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Optimized curve fitting for rigid body segments of robotic fish using biohydrodynamics simulator

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Abstract— This paper discusses optimization of parameters concerning simplified model of bio-mimetic fish robot propelled by rigid 3 link segments. Considering theoretical aspects of hydrodynamics and practical challenges in engineering realization, rigid segments optimal link-length ratio and motion parameters are numerically calculated using an enhanced rigid body fitting method (RBFM). Further the 3-linked robot fish like structure is simulated in BhT(bio-hydro dynamics simulator) to optimize and improve swimming speed of the robot fish effectively by considering various parameters such as no of joints, body length, shape of tail fin etc.

Keywords—Biohydrodynamics, robotic fish, rigid body fitting, link length ratio

I. INTRODUCTION

In last two decades, robotic research is increasing steadily where robots used to address specific biological aspects inspired by biological systems to provide solutions for complex problems. Various bio-mimetic robots that can perform operations like walking, jumping, flying, swinging to swimming have been tested and constructed [1,3,7,11]. Under the swimming category of robots, robotic fish is purely a desire enabling us to build Autonomous Underwater Vehicles (AUVs) with superior efficiency, maneuverability with lesser turbulence. Furthermore, it provides critical insights about actuation mechanism and controlled fish swimming [3].

According to nature, fish propels itself in a harmonized motion of its body, fins and tail, achieving incredible propulsive efficiency and outstanding maneuverability, which has several benefits over the marine vehicles utilizing less power consuming rotary propellers. In general, normal efficiency of swimming fish is above 80% and carangiform mode of fish is up to 90%. But conventional propeller achieves a mere 40 to 50% only with environmental pollution too. While, a fish like dolphin can swim at 20 knots following oceanic vessels with ease. Then, during hunting, pike fish can chase prey with 20G acceleration. Besides that, fish turns at a radius between 10 to 30% of its body length (BL), whereas conventional ship turns very slowly with 30 percent and above of its BL [10]. According to engineering, fish is a notable AUV prototype that is appropriate for reproduction [7]. Considerable amount of work towards robotic fish was carried out in the early 1990s by Triantafyllou [12] and, was further enhanced by Hirata [6] recently. Based on the rapid growth of aquatic robots, hydrodynamics effects of fish swimming, realizing prototypes with new materials, actuators and control technologies and many more research issues focused on the design and development of robot fish has excelled in the recent past. As a key research area having plenty of practical applications, robotic fish can be utilized as surveillance object military, undersea operations, oceanic supervisions, aquatic life observation and water pollution detection. To assemble an autonomous robot fish, many elementary issues such as imitating fish behavior, following motion parameters, sensors, actuators, hydrodynamics, video image processing, and intelligent motion control and trajectory planning have to be studied[13]. We present a simplified propulsive model for robotic fish design where motion is produced by a multi-link mechanism through an optimized ratio of each link having rigid segments.

Considering zoological theories and actuation problems in the existing fish prototypes, control parameters of the proposed propulsive model are mathematically derived to achieve optimized swimming, which can be applied in robot fish design. The rest of the paper is organized as follows. In section II, optimization parameters for simplified propulsive model are discussed and in section III rigid body based curve fitting mechanism with optimal link length ratio is proposed. In Section IV, a MATLAB based bio-hydrodynamic tool and its usage is discussed and in section V, Experimental setup and corresponding results are given. Finally, section VI conclusions and future work were discussed.

II. Related Work

Fast swimming group of fishes are having some common characteristics such as a streamlined body, carangiform mode of swimming and lunate caudal fin. To allow extensive deployment of effective biomimetic robot fish platform, a broad framework must be established having the following features (a) the analysis, design, development and control methods are pertinent to a wide range of swimming robots, and (b) key elements of the framework can be stretched in succession. In order to realize such a framework, one strategy is to (i) conceptualize and simplify the swimming action of fish model, (ii) set up a general Kinematic replica of fish swimming (iii) develop motion control methods for this set of bio-mimetic mechanism and

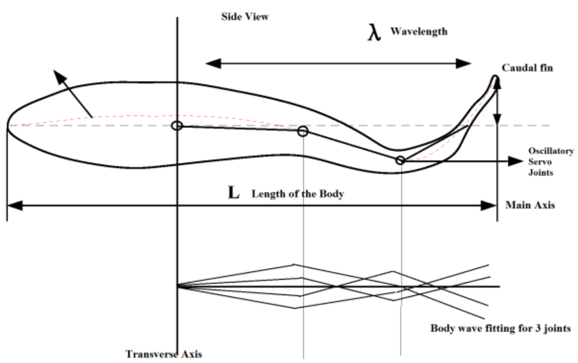

Figure 1. Body wave generated by link mechanism

(d) develop exact systems with diverse applications or tasks. Within the above points, the first step is to list out characteristic parameters influencing engineering realization with respect to fish biology.

A. *Exisiting Work (Review)*

As we have several limitations in choosing sensors, actuators, onboard microprocessor, power capacity, size of elements the practical effort to develop bio-mimetic fish mostly focus on imitating carangiform mode. Based on the biological information shown in Fig. 1 its' parts are divided in to two sections: flexible body and oscillatory lunate caudal fin, where the bendable body represented by a series of hinge joints and the caudal fin similar to laminar foil. RoboTuna (carangiform) swimming prototype was developed by Barrett et al. [4], whose undulatory motion is known for its travelling wave form across the body from head to tail(1) at first suggested by Lighthill [9].

$$Y_b(x, t) = (c1\ x + c2\ x2)\sin(kx + \omega t) \qquad - (1)$$

where Y_b represents the transverse displacement of, x denotes the displacement along the main axis, body wave number is denoted as $k=2\Pi/\lambda$, where λ indicates body wave length, linear and quadratic wave amplitude envelope coefficients c1, c2 and ω denotes the body wave frequency ($\omega = 2\Pi$ f).

According to the biological, hydrodynamic and engineering information composed from literature [4,10] characteristic parameters on swimming motion primarily having:

- The length ratio of the fish's flexible part to that of the fish-body is denoted by R_l. According to that, swimming is classified as carangiform, anguilliform, thunniform and ostractiform. When the value of R is lesser, efficiency of fish swimming surprisingly increases, but manoeuvrability reduces to a certain level.
- The number of joints and rigid segments in oscillatory part (N). Larger the value of N, better the mechanism's manoeuvrability and redundancy, but the efficiency takes its toll. Practically can't have large N value with respect to fabrication and size constraints of the robotic fish as well as faults affecting due to man-made rough calculations.
- Length ratio of each rigid segment (l_1: l_2: ...: l_N). Where l_i (i=1,2,…,N) is relatively short, hinge joints having high density and flexibility to produce large-amplitude oscillatory motion. The ratio of rigid segments in terms of length gets smaller from head to tail. However, oscillatory amplitude increases steadily and tail peduncle it reaches its maximum value.
- Characteristics of caudal fin. The aspect ratio (A_r) of the caudal fin has very important effects over propulsive efficiency which is defined as the square of span, divided by the surface area, i.e., $A_r=S^2/A$. Higher A_r caudal fin value results improved efficiency by inducing lesser drag per unit of lift or thrust produced. At the same time, caudal fin shape makes a telling blow in fish's propulsion with crescent or forked shape usually lend offers high-speed swimming.

Inspired by the propagating propulsive wave acting over the fish body, in [5], a link-based rigid body-wave fitting for robotic fish design was proposed in which discrete body-wave considered on a time variable t separated from (1) rewritten in discrete form as shown in (2) with travelling body-wave is decomposed into two parts: (a) time-independent spline curve sequences Y_b (x,i) (i =0,1,…, N–1) in an oscillation period, and (b) time-dependent oscillating frequency f described as a cycle of oscillating waves at discrete time interval.

$$y_b(x, i)=[(c1\ x + c2\ x2)][\sin(kx \pm 2\Pi/N*i)] \qquad - (2)$$

where i denotes the i-th variable of the spline curve sequence Y_b(x,i), M is defined as resolution of discrete wave that represents the degree of the overall traveling wave. Consider the oscillatory part of a fish having certain number of rotating hinge joints, it can be modeled as a planar serial (N) chain of links in an interval of 0 to $R_l \times 2\pi$ along the axial body displacement, where R_l is the length ratio of oscillatory body part affecting wavelength in producing sinusoidal wave. The link-based rigid body-wave fitting is to make the end-point of each link segment against curve made by fish body and the value of x axis for last link's endpoint equals $R_l \times 2\pi$. Ignoring the appearance, mechanical construction and cumulative error of the links' oscillation during single period is somewhat large and the performance of forward swimming is not satisfactory. In this paper, an uncomplicated method is proposed by seeking the optimal link-length-ratio (l_1:l_2: ... :l_N) in the body-wave fitting applied for the fish prototype made in our laboratory considerably improves the performance of forward swimming through optimization.

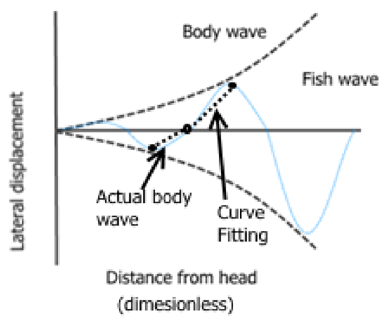

Figure 2. Acutal body wave and fitting line.

B. *Optimization of link length ratio*

As mentioned earlier, the fish's oscillatory parts takes the form of travelling body-wave shown in equation (1), with the design of robotic fish comprising series of rigid segments, making it challenging to reproduce exact motion of biological fish. So it is impossible to fit all points in mechanical skeleton fall into the ideal body-wave in the form of mathematical equation. Hence we need to ensure by keeping key elements of each link satisfying the body-wave, especially at the end points of each link to meet the motion equation. As the chain of links representing oscillatory part of the robotic fish and to have simple mechatronic system, N is usually limited to a relative small value.

In this case, the motion of the robot fish seems to be somewhat stiff. In particular, it is hard to produce smooth transitions in conjunction between two links. Consequently an elastic skin is used to cover the whole section having moving links so as to decrease the redundant hydrodynamic drag and increase the flexibility of the fish body, which can generate fishlike motion taking the form of actual fitting curve shown in Fig. 3. Unfortunately, using elastic transition leads to significant difference between the actual fitting curve and the ideal body-wave. When there is too much difference, the hydrodynamic advantages of ideal body-wave vanish. Moreover, the mechatronic system consists of multiple serial links, lot many limitations in computation and fabrication to be simplified or neglected. Therefore there is a great need to optimize the key characteristic parameters in the body-wave fitting.

III. RIGID BODY FITTING

To find a suitable method which can trade between complexity and computation with precision, we assume the body wave as a link of real objects having uniform force acting against them at any given point. Then there are series of straight line hanging from main axis toward the body wave which tend to contract when it moves and also reaches a stable state and stops there. This can be considered as target position for which a mathematical model has to be developed.

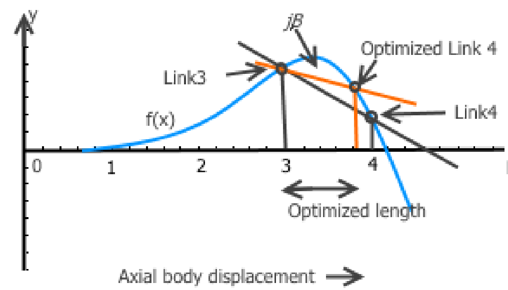

Figure 3. Optimization of link length ratio using Joint method.

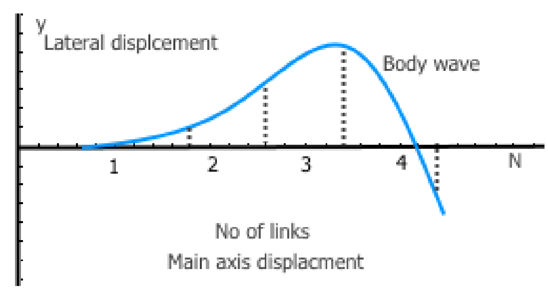

Figure 4. Rigid body fitting method for links.

Based on the movment of dotted lines as show in fig. 4, they are assumed to have a static head and moving tail and other one is assumes all the joints to be totally free leading to have multiple degrees of freedom (DoF) which is very difficult to control. A rigid body α with erection and density f_x at the location x whose acceleration is noted as β as per equation 3.

Here head is assumed to be static, hence the remaining parts only have movement which can be described as follows where xh and xt represent head and tail sections of the rigid body and *j* refers to moment of inertia followed by angular acceleration β

$$j\beta = \int_{x_h}^{x_t} f_x(x - x_t)\cos\alpha\, dx$$ - (3)

$$j = \frac{1}{3}ml^2$$ - (4)

$$\beta = \frac{3}{ml_x^2}\int_{x_h}^{x_t} f_x(x - x_t)dx$$ - (5)

Over all energy required to rotate the body with respect to erection force and angular acceleration can be described in a simple equation.

$$\frac{m}{2l_x}\int_{x_h}^{x_t}[(a + \beta x)^2 + \beta^2 x^2 tan^2\alpha]dx$$ - (6)

Erection force and angular acceleration are computed separately using equations 7 and 8. Shifting along the main axis will cause rotation of the previous segment. If the displacement is smaller than the length of the same, then angular displacement is proportional to angular acceleration. Change in Δα is shown below

$$\Delta\alpha_e = \Delta y_j * \frac{\cos\alpha}{l_i}$$ -(7)

Where lateral displacement y of the next segment and length of the previous segment is considered to calculate the angular movement for each individual rigid segment.

IV. Biohydrodynamics Simulation

This term was used originally by biologists and zoologists for the study of animal locomotion in fluid (fishes, aquatic mammals but also birds are concerned since the air is also a fluid). The investigations to understand the locomotion of aquatic animals have offered increase in scientific publications contributing to society. Such strong interest has took off by observing aquatic mammals and fishes evolved their swimming capabilities far superior to what has been achieved by naval technology. A complete knowledge of biomechanics of swimming robots allows us to improve the efficiency, manoeuvrability and stealth of underwater vehicles.

During the last five decades, numerical models have been suggested through which it qualitative analysis of swimming propulsion is done and also with the continuation of the previously developed quantitative theories. BhT [2] gathers a collection of M-Files for design and performs simulation and analysis of articulated bodies' motions in fluid based on Euler-Lagrangian formalism. More widely, BhT can also perform any kind of numeric experiments addressing the motion of solids in fluids (simulations of so-called fluid-structure interaction systems) [3]. This is a tool for designing, simulating and the analyze the animal motions in fluids modelled as systems of articulated rigid solids by incorporating the rigid body fitting method based on equations 3 to 7. It performs any kind of numerical simulation involving 2D motions of solids in aquatic environment without vortices illustrated in Fig 5 with velocity in blue line and angular acceleration in red line at each instance.

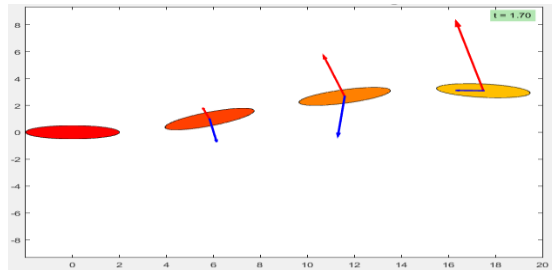

Figure 5. *Velocity and angular acceleration over link mechanism*

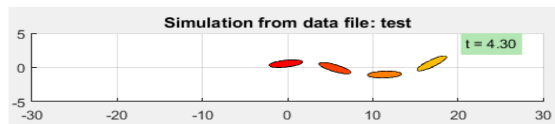

Figure 6. *3 link rigid segments forward movement*

Thrust generated by 3 link mechanism is shown in Fig. 6 at discrete time intervals. Energy is another factor affecting the performance of rigid body segments coupled by relays having lateral and longitudinal displacement. BhT analyzes the energy distribution across the hinge as well as the fluid surrounding fish body. Velocity and angular acceleration can be tested before performing continuous simulation.

V. Experimental Setup and Results

Flexible part of fish consists of many rotating hinge joints. It can be modelled as a planar of links along the main axis [14]. There are three links, i.e., (l_1 to l_4), between the joints. lj (j=1, 2, . . , N) is the link length ratio and N is the joint number. Also two end-point coordinate pairs of each link are determined (x_{j-1}, y_{j-1}), (x_j, y_j) and the joint angle between lj-1 and lj is #j [8]. Primarily, the amplitude coefficients, i.e., (c1, c2, k), are determined, and swimming functions of the discrete travelling wave are founded respectively. The joint angle of the j^{th} link can be computed by fitting them based on the body wave of i^{th} instance and the joint angles (θ_1, θ_2, θ_3) are set in an array [8] for BhT simulation. These operations are performed by the equations described in section II. Swimming functions of the discrete travelling wave are used to determine the motion of the robotic fish, as shown in Fig. 3 and 4.

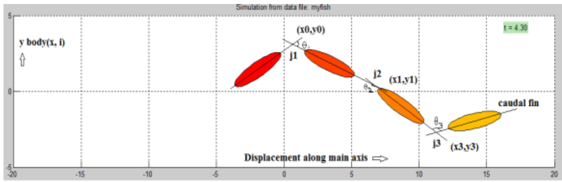

Figure 7. *Body wave curve fitting based on 3 link mechanism*

Two dimensional matrices are obtained to for each joint angle θ_{ij} is used to control the movement of the fish. Here various link length ratios as mentioned in the table 1 used for analytic fitting solution having 3 joints or links as shown in Fig. 7.

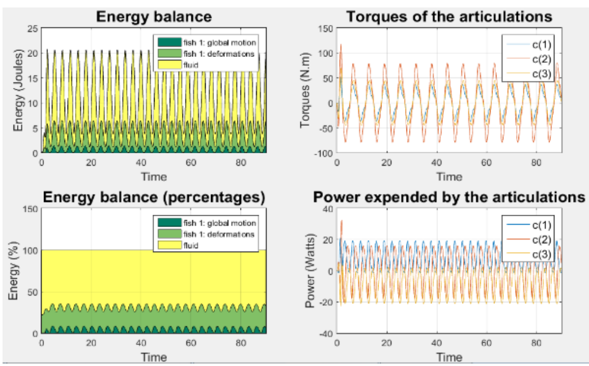

Figure 8. *Energy distribution at 3 link hinges*

Table-1 Parameters of Link Segments

Segment description	Segment Number	Length (meters)	Mass (Kg)	Moment of inertia (kg.m2)
Head Section - fixed	1	0.20	0.18	0.0072
Joint 1	2	0.10	0.07	0.0007
Joint 2	3	0.07	0.03	0.000147
Joint 3 - Caudal fin	4	0.03	0.02	0.000018

Table-2 Optimal link fitting using RBFM

Servo Link distance from head (ratio)	Curve Fitting	
	Curve Fitting Method	Rigid-body Fitting method
0	0.0	0.0
1.4	0.2	0.3
2.7	-0.4	0.2
3.6	-1.4	-0.9
4.4	-1.9	-1.9

Initializing the parameters of links segments are listed in table.1 and the distance of servo links with respect to head section is shown in table.2. Rigid body simulation method avoids the displacement parameter calculation beyond second order derivatives and produce comparatively better link length ratio even when i^{th} link is far away from the body wave. When it is too close to be fit the error region can be ignored. Here linear and square values of error distribution are computed and listed in table2.

$$L_{err} = \int_{x_h}^{x_t} (y_f - y_s)dx \qquad -(8)$$

$$S_{err} = \int_{x_h}^{x_t} (y_f - y_s)^2 dx \qquad -(9)$$

Integral of the body wave and fitting curve is calculated using equation 8. Then square error or integral of the second order derivative is calculated based on equation 9 and their differences are listed in table4.

Table-3 Speed Comparison with and without Optimal Link Length

Frequency in Hz	Steady state swimming in m/s	
	Linear fit before optimization	Linear fit after optimization
0.5	0.14	0.17
0.6	0.14	0.17
0.7	0.16	0.19
0.8	0.17	0.22
0.9	0.18	0.23
1.0	0.19	0.25
1.1	0.21	0.26
1.2	0.22	0.28
1.3	0.23	0.29
1.4	0.24	0.31
1.5	0.25	0.32

Speed of the swimming robot is also listed in table3 for varying operational frequency with respect to the relays generating body wave. Error at discrete time poinst are showing visible difference in terms of performance between joint curve fitting and rigid boy fitting methods as the second one has little and ignorable amoun of deviation in determing the location of link segments.

Similarly when operating the robotic fish at varying frequencies ranging from 0.5 to 1.5Hz it significantly gets improvement in the steady state swimming mode by generating 21% extra forward thrust.

Table-4 Optimal Link Length error distribution

Segment Number	Link length Ratio	Length (meters)	Linear error		Square error	
			Curve fitting	Rigid body	Curve fitting	Rigid body
1	1	0.4	282	-31	117	74
2	1:0.5	0.3:0.1	299	-18	135	86
3	1:0.75:0.5	0.3:0.07:0.03	244	-10	116	75
4	1:0.8:0.4:0.2	0.2:0.1:0.7:0.03	169	11	71	42

VI. CONCLUSION AND FUTUTE WORK

In this paper, the characteristic parameters in the simplified propulsive model of bio-mimetic robot fish were optimized based on hydrodynamic properties. The optimal link-length-ratio was numerically calculated by an improved constrained cyclic variable method, and applied in BhT simulation of the 3-linked robot fish.

Future research should be concentrated on multiple control parameters optimization combining with kinematics and hydrodynamics to achieve higher propulsive speed. In the meantime, developing an optimization algorithm for autonomous navigation for robot fish based on multiple sensors fusion and intelligent control techniques will also be investigated.

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