Third International Conference on
Advances in Control and Optimization of Dynamical Systems
March 13-15, 2014. Kanpur, India

Robotic Fish Design and Control based on Biomechanics ⋆

Shaurya Shriyam * **Anuj Agrawal** ** **Laxmidhar Behera** *** **Anupam Saxena** ****

* *Mechanical Engineering Department, Indian Institute of Technology, Kanpur(e-mail: shauryashri@ gmail.com).*
** *Mechanical Engineering Department, Indian Institute of Technology, Kanpur (e-mail: anuj.agrawal08@gmail.com)*
*** *Electrical Engineering Department, Indian Institute of Technology, Kanpur (e-mail: lbehera@iitk.ac.in)*
**** *Mechanical Engineering Department, Indian Institute of Technology, Kanpur (e-mail: anupams@iitk.ac.in)*

Abstract: This paper presents a theoretical framework on the design, modelling and control of a robotic fish inspired by the carangiform mode of swimming. The physical design of the robotic fish is obtained by trying to mimic the external anatomical features of a Tuna. To mimic the undulation of the fish posterior, a novel combination of manipulator link mechanism and a flexor-extensor mechanism has been used. The paper emphasizes the design and the modelling of this link mechanism and provides a kinematics model for the same. Dynamics modelling of the robotic system is based on Lagrangian methods. Finally we simulate a simple controller based on surface-swimming approximation of the developed dynamics model.

Keywords: bio-inspired robotics, flexor-extensor mechanism, carangiform, robotic fish, underwater robotics.

1. INTRODUCTION

Underwater exploration has been an important pre-occupation of researchers since a long time. In terms of scientific results, immense data of critical importance is produced by most exploration missions of such kind (Dover, 2000). From the discovery of new life forms in areas we earlier thought were inhabitable to assessing the impact of climate change on coral reefs or environmental monitoring, underwater exploration has loads of benefits.
Today underwater exploration is mainly dominated by manned or unmanned submarine-type vehicles. Submarines have been considered to be the most successful in this respect till now but clearly, they lack several important features of natural swimmers like flexibility, ease of manoeuvrability and energy efficiency which lead to fish swimming being better adapted ecologically in comparison to submarines. A new paradigm in unmanned underwater exploration has been unleashed with the introduction of robotic fishes. The efficient exploration of the unpredictable terrain and cluttered environment of the ocean seabed asks for miniature sized agents with fast response rates. A robotic fish would serve as a perfect agent for such exploration missions.
It is interesting to note that prior to the evolution of fishes, the organisms that took part in aquatic locomotion were either microscopic or not that efficient as same-sized fish. In fact, large-sized organisms that actually developed the ability to swim more efficiently were the alligators and crocodiles. They appeared over 65 million years ago while fishes are believed to have evolved in the Paleozoic era. The point worth noting is that these reptiles used an erect locomotion posture (ELP) when they had to do walking on land, otherwise they squatted and sprawled over muddy, wet grounds. It is believed that this ease of negotiation of marshy lands fostered further improvement in the designs of body to assist in swimming. Though we are not going to deal with the ethological details of this evolution, we will be rationalising the phenomena because we are going to make use of it in our bio-inspired design of robotic fish. It is not difficult to rationalise why ELP leads to better walking on ground. It leads to more compactness along horizontal direction, thus increasing line of sight and allowing sensory feedback to produce better motion planning results. However, there is a trade-off involved. Since now the head is lifted off the ground, visibility of ground is reduced. There will be lesser information available about surface unevenness and unpredictable obstacles in the form of plants or other small moving animals in immediate proximity and hence motion control is compromised. But it will appear that for terrestrial locomotion, noisy control is considered okay if it manifests under a limit, but not inefficient planning because for erect locomotion posture, direction of locomotion is perpendicular to body length. This can be attributed to the fact that on land, speed is more important than preparedness towards unpredictable events because terrestrial animals have got sun to increase their visibility of ground even via eyes located 4-6 feet above ground.
Similarly, aquatic locomotion prefers compactness along the direction of locomotion. A beautiful interpretation

⋆ The contribution of the first two authors was equal.

emerges. For aquatic locomotion, both motion control and motion planning are critical due to medium characteristics. Also aquatic life forms have to rely on very little external lighting. Hence fish has evolved its locomotion in the direction of its body length with eyes on its head so as to not be faced with decision-making regarding compromise between planning and control.

2. LITERATURE REVIEW

Recently a lot of work has happened in the field of robotic fishes. Presently, the robotics community is involved in studying the dynamics of the fish and controlling it. Several innovations have been devised as far mimicking the undulatory motion of fishes is concerned. Most popular mechanism is, of course, the use of manipulator to mimic the undulation by fitting its motion to appropriate curves. Here again the most popular curve is the one defined by Lighthill (Lighthill, 1960). Theoretically speaking, an infinite number of servos of infinitesimally small work volume are desired to actually mimic muscle action causing fish undulation; generally only about 3-5 servos are used (Yu et. al., 2005; Hu, 2006; Alessi, 2012).

Some other mechanisms have also been designed for the same purpose. Ionic PolymerMetal Composite fins have been used to propel the fish (Chen, 2010). Moreover, some good designs have been implemented to actuate the posterior body part by using power from motors (Liu, 2005). Much work has focused on trying to understand the fluid-body interaction that leads to such good speeds and high efficiency as in fish swimming. This basically turns into a problem of fluid mechanics and has been studied by many researchers as such (Kelly, 2000; Hong, 2005). Swimming flumes have been used recently to get good idea of how fishes swim (Ellerby, 2013). There has been parallel focus on devising motion control algorithms for robotic fish too (Shang, 2009).

Despite a bulk of research, there are several complex issues that remain as open problems in this field. No matter whatsoever mechanism and technology be used, the speed and efficiency of fish is still unachievable. This is probably to do with the mechanism to transfer motion to its fins and posterior, and the technique of swimming used by fishes to manoeuvre and negotiate obstacles. Fishes use body muscles to convert energy and to transfer motion efficiently to its outer body. Though such muscles have been artificially fabricated, as of now, they are too expensive to be included in commercial robotic fishes. So, innovative alternatives are the only viable solution. Hence, it was decided to use a variant of flexor-extensor mechanism to mimic undulation. The logic is that it must be more controllable and allow better manoeuvring in water because animals use it for locomotion.

In this paper, we propose a novel combination of servo motors and flexor-extensor mechanism to propel a fish structure designed meticulously in parallel to natural fish design. Section 3 describes in details the design of the fish. Section 4 briefly reviews the equation that guide the undulation of our fish robot. Section 5 describes in detail the working of the flexor-extensor mechanism to cause fish undulation. In sections 6 and 7, an extensive dynamic model is mooted and then a simplified dynamic model is used to simulate a simple PD-controller for surface swimming.

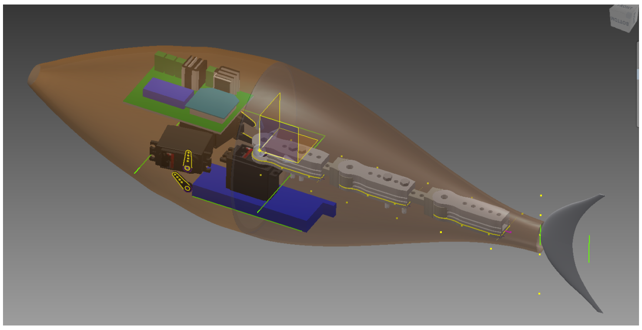

Fig. 1. This image shows the proposed 3-D model of the robotic fish. The figure clearly shows the three parts of the fish - anterior, posterior and the tail fin. It also allows a peek into the electronic control circuitry.

3. FISH BODY DESIGN

The goal of fish design presented here is to efficiently bio-mimic the design of streamlined fishes such as Tuna, which are fast aquatic swimmers in the oceans. Of the two general modes of fish swimming, viz. body-caudal fin (BCF) propulsion and median-pectoral fin propulsion, the BCF mode of propulsion is utilized by the Tuna fish. The BCF mode is further subdivided into four types, viz. thunniform, anguilliform, subcarangiform, and carangiform modes (Videler, 1993). The modes differ in the fraction of body that actively participates in undulation. A Tuna fish is observed to be using the carangiform mode of swimming (BCF propulsion). For carangiform mode, active undulation is confined to approximately the posterior one-third fraction of the body. There are three important components in the body design, viz. anterior portion, posterior portion and tail.

3.1 Anterior Body Design

The anterior portion of fish is rigid as compared to the posterior part which is entirely flexible. This is due to the skull bone mainly. Moreover, the front portion does not participate in active undulation, hence whatever inherent organic flexibility it has can be safely ignored for design and analysis purposes without severely affecting the dynamics of the fish. The total length of the fish designed was 60 cm and the head design was set to be of 22 cm in length.

Let z denote the vertical axis, y the horizontal axis and x the axis along the length of the fish, the following boundary conditions were placed on the body profile:

$$z = 0,\ dx/dz = 1.19; x = 10mm. \tag{1}$$
$$z = 220mm, dx/dz = 0; x = 60mm \tag{2}$$
$$z = 0, dy/dz = 0.577; y = 5mm \tag{3}$$
$$z = 220mm, dy/dz = 0; y = 80mm \tag{4}$$

The choice for these boundary conditions has been dictated by the goal of designing a streamlined external body profile. These boundary conditions were fitted onto a cubic curve and their plot was visualised in Matlab to confirm the same. The major axis of the ellipses slowly shifts from horizontal to vertical as one moves along the length of the fish from its nose.

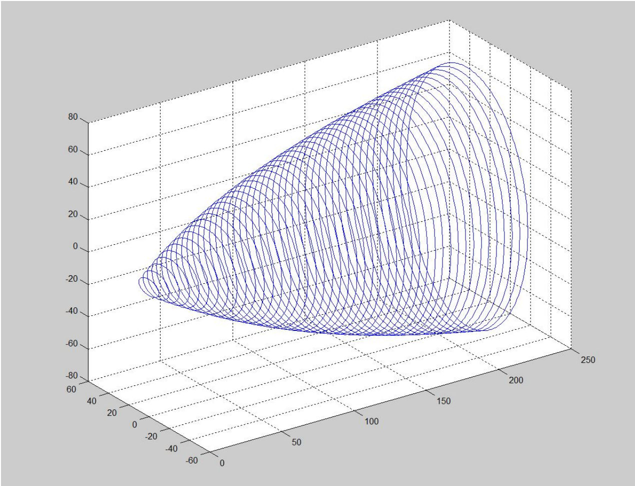

Fig. 2. A Matlab visualisation of the fish head using the Hermite cubic polynomial verifies the streamlined shape and roll stabilization.

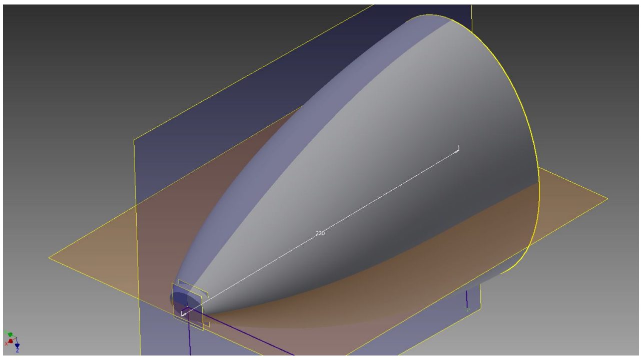

Fig. 3. The 3D-CAD model of the fish head design is based on the boundary conditions 1-4.

The head would be manufactured using Rapid Prototyping facilities and the material chosen is Polycarbonate to keep the overall weight low and achieve sufficient strength for our laboratory controlled testing conditions.

3.2 Posterior Body Design

The posterior design was trickier. The peduncle and the caudal fin attached to the posterior body are involved in thrust generation. The peduncle participates in an undulatory wave-like sinusoidal motion which passively actuates the caudal fin motion and leads to the generation of thrust in fishes (Mason, 2000). It implies that this part has to be flexible in nature. Thus, the posterior had to be designed based on compliant mechanism principles.

Following the existing tradition in fish robotics, a 3R-link mechanism is used in the subsequent sections that would be placed inside the hollow of the posterior body. This 3R-link mechanism will be responsible for mimicking the undulatory motion. A motion transfer mechanism similar to the one used in bicycles to transfer the rotational motion of the hub to the outer rim using spokes will be used here to transfer the undulatory motion of the link mechanism to the outer posterior body.

The posterior body would be fabricated using a thick waterproof fabric which will be stitched to get the required shape. The waterproof fabric would act as the skin of the fish. It would be wrapped around a skeleton system made up of thin elliptical rings which would be connected to the 3R-link mechanism through radial spokes. This framework would provide the much needed accurate balance of rigidity and flexibility in the posterior body.

3.3 Tail Fin (Caudal Fin) Design

The vertical tail fin of a Tuna fish is roughly symmetrical about the horizontal $x - z$ plane. The thrust generated by the tail fin of a fish is thought to be produced in accordance with aerodynamic principles. As the fluid moves across the tail, a non-zero circulation is produced in the surrounding fluid so that the Kutta-Joukowski condition is satisfied and a lift force acts perpendicular to the direction of the flow (Childress, 1981; Fish, 2014). A part of this lift force provides the thrust to propel the fish. Thus, the tail fin was modelled such that a cross section taken at any height of the fin would resemble a NACA 0012 aerofoil which would characterize a similar process of thrust generation.

4. CARANGIFORM MOTION EQUATION

Given below is an equation that describes the undulatory motion of the posterior of a fish in carangiform mode of locomotion. (Yu, J., 2005) Yu and Wan have also outlined a method in their research to fit in a 3R link mechanism on this curve such that the sinusoidal motion can be mimicked by just using 3 links.

$$Y(x,t) = [(c_1 x + c_2 x^2)][\sin kx - \frac{2\pi}{M} i] \tag{5}$$

We can calculate the link endpoints of each individual link by simultaneously solving the following two equations.

$$(x_{i,j} - x_{i,j-1})^2 + (y_{i,j} - y_{i,j-1})^2 = l_j^2 \tag{6}$$

$$y_{i,j} = (c_1 x_{i,j} + c_2 x_{i,j}^2) \sin(k x_{i,j} - \frac{2\pi}{M} i) \tag{7}$$

Here, i refers to the i^{th} time interval and j refers to the j^{th} link. Once the positions of links are determined, one can now determine angular positions of the links with respect to each other as well as with respect to the origin of the 3R-link mechanism.

$$\phi_{i,1} = \tan^{-1}(\frac{y_{i,1}}{x_{i,1}}) \tag{8}$$

$$\phi_{i,2} = \tan^{-1}(\frac{y_{i,2} - y_{i,1}}{x_{i,2} - x_{i,1}}) - \phi_{i,1} \tag{9}$$

$$\phi_{i,2} = \tan^{-1}(\frac{y_{i,3} - y_{i,2}}{x_{i,3} - x_{i,2}}) - \phi_{i,2} \tag{10}$$

Here, $(x_{i,j}, y_{i,j})$ denotes the coordinate of end-point of j^{th} link at time i whereas $\phi_{i,j}$ represents the angular positions of j link with respect to $j - 1$ link. All the angles in above equations are taken with their correct sign. A clockwise angle is positive and anti-clockwise angle is negative. Since, many hydrodynamics coefficients are correlated to angle of attack α, it must be calculated for assistance in further analysis.

$$\alpha = \tan^{-1}(\frac{y_{i,3} - y_{i,2}}{x_{i,3} - x_{i,2}}) \tag{11}$$

Based on the above values average angular velocities of the respective links can be calculated. Denoting by $\beta_{i,j}$ the angle that j^{th} link makes with the $x-$ axis with respect

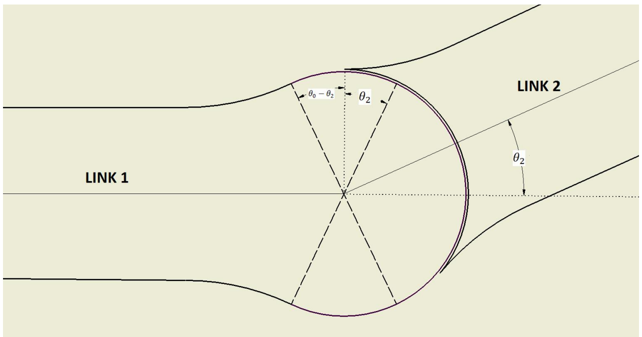

Fig. 4. In this image the trick that makes it possible to reduce 6 servos to 3 is graphically reproduced. The point worth noting is that the inspiration lies mainly in borrowing the simplicity of pulley mechanism to bridge the servo mechanism and flexor-extensor to actuate the links.

to the hinge point of first link. Note that the following relations hold:

$$\beta_{i,j} = tan^{-1}\frac{y_{i,j}}{x_{i,j}};\ \ j = 1, 2, 3. \tag{12}$$

$$\langle\omega\rangle = \frac{\sum_{i=1}^{M}(\beta_{i,j} - \beta_{i,j-1})}{M} \tag{13}$$

These values of ω_j are computed in real time depending on the angular frequency of the carangiform equation which in turns depends upon the requirement of the speed of the fish. Higher speed requirement would mean a higher angular frequency of the carangiform equation.

5. FLEXOR-EXTENSOR MECHANISM

Generally, robotic fishes use servos to directly actuate the tail links instead we have used a modified flexor-extensor mechanism in compliance with servo motors to do the same. Just as the gear helps in controlling the servo motors more finely than otherwise, so the flexor-extensor mechanism is expected to allow better control and hence manoeuvrability of fish due to bio-inspiration. A flexor extensor mechanism essentially places 2 wires one on each side of the link. An actuator is required to actuate each of the two wires. When one wire is pulled, the other one is simultaneously relaxed by the second and the coordinated movement of the two actuators results in the desired movement of the link. However, there are two problems with this mechanism which we propose to solve by our mechanism:

(1) Each link requires two actuators for the desired movement. Thus, for a three link mechanism, a total of 6 actuators would be required. Accommodation of 6 actuators inside the fish body not only takes up a lot of space but also increases the weight and the relative density of the fish.
(2) For the movement of any particular link, the two actuators need to move in a coordinated manner. If one actuator relaxes the wire on one side of the link at a faster rate than at which the other actuator flexes the wire on the other side or vice versa, one of the wires will become slack: this is undesirable.

5.1 Mechanism Description

We observed that the need for an extra actuator per link can be eliminated from the flexor/extensor mechanism if the links are designed such that the total path length for a wire attached to any of the links turns out to be a constant. This implies that the derivative of the string lengths associated with any of the links evaluates to 0 for all values of $\phi_{i,j}$.

$$\frac{ds_i}{dt} = 0\ \ \forall\phi_{i,j} \tag{14}$$

Thus, the length of the string pulled from one side of the string exactly equals the length of the string relaxed for the other side which leads to a rotation of the link by the specified angle. Also, now only one wire is used to actuate a single link to produce the same effect. An important point to note is that a mechanism has to be put in place such that the string never breaks contact with the link surface. This is because the string is in a state of tension throughout the motion and has a natural tendency to break off the surface whenever flexing takes place. If that happens, the entire mathematics behind the controller falls apart. To remedy this, we used grooves along the link surface. These channels were covered from top at proper intervals.
The string lengths along the grooves on the surface of the links can be expressed in terms of the geometrical parameters of the link as follows(Please refer to the figure 7 for a complete diagram.):

$$s_{i,2} = \alpha r_0 + 2l_1 + r_0(\theta_0 - \phi_{i,2}) + 2a_2 + r_0(\theta_0 + \phi_{i,2}) \tag{15}$$

$$\begin{aligned} s_{i,3} = \alpha r_0 + 2l_1 + r_0(\theta_0 - \phi_{i,2}) + r_0(\theta_0 + \phi_{i,2}) + 2l_2 \\ + r_0(\theta_0 - \phi_{i,3}) + r_0(\theta_0 + \phi_{i,3}) + 2a_3 \end{aligned} \tag{16}$$

Here $s_{i,2}$ and $s_{i,3}$ represent the string lengths associated with 2^{nd} and 3^{rd} links.
l_i = path length of the string on link i.
a_i = length of the path on link i where the string is tied to the link.
θ_0 = initial angle between the links.
r_0 = radius of the circular joints between the links.
α = angle subtended at the center by the circular arc of the actuator ring.

5.2 Construction

Each link is connected through a wire and a circular horn to a servo. Each of the links can be divided into three parts as follows:

(1) *Anterior Part*: This is a small portion of the link as shown in the figure which has a profile made up of two circular arcs that blend with the flat portion of the beginning of the middle part of the link. This also avoids any points of non-differentiability at the point of contact of this part with the posterior part of the previous link. Also, the profiles are so chosen so as to avoid any points of non-differentiability on the surface of the link. Smooth profile enables the free movement of the wire inside the grooves on the surface without much friction. Also, the wire slides precisely over the surface of the link, avoiding any points where the wire loses contact with the surface of the link (which would have made the precise calculation of

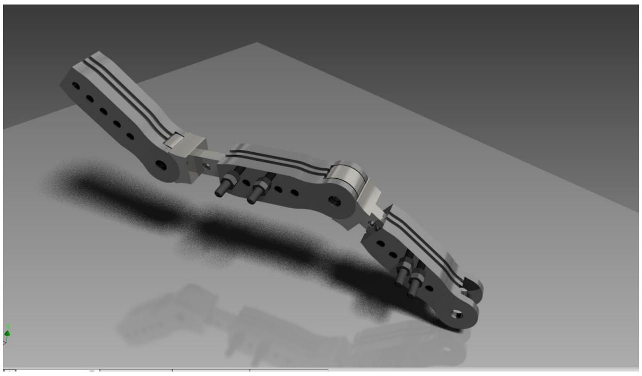

Fig. 5. This image shows the rendered image of the final 3R link mechanism. Observe how closely it resembles a manipulator. Note that strings are not shown in this figure nor the motors that will pull the links via the stings.

the running lengths of the wires much more complex). In this case however, the running length of the wire equals the length of the path of the grove assuming perfect contact.

(2) *Middle Part*: This part of the link is fairly simple in design which characterizes the flat portion of the link.
(3) *Posterior Part*: The posterior part of the link has similar two circular arcs that have the same function as described in the anterior part. The end portion also features a grooved circular arc over which the wire slides. This is the only part of the link where the length of the wire is not fixed and changes depending upon the angle between the two links.

Actuation of the 3-link flexor-extensor mechanism Actuation of link 1 is not string controlled but it is directly actuated using a servo motor attached to the anterior part of the link 1. Actuation of links 2 and 3 is done using the string mechanism controlled by a servo motor each. Actuation of all the three links is not independent. To construct a proper loo-up table to feed to Arduino, one needs the relationship between link angles and servo angles. The relationship is explained by noting the following two points:-

(1) In order to achieve a configuration of say, $\phi_{i,1} = 10°$, $\phi_{i,2} = 0°, \phi_{i,3} = 0°$, we need to rotate all the three motors by 10°.
(2) For a random configuration of $\phi_{i,1} = \alpha, \phi_{i,2} = \beta, \phi_{i,2} = \gamma$, motor 1 is rotated by α, motor 2 by $\alpha+\beta$ and motor 3 by $\alpha+\beta+\gamma$.

Note how the two sets of angles have been easily linked without any complication arising due to string lengths. This has been made possible due to the geometrical design of the mechanism.

6. DYNAMICS MODELLING

A fish is a compliant dynamical system and hence its modelling is more complex than existing vehicular systems. Several approaches have been used previously (Kelly, 2000; Lighthill, 1971). Of these the most tractable approach from the point-of-view of control theory appears to be the Lagrangian formulation in a vectorial fashion as will become evident in following discussion. A parallel can be drawn in between the modelling of the fish and an underwater submarine-type vehicle (Fossen, 2011) by making some assumptions. This is being done for the ease of simulation as otherwise we would be left with a set of partial differential equations which would add to the already existing complexity of the simulator as finite element methods are more involved to simulate.
There have been several assumptions which need explicit mention. Six assumptions have been mentioned below. A seventh assumption is mentioned later at its proper place.

(1) Fish is operating in the absence of wave disturbances, i.e. in calm and deep water.
(2) Fish is cruising at a constant positive speed U.
(3) Hydrodynamics coefficients are assumed to be constant.
(4) Contribution from off-diagonal terms in the involved tensors described ahead is neglected, i.e., a decoupled dynamics model is assumed.
(5) The effect of body flexibility is accounted for by the control forces and moments described in next section.
(6) Roll is assumed to be passively stabilized by design considerations.

Position of fish can be determined from velocities and previous position by discrete integration techniques like Euler method. The kinematics of fish can be summed up into the following equation.

$$\dot{\eta} = J_\Theta(\eta)\nu \tag{17}$$

Here η refers to the position vector of the body reference point in North-East-Down inertial reference frame whereas refers to the velocity vector in BODY frame of thee fish. Thus, $J_\Theta(\eta)$ basically refers to the Jacobian matrix required to transform from one coordinate frame to another. We choose as our reference point of analysis the center of gravity of fish, CG.

$$\eta = [N\,E\,D\,\phi\,\theta\,\psi]^T \tag{18}$$

$$\nu = [u\,v\,w\,p\,q\,r]^T \tag{19}$$

As roll is stabilized, $\phi, \dot{\phi}, \dot{p}) = 0$.

$$J_\Theta(\eta) = \begin{pmatrix} c\psi\, c\theta & -s\psi & c\psi\, s\theta & 0 & 0 & 0 \\ s\psi\, c\theta & c\psi & s\psi\, s\theta & 0 & 0 & 0 \\ -s\theta & 0 & c\theta & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & t\theta \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & \dfrac{1}{t\theta} \end{pmatrix} \tag{20}$$

Similarly the velocities at any instant can be determined by the knowledge of forces and moments and velocities at the previous time instant. This is summed up in the kinetics equation below.

$$\begin{aligned} M_{RB}\frac{d\nu}{dt} + C_{RB}(\nu)\nu \;\; &\text{(rigid-body pseudo forces)} \\ + M_A\frac{d\nu}{dt} + C_A(\nu)\nu \;\; &\text{(added mass forces)} \\ + D(\nu)\nu \;\; &\text{(viscous drag and lift)} \\ + g(\eta) \;\; &\text{(restoring)} \\ = \tau \,&\text{(control forces)} \end{aligned} \tag{21}$$

The tensors M_{RB}, C_{RB}, M_A,andC_A are determined by applying Euler-Lagrange equation to Kirchhoffs equation. The added mass terms are observed due to the added-mass method of thrust generation. The hydrodynamic damping matrix represents the drag and lift forces acting on a moving fish. For our purpose, we can neglect the lift forces. The contribution from potential damping is generally neglected for under-water vehicles. Linear viscous drag is not neglected and is modelled using the general formula.

$$F_D = \frac{1}{2} C_D \rho A u^2 \tag{22}$$

For our purposes non-linear quadratic damping must be taken into account though modelling it is much more challenging than linear damping. To keep the model simple, we can incorporate the non-linearity into C_D, thus giving C'_D.

Since we will attempt to construct a neutrally buoyant underwater vehicle (weight, W = buoyant force, B), we make a seventh assumption about our dynamical system. Denoting by x_g, y_g and z_g the coordinates of the CG and by x_b, y_b and z_b the coordinates of the centre of buoyancy, CB, we place the following initial design constraint on our robot.

$$x_g = 0; y_g = 0; z_g = 0 \tag{23}$$

$$x_b = 0; y_b = 0; z_b \neq 0 \tag{24}$$

Actually by letting seventh assumption be that of fish being neutrally buoyant system, the above equations follow directly from the sixth and seventh assumption.

$$g(\eta) = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -z_b B \sin\theta \\ 0 \end{pmatrix} \tag{25}$$

The control forces have been explained in detail in the next section. However for now it suffices to give the form of this tensor.

$$\tau = \begin{pmatrix} X_{control} \\ Y_{control} \\ Z_{control} \\ K_{control} \\ M_{control} \\ N_{control} \end{pmatrix} \tag{26}$$

Here $X_{control}, Y_{control}, Z_{control}$ refer to the body forces whereas $K_{control}, M_{control}, N_{control}$ refer to the body moments.

7. CONTROLLER DESIGN

The fish has 5 degrees of freedom, viz. surge, sway, heave, pitch and yaw. These are controlled using the 3 control inputs, viz. frequency of undulation of tail fin (), mean position of servo-link mechanism and movable mass displacement in the barycentre mechanism (Zhou, 2006).

These control inputs are explained in detail in the following paragraphs. First note that this is an under-actuated system as only 3 control inputs are available to control a dynamical system having freedom in 5 out of 6 possible dimensions.

Suppose that there is a reference speed referred to as cruise speed to be achieved by the robotic system. However, actual speed starts from zero (rest) and tries to stabilise to cruise speed value by the action of controller. The error, viz. difference between actual speed and cruise speed is multiplied by a gain factor and is used to provide feedback

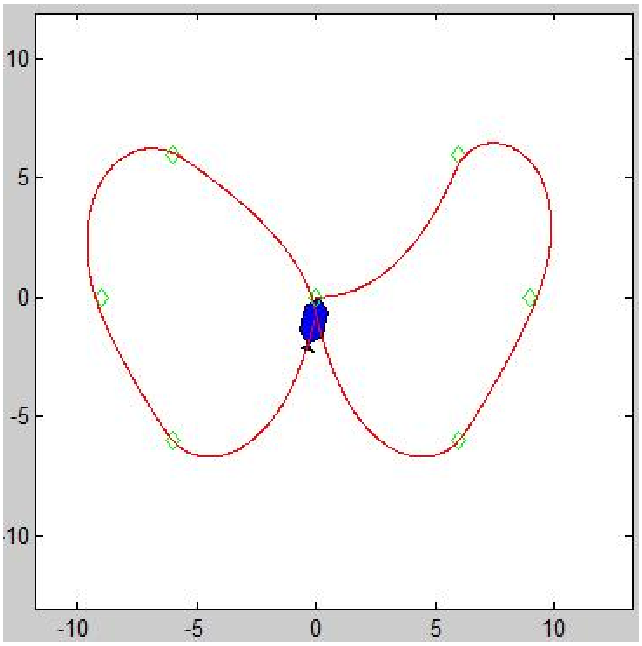

Fig. 6. In this figure, the PD-controller is benchmarked by making it negotiate a complex way-point tracking resembling the figure of 8. It proves the effectiveness of the controller in surface swimming. Future work will develop a 3D controller.

for controller action. Thus is controlled by the error in speed in the fashion of a simple proportional controller. Similarly, if a particular orientation has to be tracked then yaw angle has to be controlled. Again this is achieved by varying the mean position of the servo-link mechanism as this leads to yawing of the system. This is because initially the servo angles $\phi_{0,1}, \phi_{0,2}$, and $\phi_{0,3}$ are equal to zero. By changing the angle values, the fish is allowed to generate forces and moments along $z-$axis leading to the desired yawing. Eventually if depth control is desired then the movable mass has to be displaced to cause a change in the relative positions of centre of mass and centre of buoyancy. This will result in net moment about the COM about $x-$axis and lead to pitching action which will be then used indirectly to navigate the depth dimension.

These control inputs can be visualised as forces, generally referred to as control forces. When an error in surge speed causes a change in frequency, basically acceleration is being produced. This can be mapped to forces following Newtons second law. Similarly, an error in yaw or pitch orientation will cause change in mean position of servo-link mechanism and displacement of movable mass respectively, thus generating angular acceleration which can analogously be mapped to moments about respective axes.

Thus there are 3 layers of control. Layer 1 includes respective errors in u, θ, and ψ. Layer 2 is composed of frequency of undulation of tail fin, mean position of undulation of servo-link mechanism and location of movable mass. Layer 3 is composed of the control forces and moments in respective directions. The above discussion can be summed up in three equations as below.

$$X_{control} = k_{p1}\, Er_s \tag{27}$$

$$M_{control} = k_{p2}\, Er_y \tag{28}$$

$$N_{control} = k_{p3}\, Er_p \tag{29}$$

Here Er_s=error in surge speed tracking,Er_y=error in yaw orientation tracking, and Er_p=error in pitch orientation tracking.

8. CONCLUSION

In this paper, both mechanical and controller designs have been presented. Instead of placing a servo at each joint, placing them at the head allows us to make the posterior body flexible and light-weight. It has also been presented as to how a flexor-extensor mechanism can be exploited to mimic fish undulation. Though flexor-extensor mechanism has been used previously in connection with human arm to model undulation among a host of other kinds of motion, our novelty lay in using the particular mechanism while reducing the number of servos. Robotic fishes hold immense opportunity for innovation. About 70% of earths water bodies remain unexplored. With the burgeoning population and the concomitant pressure on land resources, exploring seas is now becoming necessary. Robotic fishes will indeed lead the show in navigating the oceans and seas efficiently.

9. FUTURE WORK

At present, the 3-link mechanism is being experimented with to get the Arduino to autonomously coordinate the three links in synchronisation to mimic fish undulatory motion. The designs of outer body are ready and their fabrication and assembly are the next logical step to be completed. A proposal has also been mooted to do water-tunnel tests or other experiments and try to throw some light on why the fish is able to generate so much thrust in forward direction with such little effort (Parry, 1949). Moreover, once the dynamics of the robotic fish is better understood, it will become possible to explore more sophisticated methods of motion control. We also plan to analyse forces involved in the compliant mechanism. Finally, a simulation of the undulation must be developed to experiment with different planning and control algorithms.

REFERENCES

Alessi, A., Sudano, A., Accoto, D., and Guglielmelli, E. (2012). Development of an autonomous robotic fish. In *Biomedical Robotics and Biomechatronics (BioRob)*, 1032-1037.

Chen, Z., Shatara, S., and Tan, X. (2010). Modeling of biomimetic robotic fish propelled by an ionic polymer-metal composite caudal fin. *Mechatronics, IEEE/ASME Transactions on,*, 15(3), 448-459.

Childress, S. (1981). Mechanics of swimming and flying *Cambridge University Press.*

Ellerby, D. J., and Herskin, J. (2013). Swimming Flumes as a Tool for Studying Swimming Behavior and Physiology: Current Applications and Future Developments. *Swimming Physiology of Fish* , 345-375.

Fish, F., Legac, P., Williams, T., and Wei, T. (2014). Measurement of hydrodynamic force generation by swimming dolphins using bubble DPIV. *The Journal of experimental biology*, 217(2), 252-260.

Fossen, T. (2011). Handbook of marine craft hydrodynamics and motion control *John Wiley and Sons.*

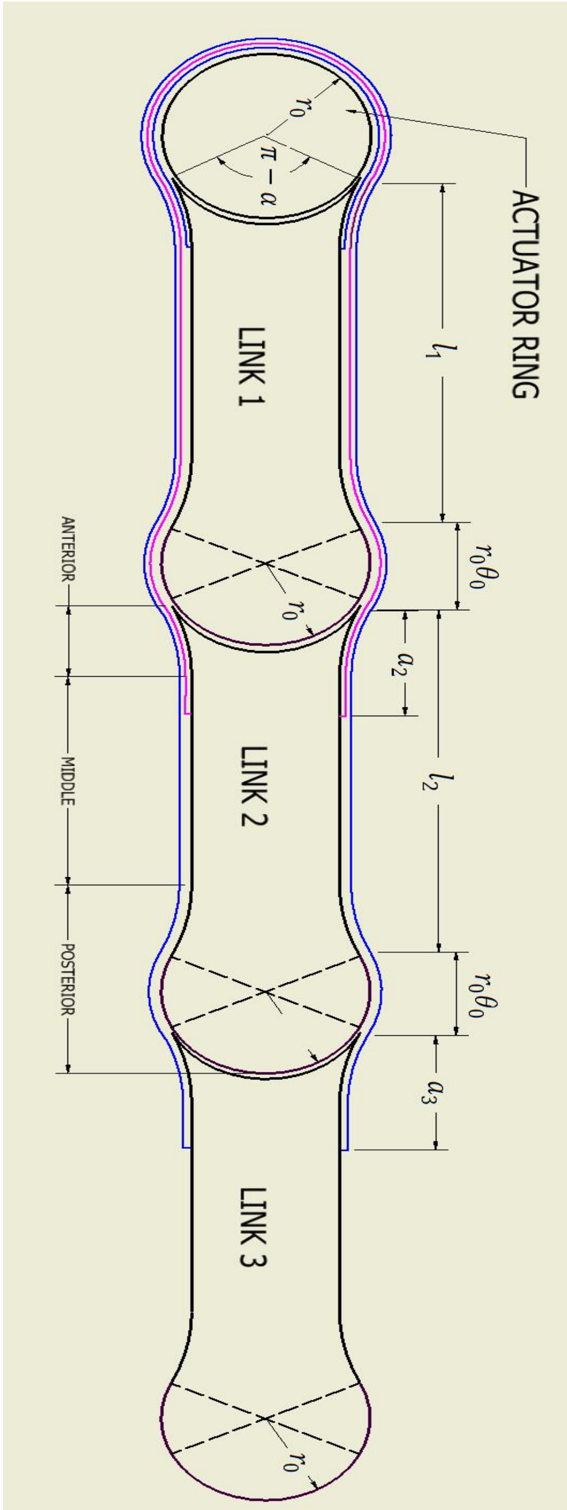

Fig. 7. A full schematic of the 3R link mechanism with the actuator ring is shown. The three curves in blue denote the strings connected to various links. Note that the string connected to link 1 is redundant here as this link is directly actuated by a servo and not using strings.

Helfman, G., Collette, B., Facey, D., and Bowen, B. (2009). The diversity of fishes: biology, evolution, and ecology. *Wiley. com.*

Hong, C., and Chang-an, Z. (2005). Modeling the dynamics of biomimetic underwater robot fish. *Robotics and Biomimetics (ROBIO). 2005 IEEE International Conference on*, 478-483.

Hu, H. (2006). Biologically inspired design of autonomous robotic fish at Essex. *Proceedings of the IEEE SMC UK-RI*, 1-8.

Kelly, S., and Murray, R. (2000). Modelling efficient pisciform swimming for control. *International Journal of Robust and Nonlinear Control*, 10(4), 217-241.

Lighthill, M. (1960). Note on the swimming of slender fish *J. Fluid Mech.*, 305-317.

Lighthill, M. J. (1971). Large-amplitude elongated-body theory of fish locomotion. *Proceedings of the Royal Society of London. Series B. Biological Sciences*, 179(1055), 125-138.

Liu, J., Dukes, I., and Hu, H. (2005). Novel mechatronics design for a robotic fish. *Intelligent Robots and Systems, 2005.*, 807-812.

Mason, R., and Burdick, J. (2000). Experiments in carangiform robotic fish locomotion. *Robotics and Automation, 2000.*, 428-435.

Parry, D. (1949). The swimming of whales and a discussion of Gray's paradox. *Journal of Experimental Biology.*, 26(1), 24-28.

Shang, L., Wang, S., Tan, M., and Dong, X. (2009). Motion control for an underwater robotic fish with two undulating long-fins. *Decision and Control, 2009.*, 6478-6483.

Dover, V. (2000). The ecology of deep-sea hydrothermal vents. *Princeton University Press.*

Videler, J.(1993). Fish swimming. *Springer.*

Yu, J., Wang, S., and Tan, M. (2005). A simplified propulsive model of bio-mimetic robot fish and its realization. *Robotica*, 23(1), 101-107.

Zhou, C., Cao, Z., Wang, S., and Tan, M. (2006). The posture control and 3-D locomotion implementation of biomimetic robot fish. *In Intelligent Robots and Systems, 2006*, 5406-5411.