«INVESTIGATION ON THE POWER EFFICIENCY OF THE CARANGIFORM AND ANGUILLIFORM LOCOMOTION OF AN ARTICULATED ROBOTIC FISH »

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Introduction

In the recent years, major advancements in electronics and mechanics assisted the development of AUV's and ROV's, helping people reaching places that could not be easily approached.

Robots are usually classified according to their mobility. Fixed robots are the most frequently met industrial robot which usually comprise from a programmable arm. These robots are eligible of completing very complex tasks which demand high accuracy and velocity. On the other hand, mobile robots were built in order to operate in hazardous and dangerous environments.

The research for more efficient and robust solutions to problems of robots motion made researchers to turn their attention to biomimetic robots.

The biomimetic approach uses animals as a model for the creation of new systems, which in contrast with conventional systems, they can adapt easily to different terrain. In this way, the robotic eel mimics the anguilliform motion of a real eel.

Progress in robotics and hydrodynamics of fish-like motion as well as new materials, actuators, and control systems has aimed on the creation of novel fish-like vehicles with the advantages in energy efficiency and manoeuvrability.

These robots have proved that can have a vast field of application, such as military detection, oceanic supervision, aquatic life-form observation, pollution search, and so on.

Robotic fish are defined as fish-like aquatic vehicles that their motion is based on their swimming skills and their structure is similar to that of an aquatic organism, such as eel or tuna, and their propulsion resembles that

of a fish. Since the composition of such machines take into consideration the biological structure and engineering technology, the robotic fish study consist of hydrodynamics based control and motion technology.

There is a large diversity of fish locomotion. The study focus on carangiform and anguilliform motion, which resemble tuna and eel respectively. Carangiform motion involves the oscillating motion of the entire body, where the largest motion occurs to the last 1/3 part of the body, and thrust is produced by a rather larger caudal 'fin'. The amplitude of this oscillation, however, is small, or zero, at the front part of the fish, increasing in the rear part. On the other hand, anguilliform motion requires the motion of all body except the "head". Locomotion is achieved by the sinusoidal motion of the body with a constant phase delay between equidistant parts of the body so that the resulting contractions lead to a travelling wave as observed by Gray [4]

The biomimetic approach to locomotion systems has several advantages, including increased underwater efficiency and agility.
However, that extensive use of unmanned systems brought to surface important issues, such as the energy autonomy and manoeuvrability in the various conditions where they operate.

This paper aims to present the aspects of anguilliform and carangiform motion in matters of manoeuvrability and energy efficiency and propose a system which will exploit the advantages of the two motions.

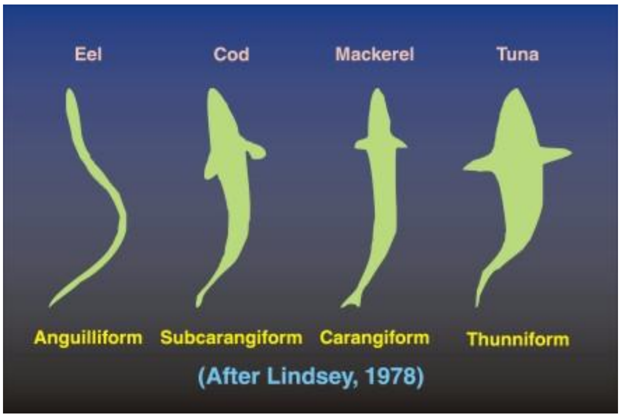

Figure 1.Different types of fish motion (After Lindsey,1978)

Aims of the project

Biomimetic robotic fish have been recently at the forefront of extensive research. As the nature of these robots is multidisciplinary, few research has been done on investigating and comparing two most common motions, anguilliform and carangiform. By taking as a basis previous research on articulated anguilliform and carangiform robots, a mathematical approach concerning the robot's hydrodynamic forces and kinematics has been set up.

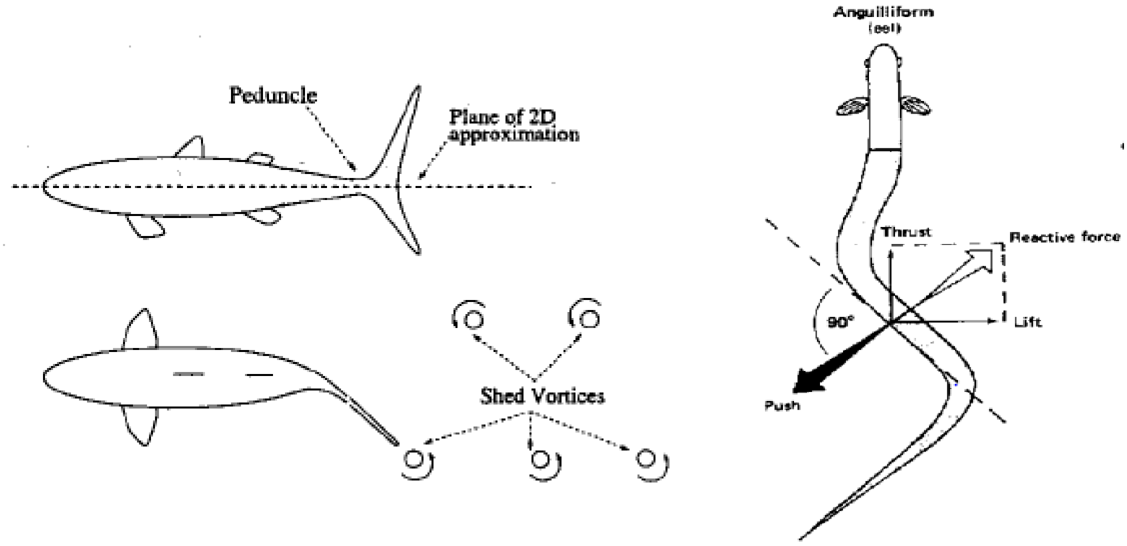

Figure 2. Carangiform and anguilliform propulsion [15]

The study will consider an articulated system, which consists of 5 links and 2 degree of freedom, in order to create a simplified approach to the system. In fewer words, the system is supposed to operate in a constant depth, on specific velocities.

The mathematical models produced for motion will be based upon the Euler-Lagrange equations for the interaction of a rigid body and an incompressible fluid. In addition in order to present the hydrodynamic forces, as these forces are related with the geometry of the object immersed and the velocity between the object and the liquid, the force distribution can be obtained by using the Navier- Stokes equation. Hydrodynamic forces will be formulated in order to describe the forces applied between the fish and the liquid analytically.

Through Euler-Lagrange formulation, the constraints of connecting links will be examined and the dynamic equation of the robotic fish will be presented, which represent the relation between the motion and the forces. Lagrange provided systematic procedures for eliminating the constraints from the dynamic equations by typically yielding a simpler system of equations. Constraints imposed by joints and by other mechanical components are one of the defining features of robots.

In particular the aims of this project is:

- Provide an insight in the field of underwater biomimetic robots.
- Build a mathematical model based on Euler-Lagrange equations describing the motion of an articulated underwater robot.
- Perform a comparison of the two most common locomotion patterns, anguilliform and carangiform, used in underwater robots in terms of energy consumption.
- Build the mathematical model in MATLAB in order to calculate the energy and power consumption aspects of the articulated robot when moving in the above locomotion patterns.
- Provide an insight on the benefits of combining the two locomotion patterns.

Critical Review

Introduction

In order to determine the characteristics real fish have, such as power efficiency, manoeuvrability, flexibility, and noiseless propulsion, an extensive study has been done on the motion of fish. As a result, numerous theories which aim to explain the motion mechanism of fish have been produced, as well as a large number of different kind of robotic fish in order to prove if those theories are correct.

To begin with, robotic fish is a topic related to robotics as well as to biology. Different kinds of robotic fish mimic the motion pattern of real fish. Therefore, fish-like robots should be approached by creating a mathematical model of the motion dynamics of the robotic fish, studying the general control issues of robots and the locomotion generation

Mathematical modelling is important to investigate the characteristics of the robotic fish. By creating a geometrical model, a mathematical explanation will be given to the fish motion and a model will be obtained. The model created assist the comprehension of the motion mechanisms used by the fish.

One of the earliest models for fish motion is the elongated body theory (EBT) [5]. EBT, assuming sinusoidal motion of the fish body, was first applied to Anguilliform fishes. EBT elaborated on the variable aspects concerning the velocity of fish and calculating the thrust obtained by the fish motion. EBT was extended by Lighthill [6], who developed the large-amplitude elongated body theory, which analyses the Carangiform locomotion. However, EBT and other studies related to it were used to describe steady state propulsion.

Biological Locomotion Mechanisms

Anguilliform Motion

The anguilliform motion belongs to a larger group of motions called BCF. In BCF motions the thrust is created by the undulation of the whole body.

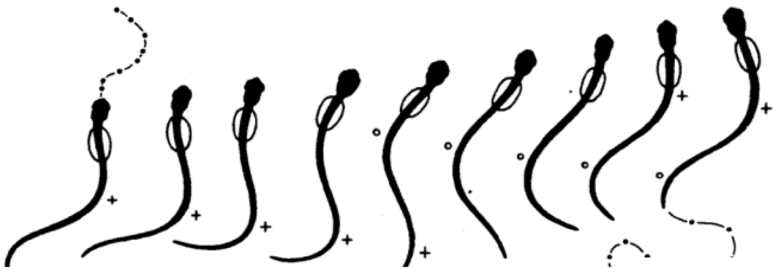

Figure 3.1 Anguilliform motion pattern [20]

In BCF modes, the propulsive wave pass through the fish body with an opposing direction to that of the movement and with a higher velocity than the swimming speed. As a result of the opposing direction of the wave, each body segment generates a force which increases the momentum of the water passing backward. A reaction force then is applied by the water on the propulsive element.

Anguilliform motion is similar to waving a ribbon, that is the reason why we consider anguilliform motion as a wave that travels along the body of the fish and not a isolated motion of the tail. The wave starts its undulation from the head with a small amplitude. As the wave transfer's at the back of the body, its amplitude increases. As a result of the body's geometry and motion, the surrounding fluid is being pushed back and consequently, thrust is created. As the amplitude of the undulation increases, the amount of fluid being pushed is increased and, consequently, acceleration is increased. The thrust created contributes to forward propulsion, while it discards water laterally and can cause important energy losses.

Thrust is proportional to the tail undulation speed, the higher the undulation the higher thrust is. The tail undulation can be controlled either by altering the undulation amplitude and/or frequency. In the case large amount of thrust is required the tail should have large inclination. By increasing the amplitude of the excitation wave combined with a more flexible tail will result in increased inclination of the tail and thrust

The main disadvantage of the anguilliform motion is the common event of accelerating the fluid from side to side not only backwards. When that occurs, the fish undulates a large portion of their body so that one part of the body moves in one direction while another moves in the opposite direction and the side-to-side forces tend to balance out. In addition, the fluid that is accelerated sideways does not contribute to the thrust generation and as a result the additional energy that is spent results in the reduction of propulsive efficiency. If the motion pattern is carefully designed to get the required thrust, energy efficiency can be improved. Anguilliform robots tend to be moderately efficient, with reported propulsive efficiencies ranging from 50% to as high as 90%.[13]

Carangiform Motion

Carangiform motion is used by fast-swimming fishes such as tuna and mackerel and, just like anguilliform, it belongs to the BCF motions. Carangiform motion uses large, high-aspect-ratio tails, and thrust is generated by undulating the rear part of the body and the tail, while the rest of the body remains almost rigid, as shown in the figure 2.3

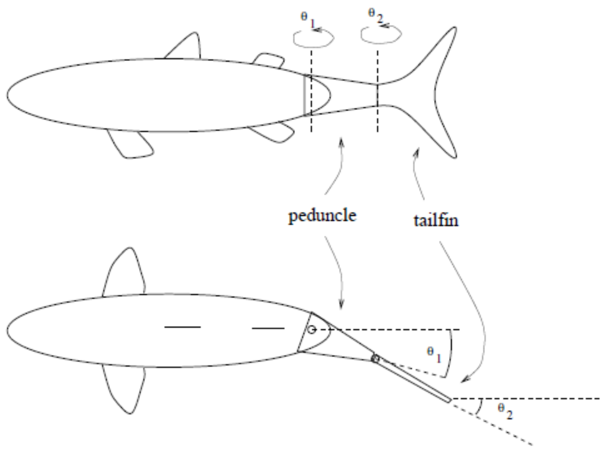

Figure 2.3 Simplified model of the Carangiform motion [15]

Because of the tail being larger than the rest of the body, this kind of motion is more efficient than the anguilliform, as more thrust is being created with less undulations. Carangiform locomotion is advantageous thank to the rear part of the body where thrust is generated, as well as the shape of the body and its small displacement which creates small turbulence [20].

The tail has an important role in this kind of motion as it minimises the amount of water that is displaced and therefore minimises the turbulence and frictional drag, with minimal or no loss of propulsive power [15]. To prevent the head being falsely positioned, the size of the tail fin

has reduced. A smaller tail fin reduces the turbulence of the surrounding water as well as the drag, while simultaneously it increases the frequency with which the tail can oscillate.
The examined model is based on an ideal carangiform swimmer that comprises of three links: a rigid body in front, a large wing-like tail at the rear, and a link connecting the tail and body.

Earlier Work on Robotic Fish

The first model of a robotic fish was built by Triantafyllou [1]. The robot he developed represented a swimming tuna. It has been found that when the tail oscillates, the tuna was able to minimise the drag it experienced while swimming at a constant speed through water. That allows us to conclude that fish swimming is efficient. On the other hand it is still under consideration if robot fish can really outperform efficient propeller designs, which have been investigated thoroughly. Increasing the efficiency remains crucial, as it would allow battery operated submersibles to operate for longer periods.

Later on Ostrowski and McIsaac presented an analytical study concerning the anguilliform locomotion and the route planning of an eel-like robot [3]. Their research presented a mathematical model which was used by computer simulations. In order to present the correctness of their mathematical models, McIsaac and Ostrowski built the REEL robot, a simple RC-controlled robot which comprises of four-links using servomotor joints. The REEL robot had many limitations in terms of modularity, efficiency and reproducibility.

Ostrowski’s and McIsaac’s robot has been widely used as a mean of observation of the application of new theories and ideas. As a result, in 2001 they introduced an updated version of the REEL robot called REEL II[10]. REEL II has been used to investigate the motion generation of the eel-like robots and also to verify the results of the research on the robot’s manoeuvring ability. REEL II experiment had set the foundations of a more accurate approach to the kinematic attitude of the anguilliform robot swimmers.

In 2010, D. Clelland ,A.H Day and C.C. Apneseth present a study in order to determine the hydrodynamic performance of different swim modes by using a three segment version of the robotic eel. The research’s concluded that for greatest performance, the phase lag ought to be more noteworthy at self-propulsion speed than at rest .The mean thrust at zero speed and the self-propusion velocity increase quadrically with swaying recurrence.

Knutsen built an anguilliform robot comprising of five links [25]. The tail had five servomotors, operating as hinge connections between links. Knutsen’s work present the implementation of an open loop control scheme, and was able to demonstrate four unique swimming patterns using the robot.

Recently Williams, Cohen, and Grillner, investigated the problem of anguillform motion, by using neural networks to control the motion. The locomotion can be described as a sinusoidal motion along the body with a constant phase delay between equidistant segments so that the resulting motion resembles a traveling wave, as observed by Gray.

In 1998 Kelly et al.[8] created a model for carangiform motion concerning the mechanics of the fish’s structure. The validity of this approach is based on the biological structure of carangiforms: Due to the long narrow peduncle, the caudal tail fin is located in a distance from the main body.

Saimek and Li [9] investigated the energy efficiency of the motion of a caudal fin swimmer by introducing a new method of motion planning, using an oscillating foil to generate thrust. The results of their research were encouraging but since they did not take into consideration the water disturbances that may occur because of the side to side motion, it can be characterised as a premature/ideal model.

In 2000, R. Mason and J Burdick of CalTec built a model of a robot fish [15], resembling to the mackerel, which comprised of one rigid body segment and three movable. The last segment of the robot is equipped with a fin, like all carangiform swimmers. The experimental model they introduced had set the foundations of moving from the theoretical study of the biomimetic carangiform motion, to an actual machine that follows the theoretical patterns and also approaches in similarity the actual carangiform motion.

In order to describe the effect of sinusoidal inputs over a cycle of fish locomotion Leonard, made a basic approach. This approach is interesting since fish locomotion involves oscillatory motions of the fins and/or body. Li and Saimek [9] have developed a Kalman filter-based estimation scheme that describes the hydrodynamic potential from a set of pressure measurements along a fish’s body.

In the early 2000’s, Hirata presented a carangiform swimmer consisting of three links, using a unique mechanical link to operate the three links by using only two servomotors [21]. The machine was built in order to study the affection of the phase angle between two links would have on swimming velocity.

Yu et al. built a four link carangiform robot for to study his team's theories concerning the control of the system from distance [23]. In this case, each of the robot's links is directly moved by a servo motor located in the link.

Watts et al. had a similar approach to Yu et al. model, with the difference that each link is moved by a DC motor with feedback, using an external bevel gear-set to drive the link following the one it is mounted to [24] and its tail fin was made from five links.

Anderson and Kerrebrock built the Vorticity Control Unmanned Undersea Vehicle (VCUUV), a sizable, 300 lb, carangiform swimmer consisting from three links [20]. The VCUUV is operated by an electrically driven hydraulic power unit which supplies pressure for its links actuation. The VCUUV is remarkable because of its capability to dive up to 10 meters, having a swimming velocity of up to 1.25 m/s, and being able to turn up to 75 deg/s.

In order perform complicated tasks, the robotic fish needs to adjust its motion in different locomotion patterns, which is possible by assigning different motion patterns to the robotic fish. The most usual locomotion patterns include anguilliform and carangiform locomotion. To achieve those complicated tasks, the fish has to combine the locomotion patterns. Since there are many aspects which have to be taken into consideration in the robotic fish's system, such as the angle of each joint angle, the oscillation frequency, the phase difference between two connecting links, and the deflection angle, it is important to determine the appropriate parameters which should be used in different operation conditions.

The research on robotic fish has offered a variety of theories and methods on how to improve them. Robots which are built are constantly testing the theories in practise in order to gain tangible results on the way the robot operate under the new parameters set.

Problems of Developing a Robotic Fish

Velocity and Efficiency Issues

The efficiency and sustainable swimming mode depends on the motion control. The swimming speed and efficiency are two of the most significant aspects of an articulated robot fish. Current researches were based on the use of the vortexes created by the robot's motion in order to generate thrust. However, using the technique of using vortexes in order to control the speed and direction of the robot, has still a lot of problems to solve. Consequently the research now turns to developing other methods such as the introduction of a caudal fin which is able to control the vortexes and also reduce resistance and improve power efficiency. [27]

Stability Issues

When an underwater vehicle is discussed, stability is one of its crucial elements which should be taken into consideration. For an underwater robot to be steady it has to have a heavier bellow section and a lighter upper section and the centre of the weight should be located in the forward part, especially when an articulated robot is concerned[20][21]. What is more, when the robot is in motion, because of its body undulations, the stability is affected greatly. Because current models are built based on Lighthil's models of elonged body theory, fluid and viscous resistance are not taken into consideration. In real circumstances, the stability of the robot depends on the way these forces are eliminated and therefore the stability is maintained.

Failure of Error Detection and FTC (Fault Tolerant Control) Issues

Since the robotic fish operate in aqueous environments, mechanical and control parts may fail and while its operators are unable to salvage it easily. In case the failure occurs, the robotic fish may operate in an unwanted way and probably get damaged. By not being able to predict a fault, the lifetime of the robot gets significantly reduced. Therefore it is important to create an error detection platform and FTC technology, so that the reliability and safety of the robot will be increased. [28]

Research on error identification and FTC technology has been carried out for long, and the methods of error detection mainly include multi-model method [29], state identification and error identification method based on particle filter [30], error identification and repair method of sensors based on information fusion [31] etc.

Classical FTC methods are separated into passive FTC and initiative FTC, but it is important that the system does not need vagueness of model and strength towards external disturbances [30]. Nowadays, the research on error detection and FTC methods is still experimental, while the research specifically on biomimetic robot fish in a real aqueous environment has just begun. The problems which need to be solved urgently include robustness, multi-fault diagnosis, soft-fault diagnosis, efficiency, self-diagnosis and self-repair, etc. For this purpose, the trends of fault diagnosis and FTC technology include several following aspects. Firstly, researchers could use the method combining qualitative reasoning with quantitative reasoning, combining qualitative model and mathematical model to establish the high level architecture (HLA) of diagnosis and FTC system. Secondly, they can improve the algorithm of particle filter and overcome failure miss-diagnosis issue, in order to improve efficiency further. Thirdly, these researchers might immediately include theoretical knowledge and practical knowledge, and then make the diagnosis, fault tolerance, modelling, and learning into integration organically.

Hydrodynamic Forces and Kinematic equations

Introduction

In order to design an underwater robot with high energy efficiency, the operating environment has to be thoroughly examined as well as the constraints of the model have to be taken into consideration. By using the Navier – Stockes equation, all the forces and torques which are applied to the robot, as a result of the effect of the aqueous environment, are calculated. That plays a crucial part in the robot's hull shape since the effect of the fluid's reaction to the motion has to be minimized in order to increase while a system for pose-stabilisation will be designed to exhibit holonomic behaviour and isotropy in its capacity to react to external disturbances [36].In addition in order to further examine the motion of an AUV system a dynamic model that takes into consideration the nonlinearities has to be developed which, on a later stage, will benefit the control design. As Lewis noted [37], there is a trade-off between precision and controllability.

Real Anguilliform and Carangiform swimmers, such as eels or tunas, have very complex shape and characteristics in order to generate thrust. In order to mimic the shape we use a simplified approach consisting from links and joints. The fish consists of N links and $N-1$ joints, where two links are connected by one joint. There is one motor on each joint, and it exerts torque to the following link. The hydrodynamic forces applied to each link are presented in figure 2.1.between the links.

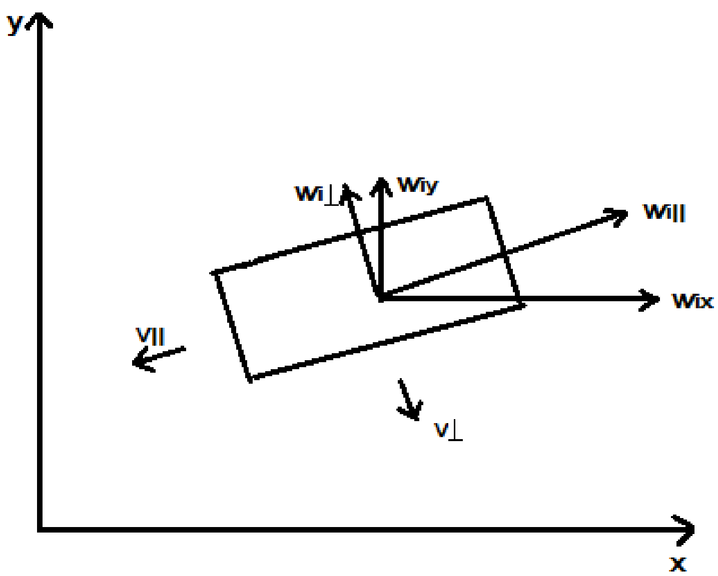

Figure2.1. External forces applied to one link

In order to describe the motion of an articulated system in terms of the time rate of change of its configuration in relation to the forces exerted, a dynamic approach is preferred. The dynamic approach consists of a set of kinematic equations and by taking into consideration the external forces applied to the link.

Hydrodynamic Forces

During the motion of the eel, the fluid that surrounds it is displaced and hydrodynamic forces apply to the outer shell. As these forces depend on the geometry of the robot as well as the relative speed of the robot, the magnitude of the forces can be calculated by using the Navier - Stokes equation. A simplified approach of the hydrodynamic forces is

Vertically: $\mathrm{w_{i\,vert}} = -\mathrm{f_{i\,vert}}(\mathrm{v_{i\,vert}})^2\mathrm{sgn}(\mathrm{v_{i\,vert}})$ (2.1)

Horizontally: $\mathrm{w_{i\,horiz}} = -\mathrm{f_{i\,hor}}(\mathrm{v_{i\,hor}})^2\mathrm{sgn}(\mathrm{v_{i\,hor}})$ (2.2)

Where $v_{i\,vert}$,$v_{i\,hor}$ are vertical and parallel forces to velocity vi respectively, and $f_{i\,vert}$, $f_{i\,hor}$ are the water resistance coefficients in corresponding directions. The notation (·) represents the sign which depends on the direction of the segment.

Water resistance coefficient f_i or water inertia, usually in kg/m, represents the added resistance of the fluid to the movement of each link. It has to be noted here that 1kg/m is equal to 1 Ns^2/m^2[44]

According to the geometric parameters, we have

$$\mathrm{v_{i\,vert}} = -\mathrm{v_{ix}}\sin\varphi_\mathrm{i} + \mathrm{v_{iy}}\cos\varphi_\mathrm{i} \quad (2.3)$$

$$\mathrm{v_{i\,hor}} = \mathrm{v_{ix}}\cos\varphi_\mathrm{i} + \mathrm{v_{iy}}\sin\varphi_\mathrm{i} \quad (2.4)$$

$$\mathrm{w_{ix}} = -\mathrm{w_{i\,vert}}\sin\varphi_\mathrm{i} + \mathrm{w_{i\,hor}}\cos\varphi_\mathrm{i} \quad (2.5)$$

$$\mathrm{w_{i\upsilon}} = \mathrm{w_{i\,vert}}\cos\varphi_\mathrm{i} + \mathrm{w_{i\,hor}}\sin\varphi_\mathrm{i} \quad (2.6)$$

where v_{ix}, v_{iy} are projection of the velocity v_i on x-axis and y-axis; w_{ix}, w_{iy} are projection of the hydrodynamic force wi on x-axis and y-axis.

Hydrodynamic forces are being applied to all links and therefore calculated in a similar way. It has to be noted that, f remains steady when the forces are applied parallel to the link, as well as in the vertical direction.

Lagrangian Formulation of the Mechanical Model

In order to describe the kinematics of an articulated system, there are two theorems which can be used. The first is the Newton-Euler formulation which describes the system as a rigid body and is force based. On the other hand, Lagrange-Euler formulation describes the behaviour of a dynamic system in terms of work and energy. Lagrange-Euler method does not take into consideration the workless forces as well as constraint forces.

The Lagrange-Euler has been preferred as its equations are brief and provide a closed-form expression in terms of joint torques and joint displacements. Additionally, the derivation is simpler and more accurate than in the Newton-Euler method. Potential energy is a function of generalised coordinates **q.**

The Lagrange-Euler general equation is[26]:

$$L(q_i, \dot{q}_i) = T(q_i, \dot{q}_i) - U(q_i) \quad (2.8)$$

Where L: the total energy of the system

U: the potential energy of the system

T: the kinetic energy of the system

q: the coordinates vector

Coordinates vector q=[x0, R0, φ0, x1, R1, φ1…]

In order to study the performance of the system we assume that it operates in a constant depth and it is moving with a constant velocity. As a result of the assumptions made, the system can be considered as two dimensional. Therefore, the potential energy of the system $U(q_i)$ is equal to zero.

Consequently 2.8 equation becomes:

$$L(q_i, \dot{q}_i) = T(q_i, \dot{q}_i) \quad (2.9)$$

The total kinetic energy stored in all links moving at a velocity V is

$$T=\sum_1^N(\frac{1}{2}m_i|V|^2+\frac{1}{2}I_i\omega_i^2) \text{ [26] (2.10)}$$

Where I : is the Inertia

$\frac{1}{2}m_i|V|^2$: is the Kinetic Energy of the link

$\frac{1}{2}I_i\omega_i^2$: is the rotational Kinetic Energy of the joint

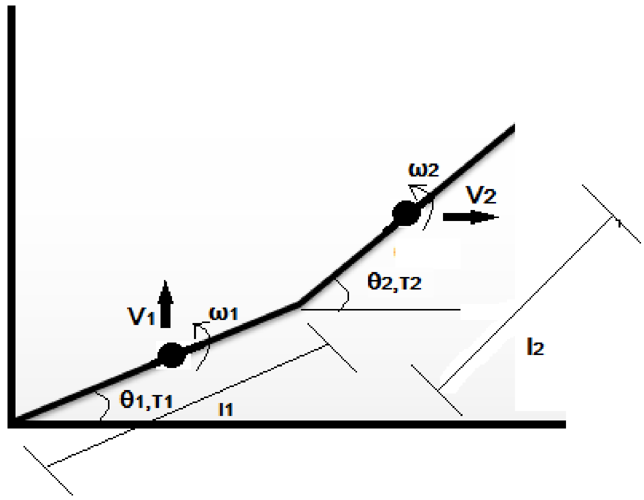

Figure 2.2. Linear and angular velocities

Linear velocities and angular velocities are dependant functions of joint angles as it can be seen in figure 2.2.

Angular velocities are given by

$\omega_1=\dot{\theta}_1,\ \omega_2=\dot{\theta}_1+\dot{\theta}_2,\ \omega_3=\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3$ etc.

To express velocities in Langrangian formulation, Cartesian coordinates are converted in generalised coordinates.

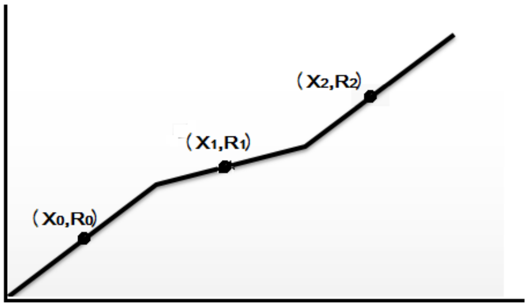

Figure2.3 . Generalised coordinates of the first three links.

In order to calculate the velocity a linear Jacobian matrix is defined

Consequently: V=$\frac{\partial x_k}{\partial q} * \dot{q} \equiv J_v * \dot{q}$ (2.11)

Similarly, in order to define the angular velocity an angular Jacobian is used.

$$\omega_\kappa = J_\omega * \dot{q} = \omega_{p(l)} + R_{p(l)} * \hat{J}_\omega * \dot{q}$$

where $J_{\omega k} = (\hat{J}_{\omega l} \ldots R^0_{p(l)} \widehat{J}_{\omega l} \ldots 0\ )$

Then the constrain force is calculated [21][26]

$$\Gamma = {J_q}^T * \lambda \ (2.12)$$

Where λ: the Lagrange multiplier

An external force vector, as presented in figure 2.1, is created as bellow

$$W = [w_{1x}, w_{1y}, \tau_1, w_{2x}, w_{2y}, \tau_2 - \tau_1, \cdots, w_{Nx}, w_{Ny}, -\tau_N - 1]^T$$

By considering the constraint forces, the dynamic equation can be expressed as

$$\frac{d}{dt}\frac{dL}{d\dot{q}} - \frac{dL}{dq} = \omega + \Gamma \ (2.13)$$

By substituting we get

$$M * \ddot{q} = \omega + {J_q}^T * \lambda \quad (2.14)$$

Where M is the mass, m, and inertia, I, matrix

$$M=\{m1, m1, I1, m2, m2, I2, \cdots\}$$

Diag means that the matrix is diagonal.

By taking into consideration the above equations, the following equation is produced

$$\frac{J(q)}{M} * J(\acute{q}) * \lambda = J(q) * \ddot{q} - \frac{J(q)}{M} * w = -\dot{J}(q) * \dot{q} - \frac{J(q)}{M} * w \Rightarrow$$

$$\Rightarrow \lambda = -\frac{\dot{J}(q) * \dot{q} - \frac{J(q)}{M} * w}{\frac{J(q)}{M} * J(\acute{q})} \quad (2.15)$$

Conclusion

The formulas above present a general model of both the Anguilliform and Carangiform motion that the articulated robot is able to perform.

The mechanical model comprises of N links and N-1 joints. Next, hydrodynamic forces are calculated in order to represent the interaction between the robotic fish and the liquid.

By using the Lagrange-Euler theorem considering constraints of connecting links, the dynamic equation of the robotic fish is calculated, which represents the connection between the motion of the fish and the forces applied on it.

Finally, it is notable that the model is crucial for simulating the dynamic motion of the fish.

Calculation of the Energy Demands of Anguilliform and Carangiform motion using MATLAB

Introduction

MATLAB is a complete mathematical software used for scientific and research computing. It is an interactive program for arithmetic calculations and data visualization combined with programming elements which make it a useful and powerful tool both in mathematical and engineering sciences [33]. In contrast with Maple and Mathematica software, MATLAB in its first editions could not perform symbolic calculations, which was fixed in the latter editions of the software.

MATLAB stands for Matrix Laboratory and, as its name states, it is a specialised software built for matrix calculations, linear system calculation etc. Moreover, it is equipped with many graphic representation routines and other routines in order to solve more complex problems such as solving non-linear systems, finding the roots of a non-linear equation etc[32][33].

The aim of this chapter is, by using MATLAB as a tool, to try and calculate the energy demands of the robotic fish. In particular, the fish will be tested for the anguilliform and carangiform motion by using the dynamic equations presented in the previous chapter. By introducing different speeds, up to the maximum speed of 1.25 m/s which is the maximum velocity experimentally achieved, the energy demand figure will be produced. Finally, it will be discussed if a system that combine both motions would be efficient and under which circumstances.

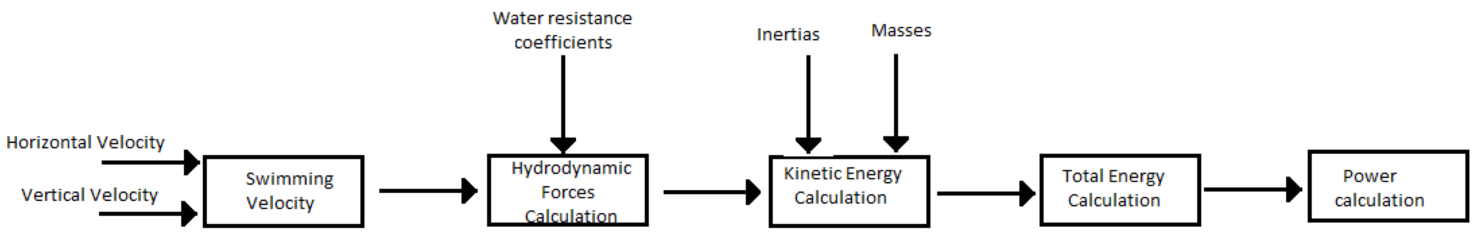

Figure 3.0 Block diagram of the Simulation process on MATLAB

In figure 3.0 the block diagram of the Simulation process that is performed on MATLAB is presented. The model get as input the perpendicular component and parallel component of the velocity in order to calculate the swimming speed on x-axis and y-axis. Using the velocities previously found, the hydrodynamic forces applied to the links of the robot are calculated using the water resistance coefficients. Having found all the parameters in the previous steps, using the inertias and masses found, the kinetic energy of the system is calculated as subsequently the total energy of the system, since the system has zero potential energy. At the last part of the simulation the total power of the system is calculated in the variable velocities examined.

Calculations on Anguilliform motion

For the calculations on the Anguilliform motion, a 5-link robot is considered, out of which the first link, the "head", is considered immovable. Each link has its own geometrical features, based on the features of previous experimental setups such as [19] [23] [25] [35]. The features of each moveable link are presented on figure 3.1.

Link	Length(m)	Mass(kg)	Inertia(kg*m)	fi vertical $(N * s^2/m^2)$	fi horizontal$(N * s^2/m^2)$
1	0,25	0,30	$1{,}25 * 10^{-3}$	3,70	1,06
2	0,12	0,17	$2{,}05 * 10^{-4}$	2,05	0,61
3	0,12	0,17	$2{,}05 * 10^{-4}$	2,05	0,61
4	0,20	0,28	$9{,}50 * 10^{-4}$	3,41	1,01

Figure 3.1. Geometrical features of each link in S.I. units

The horizontal velocities examined range from 0 to 1.25 m/s, as the maximum swimming velocity achieved by a biomimetic robot is 1.25 m/sec set by Anderson and Kerrebrock [20] , with a step of 0.25m/s. Also the vertical speed of each link is equal to the sum of the previous link's vertical velocity plus the actual velocity of the link.

Water resistance coefficient f_i or water inertia, usually in kg/m, represents the added resistance of the fluid to the movement of each link. It has to be noted here that 1kg/m is equal to 1 Ns^2/m^2[44]

Based on the above assumptions and data, a MATLAB code was built in order to calculate the energy consumed by each link on each swimming velocity. Consequently, by running the mathematical model on MATLAB, the following results are provided.

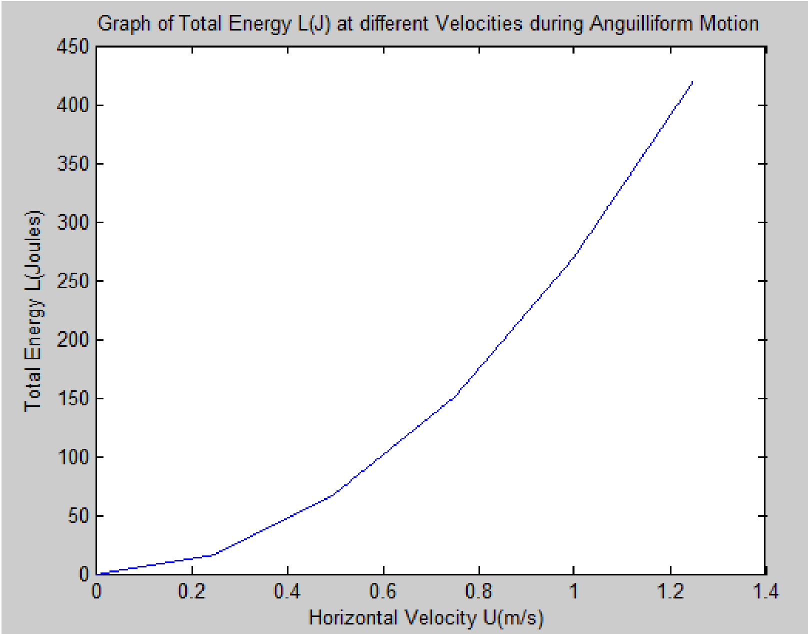

Figure 3.2.1. Total energy L of the system on each swimming velocity

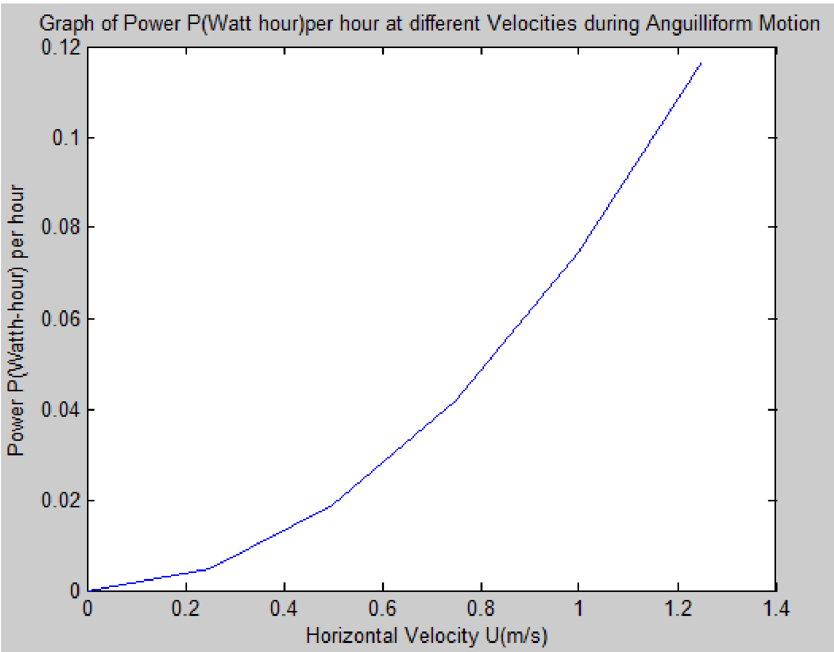

Figure 3.2.2. Power of the system per hour(Watt-hour) on each swimming velocity

In figures 3.2.1 and 3.2.2 the total energy and power of the system is presented. As it can be seen, when the robot operates by using anguilliform motion, the power consumption of the system is low when it operates in low velocities, and on higher speeds, over 0.8 m/sec, the total power consumption of the system is increased exponentially.

That results are considered as reasonable since in order to maintain a higher velocity, the system has to undulate in a larger frequency than in lower velocities. Additionally, because of the geometry of the system, which is similar to that of an eel, in higher velocities the body is not able to displace a satisfactory amount of water in order to sustain a high velocity with less undulations and, therefore, energy consumption. More analytical results on each link's total energy are shown in figure 3.3.

	Total Energy L(J) per link					
	U=0m/s	U=0,25m/s	U=0,50m/s	U=0,75m/s	U=1,0m/s	U=1,25m/s
1	0	5,48	21,94	49,36	87,75	137,11
2	0	3,10	12,39	27,88	49,57	77,45
3	0	3,10	12,39	27,88	49,57	77,45
4	0	5,11	20,46	46,03	81,83	127,87

Figure 3.3 Total Energy L(J) per link when moving at each swimming velocity

Total Energy L(J) for speed U					
U=0m/s	U=0,25m/s	U=0,50m/s	U=0,75m/s	U=1,0m/s	U=1,25m/s
0	16,7952167	67,1808668	151,15695	268,723467	419,880418

Figure 3.4 Sum of each links Total Energy L(J) per swimming velocity

Power per hour P(Watt-hour) swimming velocity					
U=0m/s	U=0,25m/s	U=0,50m/s	U=0,75m/s	U=1,0m/s	U=1,25m/s
0	0.0047	0.0187	0.0420	0.0746	0.1166

Figure 3.5 Power P(Watt-hour) consumed in each swimming velocity

In figure 3.3, figure 3.4 and in figure 3.5, the total energy L for the total of links for each swimming motion and the power consumption is presented. As said before, the power consumed by the robot is lower at the range 0-50 m/sec in contrast with the range of 0.75-1.25m/sec where power consumption increases in a larger rate.

Calculations on Carangiform motion

For the calculations on the Anguilliform motion, a 3-link robot is considered, out of which the first link, the "head", is considered immovable. Each link has its own geometrical features, based on the features of previous experimental setups such as [19] [23] [25] [35]. It has to be noted that link number two has a larger area. The features of each link moveable are presented on figure 3.5

Link	Length(m)	Mass(kg)	Inertia(kg*m)	fi vertical $(N * s^2/m^2)$	fi horizontal$(N * s^2/m^2)$
1	0,12	0,17	$2{,}05 * 10^{-4}$	2,05	2,05
2	0,2	0,31	$9{,}5 \quad * 10^{-4}$	4,5	4,5

Figure 3.6 Geometrical features of each link in S.I. units m,, $kg{\cdot}m^2$, Ns^2/m^2, Ns^2/m^2 respectively.

Similarly to Anguilliform motion, the horizontal velocities examined range from 0 to 1.25 m/s, as the maximum swimming velocity achieved by a biomimetic robot is 1.25 m/sec set by Anderson and Kerrebrock [20], with a step of 0.25m/s. Also the vertical speed of each link is equal to the sum of the previous link's vertical velocity plus the actual velocity of the link.

Water resistance coefficient f_i or water inertia, usually in kg/m, represents the added resistance of the fluid to the movement of each link. It has to be noted here that 1kg/m is equal to 1 Ns^2/m^2[44]

Based on the above assumptions and data, a MATLAB code was built in order to calculate the power and energy consumed by each link on each swimming velocity. Consequently, by running the mathematical model on MATLAB, the following results are provided.

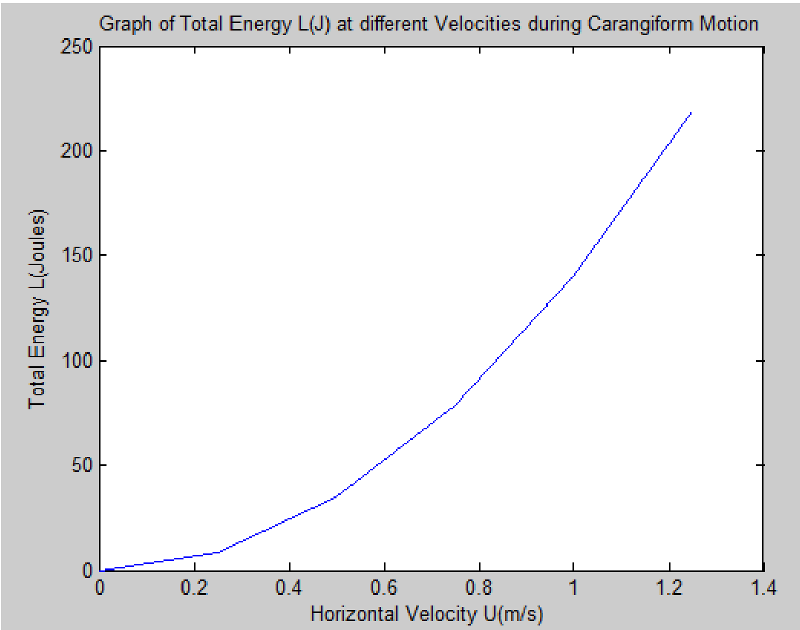

Figure 3.7.1. Total energy L in Joules of the system on each swimming velocity

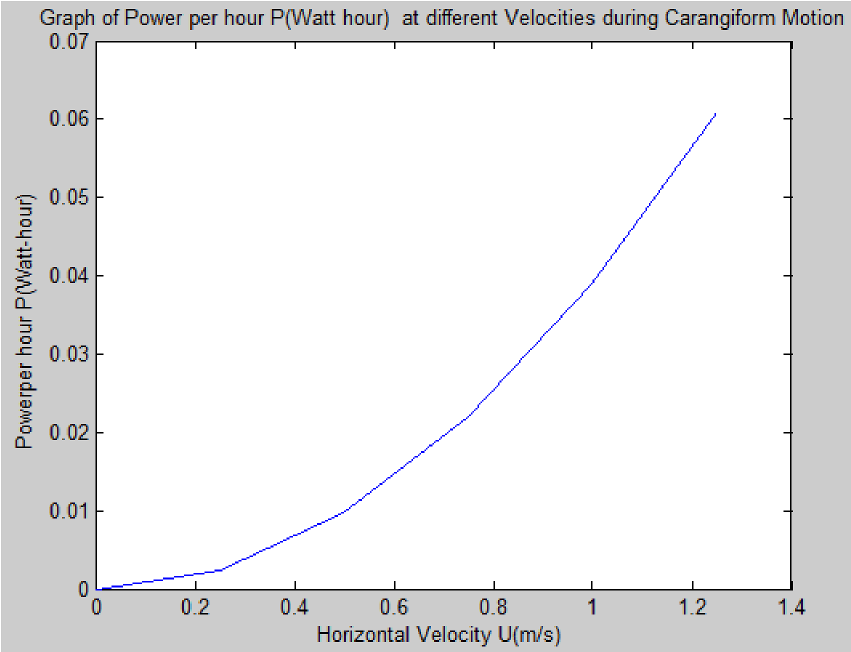

Figure 3.7.2. Power of the system per hour P(Watt hour) on each swimming velocity

In figures 3.7.1. and 3.7.2 the total energy and power of the system is presented. As it can be seen, when the robot operates by using carangiform motion, the power of the system is low when it operates in high velocities, and on lower speeds, less than 0.8 m/sec, the total power of the system is increased on a greater degree.

These results are considered as reasonable since in order to maintain a higher velocity, the system undulations are less frequent as more thrust is generated by the last link. Additionally, because of the geometry of the system, which is similar to that of a tuna, in higher velocities the body is able to displace a satisfactory amount of water in order to sustain a high velocity with less undulations because of the fin which is placed and, therefore, energy consumption is low. More analytical results on each link's total energy are shown in figure 3.7.

	Total Energy L(J) per link for speed U					
	U=0m/s	U=0,25m/s	U=0,50m/s	U=0,75m/s	U=1,0m/s	U=1,25m/s
1	0	3,10	12,39	27,88	49,57	77,45
2	0	5,67	22,68	51,02	90,70	141,72

Figure 3.8 Total Energy L per link when moving at each swimming velocity

Total Energy L(J) for speed U					
U=0m/s	U=0,25m/s	U=0,50m/s	U=0,75m/s	U=1,0m/s	U=1,25m/s
0,00	8,77	35,07	78,90	140,27	219,17

Figure 3.9 Sum of each links Total Energy L per swimming velocity

Power P(Watt) per swimming velocity					
U=0m/s	U=0,25m/s	U=0,50m/s	U=0,75m/s	U=1,0m/s	U=1,25m/s
0,00	0.0024	0.0097	0.0219	0.0390	0.0609

Figure 10 Power (Watt) consumed in each velocity

In figure 3.8, figure 3.9 and figure 3.10, the total energy L and power consumption P of the links for each swimming motion is presented. By examining the results, the total energy L and power consumption of the robot is low at the range 0-50 m/sec in contrast with the range of 0.75-1.25m/sec where the total energy and power consumption increases but with a small rate, approaching almost 220 J when swimming at top speed.

Discussion

In this paper, two versions of an articulated robot have been examined in terms of energy consumption. By setting certain restrains and assumptions an ideal environment for the experiment has been set. The restrains and assumptions are that the robot is operated on a constant depth, therefore it is considered as 2-dimensional, swimming velocity cannot exceed 1.25 m/sec[20], which is the maximum speed for which data could be acquired and also it is assumed that the motion is only forward, and that each link vertically oscillates at a constant speed, as set by the Lagrange-Euler equations.

By analysing the results for anguilliform motion, the total energy of the system increases a large rate. Since Anguilliform motion is based on the motion of the whole body [6], in order generate thrust and, consequently, build up speed, all links have to undulate. The increment of the total energy is a result of the faster undulation of the links which create the propulsion force of the robot.

Although the system's total energy seems high, that kind of motion offers great advantages. Anguilliform motion offers excellent manoeuvrability and precision [6][7][10][17], two characteristics that derive from the geometrical elements of the system. The system is flexible since it is composed of many individual links, which allows it to take immediate turns and also accelerate rapidly from one speed to another. What is more, its precision is remarkable since, again because of the articulated body, it is able to perform minor adjustments to its position and velocity which allows it to operate in tight and mazy areas.

On the other hand, the energy efficiency of the system plays an important part to the systems suitability to many operations. According to the obtained results, an Anguilliform swimming machine can only be used for usage in limited time operations. In case of offering a larger power source, since the usual source are Li-OH batteries, it would add a considerable amount of weight to the robot and therefore increase its energy demands. That issue it might be solved in robots of a larger scale but that would result into minimization of their manoeuvring abilities and limitation of operation areas.

As far as carangiform motion is concerned, its energy consumption is obviously low, as in biological carangiform swimmers. In order to create thrust, the last two segments of the body undulate. Since the last link is equipped with a fin, it is able to generate and maintain thrust easily.

Carangiform motion has some crucial advantages. As inspired by large fish such as tuna and shark, it is built for long distance travelling. Long distance traveling requires energy conservation and, consequently, the movements of the body should be at a minimum. The fin which is located in the last link allows the robot to displace much water and build up the thrust required to move at a certain speed and also maintain it. As the experimental procedure proved (fig 3.6), these characteristics minimise the total energy needed for operation. Obviously, it is the most efficient and effective movement when it is considered that in addition to the above, it also has only 2 moving parts, which means that there are fewer parts to maintain and service.

On the other hand, in order to swim using carangiform motion the robot has to "sacrifice" its manoeuvrability and precision. Those drawbacks stem from the tail fin. As the tail's undulation creates large thrust and the body is not flexible enough, the ability of changing direction fast is nearly negligible. Moreover, as far as precision is concerned, similarly to the manoeuvrability, it is very difficult to have much precision since the motion of the tailfin creates beside large thrust and a large vortex which affects the overall position of the robot in the liquid.

By examining the results of both motions, it is understood that anguilliform motion is more suitable when operating in tight and mazy areas and carangiform motion is more suitable for long distance travelling or cases that manoeuvrability does not play an important role. Consequently, it can be said that a system that combines the two motions and will operate in two different modes has great advantages and can offer deliver some notable results. The system may comprise of 5 links and on the last link there will be a retractable tail fin. When the robot operates in anguilliform motion, the retractable tail will not be used and the 4 links will undulate, the same way they do in an anguilliform robot. When it operates in carangiform motion it will deploy the retractable tail, and the links will operate in pairs- link 1, the "head", along with link2, then link 3 alone and link 4 and 5 together- in a similar configuration as the experimental.

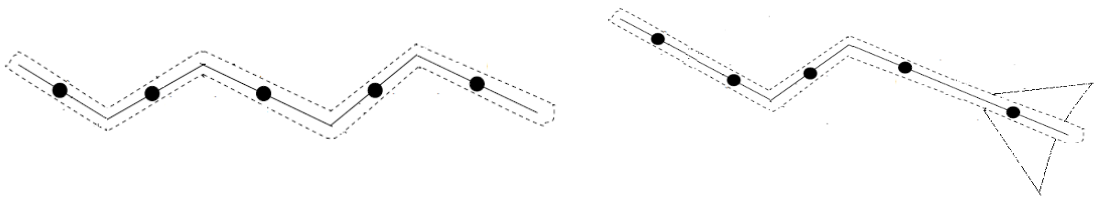

Figure 4.1 Left: Anguilliform motion swimming mode. Right: Carangiform motion swimming mode

The combination of the two motions offers a large advantage to the robot as it is able to perform much more complicated tasks. As during travelling it will use the carangiform motion, it will preserve its power and it will be able to perform any task in anguilliform motion, which will offer the manoeuvrability and precision and therefore complete its mission.

Future Prospects

The development of biomimetic robots is a multidisciplinary engineering and science section, as it combines the very recent breakthroughs of many different disciplines. Jian Song, the former president of the Chinese Academy of Engineering, had once pointed out, "the progress and application of robotics is the most convincing achievement of automatic control fields in the 20th century and the contemporary supreme sense of automation". Biomimetic robot fish could play a crucial part in the military and research fields as well as a mean of understanding complex kinematics of fish in order to develop systems which will be able to adapt their motion by examining their surrounding environment. The research on intelligent biomimetic robot fish is still on a primary stage, and a number of theories and methodologies also need to be further examined. Moreover, the application of these theories and methodologies should be constantly put into tests and accumulated.

The Environment Adaptation Technology

Since the aqueous environment varies significantly from one area to another, the robot should be able to adapt to their environment. In that matter, equipping the robot with sensors would allow it to gather information about its surrounding environment, a characteristic which will assist the robot to adapt the swimming motion that is more suitable for the specific environment that it operates. Such an improvement would prove beneficial both for the energy efficiency as well as the accuracy of the robot, which are both improved thanks to the adoptability of the system.[39] [40].

Currently, for environment sensing there are two techniques used, predictive and reactive environment perceptions. Predictive environment perception is the most simplistic, as the robot starts to analyse the terrain in front of itself[38]-[41] On the other hand, reactive environment analysis examines data of post-entry classification or recognition of terrain on which the robot perceives. In the case of reactive analysis, researchers use inertial measurement unit like sensors. There is large variety of sensors used in all these works, such as gyros, accelerometers, encoders, motor current and voltage sensors, multi-axis force sensor, tachometer etc.[40]-[42] The most major drawback of reactive environment analysis is that prior to entering a terrain, the robot cannot do the processing. On the other hand, for path or trajectory planning, predictive environment analysis is applied and usually an obstacle map is built. In predictive environment analysis, the sensors used are stereo-camera, laser, IR sensor, etc. These sensors can provide a 3D point design or a 2D point design of the area [42].

No matter the technique which is going to be used, thanks to the sensor network which will be created, the robot fish could will be granted the abilities of the self-correction and self-adaption towards the operation environment. In contrast with traditional sensors which can actually measure only one parameter, the sensors will operate simultaneously in order to provide the system with constant measurements of multiple parameters, which will allow, through an efficient algorithm, the robot to adopt to any environment.

Energy Autonomy

A crucial part in the future development of robotics is the energy autonomy of the vehicles, which is rather complex task since there are a number of parameters to take into consideration such as specific energy (energy storage per mass unit), energy density (energy storage per unit volume), charge/discharge voltage and current characteristics.

Although the robots energy demands are carefully calculated, current batteries technology limits their autonomy. Conventional power sources, such as lead-acid or nickel-cadmium batteries, are being used because of their low cost, their large variety of shapes and sizes and their low risk of explosion during recharging. [43]On the other hand, batteries using more sophisticated components, such as silver-zinc and aluminium-oxygen fuel cells, are mostly avoided. The major issues that limit the large application of those power sources are the high cost, in contrast with the common batteries, and their reaction to large pressures. Active research and development in the area of batteries has been in progress, especially with recent attention on electric vehicles that has accelerated the development of more efficient and safer batteries. In the near future, the underwater robotics community is expected to receive a great benefit from this development, which will allow robots to operate for long time periods without the need of continuous recharging.

Conclusion

In this paper, the locomotion articulated underwater robot has been examined in terms of energy and power consumption. A mathematical model based on Euler-Lagrange method has been developed in order to describe the motion and energy consumption of the articulated robot. Using the equations from the Euler-Lagrange theorem, a simulation model has been built to compare the anguilliform and carangiform motion patterns in terms of energy and power. The result of the simulations was that carangiform motion is the most power efficient motion in overall.

Appendix A- Matlab Code

Anguilliform Motion

```
U_x=[0 0.25 0.5 0.75 1.0 1.25];%1.25 maximum velocity achieved by anderson's robot
U_y=[0 2*pi 4*pi 6*pi 8*pi 10*pi];%steady angular speed ω=2*pi rad/sec
fi_ver=[3.7; 2.05; 2.05 ;3.41];%water resistance coefficients
fi_hor=[1.06; 0.61 ;0.61; 1.01];%water resistance coefficients
m=[0.3 ;0.170; 0.170; 0.280];%masses
I=[1.250e-3 ;2.052e-4 ;2.052e-4; 9.5e-4];%Inertias
t=[0 10 20 30 40 50];%time
theta=t*pi/2;
%Hydrodynamics
U_vert=-U_x*sin(3*pi/2)+U_y*cos(pi/2);
U_hor=U_x*cos(pi/2)+U_y*sin(3*pi/2);
w_ver=-fi_ver*U_vert.^2 ;%*sign(U_vert)
w_hor=fi_hor*U_hor.^2 ;%*sign(U_hor)
w=sum(w_hor)
U=U_vert+U_hor;

% Lagrange
T = 0.5*m*(U).^2+0.5*I*U_y.^2;
Tall=sum(T);

V   = 0;%potential energy
L   = Tall- V;
Power=L/3600
figure
plot(U_x,L)
title('Graph of Total Energy L(J) at different Velocities during Anguilliform Motion')
xlabel('Horizontal Velocity U(m/s) ') % x-axis label
ylabel('Total Energy L(Joules)') % y-axis label
figure
plot(U_x,Power)
title('Graph of Power P(Watt hour)per hour at different Velocities during Anguilliform
Motion')
xlabel('Horizontal Velocity U(m/s) ') % x-axis label
ylabel('Power P(Watth-hour) per hour') % y-axis label
```

Carangiform motion

```
U_x=[0 0.25 0.5 0.75 1.0 1.25];%1.25 maximum velocity achieved by anderson's robot
U_y=[0 2*pi 4*pi 6*pi 8*pi 10*pi];%steady angular speed ω=2*pi rad/sec
fi_ver=[2.05;4.50];%water resistance coefficients
fi_hor=[0.61;0.22];%water resistance coefficients
m=[0.170; 0.311];%masses
I=[2.052e-4; 4.5e-4];%Inertias
t=[0 10 20 30 40 50];%time
theta=t*pi/2;
%Hydrodynamics
```

```
U_vert=-U_x*sin(3*pi/2)+U_y*cos(pi/2);
U_hor=U_x*cos(pi/2)+U_y*sin(3*pi/2);
w_ver=-fi_ver*U_vert.^2 ;%*sgn(U_vert)
w_hor=-fi_hor*U_hor.^2 ;%*sgn(inv(U_hor))
U=U_vert+U_hor;
w=abs(sum(w_hor));
% Lagrange
T = 0.5*m*(U).^2+0.5*I*U_y.^2;
Tall=sum(T);

V   = 0;%potential energy
L   = Tall- V;
Power=L/3600;
figure
plot(U_x,L)
title('Graph of Total Energy L(J) at different Velocities during Carangiform Motion')
xlabel('Horizontal Velocity U(m/s) ') % x-axis label
ylabel('Total Energy L(Joules)') % y-axis label
figure
plot(U_x,Power)
title('Graph of Power per hour P(Watt hour)  at different Velocities during Carangiform
Motion')
xlabel('Horizontal Velocity U(m/s) ') % x-axis label
ylabel('Powerper hour P(Watt-hour) ') % y-axis label
```

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