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Prototypical Robotic Fish with Swimming Locomotive Configuration in Fluid Environment

P.Nilas, N. Suwanchit, and R. Lumpuprakarn

Abstract--**Aquatic animal has always inspired many researchers' interest to develop such living creations' behavioral robots. Numbers of animal-liked aquatic robots have been invented in the past; however, very few works involved the study of full behavioral movement of these aquatic animals. This paper presents a study and design of a robotic fish that imitate natural aquatic animals' forms of locomotion by focusing on the apparatus of swimming performances. The main research focus is the behavioral movement of the propulsion and maneuvering of a robotic fish in a fluid environment. The robot could dynamically generate a series of behavior selection network to form the operational plan, avoiding obstacle as well as fish-liked maneuver; forward, backward and turning. This robot differs from other research that not only uses the tail peduncle to propel its movement but also use pectoral fin in stabilizing and maneuvering. The proposed paradigm has been implemented to develop a prototypical robotic fish. The experiments also illustrate the conventionality, and the robustness of such a fish-robot framework.**

Index Terms—**Artificial intelligence, Intelligent robots, Motion control**

I. Introduction

THE luring locomotion of aquatic creatures has influenced many scientists' interesting to mimic such living thing behavioral movements. The robotic fish was designed to imitate natural aquatic animals' forms of locomotion by focusing on the apparatus of swimming performances, which might result in the technological evolution of underwater vehicles and robots.

Number of studies invests in aquatic animals' locomotion. One of the renowned biologists studying on such topic was Sir James Gray or Gray's Paradox. He discovered the cause of speedy movements, propulsions, and accelerations which found in the small muscles of dolphin[1]. One of the very first aquatic robots was created by a researcher team at MIT in 1995 and named as the RoboTuna or Charlie I [2, 3, 4].

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In 1999, Anderson and Kerrebrock attempted to develop an autonomic-motion robotic tuna— the vorticity control unmanned undersea vehicle (VCUUV). The invention consisted of a flexible "tuna-f shaped hull" and was propelled by an oscillating fin [5]. In 2002, a researcher team from California Institute of Technology studied on the task of trajectory stabilization for a fish-like robot focusing on carangiform-like movement of a planar carangiform fish [6]. Another paper of CIT dealt with the body shapes that influenced on underwater propulsion of aquatic animals and robots [7]. Kato et al. [8] conducted a further study on apparatus of pectoral fin motion with the robotic fish in 1998. Utilizing a pair of pectoral fin on both sides, the robotic fish can perform rendezvous and docking in a horizontal plane. These pectoral fins were controlled by a personal computer and the angles are sensed by potentiometers.

Nevertheless, relevant work employs neither the variety of momentum and angle on each articulation of robotic fish to control the movement, nor the use of pectoral fins that can react to avoid the underwater obstacles. Our goals are focused on the further experiment on efficient locomotion and propulsion of robotic fish that is controlled by suitable momentum employed on each articulation. The experimental outcome is the natural-liked apparatus of the consisting modules of the robotic structure. Automatic ability for obstacle avoidance realized by the installed sensors packed with both-side pectoral fins helps with the swimming performance. The pectoral fins are used as the control part for obstacle avoidance and speed and angle assessment for maneuver. These fins directly interact with the installed sensors that supervise obstacles and underwater environment.

This paper is organized as follows: Section 2 presents the overall design concept and system architecture for the proposed robot-fish framework. Section 3 describes in detail how to imitate the fish-maneuvering behaviors not only the natural swimming but also turning to avoid obstacles. The implementation and experiment details are presented in Section 4. Section 5 provides the results of the experiments and discusses the implications. Finally, Section 6 summarizes the contributions of this work and discusses future research directions.

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II. Design Concept

Swimming models of fish are various depended on the types and species of the fish [9]; i.e. Eel swims by waving the whole body (anguilliform locomotion), Tuna waves the tail peduncle (thunniform locomotion), Salmon uses both tail and rear body (carangiform locomotion). Furthermore, influenced by the fluid environment, robotic fish's propulsion is concerned with hydrodynamic and is hard to establish purely analytical methods. This means that exact mathematic models are difficult to be applied to specify the whole methodology by plain system. The system architecture of our robotic fish is based on the study of the natural movement of Carp Fish (Koi), Fig 1. The robotic fish consists of modulating joint that propels the body by oscillating the tail peduncle and pectoral fins.

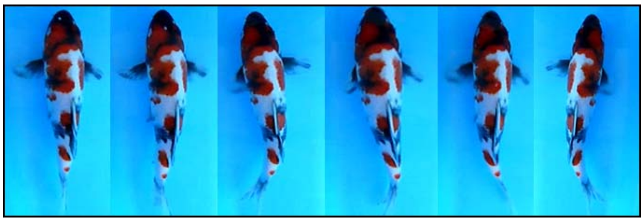

Fig. 1. Carp Fish (Koi) swimming

A. Locomotion and Movement

Forces acting on a swimming fish and robotic fish are the essential part of stabilizing and propel the body in fluid environment. The locomotion of fish 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 swims, there is transformation of momentum between the fish and the surrounding water. Majority of momentum arises from fish's locomotion such as lift, drag, acceleration. Other behavioral locomotion creates momentum transformation including cruising, propulsion, and maneuvering as shown in Fig.2.

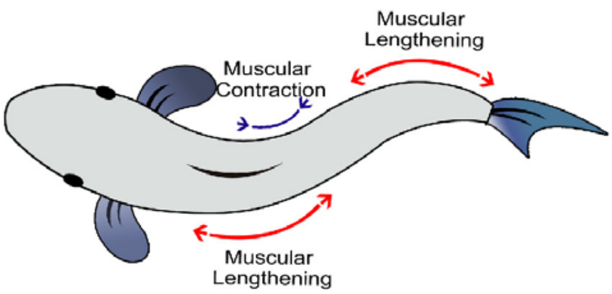

Fig. 2. Fish swimming mechanism

When fish bends its body, it creates the muscular contraction and lengthening which 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 (F_R). The reacting force is the propulsion element that could be analyzed into a lateral force (F_L) and a thrust force (F_T) component. The forward propulsion is produced from the thrust force component (F_T). While the lateral force component (F_L) 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. Fig. 3.shows the swimming mechanism created by the reacting force of the fish 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.

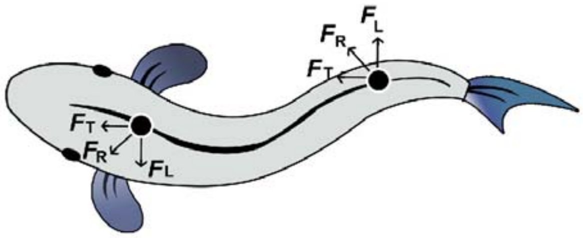

Fig. 3. Fish swimming mechanism

Marine animals' behavioral movement and locomotion are naturally fascinated and various. In this research, we employ the carangiform swimming mode with the robotic fish. The carangiform mode performs the major movement at the very end of the body and tail in order to drive forwards. In the caudal part, the oscillation caudal fin or tail peduncle has to flap rapidly. Fish starts its motion by bending its rear-half body [Fig. 4.], and then it moves the caudal fin closer to the body. Fish bends the body in to a tight 'C' shape to create the momentum of passing water that generates the reacting force (F_R) to propel forwards. Finally, the body releases and straightens into the direction of the tail peduncle. This "C" shape movement is a common locomotion for carangiform swimming mode of a fish [9]. This research adapts this fish movement to create a locomotion model of the fish cruising. Figure 5 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. Figure 5 also compares the current locomotion to the prior state. Fish body segmentation is the essential part that will lead to model the fish maneuvering and design of our robotic fish.

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Fig. 4. Fish swimming behaviors

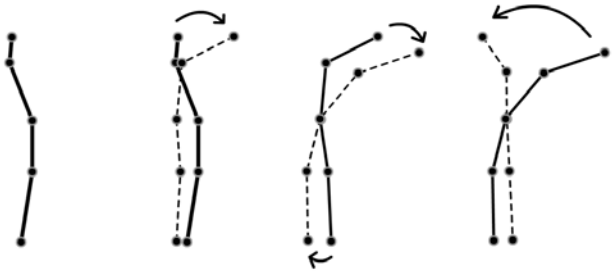

Fig. 5. "C" Shape movement model of swimming fish

B. Robotic Fish Maneuvering Model

1) Robotic Fish Body Model

According to observation of the fish's swimming behavior, we could establish the behavioral maneuver and locomotion model based on carangiform swimming mode. Fish performs the major movement at the very end of the body and tail in order to driving forwards. Fig. 6(a) shows the carangiform swimming mode of the carp fish (KOI) which could decompose into multiple joints of body modules. The greater number of the body segmented modules, the greater the propulsive swimming wave (the greater thrust force (F_T)). However, increasing of the body modules will increase the robot length as well as increase the lateral force (F_L). Thus, some researchers design their fish robot by focusing only on the body and tail peduncle [9].

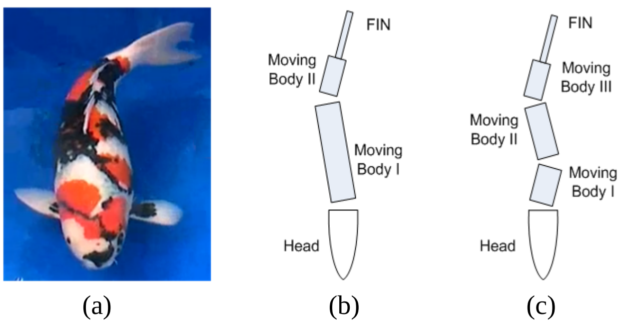

Fig. 6. Robotic fish body models

This paper analyzed the fish body into two models with five major modules: the rigid body part (head), the moving body part (rear-body), the pectoral fin, the anal fin, and the tail peduncle. The first model is composed of a moving body part, an anal fin, and a tail peduncle [Fig. 6(b)]. The second model composed of two moving body parts, an anal fin, and a tail peduncle with left and right pectoral fins [Fig. 6(c)].

2) Essential Motion Factors

Various researches have attempted to formulate mathematical models to describe the observed kinematics of fish locomotion. Many works have been hindered the variability and complexity of this natural behaviors. In this paper, we observe the fish swimming behavior and adapt the carangiform swimming mode to establish a simple mathematical model based on the "C" shape motion pattern [as describes in 2.1]. Thus, 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 oscillation 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 and the relative angle of the moving parts will contribute to the heading direction of the fish motion. The greater number of initiative and relative angle results in higher turning angle and smaller turning radian. Moreover, the number of moving joints also affects the robot motion. The robotic fish that has greater number of joints will have smoother motion pattern and smaller turning radian.

III. Implementation

Developing aquatic robot is quite different from other kind of robot because water-resistant system is required to avoid electrical short caused by underwater locomotion. Moreover, fluid environment affects on design, weight, and energy of such robot. Fundamental study for the invention includes hydrodynamic, underwater apparatus, water-resistant case, etc.

A. *Mechanical Design*

The basic study for robotic fish invention covers physical structure and natural locomotion of aquatic animals. Fish's back bone consists of small joints moving autonomously yet propelling concertedly for the same direction. Therefore, the appropriate component parts selection is taken into account for the most natural movement of the invented fish. Then, the 3D mechanical layout of the robotic fish is designed via 3D mechanical CAD program. The main components of the robotic fish are shown in Fig. 7 with following details:

1) Microcontroller : ARM7 LPC2103 with six jacks for module PWM, two set of 32-bit timer, 32KB flash ram, and multiple serial interface ports.

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2) Circuit Case : water-resistant plastic case sealed with silicone adhesive sealant
3) Battery : 2 Cells (7.4V) 6Ah Li-Po Battery
4) Servomotor Case : water-resistant servomotor case casted from superlene
5) Servomotor : servomotor with 0.14 sec/60 speed and 3.60 kg/cm torque

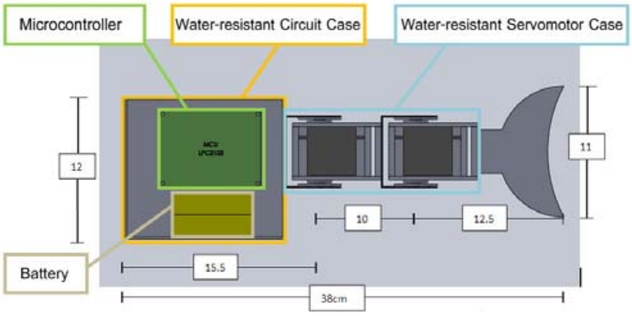

Fig. 7. Dimension and inner structure of robotic fish

B. Electrical Design

Two required electrical circuits of the robotic fish are sensor circuit and battery voltage adapter for microcontroller board and servomotor. The circuit is designed by Altium Designer 6.9

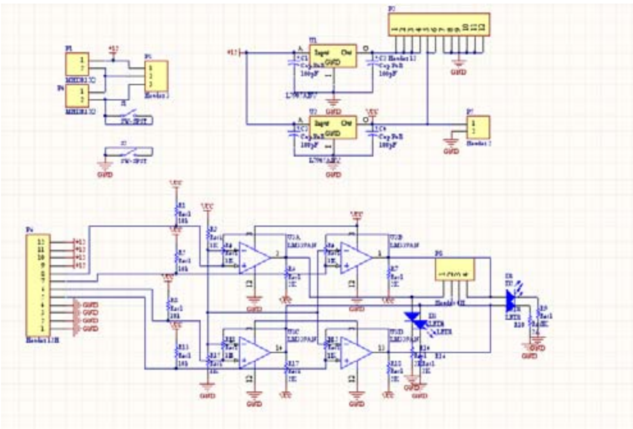

Fig. 8. Schematic circuit

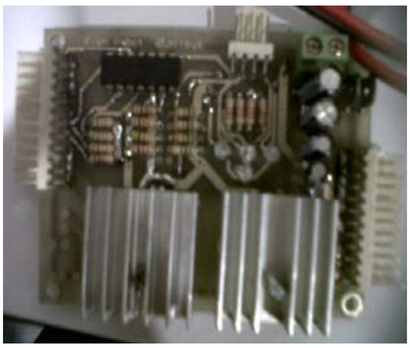

Fig. 9. Printed circuit Board (PCB) circuit

In circuit board, LT1084 CT-5 IC is used for voltage reduction from 7.4V to 5V, and LM339 IC is used for comparing voltage from sensor and adapting for microcontroller at 5V. The sensor statuses are shown through 3-mm LED. The conductive pathway on PCB needs suitable design to support heat that is converted from energy consumed. Double layer printed circuit helps with size reduction to control the overall robotic size.

C. Control Software

The variable for controlling locomotion of the robot can be tested and shown via demonstration with robotic fish simulation program (Fig. 10.), developed with Visual basic 2010. The program is combined with parameter values input section; all input parameters values can be sent to the robot via RS232 port. The embedded program in microcontroller, ARM7 LPC2103, receives signal from sensors to control the robot's locomotion. The program also gets parameter values from robotic fish simulation program to calculate with the robotic motion equation and send data to servomotors PWM function; Clock Cycle of timer 1 is organized to covert PWM signal which control servomotor position.

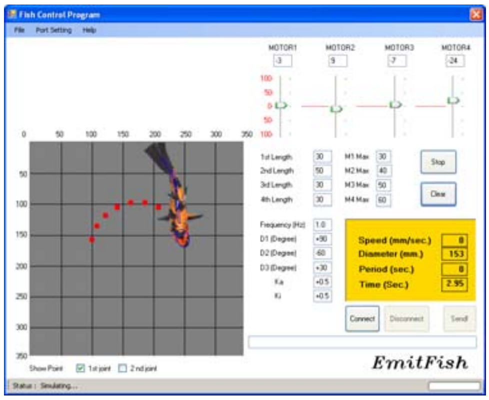

Fig. 10. Robotic fish Simulation program

IV. Experiments and Performances

A. Simulation Results

1) Velocity vs Frequency

The relation of velocity and frequency of tail peduncle oscillation configuration is shown in Fig. 11. Swimming Velocity depends on the frequency in direct relationship. In the experiments, the maximum traverse magnitude is set to be 30° and 40° for the rear body part (moving part) and the tail peduncle respectively. Then, four experiments are test by adjusting the swimming amplitude (oscillation frequency) which set to be the proportional of the maximum traverse magnitude (Ka=0.2, 0.4, 0.6, 0.8). The speed of the robotic fish is direct depends on the swimming amplitude.

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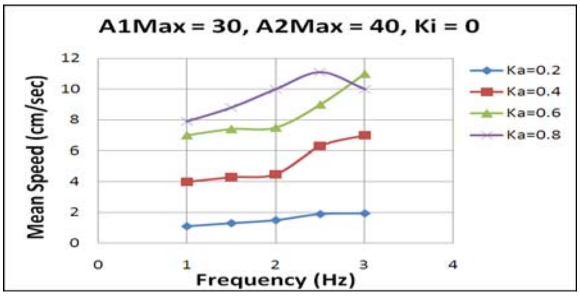

Fig. 11. Relation of velocity and frequency of tail peduncle oscillation in straight swimming fish

2) Travel Path

As shown in fig. 12 to 14 from the experimental result at different degrees: 70°, 60°, and 50° respectively, it is presented that the more the frequency (*f*) increases; the more velocity and turning radius are boosted up. This helps with turning and speed configuration of the robotic fish locomotion.

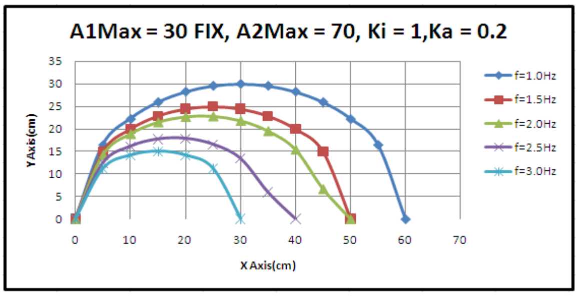

Fig. 12. Locomotion of turning-swimming in different frequency of 70° tail peduncle

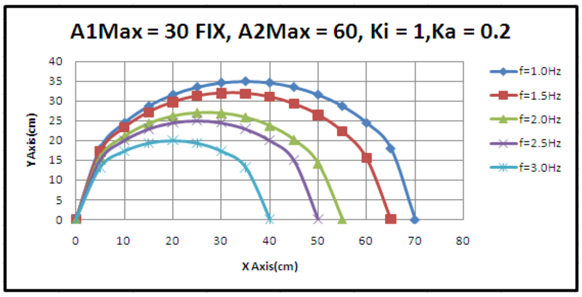

Fig. 13. Locomotion of turning-swimming in different frequency of 60° tail peduncle

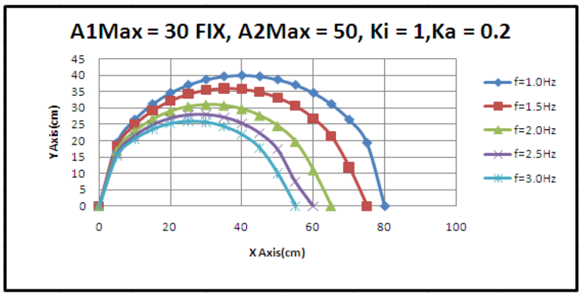

Fig. 14. Locomotion of turning-swimming in different frequency of 50° tail peduncle

B. Robotic Fish

Similarly to the Travel Path, if we rise *Ka* up, the robotic fish will swim forward with the faster speed as well as the increasing of the turning radius and turning velocity. On the other hand, the turning period will increase if the *ka* is rising, but it will decrease if the *Ka* is set to be more than 3.5 Hz. The figures 15 to 18 demonstrate swimming style with different configured *ka* and frequency.

1) Forward

Figure 15 shows forward swimming style with diverse of *f*, *ka*, and velocity change in direct relationship.

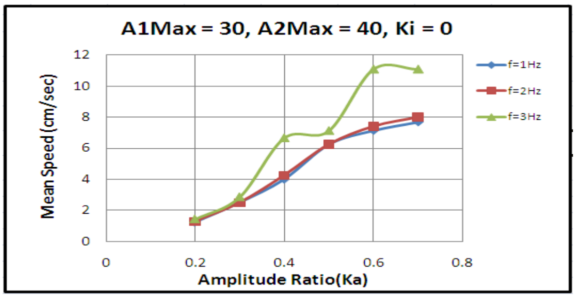

Fig. 15. Relation of velocity and Ka at different frequency

2) Turning

For turning swimming style, the figures 16, 17, and 18 show the influences of *ka* and *f* to turning-circle radius, turning velocity, and turning period respectively.

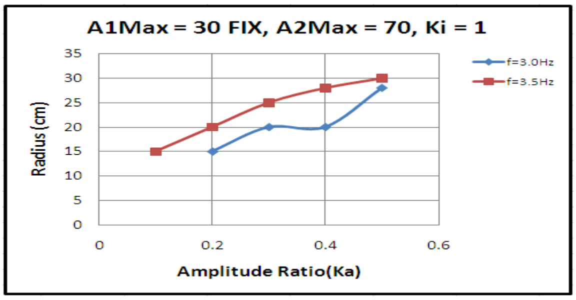

Fig. 16. Relation of turning-circle radius and Ka at different frequency

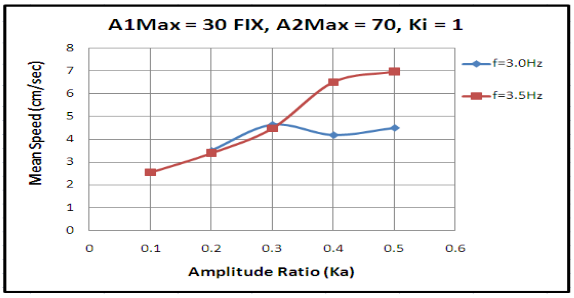

Fig. 17. Relation of turning velocity and Ka at different frequency

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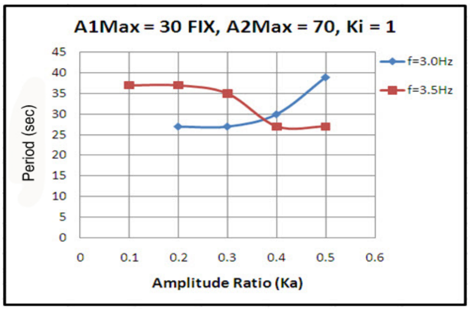

Fig. 18. Relation of turning period and Ka at different frequency Follow trajectory

3) Follow Trajectory

The trajectory configuration can be explained as following. In a curving trajectory to a target (fig.19), the *Ki* is fixed at 1, and the first-articulation servomotor is set at 30°; the other articulation is move by the locomotive equation.

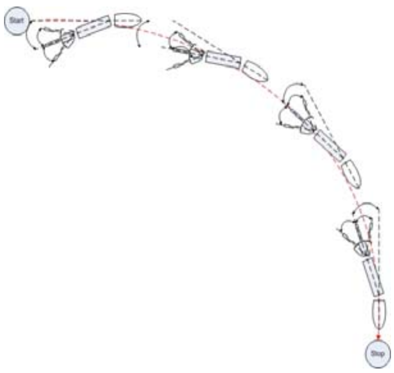

Fig. 19. Oscillation of tail peduncle for a curved trajectory

A straight trajectory (fig. 20) is simply programmed by the locomotive equation without changing any variable; each articulation will propel the robotic fish straightly to the target.

Fig. 20. Oscillation of tail peduncle for a straight trajectory

4) Obstacle Avoidance

The figure 21 shows the robotic fish's performance in obstacle avoidance. There are three patterns of swimming modes: straight, turn left, and turn right, for obstacle avoidance.

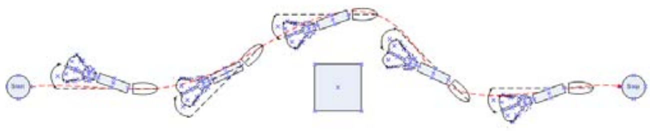

Fig. 21. Obstacle detection and avoiding path

V. CONCLUSION

We have presented a concept and prototype of designed robotic fish for imitation of aquatic animals' locomotion which aims at the apparatus of propulsion and swimming behavior among hydrodynamic of fluid environment. The swimming performances of the robotic fish are configured by the variable, and the natural-looked swimming is generated from the flexible combined joints of the robotic fish. The series of the fish swimming mode are programmed with the tail peduncle for propulsion and pectoral fin for stabilizing and maneuvering.

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