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Brief Development of Underwater Autonomous Biomimetic Fish

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Abstract: Underwater autonomous device with capability of locomotion in liquid environment has become a popular area of interest as technology closes in the gap to match with reality. However, the nature in liquid environment is complex and it is current need to overcome maneuverability, mechanism robustness, speed, operation duration and control system that still pose a major challenge. Current trend of study are experimenting on aquatic animal inspired concept to mimic the mother nature of fish swimming to provide better option for a far more dynamic and efficient technique for underwater applications. This has motivated a brief review on the fish morphology and swimming mode, the underwater biomimetic fish modelling and simulation and finally the control system development so far.

Key words: Biomimetic design, robotic fish, underwater autonomous device, swimming mechanism, control system

INTRODUCTION

Applications in underwater environment covers major areas such as ocean exploration, search and rescue mission, pipelines and sea mining operation which can be effectively executed with the employment of devices capable of underwater locomotion. In many cases, the missions in the underwater environment are dangerous or complex and inaccessible by humans. Therefore, such operation could be intelligently accomplished by autonomous or remotely operated vehicle or devices.

Research on autonomous underwater devices leads back to 1960 and since then, some thirteen of such devices were successfully developed by the 1991 (Blidberg *et al*., 1991). However, studies showed that underwater autonomous device's moving ability tend to focus on traditional technique using propellers to generate the thrust for locomotion (Nguyen *et al*., 2013a). Furthermore, small propellers driving devices had mechanism deficiency limitations underwater (Mohammadshahi *et al*., 2008). Applications in underwater environment require devices that can combine both high cruising speed and good maneuverability and propeller driven type had shown the limitation to combine both of the abilities (Barrett *et al*., 1999).

However, in the area of underwater biomimetic locomotion, especially fish-like propulsion, it is possible to provide a mechanical mobile platform to achieve the response of high cruising speed and good maneuverability. The fish swimming techniques of propulsion holds the very key for improving the propulsion performance (Triantafyllou and Triantafyllou, 1995). Among various underwater biomimetic locomotion creatures, fish appears to combine the agility in a single embodiment. Therefore, by implementing such natural fish swimming ability to the device would be an ideal method. In mother nature, however, most creatures possesses complex biological system not as limited by the stiff mechanism and standard discrete implementation in the men made devices (Anderson *et al*., 1998; Barrett *et al*., 1999; Yu *et al*., 2004).

MORPHOLOGY AND SWIMMING MODES OF AQUATIC ANIMAL

Natural life of aquatic creature had inspired researchers to study in particular the fishes as model for designing fish-like devices. Therefore, it is crucial to understand and characterise the fish locomotion in liquid environment which conceal the constraint required for designing the devices. Fish morphological features are a critical identification for the first purpose of the locomotion to match the engineering needs. Figure 1 illustrates the basic fish morphological features.

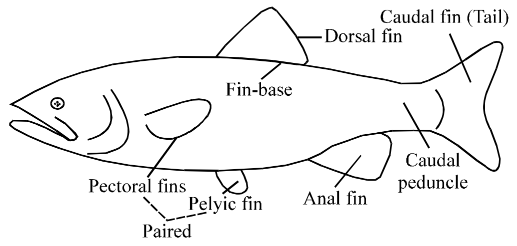

Fig. 1: Fish morphology (Sfakiotakis *et al*., 1999)

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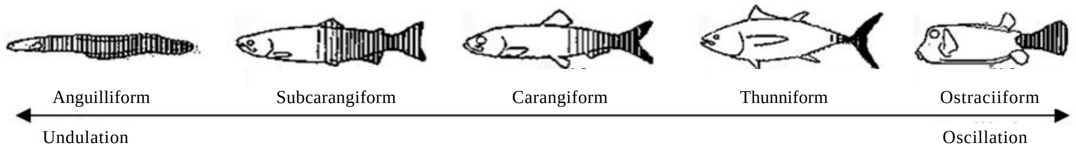

Fig. 2: Fish locomotion associated with BCF propulsion (Lindsey, 1978)

Gray (1933) investigated the fish locomotion by capturing series of photographs to record the form and position of the fish swimming motion at a known interval of time and found that the lateral wave of a fish body travels from head to tail. According to Wang *et al.* (2008), fish generated trust using their bodies to push the water away to behind and moving forward. This being by momentum transferred from the fish's body to the surrounding water (Wang *et al.*, 2008). Nguyen *et al.* (2013b) had also discovered that real fish actually changes its body shape for movement, whenever the fish body shape changes it creates propulsion force for the fish to move forward or backward.

Different types of fishes had been found to utilize different modalities for swimming. Sfakiotakis provided a review of fish locomotion underwater by classifying fish locomotion techniques into five modes for the fish using their body and/or caudal fin (BCF) locomotion to swim as illustrated in the Fig. 2 (Lindsey, 1978; Sfakiotakis *et al.*, 1999; Nguyen *et al.*, 2013a).

MECHANISMS OF FISH SWIMMING MODALITIES

In undulatory BCF locomotion, there are four modes of fish swimming techniques based on the length of fish tail fin and the oscillation strength. The anguilliform swimming (Fig. 3a) applies to fish with long and slender body like eel and lamprey. These types of fish generates propulsion using their body muscle wave from head to tail which produces a little increase in amplitude of the flexion wave as it pass along the body. The entire fish body shape can bend at least one half of sine wave and when swimming, the amplitude of the tail section being larger as compared to the head section. Also, anguilliform swimmer has ability to swim backward (Fig. 3b) which required the wave to be passed from tail to head (Gray, 1933).

Fishes swam, by implementing subcarangiform swimming mode (Fig. 4) is able to increase in wave amplitude by using the rear half of its body to generate the propulsion. Fishes such as whiting, trout and salmon utilizes this type of swimming mode to swim which have stiffer body to allow swimming at higher speed with reduced maneuverability.

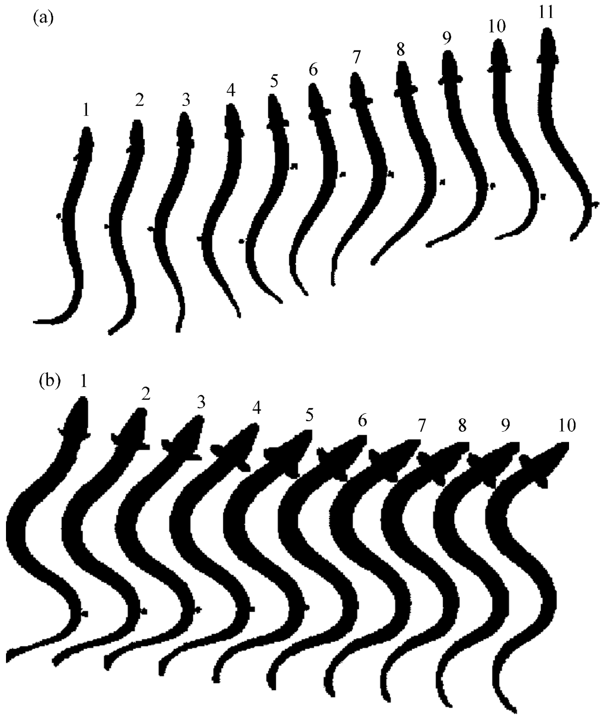

Fig. 3(a-b): (a) Forward swim of a butterfish and (b) Backward swim of eel (Gray, 1933)

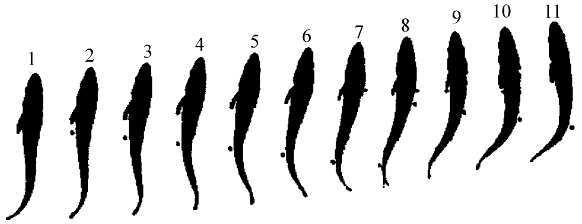

Fig. 4: Forward swim of a whiting fish (Gray, 1933)

In fishes, swim by using carangiform swimming mode, also have stiffer body and can swim faster if compared to the anguilliform and subcarangiform swimming modes as shown in the Fig. 5. The reason being the majority of the fish movement is concentrated on the rear body and tail. Therefore, this type of swimmer generally produced rapidly oscillating tail motion. Fishes like carp and swordfish are some that utilizes this type of swimming mode.

Swimmers like mackerel, tuna and shark are high-speed and long distance swimmer. This type of fishes categorized as the thunniform swimming mode, (Fig. 6), has movement mostly concentrates at the tail and so, has large and crescent shape tail.

Finally, the fishes that swim by implementing the ostraciiform swimming mode (Fig. 7), is the only classification in oscillatory BCF locomotion. The fishes utilizing this type of mode are such as boxfish and cowfish which have to rapidly oscillate their caudal fin for movement while the body remains essentially rigid. Although, this type of fish is known as slow swimmer but a study showed that this fish is featured with high level of dynamic stability and high endurance (Kodati and Deng, 2006).

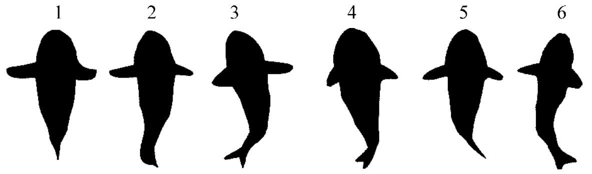

Fig. 5: Forward swim of a carp fish (Nilas *et al*., 2011)

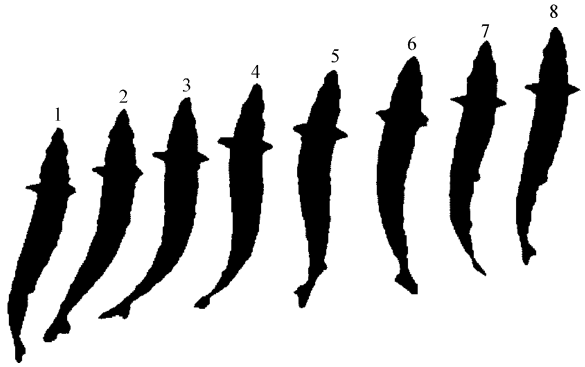

Fig. 6: Forward swim of mackerel fish (Gray, 1933)

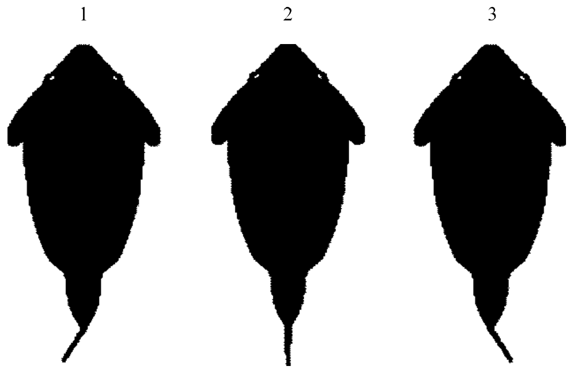

Fig. 7: Forward swim of boxfish

MODELLING AND SIMULATION

Studies on fish swimming dynamics provided an understanding for developing biomimetic robotic fish modeling and analyzing as a mathematical system. The theoretical fish locomotion can be divided into two parts, first the kinematics which treats only the geometric aspect of the motion and secondly the kinetics which is the analysis of forces causing the motion behaviour (Meriam and Kraige, 2012).

Lighthill (1960) utilizes the trajectory approximation method and proposed the elongated body theory for carangiform kinematic model. This model has been widely used in biomimetic devices by the research community (Alvarado, 2007; Barrett *et al*., 1999, 1996; Barrett, 1996; Cho, 1997; Liu and Hu, 2010; Shao *et al*., 2008; Alvarado and Youcef-Toumi, 2006; Yan *et al*., 2008; Yu *et al*., 2004; Yu and Wang, 2005). Figure 8 demonstrates the top view of the fish swimming kinematics in two dimensions.

This mathematical model of the fish swimming kinematics could be expressed as:

$$h(x, t) = (c_1x+c_2x^2)\sin(kx+\omega t) \qquad (1)$$

where, h(x, t) is the lateral displacement of the fish tail from the undulation central along x-axis direction of the tail length at time t, c_1 is the linear wave amplitude envelope and chosen to be independent c_2 is the quadratic wave amplitude envelope for doubling the amplitude of motion, both of the parameters are adjustable parameters. Respectively, k is the tail wave number which is equals to $2\pi/\lambda$, where λ is the wavelength and ω is the body wave frequency equals to $2\pi/\lambda$. Figure 9 is an illustration of fish propulsion wave base on the Eq. 1 and according to Barrett *et al*. (1996), sinusoidal propulsion wave travels from the right to left.

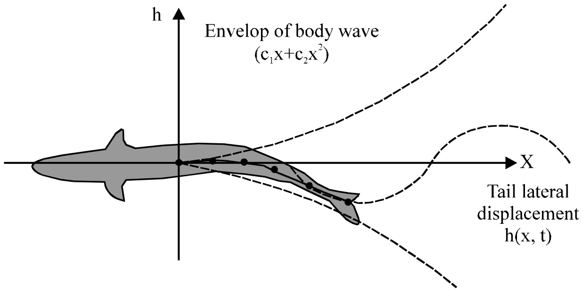

Fig. 8: Top view of fish swimming kinematic

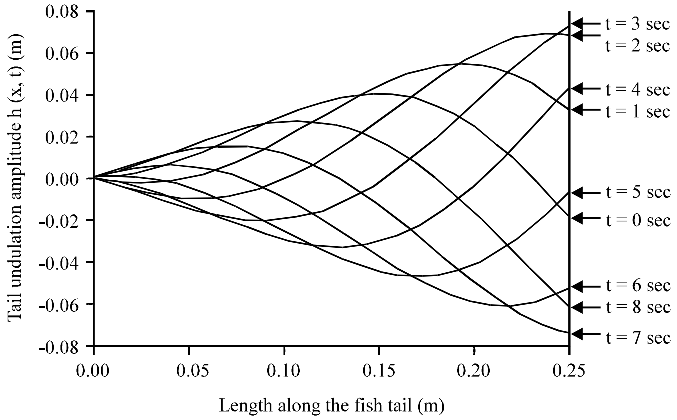

Fig. 9: Fish swimming motion generated by MATLAB software

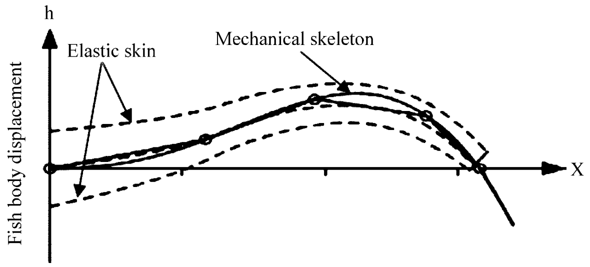

Fig. 10: Mechanical skeleton of multi-joint biomimetic devices (Yu and Wang, 2005)

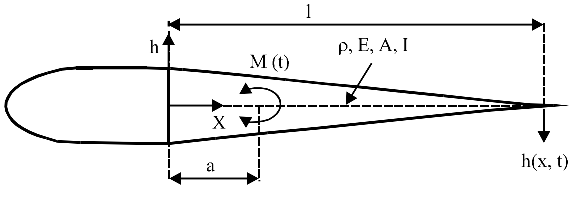

Fig. 11: Continuous flexible tail model

In general, researches on multi-joint biomimetic device utilized Eq. 1 for modeling mimetic fish-like behavior in the swimming motion. Liu and Hu (2010) had designed multi-joint carangiform swimming mode by converting Eq. 1 into a tail motion function which describes the tail motion relative to the head and discretized into a series of tail posture over time. Yu and Wang (2005) numerically calculated optimal link-length-ratio using improved constrained cyclic variable method to apply in the development of a 4-linked biomimetic device is as illustrated in the Fig. 10. Yan *et al.* (2008) had also developed a 4 Degree of Freedom (DOF) carangiform biomimetic device and experimentally investigated the influence of characteristic parameters including the frequency, amplitude, wavelength, phase difference and coefficient of forward velocity.

Another method by Beam Theory utilizes the tail section of the biomimetic device to modelled fish motion as a dynamic bending beam underwater (Timoshenko, 1974). The governing equation of the model (Fig. 11), is derived using this theory to yield as following in Eq. 2:

$$\rho A(x)\frac{\partial^2 h(x,t)}{\partial t^2}+\frac{\partial^2}{\partial x^2}\left[E(x)I(x)\frac{\partial^2 h(x,t)}{\partial x^2}\right]=f(x,t)+L_y(x,t) \tag{2}$$

where, ρ is the material density of robotic fish tail and E is the Young's modulus of elasticity which are constants. The cross-section area A(x) and the inertia moment I(x) of cross-section area of tail are a function of x. Combined E(x)I(x) term then yields the beam bending stiffness. The M(t) being time varying moment applied at distance a. The distributed forces f(x, t) is used to generalize the possible actuation input forces. The $L_y(x, t)$ term then relates the resistive interaction occurred due to interaction with the fluid environment.

A continuous flexible tail instead of multi-joint rigid bar had also been studied (Daou *et al.*, 2011; Alvarado and Youcef-Toumi, 2003, 2006). The continuous flexible tail mechanism is simple, mechanically robust, better performance, simple control technique, easy to seal and protect sensitive parts (Yang *et al.*, 2011). Similarly, Alvarado and Youcef-Toumi (2006) developed a compliant body biomimetic fish (Fig. 11), by using one servo-motor for propulsion. They utilize the Eq. 2 to achieve the lateral motion of tail by determining the vibrations of the beam from the effect of internal and external forces which are related to the material, geometry and actuator properties.

As well as, Nguyen *et al*. (2013a) analyzed reactive forces and resistive forces in order to derive Eq. 2 model for non-uniform flexible tail of robotic fish. However, they discovered that the coefficients of this equation were not constant due to the non-uniform beams but the analytical solution was used to describe the lateral movement of the flexible tail and to obtain the material, geometry and actuator properties.

CONTROL SYSTEM FOR UNDERWATER BIOMIMETIC DEVICE

The history of underwater biomimetic robotics dated back to the RoboTuna. To understand the BCF swimmer, Barrett (1994) built the RoboTuna replica to the real tuna fish (Fig. 12). It was designed to mimic actual tuna kinematics as close as possible using the reverse engineering. Movement of the tail was controlled by seven vertebrae backbone connected by six joints. Each joint is actuated by cables and driven by six large Digiplan BL34ML5B-10 brushless servo motors design by Parker Hannifin. These servo motor was hosted and supervise by the control command of 486-computer at top-level while at mid-level a 6-axis Digital Signal Processor (DSP) card design by Motion Engineering Inc (MEI) synchronize with the host for control and receive feedback. Each servo motor is attached with optical encoder STC/26, connected to a matching Parker Hannifin BL75 brushless servo amplifier driver to actuation the system. Figure 13 is a simplify body motion control hardware of RoboTuna, consisting of computer host synchronize with the DSP for control and receive feedback of servo motor. For waterproofing, the entire body was covered by Lycra sock. Numerous sensors were also connected to five computers to measure the drag force, torque and pressure for monitoring the control and to record the parameters (Barrett, 1996).

After RoboTuna, Draper Laboratories developed the Vorticity Controlled Unmanned Underwater Vehicle (VCUUV). Major subsystem of the VCUUV included

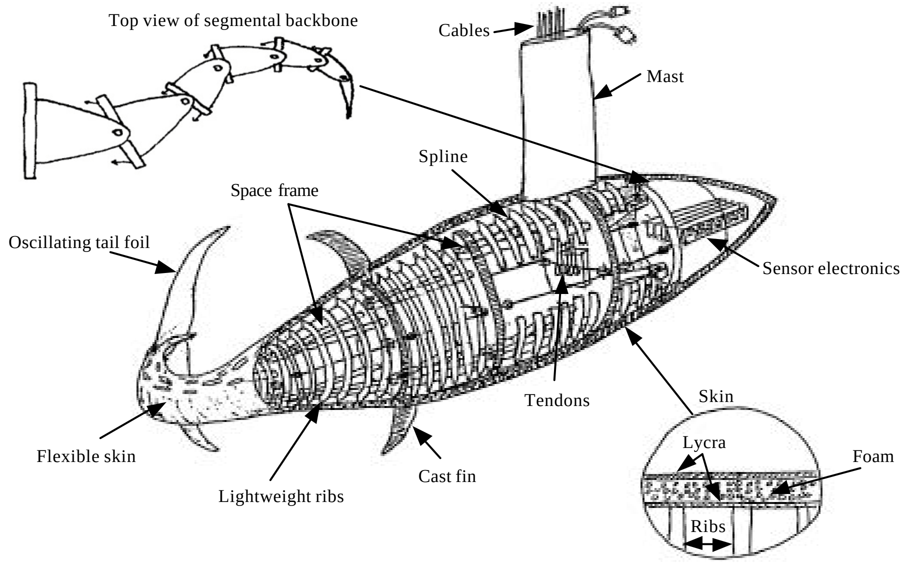

Fig. 12: Internal structure and control system of RoboTuna (Barrett, 1994)

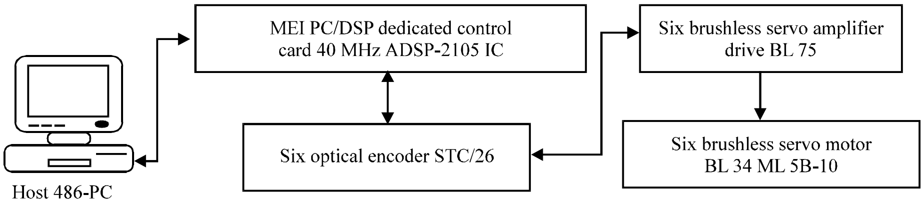

Fig. 13: Simplified body motion control hardware of RoboTuna

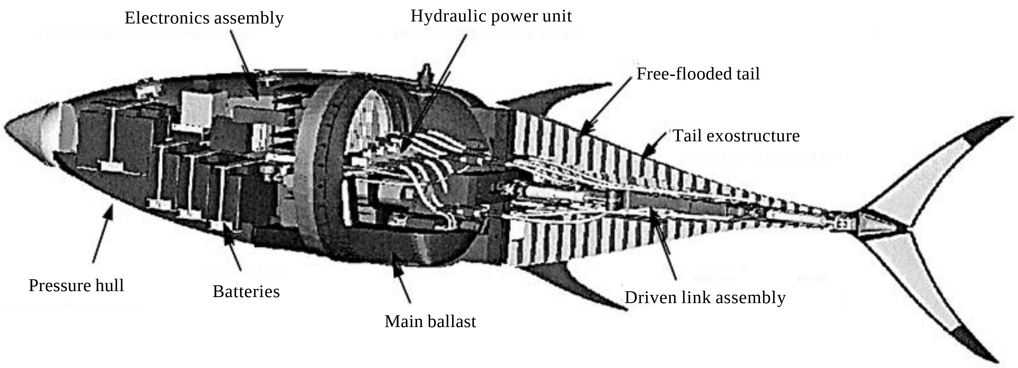

Fig. 14: Vorticity Controlled Unmanned Underwater Vehicle (VCUUV) system layout (Anderson and Chhabra, 2002)

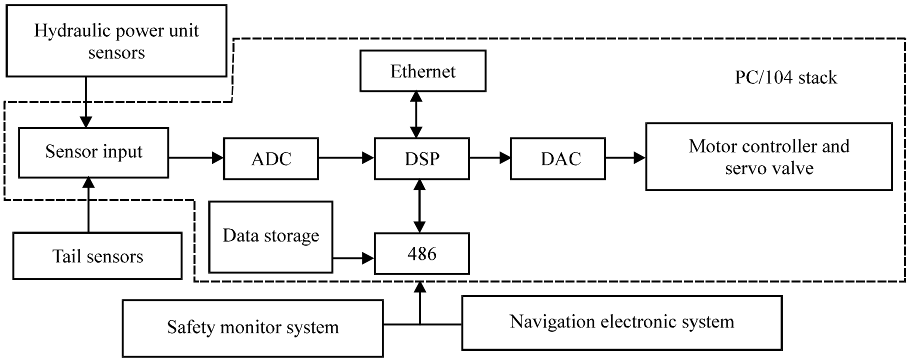

Fig. 15: PC/104 Stack of Vorticity Controlled Unmanned Underwater Vehicle (VCUUV)

internal components, pressure hull, tail-drive system and tail surface (Fig. 14). The VCUUV tail movement, supported by five vertebrae backbone with four joints, is controlled by a closed loop hydraulic system (Cho, 1997). Surrounding of tail link is coated by epoxy polyvinyl chloride (PVC) foam disks to provide buoyancy and flexibility. Like RoboTuna, the VCUUV flexible body was cover by Lycra bonded with neoprene rubber for waterproofing.

The front section of VCUUV body contains the electronics and hydraulic system and the back tail section contains the actuation mechanism. The hydraulic system consists of a reservoir, a small positive displacement pump, a pressure accumulation vessel, four servo vales and four cylinders. Actuation mechanism of three aluminium links with tail fin is driven by hydraulic cylinder. To control the actuation, PC/104 stack (Fig. 15), read and process pressure sensor feedbacks from each cylinder and sends command to the hydraulic system to the tail. In PC/104, the 486-computer functions to coordinate the actuation operation and log the data and an ethernet module for reprogram and communicate with 486. The DSP synchronize and receive command from 486 for control of the actuation. DSP read and filter the analog signal from the actuation system sensor then convert signals to digital signal sent commands to the hydraulic power unit and servo valves for moving the cylinders and actuate the tail.

Another MIT RoboPike robotic swimmer had a tail movement supported by four vertebrae backbone and three joints controlled by cables driven by high torque airplane servo motor model 9303 manufacture by Futaba, (Kumph, 2000). The skin of RoboPike is made from compliant silicone rubber to seal and protect the internal component (Fig. 16). The actuator control system, consisting of Motorola 68332 computer base on Tattletale Model 8 design by Onset Computer Inc. RoboPike do not have sensor feedback like RoboTuna and VCUUV. Therefore, the Motorola 68332 receives command from the computer host to actuate the servo motors for the tail at 70 Hz in sine wave and control of pectoral fin (Fig. 17), to move each of the pulley joint in sinusoidal swimming motion. The RoboPike was able to swim at a maximum speed of 0.3 L sec^{-1} at 1 Hz of tail beat frequency.

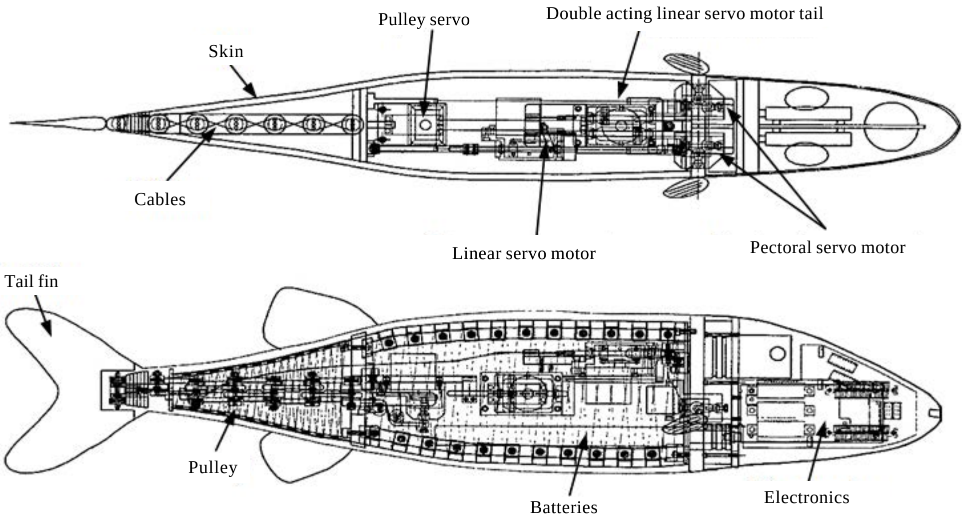

Fig. 16: Layout of RoboPike (Kumph, 2000)

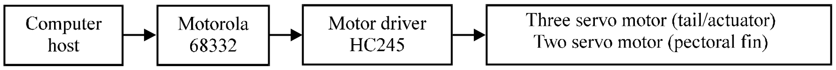

Fig. 17: RoboPike actuator control flow

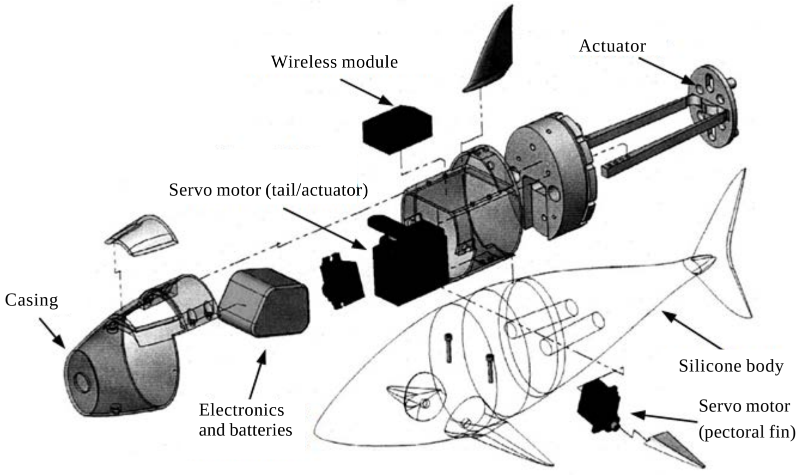

Fig. 18: Design of a complaint body biomimetic robotic fish (Alvarado, 2007)

A small complaint body biomimetic fish for swarm operation was also invented (Alvarado, 2007). Base on shark geometry (Fig. 18), one high torque HSR5995TG Hitech motor was used to actuate the tail and two small Futaba servo motor to individually control the pectoral fins. The body was made from moulded silicon with embedded servo motor for driving the tail mechanism. The servo motor oscillation produces a travelling wave for the fish body locomotion. In control (Fig. 19), it consists of a Plugapod DSP56F803 microcontroller from NewMicros or Futaba transmitter radio controller. The computer host sent command signal to Plugapod microcontroller by Radio Frequency (RF) form using ZeeBee Pro RF module as servo motor controller. However, the Futaba radio transmitter was modify to transmit sinusoidal or triangular wave form for servo motor control in desired frequency

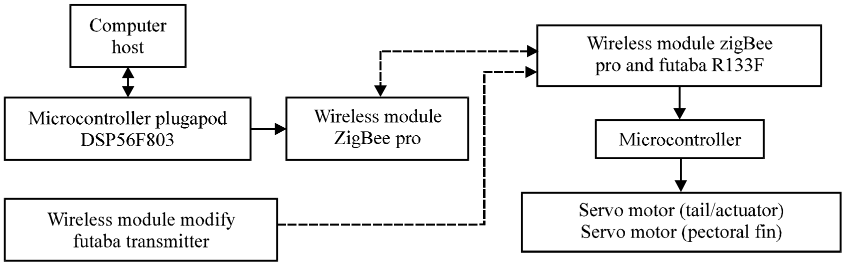

Fig. 19: Control flow of Alvarado robotic fish

tail beat. Alvarado had also designed various compliant body prototypes in his study and one of the prototypes could reach speed of 1 L sec^{-1} at 3.5 Hz of tail beat frequency.

CONCLUSION

The review of underwater biomimetic devices development found that the limitation to performance as compared to nature still lacks in the suitability of materials, mechanisms and control. Evolution of biological animal is far more advance and complex in functionality. In the man-made design of biomimetic devices, it still faces the constraint of using effective muscle and bone for actuation and to produce the necessary power and strength for locomotion and maneuverability. Technological self-actuating materials could be developed for such application to outperform biological muscles and bones for a better and more natural control system instead of electro-mechanical system.

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