Study, Design, and Implementation of Paired Pectoral Fins Locomotion of *Labriform* Fish Applied to a Fish Robot

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Abstract

Nowadays there are so many researches addressed to develop mechanical and control system of underwater vehicles. That is all motivated by its large functionality, such as seabed oil and gas explorations, scientific deep ocean surveys, military purposes, ecological and waters environmental studies, and also for entertainments. However, the performance of underwater vehicles with screw type propellers are not prospective in it efficiency and maneuverability. The main weaknesses of this kind of propellers are the production of vortices and sudden generation of thrust forces which make the difficulties of controlling the position and motion.

Fishes and other aquatic animals are efficient swimmer, high maneuverability, have ability to follow trajectories, efficiently stabilize themselves in currents and surges, create less wakes than currently used underwater vehicle, and also noiseless propulsion. These fish locomotion mechanisms mainly controlled by its caudal fin and paired pectoral fins part. They are classified into BCF (Body and/or Caudal Fin) and MPF (Median and/or paired Pectoral Fins). The study of highly efficient swimming mechanisms of fish can inspire the better underwater vehicles design of thruster and its mechanism.

The underwater vehicles or fish robots using paired pectoral fins as thruster are rarely researched. So this research is trying to contribute in this area including study, design and implementation the locomotion mechanisms of paired pectoral fins fish. Which the three kinds of its motion types are rowing (drag based), flapping (lift based), and feathering. These types of motion are used in the locomotion mechanisms of fish robot for steady swimming, braking, turning, and hovering.

This research is investigates the study of locomotion mechanism, design, and implementation of fish robot that imitate the paired fins fish locomotion mechanisms. Its paired fins are moved by two couples of servos which were controlled by an AVR ATmega8 microcontroller. This 37.5 cm x 16.4 cm x 11 cm dimensioned fish robot is made from plastic. The results of the locomotion mechanisms performance experiments of this robot will also showed and discussed.

Keywords

Fish robot, pectoral fins, servos, rowing, flapping, and feathering

Introduction

In the period of 60s, robotics design and technology largely applied to industrial robots or manipulator robots.[13] But lately, beside manipulator robots there are kinds of robots that vastly developed such as wheeled/mobile robots, legged robots, animaloid robots (flying robots, underwater robots), and humanoid robots. These things are possible caused by the development of science and technology of mechatronics, like physical system modeling (kinematics and dynamics analysis, simulations and designs), instrumentation technology (sensors, actuators, data acquisitions, data communications, and measurement systems, etc), knowledge of signals and systems, computer technology and logics systems (microprocessors, microcomputers, microcontrollers), automation technology and advanced software (modern and advanced control theory, Artificial Intelligence, etc).[2]

In the other side, the biomimetics technology is being developed. This technology is trying to catch ideas or inspirations from nature and then developed as technology products. Fish is one of the animals can give inspiration in order to make underwater vehicles. Fish locomotion mechanisms mainly controlled by its caudal fin and paired pectoral fins part. They are classified into BCF (Body and/or Caudal Fin) and MPF (Median and/or paired Pectoral Fins). The study of highly efficient swimming mechanisms of fish can inspire the better underwater vehicles design of thruster and its mechanism. Biomimetics technology have been applied vastly in underwater vehicles and or fish robots, such as Pike and Tuna robots (MIT, USA),[6] PF200-700 and UPF2001 robots (NMRI, Japan),[6] G1-G5 and MT1 robots (Essex Univ., England),[6] Aqua robot (Mc. Gill and York Univ., USA),[6] BASS-II robot

(Japan),[4, 5] Boxfish robot (California Univ., USA),[6] etc. Artificial fins and muscles made from piezoelectric material are also being developed. [17, 19] It's also inspired by the biological system of fish.

Almost of the entire fish robot that had been developed as mentioned before is mimicking the BCF type of fish. But the underwater vehicles or fish robots using paired pectoral fins as thruster are rarely researched. So this research is trying to contribute in this area including study, design and implementation of the locomotion mechanisms of paired pectoral fins fish. There are three kinds of its motion types: rowing (drag based), flapping (lift based), and feathering. These types of motions are used in the locomotion mechanisms of fish robot for steady swimming, braking, turning, and hovering. This research is investigates the study of locomotion mechanism, design, and implementation of fish robot that imitates the paired fins fish locomotion mechanisms. Its paired fins are moved by two couples of servos which were controlled by an AVR ATmega8 microcontroller. This 37.5 cm x 16.4 cm x 11 cm dimensioned fish robot is made from plastic. The results of the locomotion mechanisms performance experiments of this robot will also showed and discussed.

The main issues that push the underwater vehicles development are efficiency and maneuverability. The currently used underwater vehicles are using screw type propellers. However it performance is not prospective in it efficiency and maneuverability.[15] And the main weaknesses of this kind of propellers are the production of vortices and sudden generation of thrust forces which make the difficulties of controlling the position and motion.[5] It is different from fishes and other aquatic animals. They are efficient swimmers with high maneuverability, have ability to follow trajectories, efficiently stabilize themselves in currents and surges, create fewer wakes than underwater vehicle currently used, and also noiseless propulsion.[9] The developments of underwater vehicles are also motivated by its large functionality, such as seabed oil and gas explorations, scientific deep ocean surveys, military purposes, ecological and waters environmental studies, entertainments, seabed archeology explorations, environmental preservation, marine resources explorations, and seabed mapping.[6, 9, 18]

However the applications of this biomimetics technology are not free from problems to be faced. The main problems are the basic differences between the biological elements (which are wet, soft, and flexible) and the products of technology (which are dry, hard, and stiff). Biological systems are very complex, can adapt appropriate to its needs and circumstances, effective, and efficient. But the robots mechanical systems consist of elements that have low flexibility, efficiency, effectiveness, and limited work circumstance. These differences will always make distance (gap) between the design (of science and technology) and the biological system. But in the same time that problems will make it more and more interesting to be researched.

Approach and Methods

I. Study of Paired Pectoral Fins Locomotion System

Review of Fish Locomotion System

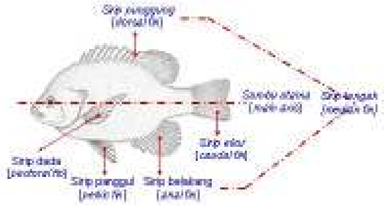


Figure 1 – Parts of fish locomotors

Fish body parts that functionality as locomotors are caudal fin, anal fin, dorsal fin, pelvic fin, and paired pectoral fins. Look at Figure 1. However there is no such a fish that use this locomotors all at once, mostly they use one of it as the main locomotors or it combination.[x] This fins functionality are based on fish type of locomotion and its circumstances.

According to the fins that used as locomotors, fishes are categorized into 2 types [15] viz.: BCF (Body and or Caudal Fin) type and MPF (Median and or Paired/Pectoral Fins) type. And according to the type of fins locomotion, fishes are categorized into undulatory type and oscillatory type. Look the diagram at Figure 2.

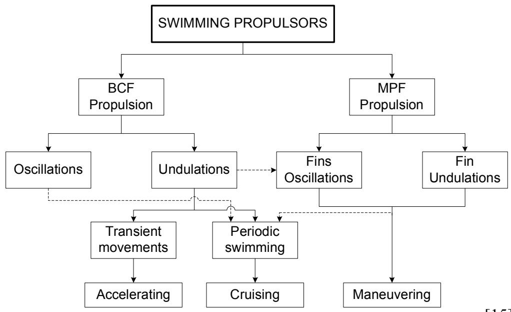


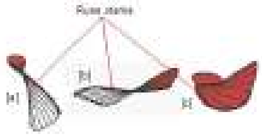
Figure 2 – Diagram of swimming propulsors [15]

In BCF type of fish locomotors, thrust forces are generated by posterior body and or caudal fin. Mostly, these types of fish locomotors are use undulatory type of fins locomotion. Undulatory locomotion is type of movement that generates wave shape on fin surface. MPF type is use median and or paired pectoral fins as thrust forces generator. This type tends to use oscillatory type of fins locomotion.[15]

Anatomy and Morphology of Pectoral Fins

Labriform fish has pectoral fins which are located at confine ventrolateral. Pectoral fin has fin base which function is to attach fin to fish body. This fin base orientation is different according to pectoral fin type of oscillating motion. Fish with drag-based type of fin motion has flat fin base orientation. But fish with lift-based type of fin motion has more incline fin base orientation. Look at Figure 3[A]. Pectoral fin structures consist of short, thin, and thick rays that are connected to a cartilage pad. It also has muscles that control the fin relative to body by change it shape. That muscles make fish can move it pectoral fins with sort of fin surface orientation. Look at (Figure 3[B]).

[A]



[B]

Figure 3 – [A] Pectoral fins base orientations [B] Pectoral fins surface orientation when [a]hovering [b]turning [c]braking [7]

Fins rays length is also determine the shape of pectoral fin. The shape of this fin has important consequences in propulsion mechanism according to the type of fin motion when swim fast or slow.[16] For fish that has much maneuver has thicker, wider, and paddle shaped fin. But fish that swim fast commonly has wing shaped, thiner, and more taper fin. This shapes of fin showed in Figure 4. There are some parameters usually used to describe fins shape: Aspect Ratio (AR), fin rays length, and fin area distribution. Aspect Ratio is a dimensionless unit and defined as fin span squared devide by projected fin area. The paddle shaped fin has AR ± 2 and wing like fin has AR ± 4.5. The higher AR, the longer main fin ray but the more narrow fin area, and vice versa. [16]

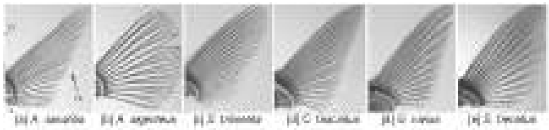


Figure 4 – Pectoral fin shapes [16]

Oscillatory Motion Mechanism of Pectoral Fin

There are 2 main oscillatory motion of pectoral fin, viz. rowing and flapping. Both of them grouped into 2 type of motion: drag-based and lift-based. Rowing mode of motion is a drag-based type of motion that generates thrust forces using anterior and posterior motions of fin. Flapping mode of motion is a lift-based type of motion that generates thrust forces by it up and down motions of fin. [15] These kinds of pectoral fin oscillatory motions are illustrated in Figure 6.

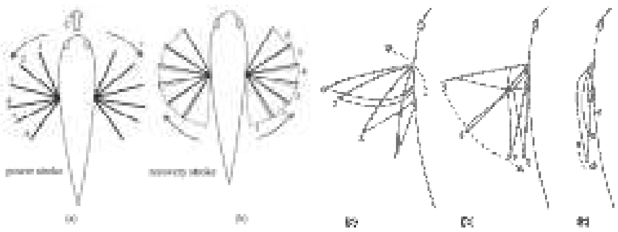


Figure 5 – Top viewed of rowing type of pectoral fins: [a] power stroke phase [b] recovery stroke phase [15]

As showed in Figure 5, rowing motion of pectoral fin consists of 2 phases: power stroke phase and recovery stroke phase. Thrust forces generated when it is the power stroke phase. In that moment, fin displaces amount of mass to backward so it generates a forward force as an acceleration reaction. The thrust forces in fish body with rowing motion are not continues.

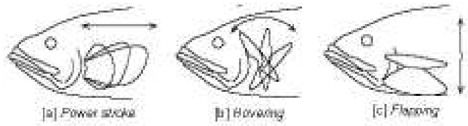


Figure 6 – Types of pectoral fin motion [15]

On lift-based model, oscillating motion done by flapping the fin up and down in an area almost perpendicular to the main axis of the fish body laterally (Figure 6). This flapping motion consists of 3 phase, viz. abduction phase, adduction phase, refractory phase as illustrated in Figure 5. In every phase it generates lifting force which also generates forward thrust force in the same time.

Maneuver Locomotion Mechanisms of *Labriform* Fish

a. Steady Swimming and Braking

When steady swimming, the swimming fish is generating the resultant of thrust force by the oscillating fin motion in front direction. The oscillatory motion of fin that is used can be the drag-based model, lift-based model, although the combination of both model. Figure 7 is an illustration of this steady swimming. The 1^{st} – 2^{nd} sequence are recovery stroke phase, 3^{rd} – 6^{th} sequence are power stroke phase, 7^{th} sequence is a brief phase before the recovery stroke phase come to begin again.

The illustration of flapping stroke model of fish showed in Figure 8. The 1^{st} – 3^{rd} sequence are abduction phase, 3^{rd} – 5^{th} sequence are adduction phase. Refraction phase occurred after and before the adduction phase and abduction phase.

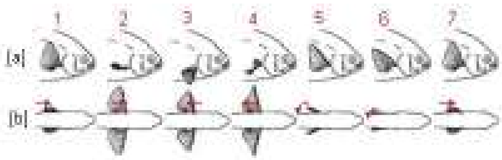


Figure 7 – Rowing stroke mode of pectoral fins when steady swimming: [a] laterally [b]dorsally viewed [10]

Braking is a motion that is used when decelerating steady swimming although when changing to another maneuver motion. The surface fin orientation is changed when braking as shown in Figure 3[2c]

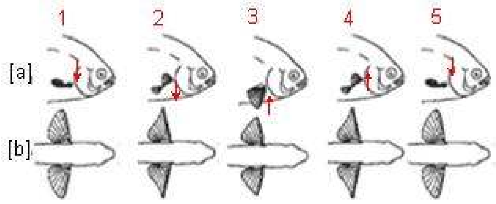


Figure 8 - *Flapping stroke motion of pectoral fin when steady swimming: [a]laterally [b]dorsal viewed* [10]

b. Turning

It is different from motion when steady swimming where paired pectoral fins doing the same motion in the same time. This turning motion generates different thrust force in the 2 side of its body. To generate more thrust force, it move larger angle of the angle trajectory of fins. Fish will turn to left when larger thrust force generated in the right side of the fish body, and vise versa.

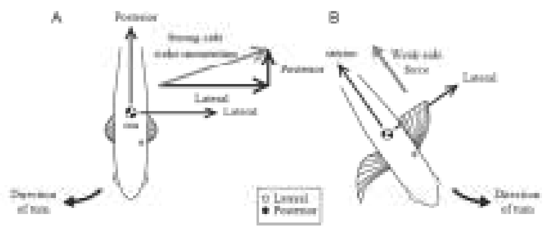


Figure 9 – Turning and avoiding obstacles motion [8]

This turning motion shown in Figure 9. When fish want to turn to left, the right pectoral fins moved with larger angle and higher power. This thrust force direction is to backward (posterior). The surface orientation of fin is changed (look at Figure 3[B-b]) so thrust force will generated in the left side. The resultant of this 2 forces (to the posterior and anterior direction) will determine the turning angle of fish. While the right fin is used to directs the turning angle and stabilizes fish position when turning. So as vise versa. This turning motion is also used to avoid obstacles or predators.

c. Hovering

Fishes are also doing hovering motion to hover in a certain position in water, when rest or not in swimming condition. During hovering, fins are twisted and alternated left and right so this movements result in one fin generating positive thrust while the opposite fin generates negative thrust. The fin surface orientation when hovering showed in Figure 3[B-a].

II. Design of Fish Robot

Mechanics of Robot

The mechanical design of fish robot body is shown in Figure 10. This robot body is 37.5 cm x 16.4 cm x 11 cm dimensioned, shaped like box, has ~4,736.49 cm^2 surface area, and has volume ~5,887.63 cm^3 (designed and calculated using SolidWorks® 2005). The head will be of conical design, which will allow reduced drag. The tail will have an elongate conical configuration tapering to reduce drag.

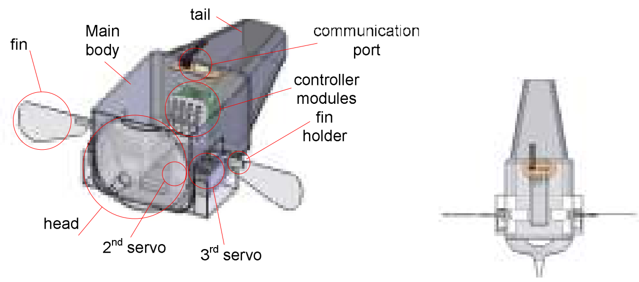


Figure 10 – Mechanical design of fish robot: isometric and top viewed

To obtain types of pectoral fins motion like rowing, flapping, and feathering (hovering), it is use 2 couples of servos which are a couple in each side of its body. The configuration of these servos set used in this robot is shown in Figure 11.

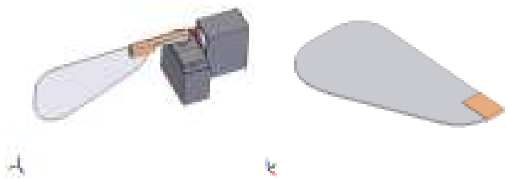


Figure 11 – Design of actuator and fin

Two servos are combined, become an actuator which move one fin (right side or left side). One is functioned to generate the basic motion which is flapping, and one is functioned to regulate the angle of fin surface orientation. This actuator motions is illustrated in Figure 12. The flapping motion that moved by the 2nd servo (M2) is occur on plane J with angle span α $(-90^0<\alpha<+90^0)$. And the 1st servo (M1) motion occur on plane I with angle span θ $(-46^0<\theta<+90^0)$. Angle $\theta= 0^0$ is on +Z axis while angle $\theta= -46^0$ and $\theta_1= +90^0$ are on +X axis and –X axis. The angle $\alpha= 0^0$ is on the plane that determined by trajectory of the 2nd shaft (L2) of servo (the plane is a half-cylinder cover like).

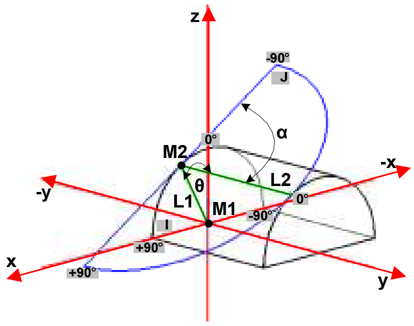


Figure 12 – Model of actuator locomotion

Fin is the actuator part that functioned as shaft of the 2nd servo (L2). And this fin motion will determine whole motion of the fish robot body. The fin is paddle shaped fin as shown in Figure 11. It has ~70.6 cm^2 surface area, ~9 cm fin length span, and Aspect Ratio (AR) ~1.2 (designed and calculated using SolidWorks® 2005).

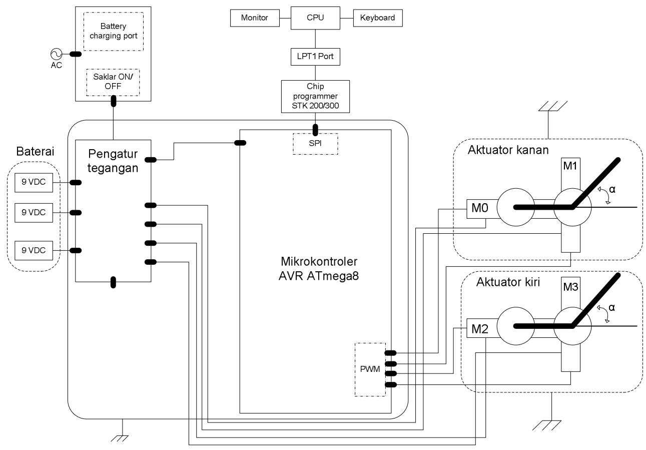


Figure 13 Control system block diagram

III. Implementation of Fish Robot

Implementation

A fish robot prototype has been made according to the study of MPF type fish and the mechanical design, shown on Figure 14.

Figure 14 Fish robot prototype

Figure below is a configuration of 2 servos that used as actuator in this fish robot. This actuator attached inside on the fish robot body. While the right side figure is pectoral fins prototype. It is consist of 2 parts, viz.: fin base (made of wood) and the fin itself (made of plastic).

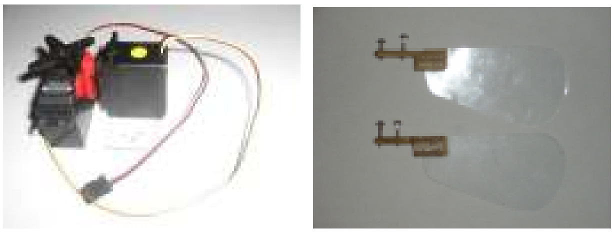


Figure 15 Pectoral fin actuator and pectoral fins prototype

With this configuration of pectoral fin actuator, it can accommodate the rowing, flapping, and feathering type of natural pectoral fin locomotion. The 3D model kinematics of this actuator is shown on figure below.

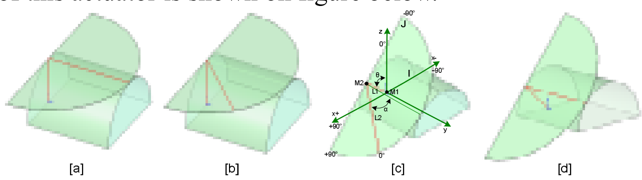


Figure 18 The 3D model kinematics of pectoral fin actuator

IV. Experimentation (Swimming Tests)

The swimming tests of the fish robot were conducted in a 3 m diameter of circular-pool and a water level of 20 cm. The experiments were performed to examine how the paired pectoral fins locomotion systems affect the swimming performance of the fish robot.

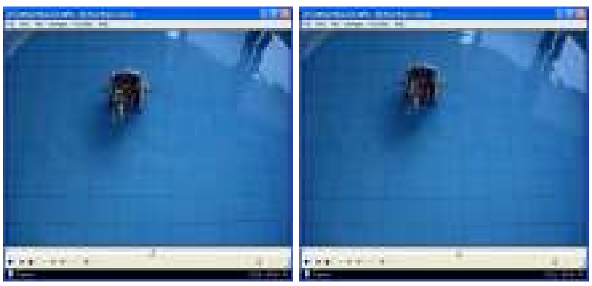


Figure 17 Fish robot swam using rowing stroke type of pectoral fin motion

Results

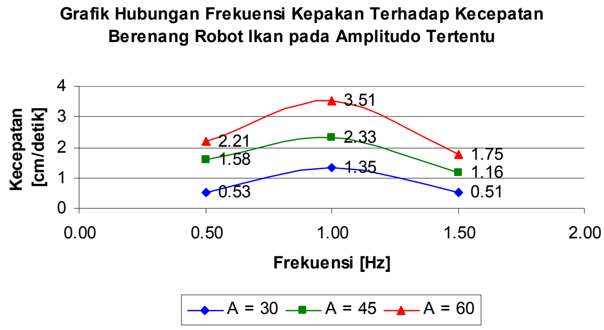


Figure 19 Relational graphics of flapping frequency and swimming speed on some flapping amplitudes

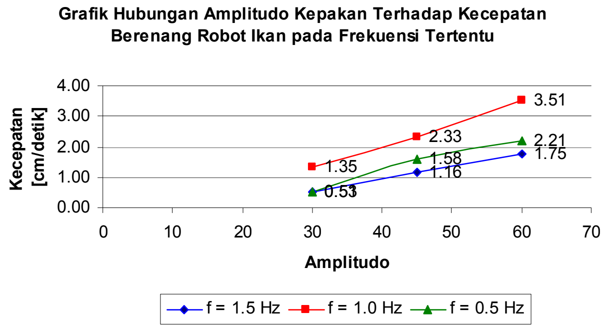


Figure 20 Relational graphics of flapping amplitude and swimming speed on some flapping frequencies

Discussion

Conclusion

Acknowledgements

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