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Design and 3D Simulation of a Robotic Fish

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***Abstract*— Fish-like swimming could have considerable amount of energy savings while it is used for small autonomous underwater vehicle. But, analysis of fish motion dynamics in the water, demands great attention. Here, in this work, we analyze fish motion dynamics in the water and design a robotic fish which is capable of navigating in three dimensional space with the use of pectoral fins. The robotic fish movement in a three dimensional space is simulated in MATLAB and Autodesk 3Ds Max. The skeleton of the fish which consists of 3-joint mechanical tail (rear part) and two pectoral fins, are designed and fabricated. The joints are actuated by servo motors. Experiment shows that the mechanical tail is capable of generating near sinusoidal wave through its body. The control signals for the servo motors are generated by an onboard Atmega-128 micro controller.**

I. INTRODUCTION

Nature is the source of inspiration for many researchers as it provides the simple solutions of many designs which are results of years of evolution. The Fish is one of such inspiration because of its ability of swimming with high efficiency and maneuverability. The propulsion method of fish is much more efficient than that of conventional rotary propellers which disturb the water it passes through.

Since last two decades, researchers have been working to understand and mimic fish motion in robots. In 1994 first robotic fish Robotuna was developed at MIT [6], where they tried to mimic the Tuna fish. Subsequently Robopike was developed with waterproof hull [10]. It was 32 inches of fork length. The pike was chosen because of its excellent accelerating and turning abilities. Spiral spring was used to form the exoskeleton of the fish. A supervisory controller was developed to control the fish motion. Human intervention was needed to navigate it. Mitshubishi heavy industries developed the robotic fish Coelacanth [14]. While these fishes were comparatively big in size, micro robotic fish was also developed by Nagoya University using ICPF Actuators[8]. Tokai University designed a robot Blackbass[9] in order to research the propulsion characteristics of pectoral fins. The National Maritime Research Institute in Japan developed several kinds of robotic fish prototypes[11]. Essex University has also developed nice fish-robot [1]. Jessico, one of the smallest fishes (20cm,100g) was developed in france[12]. Highly manoeuvrable Manta Ray was developed by Evologics which has buoyancy variation system and hydrojet propulsive mechanism.

Earlier, the work was done to mimic the mechanics of the fish. Later on, the focus was on autonomous control, navigation and realistic design.

The rest of the paper is organised as follows. Section II explains the mathematical modelling of the robotic fish. Section III and IV describes the design and simulation using the fish model . Further there is a brief description about the mechanical tail in section V. Finally the paper ends with the conclusion.

II. MATHEMATICAL MODELS OF THE ROBOTIC FISH

Here we study the mathematical model of the robotic fish dividing it in three section. Then we analyze up and down motion of the robotic fish using these models. These models are namely joint kinematics model, hydrodynamics model and a kinematics model .

A. Joint Kinematics Model

The robotic fish uses carangiform motion for its propulsion in which the front part which is head, doesn't contribute to the forward motion and the entire movement is concentrated at the rear part of the body. Carangiform swimmers generally have rapidly oscillating tail which produces high speed propulsion. This carangiform motion can be analyzed by a travelling wave [1] which starts from middle of the body with low amplitude and as it propagates towards the tail its amplitude increases. When this wave propagates backward, it generates force in the heading direction of fish which gives forward displacement. The parameter vector E = $\{c_1, c_2, k, \omega\}$ is the key element in determining the kinematics of the fish-tail. The traveling wave can be represented by the following equation

$$y_{body}(x,t) = (c_1 x + c_2 x^2) sin(kx + \omega t) \quad (1)$$

where y_{body} is the transverse displacement of the tail unit; x is displacement along the main axis; $k = \frac{2\pi}{\lambda}$ is the wave no. ; λ is the wave length; c_1 is the linear wave amplitude envelope; c_2 is the quadratic wave amplitude envelope; $\omega = 2\pi f$ is wave frequency; f is the oscillating frequency or flapping frequency of the tail; and t is time.

In case of a natural fishes the generation of this wave is easy as the body constitutes many vertebral joints but in our case we have only three joints. Hence we approximate the wave by fitting the links on the wave [4] (i.e. only the end points will lie on the perfect wave). Let the length of each link be $l_j (j = 1, 2, 3)$, to keep it non-dimensional, the

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ratio of the links must be normalized as to be independent of its actual size, i.e. $l_1 : l_2 : l_3 = m[l_1{}' : l_2{}' : l_3{}']$, where m denotes the length factor, $l_j{}'$ indicates the normalized length of the jth link, and especially l_1 equals 1. Also let two endpoint coordinate of each link l_j be $(x_{j-1},\ y_{j-1})$ and $(x_j,\ y_j)$, respectively, and the joint angle between l_{j-1} and l_j be ϕ_j.

Once the amplitude coefficients (i.e. $c1$ and $c2$) and k are determined, the shape of the propulsive wave at any time instant can be found. Mathematically, the jth links joint angle ϕ_{ij} at the ith time ($i = 0, 1, ..., M-1$) can be calculated by fitting the current wave. Here the time period of one oscillation is discretised into M units and then each unit is provided an index i. In our simulation M is 100. So this sequence repeats itself again and again periodically to produce the wave. The joint angle at i^{th} interval for joint j can be calculated using the following equations [4].

$$\begin{cases} (x_{ij} - x_{ij-1})^2 + (y_{ij} - y_{ij-1})^2 = l_{ij}^2 \\ y_{ij} = (c_1 x_{ij} + x_{ij}^2)\sin(k x_{ij} - \frac{2\pi i}{M}) \\ \phi_{ij} = \tan^{-1}(\frac{y_{ij} - y_{ij-1}}{x_{ij} - x_{ij-1}}) \end{cases} \tag{2}$$

where i indicates i^{th} interval of time and j denotes joint number. Since these equations are much complex to compute and hence they cannot be solved by onboard microcontroller and should be solved in advance using some offline technique. Solutions of these equations are numerical values of joint angles ϕ_{ij} which is then stored as a $M \times 3$ matrix called servo look-up table as shown in (3). This matrix is used as primary oscillatory data related to the movement of fish-tail. This data can also be fed into the onboard microcontroller which controls servos of the robotic fish. By tweaking the delay of i^{th} interval, we can control the oscillation frequency. Reduction of number of time intervals in one period will also increase the oscillation frequency but it decreases the time resolution. Hence some trade off is made while selecting M. Here the time interval is assumed to be fixed as it's the time of one iteration of the micro controller.

$$\text{Angledata} = \begin{bmatrix} \phi_{11} & \phi_{12} & \phi_{13} \\ \phi_{21} & \phi_{22} & \phi_{33} \\ \vdots & \vdots & \vdots \\ \phi_{M1} & \phi_{M2} & \phi_{M3} \end{bmatrix} \tag{3}$$

When fish turns a deflected angle θ_d, it acts as an offset in first and second joint. So the actual control data for fish joints is sum of deflected angle and previous angle data from servo look up table. If our angle vector is $\Theta = \{\theta_1, \theta_2, \theta_3\}$ then:

$$\begin{aligned} \theta_1 &= \theta_{1T} + \theta_d/2 \\ \theta_1 &= \theta_{2T} + \theta_d/2 \\ \theta_1 &= \theta_{3T} \end{aligned} \tag{4}$$

where $\{\theta_{1T}, \theta_{2T}, \theta_{3T}\}$ is the data stored in servo look-up table.

B. Hydrodynamics Model

Consider a fish heading in forward direction then the forces acting on it are buoyancy, gravity and lift in vertical direction and thrust and drag in horizontal direction. We are assuming that the mass and volume of our fish is such that its density is almost equal to water so that the buoyancy and gravity balances each other. Thus the only vertical force remains is lift which is generated by fish itself using its pectoral fins.

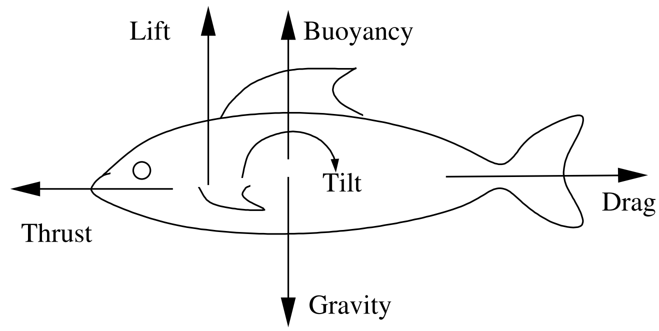

Fig. 1: Forces acting on the Fish

Considering the viscous drag which can be calculated using the equation

$$D_v = \frac{1}{2} C_f S U^2 \rho \tag{5}$$

where C_f is a drag coefficient which depends on the Reynolds number i.e geometry of our fish, S is the weighted surface area, in our design S is approximated as the curved surface area of cylinder whose length is equal to the length of fish L and diameter equal to the maximum height of the fish. U is the forward velocity of the robot fish and ρ is water density. The Reynolds number is defined as:

$$Re = \frac{LU}{v} \tag{6}$$

where U is the forward velocity of the fish and v is the kinematic viscosity of water (i.e. .86mm^2/s, fresh water at 80° F i.e. at room temperature). The laminar and turbulent drag coefficients are $1.328Re^{-0.5}$ and $0.074Re^{-0.2}$ respectively and the drag coefficient C_f is equal to the sum of these coefficients [2].
There is a stable prominent parameter named Strouhal number for BCF [3] :

$$St = \frac{fA}{U} \tag{7}$$

where f is the oscillation frequency, $A = 2(c_1 x + c_2 x^2)|_{x=taillength}$ is the tail-beat peak-to-peak amplitude and U is the average forward velocity. St lies in a specific range ($0.25 < St < 0.40$) at constant swimming velocities. In our robotic fish, St is about 0.4 and (7) can be used to compute the maximum velocity U_{max}. Maximum viscous drag D_{vmax} can then be calculated using (5). When thrust force F_{thrust} equals D_{vmax}

$$F_{thrust} = \frac{1}{2} C_f S U_{max}^2 \rho \tag{8}$$

where ($C_{fmax} = 1.328(LU_{max}/v)^{-0.5} + 0.074(LU_{max}/v)^{-0.2}$ and $U_{max} = fA/St$), the fish is stationary.

For motion in vertical direction, the pectoral fins act as a hydrofoil like in case of submarine. The robotic fish controls the vertical motion by changing the attack angle β of the pectoral fins to generate lift force. The traditional lift force calculation equation is used here, as shown in (9).

$$F_{lift} = \frac{1}{2} C_L(\beta) S_p U_{max}^2 \rho \tag{9}$$

where S_p is weighted surface area of the pectoral fins and $C_L(\beta)$ is the Lift coefficient which depends on the geometry of the fins and attack angle β. We are making cross section of pectoral fins as symmetric airfoil(or hydrofoil). For symmetric hydrofoil $C_L = 0$ when $\beta = 0$ and also C_L is a linear function of β which can be observed from the C_L vs β plot of NACA0018 airfoil (figure 2) which is a symmetric one. The shape of the airfoil is shown in figure 3. This plot and profile details are simulated as in [5]. From the plot we can observe that C_L can be expressed in terms of beta as:

$$C_L = 0.125\beta \tag{10}$$

Where β is the angle of attack in degrees. The expression above is also almost equal to 0.11β which is the Lift coefficient of thin airfoil with infinite wing span. Hence this C_L is also consistent with thin airfoil theory.

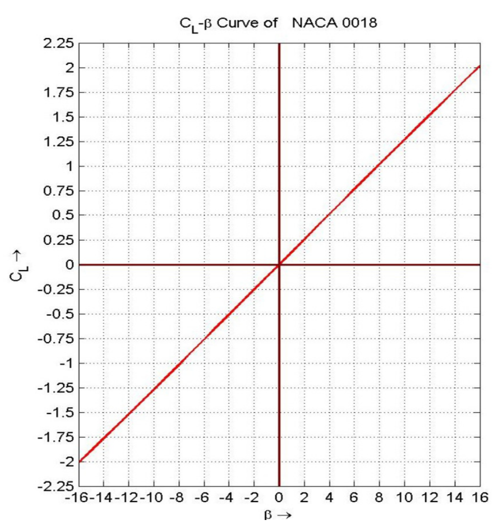

Fig. 2: Plot of lift coefficient C_L vs attack angle β

Here the interesting thing is that the lift force generated by the pectoral fins is offset in forward direction from center of gravity by a distance D . Hence it produces moment in such a way that the fish tilts from its horizontal orientation as shown in figure 4. This tilt in case of airplanes is avoided but in our case it is very beneficial. As the direction of thrust is also not horizontal, it now contains vertical components which support vertical motion. When the fish is tilted the Lift force

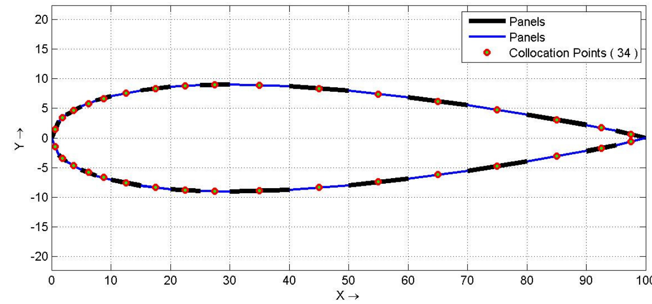

Fig. 3: Profile and mesh details of NACA0018 airfoil.

is also not in vertical direction which should not be called lift hence it is marked as $lift'$ in figure 4. For simplicity we assume that as fish gets some tilt about 30° it changes its pectoral fin's attack angle to zero. Which makes lift zero(for symmetrical shape hydrofoil $C_L = 0$ for $\beta = 0$). Therefor, only thrust force will be acting along heading direction. Fish can come to its previous orientation (parallel to the horizontal axis) again by making its pectoral fin's angle of attack zero.

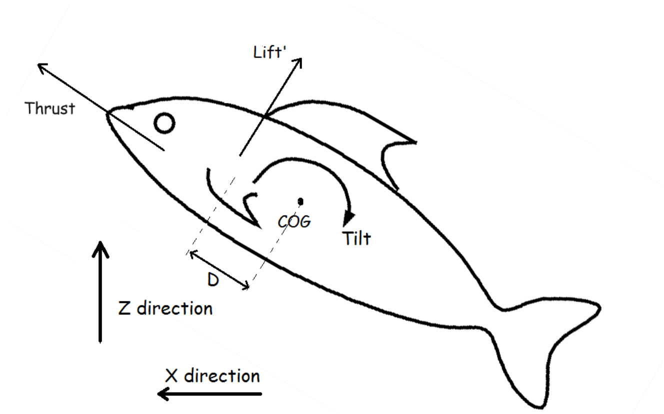

Fig. 4: Forces acting on the Fish in tilted mode

C. Kinematics Model

Kinematic model of the robotic fish includes the motion in horizontal as well as in vertical direction. When the fish is moving in horizontal direction its motion can be analyzed as in [1]. Thus, the acceleration in horizontal direction can be given:

$$a_t = \frac{F_{ty} - D_v}{m} \tag{11}$$

Where F_{ty} is thrust force component in heading direction. $F_{ty} = F_{Thrust} cos(\theta_d)$. θ_d is the deflected angle defined as the angle between the robotic fish heading and center line of its tails oscillation (namely the Deflected Axis). When the robot fish swims without turning, $\theta_d = 0$, otherwise $\theta_d \neq 0$.

The turning angular velocity can be calculated as [1]:

$$V_r = 1.2 f sin(\theta_d) \tag{12}$$

When angle of attack of pectoral fins $\beta \neq 0$ the fish gets some tilt. Angular acceleration of tilting can be calculated as:

$$\alpha_t = \frac{F_{lift'} D}{I_{COG}} \tag{13}$$

where I_{COG} is the moment of inertia of fish about an axis passing through Centre of Gravity and is perpendicular to the plane of fish and D is the distance of centre of Pectoral fins to COG. As the fish gets some tilt about 30° which results in angle of attack of its pectoral fins $\beta = 0$. Then the motion of the fish can be summarised as:

$$\begin{cases} U_x = U cos(\alpha) \\ U_z = U sin(\alpha) \\ V_r = 1.2 f sin(\theta_d) \end{cases} \tag{14}$$

Where U_x is the horizontal component of the heading velocity U of the fish and similarly U_y is the vertical component.

III. Hardware arrangement of the robotic fish

The design of our robotic fish is inspired by the natural fish Rohu. As it is discussed earlier that the tail is the most important part (which is the rear part of the body) for carangiform motion. We use three servo motors which help to generate wave at the rear part of the body and two servos in the front part to generate side fins movement. The mechanism is shown in figure 5 and 6. The last servo is coupled to the tail fin which has the maximum amplitude of oscillation. At the front part which is head where four infrared sensors are mounted. These sensors make the fish capable of sensing obstacle in its trajectory. A 7.2V Lipo battery is the power source for servo motors and other equipments of the fish. The stomach of fish is filled with the battery, microcontroller board and two small servos. These servos are used to operate pectoral fins. There is a tilt sensor module which provides the measurement of elevation, is assembled beside the microcontroller board.

IV. Simulation

We use Autodesk 3ds Max to design the simulation model of the robotic fish and for viewing the simulated result, we use VR sink block in Matlab simulink. The various parameters of robotic fish model, water environment and dynamic parameters are tabulated as the following.

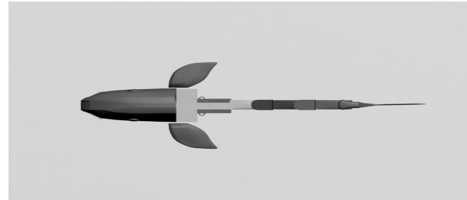

Fig. 5: Top view of the simulation model.

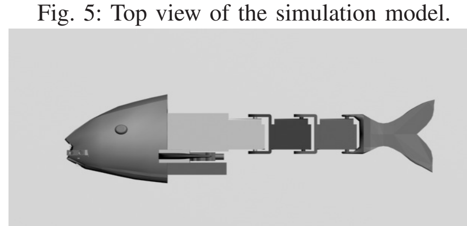

Fig. 6: Side view of the simulation model.

Parameters	Symbol	Value
Total Length	L	45 cm
Tail Length	L_t	25 cm
Weighted surface area	S	0.23 m^2
Pectoral fins area	S_p	$50 cm^2$
Strouhal Number	St	0.4
Mass	m	0.6 Kg
Moment of Inertia	I_{COG}	.0136 Kg/m^2
Drag coefficient	C_{fmax}	0.0132
Lift coefficient	C_L	.125 β
Pectoral fin offset	D	5 cm
Tail end Amplitude	A	22.62 cm
Frequency	f	0.5 Hz
Kinematic Viscosity	ν	$8.6 \times 10^{-7} m^2/s$
Density of water	ρ	1000 Kg/m^3
Maximum velocity	U_{max}	0.28 m/s
Thrust force	F_{thrust}	0.12 N

In simulation, Robot fish takes about 6 seconds to reach its maximum velocity from zero velocity as observed from figure 7.

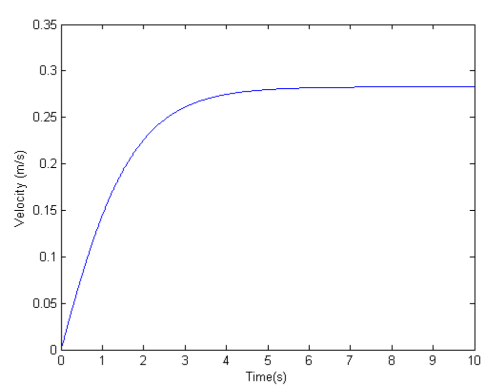

Fig. 7: Velocity vs Time plot

A trial of fish swim is taken in such a way that the fish first starts from the origin and moves straight till it gains maximum speed. Then it starts turning and lifting. The trajectory of the trial is shown in figure 8. Figure 9 shows image sequences of the fish while it is moving in 3D trajectory.

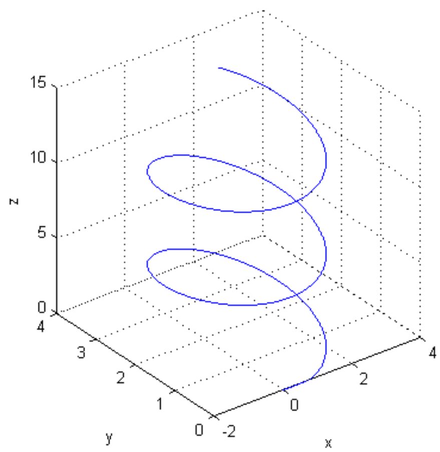

Fig. 8: 3D trajectory of the fish in a trial

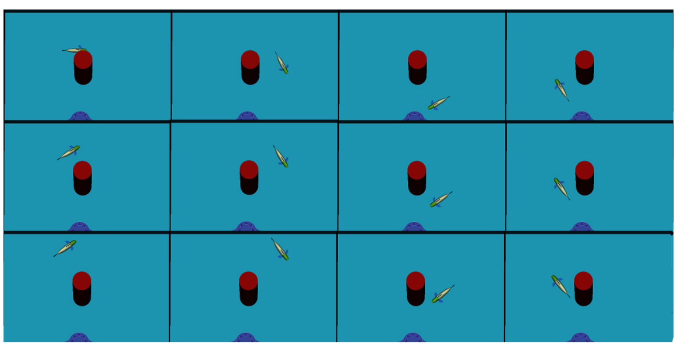

Fig. 9: Image sequence of the fish 3D motion in the trial

V. Mechanical tail and pectoral fins

We develop a three joint mechanical tail along with two pectoral fins (figure 10 and 11) based on the mechanism described in previous sections. The servos here are coupled with each other with clamps, made by polymer. The servo motors in the front part of body (shown in figure 10), provide the driving force to the pectoral fins. Whole structure of the robotic fish is designed in Autodesk 3Ds Max and fabricated in a rapid prototyping machine. Atmega-128 microcontroller is used to fabricate the control circuitry. We generate the solution of equation (2) using matlab and store that result in matrix form as in equation (3). The matrix contains values of angle of each servo at each instant of time. The matrix is then copied to the micro controller code with required changes. This data of angle is then equated dircectly to the control angle of servos. This arrangement is able to generate a near sinusoidal wave.

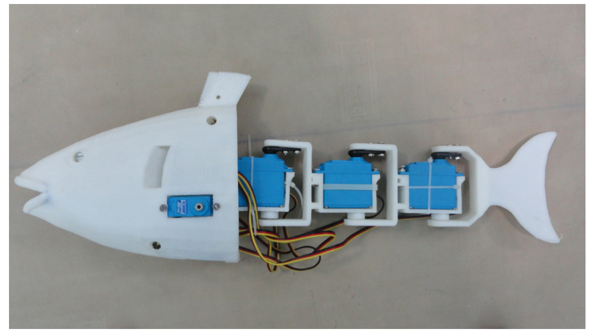

Fig. 10: Side view of the fish skeleton

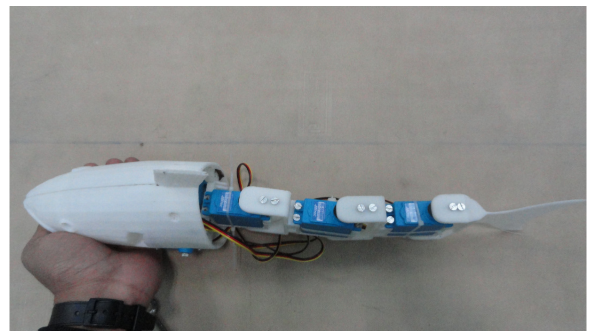

Fig. 11: Top view of the fish skeleton

VI. Conclusions

In this current work, we study the mathematical modelling of the robotic fish. Using this mathematical model we simulate the fish movement in a given trajectory in three dimensional space. The fish we design, is able to change its position in vertical direction and it is achieved by the application of pectoral fins. The thrust generated by these fins, is producing a force in vertical direction which causes the acceleration in that direction..

We fabricate a three joint mechanical tail which is capable of generating near sinusoidal wave, propagating through its body. Since, the microcontroller is able to regulate oscillation frequency of the tail, velocity control schemes can be implemented on the fish.

The obstacle avoidance strategies can be realized using sensor which are mounted at the front part of the fish. Wireless devices can be mounted so that it can communicate with the outside world. Further, the fish can be equipped with pollution sensors (which provides the percentage level of particular component in water) so that, the composition of the water can be determined. Our vision is to make a robotic fish which can navigate deep inside a water body and provides information about the pollution level of the water.

References

[1] Jindong Liu, Huosheng Hu, "A 3D Simulator for Autonomous Robotic Fish," *International Journal of Automation and Computing* 1 (2004) 42-50

[2] C. S. Wardle, A. Reid, "The application of large amplitude elongated body theory to measure swimming power in fish," *Fisheries Mathematics*, J. E. Steele, Ed. New York: Academic, pp. 171191, 1977.

[3] M. Sfakiotakis, D. M. Lane, J. Bruce, C. Davies, “Review of fish swimming modes for aquatic locomotion,” *IEEE Journal of Oceanic Engineering*, vol. 24, no. 2, pp. 237252, 1999.
[4] Junzhi Yu, Shuo Wang and Min Tan, “A simplified propulsive model of bio-mimetic robot fish and its realization,” *Robotica (2005)* volume 23, pp. 101107.
[5] Divahar Jayanarayan, “Panel method based 2-D potential flow simulator,” http://www.mathworks.com/matlabcentral/fileexchange/12790.
[6] D. S. Barrett, “ Propulsive efficiency of a flexible hull under water vehicle,” *Ph.D. dissertation, Massachusetts Institute of Technology*, Massachusetts Avenue, Cambridge, 1996.
[7] K. Streitlien, G. S. Triantafyllou, M. S. Triantafyllou, “Efficient foil propulsion through vortex control,” *AIAA Journal*, vol. 34, pp. 23152319, 1996.
[8] S. Guo, T. Fukuda, Norihiko Kato, Keisuke Oguro, “Development of underwater microrobot using ICPF actuator,” *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 18291834, 1998.
[9] N. Kato, “Control performance in the horizontal plane of a fish robot with mechanical pectoral fins,” *IEEE Journal of Oceanic Engineering*, vol. 25, no. 1, pp. 121129, 2000.
[10] http://web.mit.edu/towtank/www/Pike/pike.html
[11] http://www.nmri.go.jp/eng/khirata/fish/
[12] www.robotswim.com/
[13] www.festo.com/net/en_corp/SupportPortal/Downloads/146913
[14] http://www.jaea.go.jp/09/aquatom/exhibit_1f.html