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Bio-Inspired Swimming Techniques for Robotic Fish using Fow and Pressure Sensing Mechanism (Computational Bio-Mimetic)

S. Rajamohamed[1*] and P. Raviraj[2]

[1]MS University, Tirunelveli - 627012, Tamil Nadu, India; Raja_delip@yahoo.com
[2]KIT, Coimbatore - 641 402, Tamil Nadu, India; drpraviraj@gmail.com

Abstract

This paper presents the findings of our research work to develop bio-inspired techniques for robotic fish navigation based on flow sensing and efficient cum optimized propulsion with a tractable mechanism inspired by fish. We describe the outcomes of simulation for stream flow sensing to choose angle of attack (Rheotaxis) and tail fin based propulsion investigations using SOLEIL with respect to salmon and zebra fish models. To detect difference in pressure on either side we have used Bayesian estimation of flow speed and orientation (direction) by ingesting pressure measurements into 2D & 3D potential flow model. Subsequently based on flow and pressure we have formulated suitable propulsion system to counter up and down streams.

Keywords: AUV, Biohydrodynamics, Bio-mimetic, Fin Propulsion, Karman Vortex, Rhetoaxis, SOLEIL

1. Introduction

When it comes to the design of an autonomous underwater robot it's always a tough ask due to amount of work involved in it and it is also influenced due to the environmental properties such a liquid flow and its pressure etc[1,2]. The advantages of biologically inspired system is to get the best out of nature as it serves as a real time example while designing such systems with high cruising speed and acceleration, good maneuverability and high efficiency. Mainly it should have controllability in unexpected situations or coming out unscathed in extreme conditions. Yellow fin tuna can swim with a speed up to 40 knots and also maintaining superior agility while some of them can swim in the reverse direction in no time and also loosing very less amount of energy compared to 50% loss of underwater vehicles[3]. The field of bio-mimetic system has got certain objectives such as 1. to use biological structures to modify design, assembly, and putting things together with sensors in the autonomous robots[4]. 2. to develop control algorithms inspired from biological life for data acculturation to achieve specific goals, such stream direction identification and following, selecting a suitable propulsion strategy from the accumulated data and so on[5,6].

1.1 Fish Sensing Water Flow (Upstream/ Downstream)

A Natural example of a sophisticated biological flow sensing system is the lateral line One prominent example of an advanced biological flow-sensing system is the lateral-line system present in aquatic vertebrates, mainly fish, used to detect movement and vibration in the surrounding water. The sensory ability is achieved via modified epithelial cells, known as hair cells, which respond to displacement caused by motion and transduce these signals into electrical impulses via excitatory synapses and they sense local flow velocity and pressure-difference information using a lateral-line sensory system. The uses of the lateral-line system in fish include orienting in flow (rheotaxis), schooling, detecting obstacles, and avoiding predators. For example, the Chinook salmon fish

** Author for correspondence*

relies on the lateral-line system for orienting, navigating, and schooling[7]. The lateralline system often runs the length of the fish and is made up of receptors, known as neuromasts, ranging in number from under 100 to well over 1000[8]. The neuromasts consist of ciliary bundles of hair cells that serve as mechano-electrical transducers with directional sensitivity covered in a gelatinous outer dome called a cupula[9]. Neuromasts exist in two types: superficial neuromasts, which are located on the exterior surface; and canal neuromasts, which are located between pore entrances of a subdermal lateral-line canal. Superficial neuromasts serve as flow velocity sensors, whereas canal neuromasts, responding to pressure-driven flow in the canal, measure pressure differences[10].

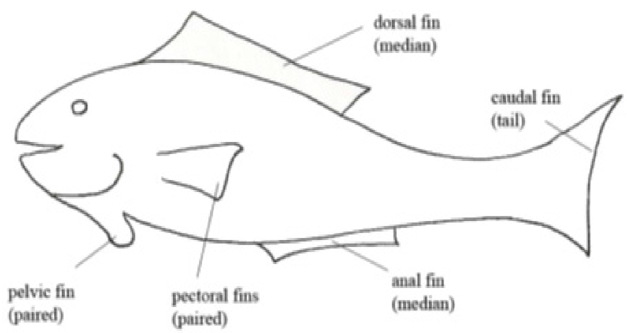


Figure 1. Fish Anatomy.

1.2 Fish Propulsion

A great deal of study has been ongoing to design underwater bio-mimetic robots and it has very complex system copied from marine creatures to solve problems naturally. Generally fish swim in two different ways 1. periodic movement of few parts of fish generating thrust 2. median / pectoral fin based movements. These two are classified as BCF and MPF respectively. BCF is used by more than 80% of the fish category due to its fast and efficient swimming style. Since MPF based swimming is a very slow and highly maneuverable technique it is very rare in marine creatures. Further the BCF propulsion system is divided to four sub categories shown in Figure 4 such as (anguilliform) whole body undulation, (subcarangiform) undulations confined to final half of body, (carangiform) undulations confined to final third of body, and (thunniform) undulations confined to the caudal fin and peduncle only[11]. Scientists have identified two primary phenomena at work during fish swimming that are responsible for propulsive thrust. The first is an added-mass effect whereby the fish body imparts momentum to the water directed backward and an equal opposing force is exerted on the fish propelling it forward. The second is a vorticity effect whereby the vortices in the fish body's own wake impart a propulsive force, as the vortices in the fish's wake have a rotation and effect opposite that of a classical drag inducing Karman vortex street[12].

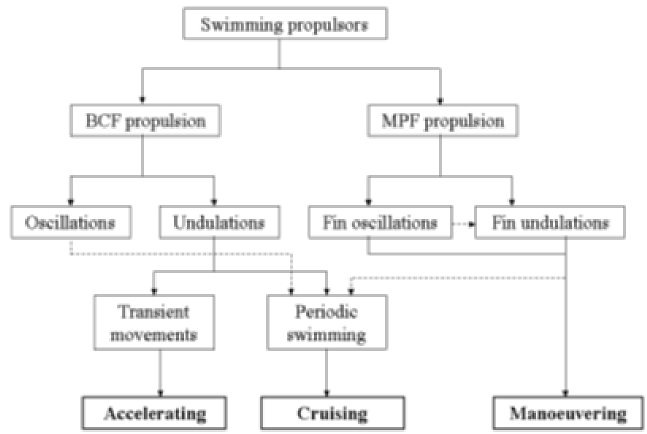


Figure 2. Swimming models classification adopted from[15].

1.3 SOLEIL

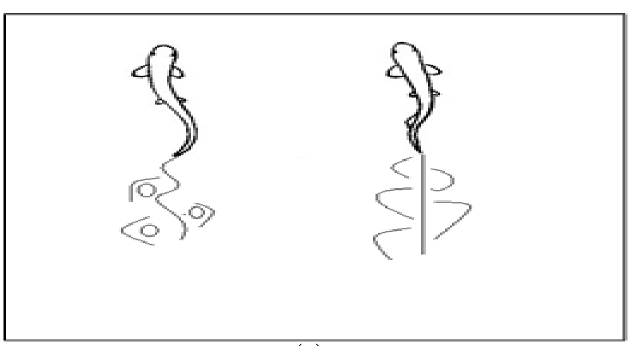
SOLEIL (SOLveur d'Equations Integrales pour la Locomotion) is a Matlab[13] suite of functions for simulating the swimming motion of a fish in a perfect fluid with open source license. It can be used to test to locomotion of fish inside perfect fluids using built-in packages and provides solutions for the problems related to motion planning, optimal swimming strategies, optimal fish shapes[14]. In SOLEIL, the fluid is assumed to be perfect and the flow potential. The hydrodynamics forces are computed by means of integral equations set on the surface of the fish (no 3D meshing required). The shape of the fish and its way of swimming are defined by Matlab functions which can be easily modified.

2. Background

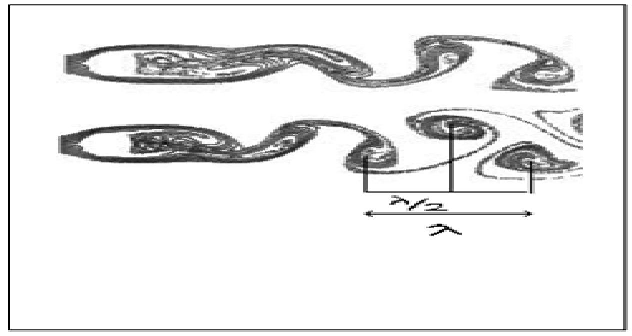
Several bio-inspired AUVs have been built for various reasons. Despite the fact that all of these robots aim to provide alternatives to propellers, their propulsion mechanisms differ substantially. Some of the bio-inspired AUV are Aqua Penguin, a new AUV with a very bendable body that can move smoothly in any direction[16]. SHOAL, an underwater robot having only one servo motor to actuate its caudal fin built by BMT Group[17]. FILOSE , 7th framework, European Agency to sense flow (upstream) using artificial lateral line with caudal fin movement[18].

2.1 Propulsion Methods

In a Karman street, two vortices of opposite rotation are created per oscillation shown in the above Figure 3 and λ denotes the wavelength. The reverse Karman street is similar to this, but the opposing vortices created have the reverse sign. Oscillating foil can take many forms and their vortices lend only dynamic instability to the fluid flows resulting in a reduction in thrust, and sometimes drag on the foil. It also affects the parameters such as frequency of oscillation, amplitude of sweep, and velocity. Generating locomotion in liquid environment involves the transfer of momentum from the body to the surrounding environment and vice versa. The main momentum transfer mechanisms are via drag, lift and acceleration. The forces acting on the swimming body often measured in body lengths l per second (BL/s), are weight, buoyancy and hydrodynamic lift in the vertical direction, along with thrust and resistance in the horizontal direction. But fish can adapt to the surroundings to reduce the amount of effort it produces to swim. It can alter its path in-order to synchronize with vortices being shed from upstream objects. When doing so it does not need change their tail flopping frequency and at the same time maintaining its swimming speed[19]. In reality, at ultimate swimming speed is measured based on the length of the body per second, the tail wave speed is greater than the speed of the flow around the fish as the forces on the body are balance by drag[26]. Several swimming modes are shown in Figure 4.



(a)



(b)

Figure 3. (a) karman street generated by fin and (b) Karman vortices with r=75 and r=125.

2.2 Flow Sensing Methods

Rheotaxis and Station-holding are the two important fish behaviors for bio-inspired robotics. Firstly orientating itself towards the oncoming flow of upstream where station-holding, and protecting itself and swimming behind an upstream obstacle. Exact purposes of lateral-line sensing modalities in carrying out these behaviors have an important role to play. Artificial lateral-line system provides an additional sensing modality in unknown and unsteady flows. Moreover, it would provide indispensable sensory information in dark, murky, or cluttered environments, where traditional sensing modalities like vision or sonar may be impaired. The first artificial lateral line to sense flow of water was developed in 2006[20]. In 2012, Tao and Yu[21] provided a comprehensive review of biomimetic hair flow sensors, followed by analytical work on a model for flow sensing of a Karman vortex street were also performed. In this paper, we particularly concentrate on closed loop rheotaxis demonstrated by Salumae et al.[18] using pressure sensor and a Braitenberg controller followed by station holding in similar environment[22]. We have deployed a reduced order fluid-mechanics model for flow across streamlined body based on potential-flow theory. Bayesian filtering helped us to create a dynamic flow-sensing control loop for rheotaxis property and subsequently validated our potential-flow model with help of SOLEIL Computational Fluid Dynamic (CFD) simulations were performed.

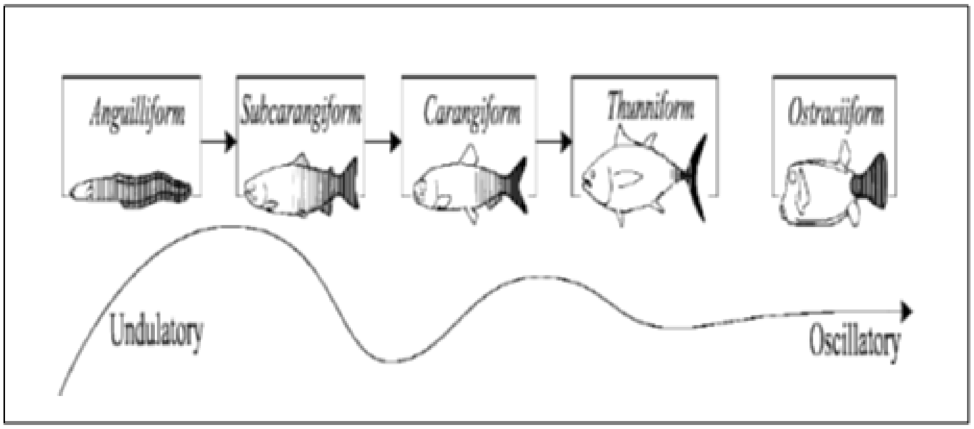


Figure 4. Swimming models classification adopted from[15].

3. Measuring Pressure Difference For Rheotaxis

To measure the difference in pressure across the fish body in perfect liquid flow conditions we have used a reduced order hydrodynamics model which has to predict the pressure difference using two sensors placed in the body of the robot fish. To estimate the flow parameters based on sensor measurements in perfect flow liquid environment using potential flow theory we have used Joukowski transformation[23] $\xi = Rei\theta - \lambda$ be a disk of radius R centered at λ and 2D transformation equation follows

$$Z = \xi + b^2/\xi C \quad (1)$$

and assume U be the free stream flow speed and α be the angle from which to induce rheotaxis. Using (1) velocity potential

$$\omega(\xi) = U(\xi + \lambda)e^{-i\alpha} + R^2/(\xi + \lambda)^*Uei\alpha + 2iRU\,Sin(\alpha)\ln(\xi + \lambda) \quad (2)$$

the above equation (2) states point at which rear stagnation must occur towards the tail end of fin by representing uniform flow, boundary conditions and Kutta conditions relevant to the body of the fish[24]. The conjugate flow around the body in z coordinates $f^*(z)$ represented by equation (3).

$$f^*(Z) = \partial\omega/\partial\xi \; (\partial Z/\partial\xi)^{-1} \quad (3)$$

the predicted pressure values by potential flow model in

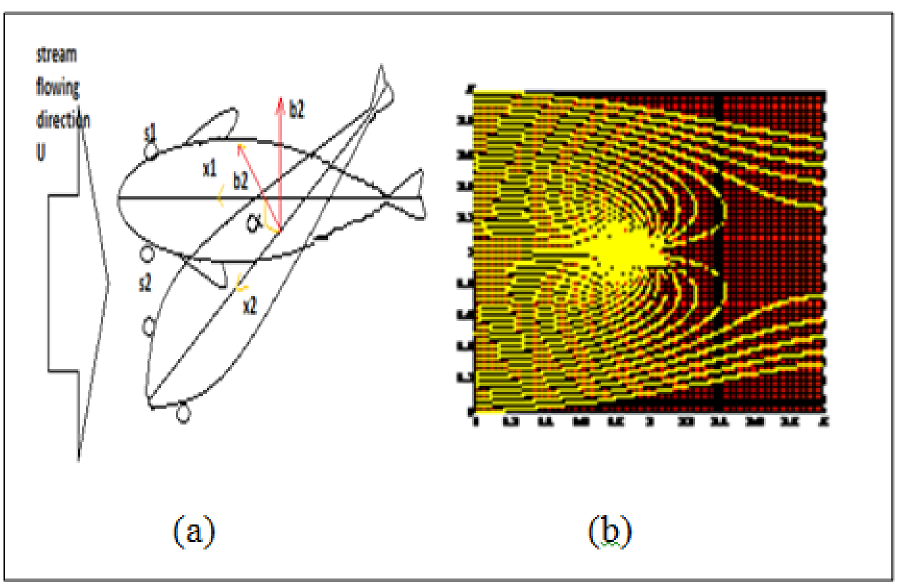


Figure 5. (a) Reference frames and flow field parameters and (b) 3D Flow model.

connection with Bernoulli's principle for zero viscosity conditions fluid across the body of the fish with sensors located in opposite directions.

$$v/2+gz+p/\rho = C \quad (4)$$

Where v is represents local speed, g refers to acceleration of gravity, z is the elevation, p is static pressure, and C is a constant referring to energy of the fluid that passes through the body. When the equation (4) is applied to two points that lie at the same elevation along the body finds the pressure difference at second point acting as the pressure stagnation comparatively.

Figure 5b illustrates the difference in pressure between two sensor locations. For a random angle value stagnation pressure to be measure and the pressure difference is good enough rather finding the stagnation pressure.

$$\Delta p=p1-p2= \rho/2\ (v1^1-v2^2) \quad (5)$$

The potential velocity chosen based on the flow speed relevant to the length of the body and here our fish length is approximately 30cms. Total angle coverage is limited to α Є (-200,200) to avoid stall condition. In both 2D and 3D flow models noise signal is also present and it is due to the errors in calculating differential pressure between two sensors. Additive noise in the pressure measurement process for successive instances are represented by equation (6) and the difference in pressure with noise is shown in the following equation

$$p_i=p_i+\eta_i \quad (6)$$

$$\Delta p= \rho/2(|f^*(z_1,\Omega)|^2-|f^*(z_2,\Omega)|^2+ \eta_{2=}\ \eta_1 \quad (7)$$

$$\Pi(x|y)\ \alpha\ \Pi(y|x)\ \Pi(x) \quad (8)$$

Here x is an unknown quantity, based on the measurement of y. η refers the Gaussian distribution with variance to be introduced σ2 and Ω is expressed as {U, α}T When the term U i.e. potential flow is zero then α cannot be observed or in other words noise signal causes such problems when the pressure difference is very low. Variances S1 and S2 are collected from two sensors to calculate noise distribution during free stream flow and also cause noise in the pressure measurement.

3.1 Rheotaxis Framework

Rheotaxis is a property possessed by very few fish types explained in section 1.1 earlier to be realized from pressure measurements leading to flow filed parameters using Bayesian filtering technique. It is mainly used when an unknown quantity involved and uses assimilation of measurements. Here we have used grid based Bayesian estimation in which a finite volume of parameter space is discretized, and the probability density functions are approximated on this grid. Normalization is performed by summing the weights of all the grid points and dividing by the total value. The assumption of white Gaussian measurement noise results in a Gaussian likelihood function.

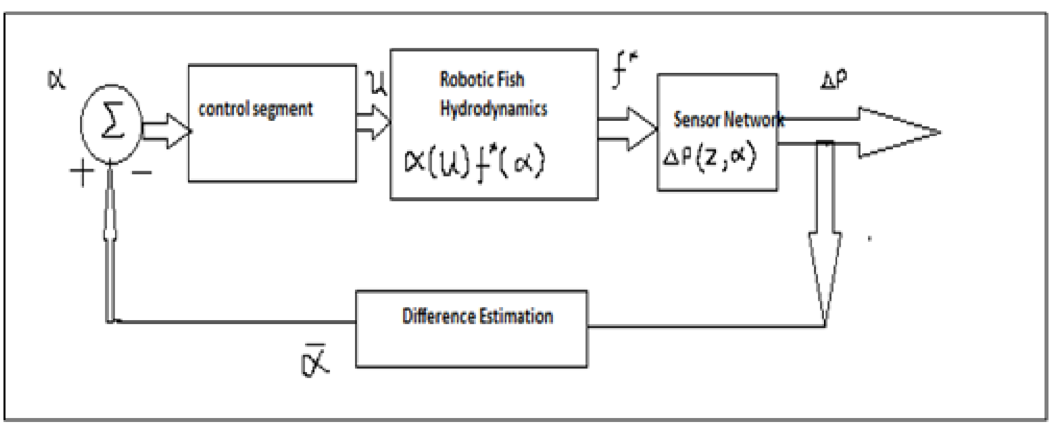


Figure 6. Bayesian estimation based control structure for Rhetoaxis.

$$\Pi(\Delta p/z,\Omega)\alpha \exp\left(-(\Delta p-\Delta p(z,\Omega))^2/2(\sigma^2_1+\sigma^2_2)\right) \quad (9)$$

Here we choose the value for the term σ21, σ22 based on maximum relevant flow speed. Pressure sensors give us a sequence of measurements at specific time intervals including assimilation at a given time t is

$$D(t-\Delta t)=\{\Delta p(t-\Delta t),\ldots,\Delta p(t_0)\} \quad (10)$$

Systems knowledge evolves by comparing state evolution equation and the measurement equation at various time sequences and can be augmented with new information, known as Bayesian filtering.

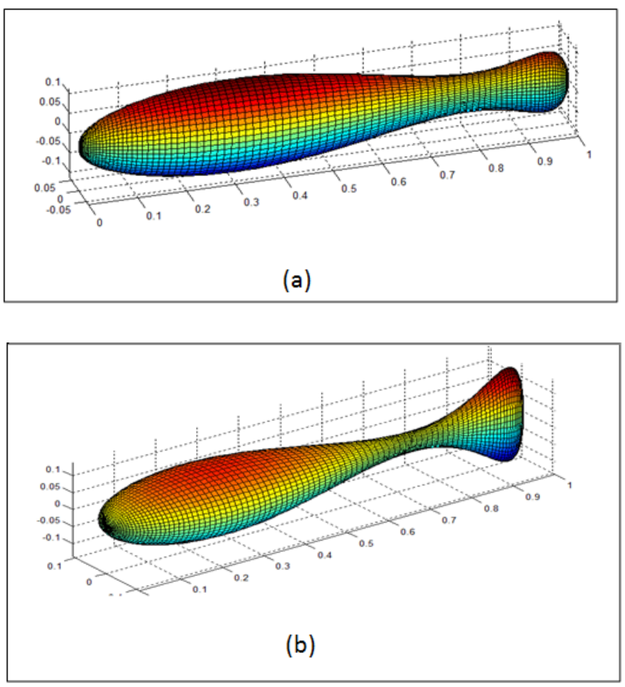


Figure 7. (a) Fish model with flat body and (b) wide body and elevated tail fin.

3.2 Dynamic Control for Rheotaxis

The above Figure shows the structure of control system to perform rheotaxis with reference to flow pressure and speed and generating commands to change the angle i.e α=u where u is the control input and robot fish moves α and u values are estimated based on equation (11). Since the Bayesian filter is applied during movement, it is essential to account the next motion of the fish. The fish types which are swimming based on fin undulation having rhetoaxis property such as salmon and zebra fish models can be designed and controlled using framework that uses simple calculation and less complexities.

4. Bio-Inspired Propulsion

Robotic fish should be able to navigate in any type of conditions inside water environment and capable of dealing with stream flow, vortices, and avoiding obstacles etc. we propose a novel approach to optimize the propulsion mechanism of robotic fish using Lighthill's fish swimming model with c-term wave envelope for tail fin undulation[6]. Each c-term's characterization is having some sort influence in determining swimming efficiency after verifying number of trial values using simulation techniques[25,27].

4.1 Tail with Fin Activated Undulation

Fish tail provides the propulsive force and control surfaces enable directional control of the same. According to Lighthill's biofluid dynamics fin causes an oscillation by swinging its tail and to reach certain speed while swimming it has to flap its fin at particular frequency depending distance and time.

$$y_{body}(x,i)=(c_1x+c_2x^2)(\sin(kx+(2\Pi/M)*i) \quad (11)$$

Here robot fish body' tail section having multiple links decomposed in to M number of time periods separated by time interval i. equation (11) gives the frequency at which the tail section must flap to attain required speed. The constraints applied to each link must result in the actual link length l, and that the j-th tail link must fit the curve. The result is a system of equations to get normalized length of the fin setup.

$$(x_{i,j}-x_{i,j-1})^2+(y_{i,j}-y_{i,j-1})^2=l_j2 \quad (12)$$

$$Y_{i,j}=(c_1x_{ij}+c_2x_{ij}^2)\sin(kx_{ij}+2\Pi/M^*i) \quad (13)$$

Fin Oscillation is represented in the form of a 2D matrix for each time step. The model can be used to set the angular information of robot fish's servomotors to set or to control its states. Scaling the angle to a servo motor articulation again can be decided by the type of servo and its durability with + or – angular deviations.

5. Experimental Results

All the experiments were done using the open source simulator called SOLEIL described in section 1.3 and also using MATLAB. Section 5.1 will discuss about the pressure difference detection using pressure sensors to imitate rheotaxis in fish types like zebra and salmon etc when an upstream attacks them.

5.1 Flow Sensing Simulation Specifications

A mesh model of the fish such as salmon or trout with narrow body and generic tail fin size and wide body with elevated tail fin have been designed using SOLEIL also shown in the following Figure 7 a and b respectively. Any type of shape and size specifications can be designed using the system and mesh model can be generated instantly.

5.2 Experiment 1: Flow Sensing and Rheotaxis

First of all we identify the uniform flow direction by measuring the difference between two sensors virtually modeled (MS5407-AM) used in FILOSE project for better understanding. Sensor based controller framework senses the region with high pressure and directs fish in to that direction. During uniform flow it maintains the same position until there is a change of pressure in water flow. Movement of the fish body is limited to -200 to 200 degrees in this case and in Figure 8a without feedback fish starts to move even beyond the limited angle in either direction. In Figure 8b fish is swinging to the sideways like sine waveform when the feedback system is not supported. Fish determines the angle which it has to attack as part of its rheotaxis property is up to the stream flow and its direction shown in Figure 9.

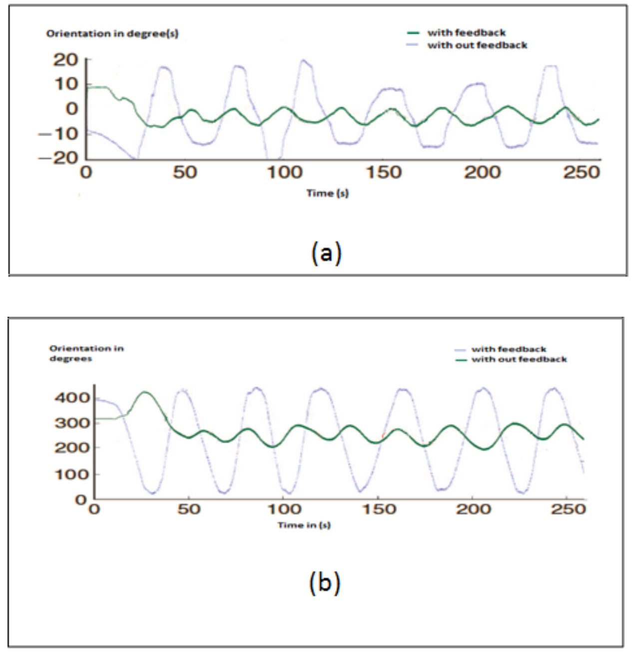
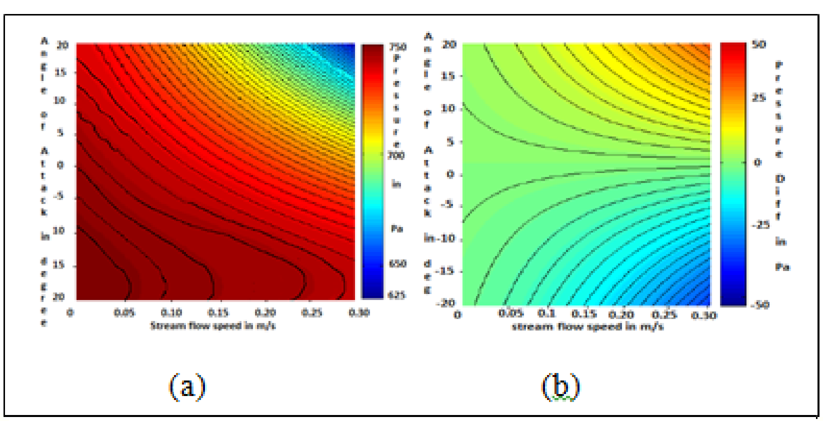


Figure 8.

5.3 Experiment 2: Adapting to Flow based Schemes

The fish model has always encountering a problem called drifting or side-slipping with respect to the incoming flow due to the passive dynamics. This can be controlled by readjusting the fish model but in real-time it becomes a tough ask due to unknown location and orientation. Speed with respect to flow helps in reducing energy consumption and allowing stable schemes of swimming. In Figure 9 there are two different schemes with their flow compared with their respective schemes in unknown positions and directions. The average deviation from the desired scheme is reduced by 7% for scheme -1 and it



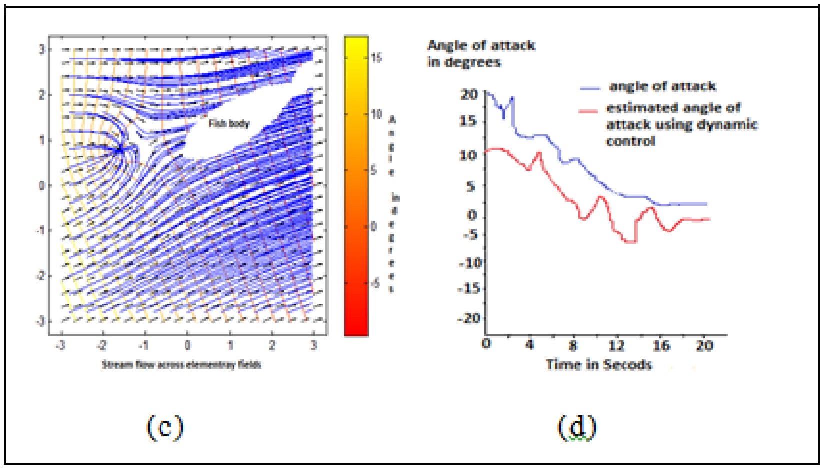


Figure 9. (a) Pressure of fluid for single sensor, (b) Differential pressure of two sensor, (c) Potential flow of stream, and (d) Bayesian filter based Rheotaxis.

is due to the parallel flow disturbing the fish dynamics which is ignorable. In Scheme-2 90% of the time flow is perpendicular to the desired scheme and having lot many variations. In the closed scheme tests we can extend the experiment by calibrating the error deviation to identify exact trajectory against the desired one.

5.4 Experiment 3: Energy Reduction using Vortices

Energy is a big concern for robots especially which are operating inside water and having many unknown parameters. After sensing the direction of water flow it has to decide which way might be the best or safe to navigate with respect to the environmental pressure. To achieve this we adjust the tail fin swinging frequency to generate a particular karman vortex as shown in Figure 10. When the tail bends against high pressure area generated by karman vortex, it makes use of the increased lift force induced due to the difference in pressure on either sides. Figure 10a shows the position of the tail fin with maximum thrust and Figure 10b with minimum thrust. This is directly in relationship with karman vortexstreet generated by the tail swinging action performed by fish to produce thrust and this was tested with different stream flow speeds.

5.5 Experiment 4: Effects of Tail Fin Length on Swimming Speed

One of the parameter that affects the swimming speed of a fish is its tail fin length but it has several other parameters such as body shape, mass, muscle, respiratory system and its growth etc. In Figure 11 a change of 5 cm in length causes a decrease in swimming speed from 30cm/s to 21 cm/s for tail length of 5 to 10 cm. but when we decrease the stiffness by reducing muscle component of tail fin then again speed increases suddenly to the high 30cm/s. Speed rate changes around 25-35% whenever there is

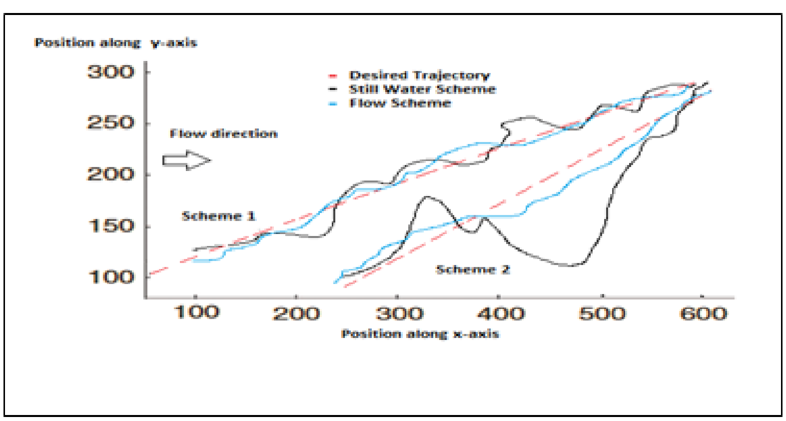


Figure 10. Flow assisted swimming schemes.

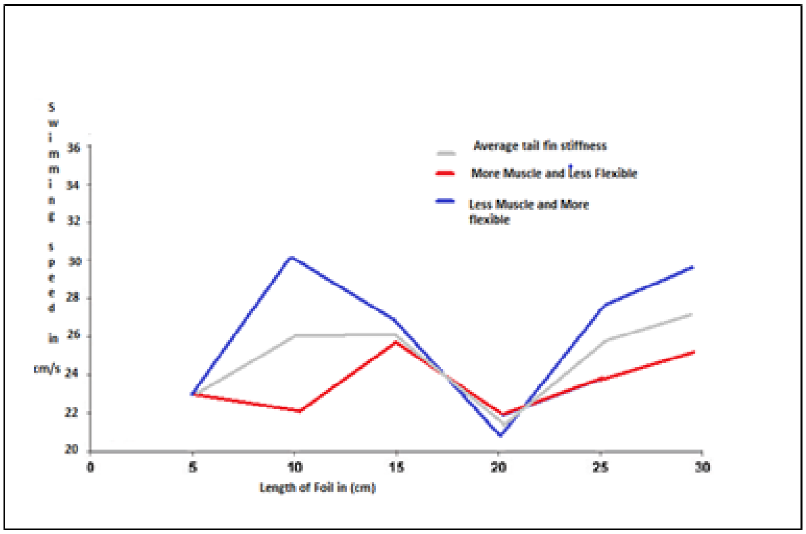


Figure 11. Unexpected non-linear effects of tail fin length on swimming speed.

a change in the length of the tail fin along with its size (muscle). Tail fin movement should be happening in a continuous manner to achieve otherwise it will damp at some stage. Further we can also decide what should be length and thickness of the tail fine to achieve specific speed for swimming.

6. Conclusion

Robotic fish inspired by the properties of natural fish such rhetoaxis and flow sensing throw body line have been tested and it plays a major role in testing underwater robots in several aspects and to certainly help improve the hydrodynamics of robotic fish using sensor network and our future work is to identify fin related effects and shapes in improving swimming efficiency etc.

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