the robot in order to perform better maneuvering and smaller-radius turning circle. From the experiments, more active articulations of the robotic fish result in higher maneuverability and flexibility of the robot.

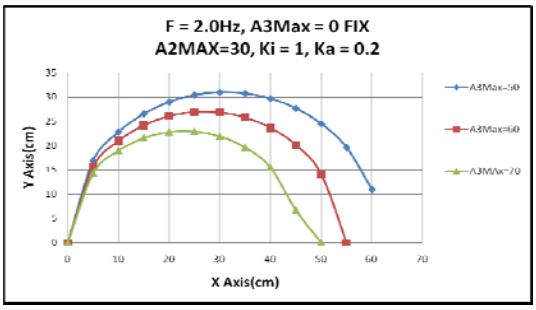


Fig. 12. Turning radius with rigid body part I, oscillating body part II at 30˚, and body part III at 50˚, 60˚ and 70˚

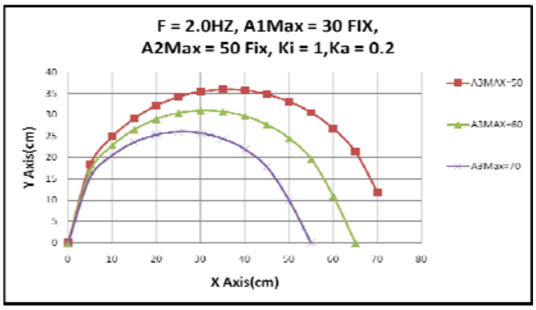
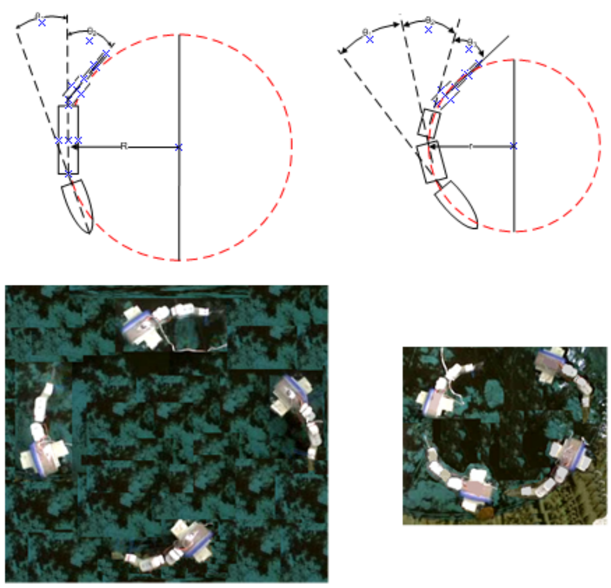


Fig. 13. Turning radius with oscillating body part I at 30˚, body part II at 50˚, and body part III at 50˚, 60˚, and 70˚



(a) (b)

Fig. 14. Curving trajectory comparison of 2-joint and 3-joint robots

Fig. 14 demonstrates the robotic fish travel in a curving trajectory. The robot had been setup into two configurations: 2 and 3 body joints. The greater number of initiative angle and relative angle result in higher turning angle and smaller turning angle. The robotic fish with greater number of joints have smoother motion pattern and smaller turning radius.

D. *Obstacle Avoidance*

Fig. 15 shows the robotic fish performing obstacle avoidance. There are three behavioral swimming modes involved: subcarangiform, carangiform, and thunniform for driving and obstacle avoidance.

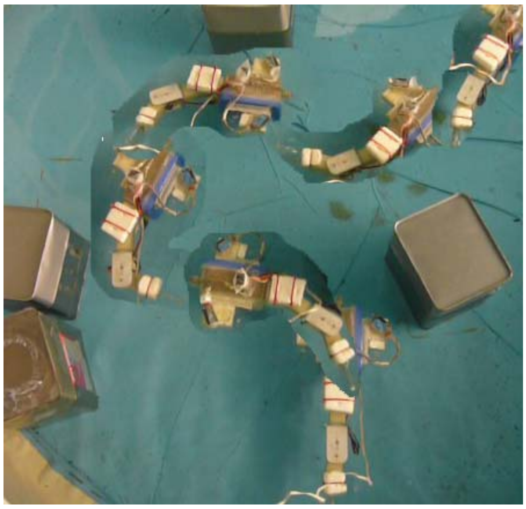


Fig. 15. Obstacle avoidance path of the robotic fish

Applied with multi-locomotive swimming, the robot performs more efficient movement for obstacle avoidance. This adaptive three swimming models react to the infrared sensors that detect and supervise underwater environment. The signal from the sensor is sent to the controller which calculates the distance and position of the facing obstacles to control the robot locomotive models. Then the controller adaptively selects the locomotion modes. The demonstration of adaptive multi-locomotion (Fig. 15) presents the sequence of robotic fish speedily driving with thunniform mode. Subcarangiform is applied when the sensor detects the first obstacle to respond the swerving and avoiding obstacles function. Carangiform is activated when the underwater obstacles are almost cleared, and finally locomotion change to thunniform for straight trajectory.

V. CONCLUSION

Our result has indicated the concept and portrayed the prototypical robotic fish that mimics natural locomotion of aquatic vertebrates' mechanism with straight, turning, and maneuvering swimming. Composed of multi-locomotion, the robot performs subcarangiform, carangiform, and thunniform that react to suite the real underwater environment and condition, including obstacles detected by the sensors and calculated by the controller which selects the swimming mode. The designing of apparatus—tail peduncle and pectoral fin—focuses on propelling and other fish-liked behavioral movement. Swimming performances are configured with different parameters.

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