Design, Building and Testing of a Robotic Fish

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Summary

This report overviews the transformation of the initial design idea of a robotic fish into a fully tested and functioning prototype. The project’s robotic fish comprises a streamlined body and an oscillating tail, which was designed based on a flapping aerofoil configuration. Additionally, the low cost biomimetic robot fish is capable of swimming in a horizontal path at a variety of speeds controlled by user input. Detailed design and manufacturing considerations for both the mechanical and control systems are reviewed throughout the report. Two tests to assess the performance of the swimming model are presented. Furthermore a relationship between the model’s swimming velocity and the tail’s oscillation amplitude and frequency is portrayed.
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**Nomenclature**

- **BCF** – Body and Caudal Fin
- **MPF** – Median and/or Paired Fin
- **$F_B$** – Buoyancy Force [N]
- **$\rho_w$** – Density of water [kg/m$^3$]
- **$V_f$** – Volume of immersed fish [m$^3$]
- **$g$** – Gravitational Acceleration [m/s$^2$]
- **$F_L$** – Hydrodynamic Lift Force [N]
- **$C_L$** – Hydrodynamic Lift Coefficient
- **$S$** – Front Cross Sectional Area Fish [m$^2$]
- **$U$** – Velocity of Swimming Fish [m/s]
- **$F_D$** – Drag Force [N]
- **$C_D$** – Hydrodynamic Drag Coefficient
- **$J$** – Thrust Force [N]
- **$W$** – Weight [N]
- **$m$** – Mass of fish [kg]
- **$St$** – Strouhal Number
- **$A$** – Amplitude of Tail Beat [m]
- **$f$** – Frequency of Tail Swing [Hz]
- **$Re$** – Reynolds Number
- **$U_\infty$** – Upstream Velocity [m/s]
- **$\mu$** – Dynamic Viscosity [kg/ms]
- **$\nu$** – Kinematic Viscosity [m$^2$/s]
- **$l$** – Length of Fish [m]
- **$\alpha$** – Angle of Attack of Caudal Fin [degrees]
- **$b$** – Fin Span [m]
- **$S_C$** – Caudal Fin Surface Area [m$^2$]
- **$\lambda$** – Caudal Fin Wavelength [m]
- **$G$** – Centre of Gravity of Tail
- **$S_A$** – Area of the Tail [m$^2$]
- **$v_G$** – Speed of Tail [m/s]
- **$r$** – Distance between G and Pivoting Point
- **$T$** – Torque of Fin [Nm]
- **$T_{\text{max}}$** – Maximum Torque [Nm]
- **$V$** – Velocity of the fish relative to the flow [m/s]
- **$B(x)$** – Cross-sectional Area of the Fish [m$^2$]
- **$y$** – Sideways displacement [m]
- **$x$** – Forwards Displacement [m]
- **$t$** – Time [s]
- **$P$** – Power [W]
- **$Q$** – Work [J]
- **$c$** – Caudal Fin Cord [m]
Chapter 1: Introduction

According to Christensen (2011) in the past 100 years, 80% of fish biomass in the world’s oceans has been lost. This figure represents an alarming fact as fish are a vital component of marine habitats and to some extent to human’s daily lives. In developing countries, fish do not only provide a major source of protein on each individual’s diet, but also a source of income as an export product. What is more, after approximately 530 million years of evolution and natural selection fish have developed a highly sophisticated propulsion mechanism (Hebert, 2004). Fish propulsion is more than 90% efficient, while classic rotary propeller propulsion is only between 40% and 50% efficient, noisier and less manoeuvrable. (Tong, 2000) With this in mind, it is not a coincidence that in recent years robotic fish have become a topic of increasing interest within the scientific community. In our modern world the applications for a robotic fish are very vast, ranging from military and defence, robotic education, nature conservation, and even state of the art medical techniques.

Based on this, the University of Manchester’s School of MACE has proposed the manufacture of an autonomous robotic fish with the ultimate goal of aiding underwater nature conservation. The manufactured robotic fish will not only be used outdoors but will also be employed during open days to attract future candidates. Due to the complexity and time scale of the required work, it has been decided that the project will be accomplished in various subsequent years. Last year’s project produced a polyurethane foam robotic fish with an integrated control system capable of swimming at different velocities. However, a new design direction has been adopted this year and the robotic fish mechanical system had to be completely redesigned.
The following report outlines the design, building and testing of a biomimetic robotic fish. When completed the project aims to examine the transformation of the initial design idea into a fully functioning and tested robotic fish. In order to accomplish this, the project has been divided into 4 main stages namely; 1) Literature Review, 2) Design, 3) Building and 4) Testing & Evaluation. To enhance the understanding of the subject and provide a scope for the project, the Literature Review involved extensive research of what had already been accomplished in this field. The second stage comprised the design of the propulsion mechanism, the control system and the housing of the robotic fish; by compiling the knowledge acquired in the previous step. Thirdly, the building phase transformed the design into a prototype ready for testing. The final stage assessed the already built robotic fish against the project’s objectives in order to evaluate the performance of the model, drew conclusions and suggested improvements for future work. The detailed project management record and a relevant Gantt chart can be found in Appendix A.

Preliminary design constrains were adopted in order to establish a design direction and project realisation; these included the overall financial cost and the maximum length of the model. The cost was determined by a set budget of £100 provided by The University of Manchester while the maximum length of the robotic fish was taken as 0.5m. This maximum length ensures that the robotic system could be built with the available equipment and could be tested at the aquatic facilities of the university. Furthermore, the model should meet the following objectives:

1. The model must be controlled by user-input and be able to swim in a horizontal trajectory
2. The model must be able to swim at a variety of speeds controlled by the user
3. The model must be neutrally buoyant and have a biomimetic appearance
Chapter 2: Literature Review

The Oxford Dictionary (2015) defines fish as “a limbless cold-blooded vertebrate animal with gills and fins living wholly in water”. The evolution of fish has produced some of the most diverse and best swimmers on Earth. Initially fish were jawless feeders and then evolved into thousands underwater species (Fortey, 2009). Nature has always been a source of inspiration for engineers, and hence in order to initiate the design of a robotic fish, fish physiology had to be studied in depth. The following Figure 1 depicts the terminology used to describe fish’s morphological features. This terminology is the most commonly found in literature and is also used throughout this report.

2.1 Fish Locomotion and Classification

After millions of years of evolution and natural selection fish exhibit a large variety of swimming behaviours. These motions can be classified into undulatory or oscillatory movements of their body or fins. (Lui & Sun, 2011) In oscillatory motion the propulsive structure moves back and forth without forming a wave, while in undulatory motion the propulsive structure movement creates a wave. In general, the fish swimming motion can be seen as propulsion mechanisms or temporal features. (Webb, 1984)

Fish propulsion mechanisms are generally divided into two categories; Body and Caudal Fin (BCF) locomotion and Median and/or Pair Fin Locomotion (MPF) locomotion.
Both BCF and MPF are dependent on the fish physiological mechanism and can be further classified into undulatory and oscillatory propulsion. Most fish swim by BCF locomotion, which involves "bending their bodies into a backward-moving propulsive wave that extends to its caudal fin". (Sfakiotakis, et al., 1998) Other fish swim by MPF locomotion, which involves the use of their median and pectoral fins. From various studies it is estimated that 15% of fish families use MPF as propulsion mechanism. While a much larger number that regularly depend on BCF for propulsion, uses MPF for stabilisation and manoeuvring. (Sfakiotakis, et al., 1998)

Under BCF and MPF there is a broad range of sub classifications associated with the motion (oscillatory or undulatory) employed. Each of the modes can be seen as a continuum spectrum rather than discrete groups. The following Figure 2 portrays the swimming modes for BCF and MPF locomotion in which the shaded areas of the fish contribute to thrust generation.

Figure 2- Transition of Oscillatory to Undulatory Swimming Modes, reproduced from (Sfakiotakis, et al., 1998)
Generally, fish that use the same propulsion mechanism exhibit the same morphology. Hence, Webb (1984) identified three basic fish morphology models, based on their specialisations for cruising, accelerating and manoeuvring. Describing these models is beyond the scope of the project, however it is important to highlight the optimal mode for cruising and hence periodic swimming is associated with Thunniform propulsion.

2.2 Forces and Moments Acting On a Swimming Fish

Water is the medium in which fish move, and hence its main locomotive properties have influenced the evolution of fish. Water’s density almost matches the density of the animals and thus it almost entirely counter-balances the weight of gravity. Additionally, due to water’s incompressibility, any motion executed by the fish will set the water in motion and vice versa. Thus, swimming comprises mainly the transfer of momentum between water and fish. (Sfakiotakis, et al., 1998)

In a two dimensional frame, swimming fish undergo five forces namely; Drag, Thrust, Weight, Buoyancy and Hydrodynamic Lift. These five forces are shown in Figure 3.

2.2.1 Buoyancy Force

Buoyancy is caused by the pressure difference acting on opposite sides of the fish. From Archimedes’ principle it is possible to say that the magnitude of the buoyancy force on the submerged fish is equal to the weight of the displaced water. Equation (1) portrays
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this relationship. Additionally, if the Buoyancy force balances the Weight of the fish, the fish will neither float nor sink. This state is known as Neutral Buoyancy.

\[ F_B = \rho_w V_f g \]  \hspace{1cm} (1)

2.2.2 Hydrodynamic Lift

The Hydrodynamic Lift force exerted on a swimming fish is analogous to the aerodynamic lift generated on an aerofoil. The pectoral fins of the fish act in a similar manner to aircraft wings. When water passes through the asymmetrical fin shape it gives rise to a pressure difference across the fin. This pressure difference produces lift, which acts perpendicular to the direction of the fluid flow. Since the shape of the fin and the density of water remain constant, the lift is proportional to the square of the fish’s swim velocity and the lift coefficient. The lift coefficient is a dimensionless coefficient that is commonly determined experimentally, and depends on flow conditions, geometry and inclination of fins. The following Equation (2) shows the lift formula that can be used to analyse the lift exerted on a swimming fish.

\[ F_L = \frac{C_L}{2} \rho_w S U^2 \]  \hspace{1cm} (2)

2.2.3 Drag

The drag force exerted on a swimming fish mainly comprises three main types of drag; Viscous or Friction Drag, Form Drag and Vortex or Induced Drag. Viscous Drag arises from the skin friction produced between the fish and the fluid’s boundary layer, especially in areas of flow with large velocity gradients. Form Drag is created by the pressures formed in moving water aside for the fish to pass. Form drag depends on the fish shape and hence the majority of fast-cruising fish have streamlined bodies. Ultimately, Induced Drag is due to the energy lost in the vortices formed by caudal or pectoral fins as they generate thrust or lift. (Sfakiotakis, et al., 1998) The overall Drag force exerted on the fish is the summation
of each of the aforementioned types of drags. This can be simplified to the following
Equation (3), where $C_D$ represents the fish’s form and viscous drag coefficient and depends
of the flow’s Reynolds number.

$$F_D = \frac{C_D}{2} \rho_w S U^2$$

2.2.4 Weight

Weight arises from the mass of the fish in the Earth’s gravitational field. According
to Newton’s Second law, a force equals mass times acceleration.

$$W = m g$$

2.2.5 Thrust

The thrust force is generated by the fish in order to propel itself in the water. There
are two main propulsion mechanisms BCF and MPF, however this project will utilise BCF as
main locomotion system. Therefore, thrust can be estimated to the one produced in
flapping aerofoil propulsion. If the Lift Force $F_L$ and the lateral velocity of the aerofoil
$v$, are properly phased the average Trust $J$ is given by Equation (5).

$$J = \frac{F_L v}{2U}$$

2.2.6 Moments

A swimming fish can move by three different moments; yaw, pitch and roll, as
illustrated in Figure 4. Dorsal, anal and pelvic fins are used to reduce the rolling moment on
the fish. Pectoral fins reduce the pitching moment by stabilising the fish and inducing
hydrodynamic lift. By changing their angle of attack, pectoral fins can create drag and
hence help decrease the fish’s swimming velocity. Yaw is created by the caudal fin when
the fish is propelling itself through the water. In reality, the fish will use a variety of
movement of its fins in order to control its dynamic stability.
2.3 BCF Locomotion Study

BCF locomotion is particularly effective for cruising continuously and accelerating quickly. These two characteristics make the BCF locomotion a suitable propulsive mechanism for this project’s final model. In order to further expand the knowledge and understanding of the BCF propulsion, its locomotive dynamics should be considered.

To generate thrust for BCF swimming fish rely on two different phenomena; the added mass effect and the vortices effect. The added mass effect reflects on the fact that when the fish moves its caudal fin sideways to propel itself, it sets some water in motion. Thus the lateral movements seem to carry the “added mass” of the water (Imperial College, n.d.). This phenomena is also related to Newton’s Third Law of motion as when the fish transfers momentum to the water by flapping its tail, the water will exert an equal and opposite reaction on the fish, hence propelling it forwards.

On the other hand, the vortices effect refers to the phenomena where the vortices in the fish’s own wake impart a propulsive force. This occurs as the vortices’ rotational direction is always compatible with the desired direction of thrust, leading to a highly efficient jet. (Triantafyllou & Triantafyllou, 1995) This type of vortices is referred as a reversed von Kármán vortex street, and is shown in Figure 5.
In order to achieve high efficiency by BCF propulsion, two dimensionless parameters should be considered; the Strouhal number and the Reynold’s number. Both parameters are defined below:

\[
St = \frac{f A_{\text{max}}}{U} 
\]

(6)

\[
Re = \frac{U_{\infty} \rho_w l}{\mu} = \frac{U_{\infty} l}{\nu} 
\]

(7)

The Strouhal Number relates the frequency of the tail swing, \( f \), the width of the jet, \( A_{\text{max}} \), and the speed of the fish, \( U \). By analysing different flapping aerofoils, it is possible to observe that the thrust inducing vortices (reversed von Kármán vortex street) form when Strouhal number is between 0.25 and 0.35. (Triantafyllou & Triantafyllou, 1995) This leads to the general conclusion that the propulsive efficiency is optimised in between the aforementioned Strouhal number values.

Reynolds number is defined by Equation (7), where \( U_{\infty} \) is the upstream velocity, \( \mu \) the fluid’s dynamic viscosity, \( \nu \) its kinematic viscosity and \( l \) the length of fish. The Reynolds number is frequently used in fluid dynamics to indicate the relative significance of the
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fluid’s viscous effect compared to the inertia effect. At high Reynolds number, the viscous effects of water and hence viscous drag can be neglected. Whereas, at low Reynolds number the viscous effects of the fluid are significant and must be taken into account (Schetz & Fuhns, 1999). For the stated Strouhal number values for optimal efficiency, the associated Reynolds numbers have been determined experimentally. The values obtained are in the range of $10^4 \leq Re \leq 10^6$, which suggests that the viscous effects of water have a perceptible role on fish’s swimming mechanism. (Sfakiotakis, et al., 1998)

In BCF propulsion, the caudal peduncle and fin can be approximated to a flapping aerofoil. The empirical angle of attack $\alpha$, values obtained to achieve the highest propulsion efficiency range between 15 and 25 degrees. (Triantafyllou & Triantafyllou, 1995) This proves a major distinction between airplane flight and flapping propulsion, as generally wings are kept to an angle below 15° to prevent stalling.

### 2.3.1 Elongated Body Theory

In 1960, M. J. Lighthill proposed that BCF locomotion can be described by the following travelling wave model:

$$y(x, t) = [c_1 x + c_2 x^2][\sin(kx + \omega t)]$$

(8)

where $y$ represents the sideways displacement and $x$ the forwards displacement. $t$ is the time, $\omega$ is the wave frequency, $c_1$ and $c_2$ are linear and quadratic wave amplitudes and $k$ is the body wave number. As $k$ increases the swimming motion changes from oscillatory to undulatory. Using this model is possible to observe that head of the fish is kept straight (i.e., $y(0, t) = 0$) and the caudal fin has the largest displacement.

Following this, fish swimming was further modelled until 1970, when Lighthill proposed his Elongated Body Theory (EBT). EBT can be extended to predict the instantaneous reactive force between the fish and water for fish motions of arbitrary
amplitude. According to this theory the instantaneous push per unit length of the fish is defined by:

\[ L(x, t) = -\rho_w \left( \frac{\partial}{\partial t} + \frac{\partial}{\partial x} \right) \{ V(x, t) B(x) \} \]  \hspace{1cm} (9)

where \( V(x, t) \) is the velocity of the fish relative to the flow, \( B(x) \) is the cross-section area of the fish body. Finally \( x \) varies from 0 to \( l \), according the length of the fish. Moreover, over a long period of time mean work done by the fish is:

\[ \bar{Q} = \rho U A (l) \left( \frac{\partial y}{\partial t} \frac{\partial y}{\partial x} \right) \]  \hspace{1cm} (10)

Where \( \frac{\partial y}{\partial t} \) is the traversing velocity of the fish. Subtracting the rate of kinetic energy of lateral fluid shedding the mean thrust is:

\[ \bar{J} = \left[ \frac{1}{2} U A (l) \left( \frac{\partial y(x, t)}{\partial t} \right)^2 - U^2 \left( \frac{\partial y(x, t)}{\partial x} \right)^2 \right] \right|_{x=l} \]  \hspace{1cm} (11)

The cruising speed, \( U \) of the fish is achieved when the mean thrust is equal to the mean drag force (Equation 3):

\[ U = \left[ \sqrt{\frac{m}{C_D \rho_w S + m \left( \frac{\partial y(x, t)}{\partial x} \right)^2}} \right] \right|_{x=l} \]  \hspace{1cm} (12)

The mean power of the fish is:

\[ \bar{P} = \rho U A (l) \left( \frac{\partial y(x, t)}{\partial t} \frac{\partial y(x, t)}{\partial t} + U \left( \frac{\partial y(x, t)}{\partial x} \right)^2 \right) \]  \hspace{1cm} (13)

Finally, the propulsion efficiency is defined by:

\[ \eta = \frac{\bar{J}}{\bar{P}} \times 100 \]  \hspace{1cm} (14)
2.3.2 Caudal Fin Shape

The caudal fin of a fish does not only contribute to its manoeuvrability, but also its propulsive efficiency. This is due to the fact that the caudal fin generates thrust, but it can also reduce or increase drag according to its shape. Fish show different designs of caudal fin particular to their specialization; cruising, acceleration or manoeuvring. The range of existing caudal fin geometries shows the fish’s evolution and adaptation over millennia. The following Figure 6 depicts some of the most common caudal fin shapes and their usage.

![Figure 6 - Caudal Fin Shapes, adapted from (Crenshaw, 1994)](image)

Generally fish that swim by Thunniform have a symmetrical lunate caudal fin (Blake, 1983). Their caudal is stiff however during a powerful stroke it shows slight flexibility, and has a high aspect ratio (Habib, 2014). By having a high aspect ratio there is a reduction in the boundary layer separation that becomes important when swimming at large speeds. The lunate shape involves a moderate leading sweep angle, paired with a sharp trailing angle. Moreover, according to Zhu's (2008) models a flexible fin is 20 – 30% more efficient that a rigid fin, however it sacrifices thrust.

2.4 Associated Robotic Fish Models

A number of projects have been undertaken in the field of robotic fish, in the attempt to replicate fish swimming mechanisms and match their high level of propulsive efficiency. It shall be pointed out that research in this field is still very limited and much
work is still needed. In general the implementation of a robotic fish can be divided into prototyping and control. For the majority of the current robotic fish the mode of control is semi-automatic, in which a human operator directs the dynamic behaviour of the model (Du, et al., 2015). The following case studies show the most representative examples of robotic fish around the world.

1. **MIT’s Robot Fish**

   The Massachusetts Institute of Technology (MIT) developed its first robotic fish in 1994. The project aimed to mimic the dynamics of a bluefin tuna in the hope of replicating tuna’s high levels of efficiency and manoeuvrability (Isla, 1995). The Robotuna prototype has a metallic skeleton and a thin lycra cover, as shown in Figure 7(a). The model has a similar degree of efficiency as real tuna, however if fails to implement the same bursts of acceleration as real animals. Latest MIT robofish is the Soft Robotic Fish (Fig. 7(b)), which uses carbon dioxide flows through flexible channels to actuate the propulsive undulatory motions. The Soft Robotic fish can execute an escape manoeuvre in just a fraction of second, almost as fast as real fish (Manchense, 2014). The model’s propulsive system is coated by a skin made of soft silicon.

![Figure 7- (a) RoboTuna exacted from (Science Museum, 2000), (b) Soft Robotic Fish exacted from (Manchense, 2014)](image)

2. **Macro-Fibre Composite Actuated Piezoelectric Robotic Fish**

   This project is centred around the use of bimorph propulsors made of Macro-Fibre Composite (MFC) piezoelectric laminates. By employing MFCs there is a balance between the actuator force and the velocity response, which offers noiseless and
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Efficient propulsion for the model (Ertuk, 2015). The MFC tail is set in a cantilever configuration as portrayed in Figure 8.

3. Wire Driven Robot Fish

The wire driven robotic fish comprises a streamlined body and a flapping tail. The tail is driven by a biomimetic wire mechanism, which represents the fish’s skeleton and muscles. The wire driven robot can replicate various swimming modes with the use of one actuator, thus having a simple structure and high efficiency (Z. Li, 2015). Following Figure 9 shows the project’s prototype and its mechanism.

4. Tai-Robot-Kun

The Tai-Robot-Kun developed at the University of Kitakyushu is a 7kg extremely realistic robotic fish. It is covered in a silicon body with hand painted scales as seen in Figure 10. The Tai-robot-Kun comprises a silent propulsive system with a flexible oscillating fin, which can continuously operate up to one hour.
Chapter 3: Design

This section of the report discusses the undertaken design process in order to achieve a fully functioning prototype able to meet the aims and objectives set at the start of the project. The design phase was an iterative process to arrive to an optimal final design and has been split into main sections in order to avoid overlooking any parameters.

3.1 Model Initial Configuration

To decide upon a feasible design configuration, research and study on fish swimming modes, applied hydrodynamics and case studies were completed. It was decided that the most realistic robotic fish configuration for an undergraduate level of knowledge and the available time was a basic single joint design. The single joint design is analogous to oscillating foil propulsion, where the oscillating foil is comparable to a flapping tail as seen in BCF locomotion. The flapping aerofoil configuration allows the model to have a simple mechanical design and control as only one actuator is required. The model’s swimming performance can be optimized by modifying the tail’s flapping frequency and amplitude, hence meeting the project’s objectives. Figure 11 portrays the simplified prototype’s configuration.

The robotic fish model consists of a stationary front or main section that houses all the electronic components of the control system and an oscillatory rear section or caudal peduncle and fin. The flapping tail represents approximately one third of the entire length.
of the prototype. The front section is connected to the flapping caudal peduncle and fin by a shaft which is driven by an electric actuator.

Based on the length of the propulsive section of the body, the robotic fish swimming is classified as Carangiform mode. However, it shall be noted that due to the fact that the configuration is single jointed the produced motion is oscillatory rather than a mixture between oscillatory and undulatory as seen on real fish. For the purpose of this project and subsequent analysis the project’s model swimming behaviour is assumed to be Carangiform.

3.2 Mechanical System

The model’s design was carried out using SolidWorks 2014 software and taking into consideration hydrodynamic behaviour, weight, waterproofness and biomimetic appearance. The robotic fish’s main body was inspired by the American Shad fish portrayed in Figure 1. American Shads are widely known for their ability to attain high sprint speeds estimated by Weaver (1965) to be in the range of 4.3 and 4.6\(ms^{-1}\). The American shad’s streamlined body geometry reduces drag whilst conveying a natural appearance.

What is more, as the robotic fish oscillates its tail from left to right, it will slightly move its front body. As the front body moves the nose of the model will no longer be parallel to the water flow. This can result in the fluid coming off easily from the body surface and causing turbulence. To reduce this effect the robotic fish’s nose has been designed to be round. The following Figure 12 illustrates the phenomena described above.

![Figure 12- Shape of nose, extracted from (Hirata & Kawai, 2001)](image-url)
The housing has an overall length of 0.35m and a biomimetic shape, as shown in \textit{Figure 13(a)}. The streamlined body shape reduces the form drag and hence increases the model efficiency as less power is required for propulsion. The front section extends approximately 0.175m and the housing’s maximum width is 0.102m while its maximum height is 0.120m.\footnote{Note that all the dimensions portrayed in figures extracted from SolidWorks 2014 Software are given in mm, while the report utilises m}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure13.png}
\caption{Housing Design CAD (a) Right View (b) Front View}
\end{figure}

In order to prevent the robotic fish from rolling and pitching whilst swimming, dorsal and pectoral fins were added to the main body. The dorsal and pectoral fins need to be sufficiently large to keep the model stable but should not significantly increase the drag force. Several dimensions for the fins were tested by producing simulations of the fluid flow around the model. SolidWorks 2014 software was used for designing the robotic fish housing with different sized fins and also for undertaking the fluid flow simulations. The first step for carrying out the simulation included creating new geometries for the robotic fish housing. After that, the simulation was initiated and the water flow around the model was set to an arbitrary velocity of 0.5m/s along the Z-axis of the model (\textit{Figure 14}). Next, the Force in Z direction, which corresponds to the drag force of the robotic fish was recorded. Finally, contour plots and goal results were displayed to obtain a clear understanding of how the geometry of the added fins influences the robotic fish’s drag force. The computational domain, the resolution result level and the fluid velocity were kept constant throughout all the simulations. The following \textit{Figures 14-16} show the pressure contour plots obtained for three housing geometries.
From *Figure 14* to *16* it is possible to observe that the highest pressure area (denoted in red) for the three different geometries occurs at the same position, the nose of the model. The nose of the model represents the robotic fish’s stagnation point as the velocity for the fluid flow is zero and the hence the static pressure has a maximum magnitude. Moreover, design c)’s pectoral fins have higher pressure acting on them (denoted in yellow) compared to design b)’s pectoral fins. The pressure difference between the front and the back of design c)’s fins gives rise to drag. This can be seen in *Figure 16*, as the contour plot is dark blue on the back of the pectoral fins and yellow at the front. The relevant drag force results obtained from the SolidWorks 2014 fluid flow simulations are displayed in *Table 1*.

**Table 1 - Drag Force Simulation Results**

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<tbody>
<tr>
<td>a)</td>
<td>0.171615</td>
<td>0.170425</td>
<td>0.174026</td>
</tr>
<tr>
<td>b)</td>
<td>0.182144</td>
<td>0.179141</td>
<td>0.183715</td>
</tr>
<tr>
<td>c)</td>
<td>0.233101</td>
<td>0.230283</td>
<td>0.240547</td>
</tr>
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</table>
Design c)’s dorsal and pectoral fins represent a 35% increase to the original averaged drag force, while design b)’s fins increase the original averaged drag force by only 6%. Additionally, as expected design c)’s drag force is greater than design b)’s one. This is due to design c)’s larger pectoral fins and hence larger contact area with the fluid flow. These values seem reasonable taking into account the fact that three new surfaces have been added to the original model. For the sole purpose of designing the housing of the model the obtained results from SolidWorks 2014 are acceptable, however if more accurate results to predict the swimming behaviour of the robotic fish are needed, it is recommendable to use ANSYS Fluent or similar more advanced simulation software packages.

Overall it is possible to say that the benefits of having dorsal and pectoral fins within the robotic fish housing outweigh the increase of the original drag force. For instance if the robotic fish cannot remain stable in water due to large moments it will be very difficult to swim in a straight path, however if the model is stable but the drag force is large it will swim in a straight path but very slowly. Based on this, the chosen model to be taken forward was design b). With the added fins the maximum height of the robotic increases to 0.136\(m\), while its maximum width increases to 0.151\(m\).

*Figure 17- Finalised Housing CAD Front View*
The robotic fish’s housing front section and rear section are composed of two 5mm thick shell parts and are symmetric about the Z-axis. The Z-axis also acts as the partition line for the parts, which are secured to each other by four M5 bolts. The hollow housing parts help approximate the density of the model to the density of water by reducing the weight of the robotic fish while maintaining its same initial volume. The internal area also provides a secure, waterproof space for the control system electronics and the propulsion mechanism. What is more, some internal flanges were added to the front shell parts to prevent the control system components from moving around as the model swims. The unexpected change of position of the components can lead to a change of the location of the centre of gravity and therefore to major stability problems. A small open compartment has been added just below the centre of gravity of the model to increase the mass of the robotic fish in order to achieve neutral buoyancy. This process was completed during the testing phase of the project. *Figure 18* illustrates the finalised housing parts in two different views.
Achieving a completely waterproof robotic fish is critical to the success of the project. It is assumed that the robotic fish must be able to operate at a range of temperatures between 2°C and 30°C and at a maximum depth of 0.5m below the water’s surface. The corresponding maximum hydrostatic pressure is 4905 Pa, taking the density of water as 1000 kg/m³ and the gravitational acceleration as 9.81 m/s². Based on these constraints a 2mm nitrile rubber O-ring cord was selected to be fitted around the model’s perimeter to provide a static seal for the mechanical system. Nitrile rubber has an operating temperature range of −30°C to 100°C, which is clearly within the operating temperatures of the project’s model (The Seal Man, 2004). The maximum recommended pressure for the 2mm O-ring seal based on the hardness and the gland clearance is 50 bar, once again clearly well above the maximum operating pressure for the robotic fish (The Seal Man, 2004). Furthermore, the O-ring groove was designed according to manufacturer’s specifications and split between the left and right hand side components, to facilitate and ensure the parts’ alignment. It is possible to observe the O-ring groove for the front and rear sections in Figure 18 (b).

3.2.1 Caudal Fin Design

The caudal fin design is essential to maximise the propulsive efficiency of the model, however as illustrated in Section 2.3.3 there are various different caudal fin’s shapes. To recapitulate, the project’s prototype intendeds to replicate Carangiform swimming mode by using a single joint design.

Thunniform mode is the most efficient, and its swimmers utilize a symmetrical, lunate-shaped caudal fin characterised by a high aspect ratio (Blake, 1983). The caudal fin’s high aspect ratio ensures there is a reduction in the boundary layer separation, which becomes important when swimming at large speeds. However, as the project’s model does not intend to swim at particularly high speeds the aspect ratio constraint can be
overlooked. In light of this, a forked shaped caudal fin can be regarded as the next most efficient caudal fin geometry. Forked shaped caudal fins are adequate for cruising at fast speeds for long distances, and are mostly used by Carangiform swimmers. Furthermore, according to Zhu's (2008) models the caudal fin must be flexible in order to attain high efficiency values.

Based on the aforementioned facts the design of the caudal was taken forward. Various caudal fin designs were considered, finally selecting a flexible symmetrical forked-shaped flexible caudal fin as shown in Figure 19. The fin's span is 0.120 m and its surface area was calculated using SolidWorks 2014 to be $5.55 \times 10^{-3} \text{ m}^2$.

### 3.3 Propulsion Mechanism

The propulsion mechanism of the robotic fish refers to the set of components that will produce the propulsive oscillating movements of the caudal peduncle and fin. The robotic fish's propulsion mechanism comprises an electric actuator, a shaft and a rectangular driver.

#### 3.3.1 Electric Actuator Selection

The electric actuator represents a critical component for the project's model, as it will act as the engine to provide the power to create the propulsive sideways oscillating movements. To ensure the correct selection of the electrical actuator the necessary propulsive torque for the model was estimated. To do so, the area of the caudal fin and peduncle $S_A$, the distance between the centre of gravity of the tail and the pivoting point $r$, the length of oscillating tail and fin $c$, and the maximum amplitude angle $\theta$, have been set to be the following determined values.

![Figure 19 - Caudal Fin CAD](image)
The oscillating frequency for the caudal peduncle and fin is directly proportional to the Strouhal number at which the model swims, the model’s swimming velocity and the maximum required torque to drive the propulsive tail. Therefore, to estimate the maximum required torque the largest Strouhal number for an efficient oscillating aerofoil, 0.35, was employed. Additionally, the robotic fish’s maximum swimming velocity was estimated to be 0.50 m.s\(^{-1}\). With the aid of the Strouhal number definition and the set parameters previously mentioned, the oscillating frequency of the model was calculated to be 0.47 Hz.

The maximum torque needed for the actuator to drive the oscillating caudal peduncle and fin should be greater than the largest drag force acting on it while it oscillates. To determine the largest drag force for the oscillating caudal peduncle and fin the Chen’s (2008) model was employed. The Chen’s (2008) model simplifies a BCF swimming fish by assuming that the fish’s tail is rigid and neglecting the fish’s body resistance. The maximum torque was estimated to be 0.02363 \(N\) or 0.2409 \(kg \cdot cm\), which can be readily provided by a servo motor. Detailed calculations and derivations may be found in Appendix B.

A servo motor represents a viable electric actuator for the model, due to its size and operation. When servo motors are commanded to move, they will move to the desired position and hold it. If an external force pushes against the servo motor, while it is holding its position, the servo motor will resist from moving. The maximum force the servo can exert is its torque rating (RobotZone, 2015). Additionally, several robotic fish prototypes such as the ones made by Chen (2008), Lui (2011) and Du (2015) utilise servo motors to propel their systems forward.
The previously calculated theoretically calculated maximum torque is $0.2409 \, kg \cdot cm$, which represents a very small value. In order to assess the reliability of this result and the possibility of using a servo motor for the finalised robotic fish model, an experiment was carried out. A $(0.005\times0.20\times0.05\,m)$ piece of high density polyethylene, analogous to the model’s caudal peduncle and fin was attached to a Futaba S3003 servo motor using zip ties. The servo motor was connected to a microcontroller board which was previously programmed to make it oscillate. During testing the polyethylene piece was completely immersed in water whilst the servo motor oscillated. Figure 20 portrays the test set up, while Figure 21 shows the experiment in progress.
The Futaba S3003 servo motor provides a torque of $3.5 \text{ kg} \cdot \text{cm}$ according to manufacturer’s specifications (Futaba, 2015). During testing the servo motor worked as expected and easily oscillated the immersed polyethylene piece. From observation and actual holding of the servo motor during testing it is possible to conclude that the rough approximation of the torque previously calculated is reasonable for the preliminary purpose of selecting a servo motor to be used in the project’s prototype.

### 3.3.2 Finalized Propulsion Mechanism

The propulsion mechanism of the system consists of a servo motor, a $5\text{mm}$ shaft and a rectangular $(0.010\times0.010\times0.030\text{m})$ driver. The servo motor is fixed to the shaft thanks to the lower adapter built into the shaft. The rectangular driver, on the other hand, is fixed to the top part of the shaft by a $4\text{M}$ horizontal screw. The propulsion mechanism also contains a nitrile shaft seal and a $5\text{mm}$ ball bearing. The following Figure 22 portrays the completed propulsion mechanism.

![Figure 21 - Propulsion Mechanism CAD](image)

Leakage of water inside the robotic fish represents a potential failure of the project as the water can completely damage all the control system electronics, and also represents a hazard in the laboratory. In light of this, the shaft connecting the front and rear sections of the model was identified as the weakest point in the assembly. The spaces between the housing and the rotating shaft need to be completely sealed in order to prevent water from
intering the model. To exclude water, dirt, dust or any other substances from mechanical equipment whilst maintaining lubrication two main types of seal are widely used; lip seals and face to face seals. Face to face seals (Figure 23 (a)) are commonly used in large marine applications and consist of two dissimilar flat faces. As the faces rotate the fluid itself is used to lubricate the seal and create a film to prevent further leakage into the assembly. On the other hand, lip seals consist of an outer case that seals against the housing bore and a sealing lip made of an elastomer material that seals dynamically and statically to the shaft. The lip has a sealing edge that is pressed against the shaft by a garter spring. Lip seals are commonly used in industrial applications, an example is exhibited in Figure 23 (b).

![Figure 22 – (a) Face to Face Seal, (b) Lip Seal, extracted from (SKF, 2016)](image)

Based on the available space on the model and the complexity of the seal required for the project a nitrile lip seal was chosen. Nitrile shaft seals have an excellent resistance to petroleum based oils, hydraulic fluids and water up to 100°C. What is more, according to manufacturer’s specifications it can resist a static pressure of up to 1 MPa and a velocity of 30 m/s, well above the capabilities of the robotic fish (SKF, 2016).

Additionally, to reduce the friction between the rotating shaft and the stationary housing a 5mm ball bearing was fitted. In large scale maritime applications such as submarines, stern tubes are used to prevent water from entering through the propeller shaft. Stern tubes consist on a series of mechanical seals and bearings joined together to minimise leakage probability. Due to the reduced available space in the model and its mild
operating conditions it was decided that instead of using a stern tube, a bearing and a shaft seal will be employed separately.

Overall, the propulsion mechanism operates by transforming the electric input into oscillations of the model’s caudal peduncle and fin. The servo motor converts the electric input into movements of its plate. As the servo motor moves the shaft and the rectangular driver translate these oscillations from the front section of the robotic fish to its rear section. Due to the driver’s large contact area with the model’s rear section there is sufficient force to “push” the caudal peduncle and fin from left to right successively. For instance, as the tail of the model moves sideways, the robotic fish propels itself forwards. Figure 24 depicts the propulsion mechanism’s two end positions at 45° of the centre line.

The robotic fish propulsion mechanism has been designed within the practical need to swim and adjust the frequency and/or amplitude of caudal peduncle and fin in order to meet the Strouhal number values associated with optimal flapping propulsion efficiency.

In the Strouhal number calculation, frequency and amplitude of the propulsive element are independent variables which can be directly modified through the electric actuator settings. In contrast, velocity is a dependent variable, which is difficult to control as it links various different variables eg. drag, thrust, caudal fin area and shape, etc. To control exact swimming speed of the prototype is beyond the scope of the project.
however by adjustment of frequency and amplitude is theoretically possible to achieve a Strouhal number to fit the ideal range for an oscillating foil. What is more, by modifying the frequency and/or amplitude of the oscillating caudal peduncle and fin it is possible for the robotic fish to change its swimming velocity and hence comply with the project’s objectives.

### 3.4 Control System

The project’s prototype aims to swim along a straight path, at variable speeds controlled by the user. In order to achieve this, the robotic fish’s control system must be able to:

1. Power the propulsive system for an extended duration of time, at least long enough to test the prototype.
2. Control the system whilst the robotic fish is submerged in water.
3. Control and modify the amplitude and frequency of oscillation of the servo motor and hence the swimming velocity of the model.

The model’s control system consists of a microcontroller, a wireless transceiver, an electric actuator and a power supply. Each of the control system’s components is reviewed and the process behind their selection is exhibited in the following subsections.

#### 3.4.1 Electric Actuator

In the previous section a servo motor was shortlisted as the appropriate electric actuator for the model. The main advantage of using a servo motor compared to a conventional DC motor includes the fact that it has the capability to rotate in a 180° arc and have its position controlled, meaning that unless directed otherwise the servo motor will remain stationary in its final position. Moreover, servo motor’s small dimensions and lightweight make it an ideal actuator for the robotic fish’s control system. The servo
motor’s rotation operates mainly by the reception of pulses sent by the user and can stay in a set position if needed. After careful consideration and following the feasibility test, it was decided that the model would be equipped with the Futaba S3003 servo. The Futaba S300 provides a torque of 3.5 kg-cm, has a standard size of 0.399x0.201x0.361 m and 37 g weight as well as being inexpensive (Futaba, 2015). These characteristics make the Futaba S300 an ideal servo for the proposed project.

3.4.2 Microcontroller

To control the behaviour of the robotic fish and thus the servo motor itself, a microcontroller needed to be implemented into the control system. The microcontroller acts as the “brain” of the system, while the servo motor behaves as the “engine”. The microcontroller ensures that the specific commands from the user are performed by the servo motor. A microcontroller can be described as an entire computer in a single integrated circuit (IC) with the capacity to store and process information using its Random Access Memory (RAM) and its programmable input/output signal peripherals.

It shall be noted that programming a microcontroller on its own requires more in depth electronics knowledge than programming a circuit board with an integrated microcontroller; hence the latter option was favoured. Arduino Nano board was selected since it is a specially designed circuit board for programming and prototyping with an integrated Atmel ATmega168 microcontroller. Arduino simplifies the amount of software and hardware development required to get a system running, representing an ideal board for beginners. What is more, Arduino has a large community of users that are able to offer support if needed.

The Arduino Nano can be powered by the Mini USB connection or by an external unregulated 7-12V power supply, thanks to its built-in voltage regulator. It also has 14 digital pins (used for driving servos) and 8 analogue pins (used for integrating sensors) as
well as an Arduino library for supporting programming. Additionally, the small size of the component proves an advantage compared to other circuit boards as Arduino UNO. The following Figure 25 shows the Arduino Nano circuit board.

![Arduino Nano Circuit Board](image)

**Figure 24 - Arduino Nano Circuit Board, adapted from (Arduino, 2016)**

The Arduino Nano controls the Futaba S3003s servo motor by transmitting a timed pulsed signal to a digital pin, which is connected to the servo motor’s signal wire. (Arduino, 2016). The angle of the servo motor is determined by the duration of the pulsed-width modulation signal. For example, if the servo motor expects a pulse every 20\(\text{ms}\), a 1.5\(\text{ms}\) pulse will make it rotate to the 90° position. Figure 26 portrays the different signal pulses that will result on the respective servo motor’s angular position.

![Servo Motor Position Control](image)

**Figure 25 - Servo Motor Position Control, extracted from (Grahame Holmes, 2003)**

### 3.4.3 Wireless Transceiver

To control the robotic fish dynamic behaviour the microcontroller development board needs to be connected to an interface. However, utilizing a physical connection as a micro USB cable results impractical. This is mainly due to the fact that having an electrical connection so close to water represents a hazard. But not only that, as the robotic fish
Design, Building and Testing of a Robotic Fish

swims the cable can affect the dynamics of the fluid and even become tangled with the prototype itself. In light of this, it was decided that the control system will include a wireless transceiver to effectively receive commands from the user and provide feedback without the need of a physical connection.

There are many types of transceivers available on the market, however based on previous successful examples from the Arduino community, the Xbee and Bluetooth modules were shortlisted. The Xbee and Bluetooth modules represent ideal transceivers for which their compatibility with the Arduino Nano circuit board has already been verified.

On the market there are various different types of Xbee models, with telemetry ranges from 100m to 64km. Xbee transceivers work in pairs, as bi-directional communication is needed; hence one could be integrated to the Arduino Nano on the robotic fish and the other one to the computer being used to send the amplitude and frequency commands. On the other hand, Bluetooth modules can operate up to 100 m and also work in pairs. Nevertheless, the Bluetooth module can be easily paired with a computer with Bluetooth capabilities. Both modules use short wavelength radio waves with an approximate frequency of 2.4GHz (Bluetooth SIG, 2016) (Arduino, 2016).

One of the main issues with wireless underwater communication is that water absorbs high frequency (above 500kHz) electromagnetic waves, thanks to its hydrogen bond (G. Kaatze, 2002). Additionally there are many problems inherent to water such as reflection, refraction, energy dispersion, etc. that degrade the communication between devices. For these reasons the majority of deep underwater vehicles, such as submarines operate with acoustic wavelengths at much lower frequencies between 0 – 400kHz (Nasri, 2008). Some imminent problems with using this type of communication for the project’s model are that; the transducer is piezoelectric, the available electronics
knowledge is limited, the compatibility with the Arduino Nano circuit board unknown and the high cost of the equipment.

What is more, case studies such as the Wire Driven Robot fish (Z. Li, 2015) and the Zebrafish Robot (Sachit Butail, 2015), show that it is possible to successfully control an underwater robotic fish by Bluetooth. This project’s robotic fish model only intends to swim at a maximum depth of 0.50m and doesn’t need at high rate of transmission of data, hence the use of the BlueSMIRF RN-42 Bluetooth module was deemed acceptable. This module operates in the range of $3.3V$ up to $6V$ and has a transmission distance of $20m$, whilst maintaining small dimensions ($0.045x0.016x0.039\ m$) and being less expensive than Xbee transceivers (Roving Networks, 2010). The main reason this module was preferred was because of its transmission distance, which is large enough to account for any degrading in the underwater communication. If in future longer distance control is needed and more budget is available, the Bluetooth module can be exchanged for a lower operating frequency transceiver such a GW100B duplex wireless communication module.

3.4.4 Power Supply

To determine an appropriate power supply for the model’s control architecture, a small test was carried out. The Futaba S3003s servo motor, the Arduino Nano circuit board and the BlueSMIRF RN-42 Bluetooth module were wired to each other and connected to a socket by a micro USB cable, as shown in Figure 27. As the servo motor was instructed to oscillate, the maximum current drawn was measured to be $15.82\ mA$ utilising a multimeter. Then a load was applied to the servo motor by trying to stop its motion with a hand, and the maximum current drain was measured to be $18.7\ mA$. Additionally, whilst the servo motor was oscillating the maximum current drawn from the Arduino Nano’s digital pin was $3.2\ mA$. 
The Arduino Nano’s 5V pin can tolerate 1A current, meaning that the servo motor can be directly connected to it, as maximum current drain by the Futaba S3003s was measured to be 18.7mA. Furthermore, the Arduino Nano’s digital pin can provide a maximum current drawn of 40mA and the maximum measure current drawn was only 3.2 mA (Arduino, 2016). Therefore, it is safe to use the Arduino board to drive the servo motor.

Based on the experiment results and considering operation during a prolonged period of time it was decided that the control system will utilise 4 AAA batteries as well as a 9V battery as power supply. The 4AAA batteries provide a maximum current draw of 2A and were used to power the servo motor, while the 9V battery powered the Arduino Nano and the BlueSMIRF RN-42. Even though the voltage from the power supply is higher than the one needed by the control system’s components, no resistors were added to the circuit. This is due to the fact that the Futaba S3003s servo motor, the Arduino Nano circuits board and the BlueSMIRF RN-42 Bluetooth module have integrated voltage regulators and the supplied voltage is within the manufacturer’s limits. It is important to highlight that a 9V battery on its own will be able to drive the complete control system, however the model’s operation time will be limited. This proves a disadvantage for the robotic fish as it will function underwater and the control system compartment will be sealed, hence it is not practical to replace the batteries very often.
The following Figure 28 shows the finalised control system wiring diagram.

![Finalised Control System Wiring Diagram](image)

### 3.5 User Interface Platform

To initiate the controlled movements of the robotic fish, there must be an intermediate interface to allow the user to input commands. The most common way of doing this is by implementing a standard remote controller. This type of interface only allows for unidirectional communication, meaning that it is possible to control the dynamic behaviour of the model however it is not possible to feedback useful information. From the practical point of view the remote controller interface will limit the development of the model as if in the future sensors are added the information gathered by them will not be processed. For example, if the model was used to monitor the water environment near an oil platform it would be expected to constantly sense the water to determine if there is a leakage in the pipelines.

In light of this, the user interface platform was chosen to be LabVIEW software on a computer with Bluetooth capabilities, so it could be paired to the control system architecture. This interface platform represents a powerful data processing tool as well as a
remote controller for the model. Even though the scope of the project doesn’t include sensors it is important to allow the project for further development.

LabVIEW software provides a user friendly interface as well as easy compatibility with Arduino Nano. The LabVIEW Interface for Arduino (LIFA) is an interface specially developed for Arduino platform microcontroller that allows developers to acquire data from the Arduino and process it in the LabVIEW Graphical Programming environment. The LabVIEW user interface was created to allow the user to vary the servo motor’s oscillating frequency and amplitude and hence the overall robotic fish’s swimming velocity. The interface front panel is shown in Figure 29. The COM Port control allows for the selection of the port to which the robotic fish’s Bluetooth Module is connected to. Both the caudal fin amplitude and frequency knobs allow for gradual change of the parameters in order to facilitate the observation of the system, however there is also the possibility to input exact parameters to obtain accurate results. The amplitude and frequency indicators receive the servo motor parameters that are being used at the moment. When the system is functioning adequately, both the input and the indication values are the same. Having indicator in the front panel ensures the user is aware of the well-functioning of the code, and can help troubleshoot the programme in a more effective manner. The oscillating period is calculated within the code itself and is seen as an output of the programme on the front panel. Finally the Stop button aborts the programme when pressed.
The LabVIEW code was programmed using a series of program blocks, sequence structures, time delays and Arduino Toolkit specific blocks. Figure 30 shows the LabVIEW graphic programming window.

![Figure 29 - LabVIEW Programming Window](image)

### 3.6 Stability

The robotic fish’s stability is key to the success of the project as it determines the model’s posture and balance in water. The model’s stability can be classified into dynamic and static. Dynamic stability refers to the model’s stability under the inertia of momentum while swimming. On the other hand, static stability refers to the stability of the robotic fish when it is not moving and its inertia of momentum is zero. Dynamic stability of the model falls under complex theory and far exceeds the available undergraduate knowledge of the matter; hence only static stability will be accounted for in this project.

The robotic fish’s stability is influenced by both, its centre of buoyancy and its centre of gravity. When the model swims it could be regarded as a submerged body, therefore the analysis of its static stability could be made based of the concept of an immersed body. The robotic fish is required to have a stable equilibrium, which means that the model will return to its original position by retaining the originally vertical axis as vertical if disturbed (Ickikizaki, 2007). As the prototype oscillates its tail and inclines, a stable equilibrium will enable it to return to its upright position and continue swimming. In
order to obtain this type of equilibrium the centre of gravity, $G$, of the model should be collinear and below the model’s centre of buoyancy, $B$. *Figure 31* shows the submerged robotic fish in stable longitudinal equilibrium, while *Figure 32* shows the model in stable transverse equilibrium.

When the model inclines, the centre of gravity, $G$, causes a righting moment equal to $F_B \times \overrightarrow{BG} \sin \beta$, where $F_B$ is the buoyancy force and $\beta$ the angle of deviation from the
reference axis. If distance between $G$ and $B$ increases, so will the magnitude of the $\overrightarrow{BG}$ vector. This will lead to the increase of the righting moment, meaning that the model will be able to right itself more rapidly. This same principle can be applied in both the longitudinal and transverse directions of the robotic fish.

To accurately calculate the position of $G$ and $B$ for the model, SolidWorks 2014 was utilised. The centre of buoyancy of the model can be seen as the centre of gravity of the displaced water by submerged area. As the entire model is submerged, $B$ was calculated as the centre of gravity of the entire solid housing. It is important to highlight that the housing inside was made solid and that the caudal fin and the main body were made from the same material in order to represent the volume of the displaced water. Using SolidWorks’ centre of mass feature, the centre of buoyancy for the model was found to be located at $(0,0,166.78\text{mm})$ in the $X$, $Y$ and $Z$ axis respectively, when the origin is located at the nose of the robotic fish. The centre of buoyancy’s location is shown in two views in the following Figure 33.
To calculate the position of the robotic fish’s centre of gravity an assembly including the model’s housing, all the control and propulsion systems’ components as well as the caudal fin was created. In order to accurately represent each component in SolidWorks 2014 their dimensions and weights were recorded in a table as seen in Appendix C. Using these specifications a CAD model for each component was created and the final assembly was completed. Once the final assembly was ready, the Centre of Mass feature in SolidWorks was utilised to determine the model’s centre of gravity. The robotic fish’s centre of gravity is located at \((0, -5.91, 168.35\, \text{mm})\) in the X, Y and Z axis respectively, when the origin is located at the nose of the model. Figure 34 shows the model’s finalised assembly and its centre of gravity.

Figure 34 – Robotic Fish Centre of Gravity CAD
Taking into account the dimensions and masses of the components there only a limited number of ways in which they can be arranged within the robotic fish housing to make the centre of buoyancy collinear and above the centre of gravity. In light of this, a difference of only 2mm in the Z axis has been deemed reasonable and accurate enough to proceed with the building stage. Once the assembly of the prototype was finalised building tests were carried out to determine and improve the horizontal stability of the model.

The approximate density for the final model was calculated to be approximately 600 kg/m³, by using the components weights (assuming the housing is made of ABS thermoplastic polymer and the caudal fin of silicone) and overall the model’s volume (determined by SolidWorks 2014). The density of the robotic fish is less than water’s density (1000 kg/m³), meaning that the model will be buoyant. To obtain a neutrally buoyant model, theoretically the mass of the robotic fish needs to be increased by approximately 0.74 kg. After building, subsequent tests were carried out in order to empirically determine the needed mass for the model to be neutrally buoyant. The added mass was be located in the compartment just below the centre of gravity, in order to avoid affecting the stability of the model and prevent the added weights from moving around whilst the prototype swims. What is more, as mass is increased the centre of gravity will move downwards, meaning that the $\vec{BG}$ vector will increase. As seen before if the $\vec{BG}$ vector is larger the model will be able to upright itself more rapidly. The following Figure 35 shows the compartment where weights were added.
Overall, the finalised robotic fish design has total length of 0.441m, a maximum height of 0.136m, a maximum width of 0.151m and an approximate weight of 1.13 kg. The length of the prototype adheres to the project’s constraints as it is smaller than the specified maximum length of 0.5m. What is more, the streamlined bio-inspired housing geometry conveys a natural appearance and therefore aids the compliance of one of the project’s objectives. The model’s waterproof housing contains all the propulsive and control systems’ components. The biomimetic design also comprises a flexible caudal fin to increase the model’s swimming efficiency. The following Figure 36 portrays an exploded view of the final robotic fish design including all the propulsive and control system components.

![Figure 36 - Exploded View Complete Final Design CAD](image-url)
Chapter 4: Building

Once the design of the model was finalised, the next stage of the project was building. The building phase was divided into two main sections; manufacture and assembly. This section overviews the manufacturing of individual mechanical components and the integration of the control and propulsive systems into the final assembly. The building stage was completed by investigating a number of solutions that will suitably fit the models requirements and the financial cost constraint of the project. The end of this section portrays the project’s cost budget for the final assembly.

4.1 Manufacture

The first step in building the model was the manufacture of the different sections. The manufacturing process has been split up in the following subsections, as each one involves a different process.

4.1.1 Housing Manufacture

The housing manufacture involved the construction of the 4 shell parts that compose the outer biometric surface of the prototype. Based on previously undertaken similar project by students Zhao and Wesley two main manufacturing techniques were shortlisted; 3D printing and ultra-high density polystyrene (UHDP) cutting. UHDP cutting represents a major advantage in terms of costing as the material is cheap and can be easily shaped by using a hot-wire cutter. However, UHDP has a density of only 350 $kg/m^3$, just 3.5% of water’s density. This will make the model extremely buoyant which will defy one of the project’s objectives. What is more, by using a hot-wire cutter the level of precision of precision is very limited and it is extremely difficult to make shell parts by using this technique.
For these reasons 3D printing was chosen to manufacture the robotic fish’s housing. Nevertheless there are some advantages and disadvantages to this manufacturing technique. For instance, once a prototype is printed there is very little flexibility in the change of design as it will involve printing the complete housing again. Another drawback from this technique is the fact that at the University of Manchester, the school of MACE has only one high accuracy 3D printer available for undergraduate students, meaning that the waiting times can be long. The advantages of 3D printing however include high precision of intricate customisable designs and straightforward manufacture. Opposed to traditional moulding and cutting methods, 3D printing offers the opportunity to create hollow, complex shapes. This represents a great advantage as the housing for the robotic fish has been specifically designed for this project. As more time is taken to evaluate the final design there will be a lower probability of having to modify the first prototype. What is more, 3D printing represents a relatively simple process in which the desired shape model created on SolidWorks 2014 will be simply converted to .STL format. The material used for 3D printing is Acrylonitrile Butadiene Styrene (ABS) thermoplastic polymer, which has a density of $1000 \text{ kg/m}^3$, same as water’s density. The use of this material proves an advantage to the project as it will aid the construction of a neutrally buoyant model.

The 3D printing of the four shell parts of the model took approximately 55 hours, using the University’s 3D printer hence representing no extra cost to the project. However, the waiting time was of approximately two weeks and a half presenting a significant delay for the entire project. The finalised 3D printed housing is shown in the following Figure 37.
4.1.2 Caudal Fin Manufacture

The finalised design for the robotic fish included a flexible caudal fin in order to increase the propulsive efficiency of the model. Silicone represents a viable material for manufacturing the caudal fin due to its degree of flexibility and its wide range of operating temperatures (−65°C – 200 °C). The selected manufacturing technique to produce the model’s caudal fin was moulding. As opposed to cutting, this technique allows for a high precision repeatable process and hence it was favoured. Using the previously specified geometry for the caudal fin, a mould was designed in SolidWorks 2014. The mould was then 3D printed and sanded to allow for a better surface finish of the final product. The 3D printer used for the mould was a less accurate one than the one used for the housing manufacture, hence the waiting time was only of approximately two days. Figure 38 shows one side of the caudal fin’s 3D printed mould.

![Caudal Fin 3D Printed Mould](image)

Once the mould had an appropriate surface finish it was clamped and the liquid silicone was poured in. Additionally, to prevent the caudal fin from being too flexible a 0.8 mm diameter wire was inserted in the middle of the mould. After the silicone solidified and cured the mould was released, the final product is portrayed in Figure 39.
4.1.3 Propulsion Mechanism Manufacture

The propulsion mechanism manufacture included the construction of the 5mm shaft with servo adapter and the rectangular driver. These two components can be easily manufactured by using conventional machining methods such as milling, within The University of Manchester workshop. Two materials were considered for the propulsion mechanism manufacture namely; stainless steel and aluminium. Both material are suitable for conventional machining and have high anticorrosive properties, making them both optimal for this projects use. Moreover, stainless steel has an ultimate tensile strength of 520MPa while aluminium’s one is 310MPa. Clearly, stainless steel is stronger than aluminium; however the stresses on the model’s propulsive system will be much smaller, meaning that none of the materials will be even close to their yield stress. What is more, stainless steel is approximately two times denser than aluminium. This represents a drawback for stainless steel, as if the model is too heavy it will sink. Hence is favourable to have a buoyant model to which mass can be added later to make it neutrally buoyant. In light of this, aluminium was chosen for manufacturing of the propulsive system. Figure 40 exhibits the machined components.
4.2 Assembly

The assembly of the final model involved putting the housing and the control and propulsion systems components together. Firstly the O-ring cord was fitted in the model’s groove by using a splicing kit. Due to the fact that the O-ring groove was split between the two sides of the model to ensure alignment, it was very difficult to fit the O-ring in place and close the prototype. In light of this, it was decided that the O-ring should be superglued to one side of the housing, shown in Figure 41. This solution is far from ideal but ensures the correct installation of the O-ring and facilitates closing the housing. What is more, as the O-ring doesn’t have to withstand large hydrostatic pressures, it is very unlikely that it will extrude. This means that the fact that it is glued could be overlooked. Additionally, rivets were fastened to the front and rear sections of the housing utilising epoxy adhesive. Epoxy adhesive ensures that the rivets are secured and that they will not extrude as the M5 bolts are tighten in. Rivets can also be observed in following Figure 41.
It shall be noted that the 3D printed housing parts are not completely solid as it would take excessive amounts of time and resources to do so. Therefore, only the external areas consist of closed packed ABS layers while the internal area has a honeycomb arrangement. This structure gives rise to porosity, which in turns favours water absorption. To prevent water from entering the prototype through the housing walls a matt varnish was applied to all the 3D printed parts. To ensure correct application all the surfaces were sanded and cleaned first. Once this job was finished several thin layers of varnish were applied and left to dry overnight (Fig. 42).

When the housing parts were dry and ready, they were attached to each other by four M5 bolts. Additional rubber washers (O-rings) were added to the bolts to prevent water for entering the prototype through their thread. Unfortunately, it was noted that the right hand side and the left hand side parts did not perfectly coincide with each other. The gaps between the housing parts were small but noticeable, and completely defeated the waterproofness of the model. This dimensional difference between the SolidWorks design and the actual 3D printed parts can be attributed to different ABS cooling rates, which lead to the uneven shrinkage of surfaces. At this stage of the project it was not viable to reprint the housing and even if that was possible there was no certainty that the new parts will have a better dimensional accuracy. Hence it was decided that a variety of
waterproofing methods will be tested, and only after obtaining positive results the control and propulsion systems added to the assembly. The assembled housing and caudal fin are portrayed in Figure 43.

![Figure 43 – Housing and Caudal Fin](image)

The control system components were wired together as shown in the following Figure 44. And later on, the propulsion mechanism components were assembled to the servo motor (Figure 45). The shaft was secured to the servo motor plate by three M2 nuts and bolts. Additionally, Loctite thread sealant was used to reduce the probability of the bolts becoming undone by the servo motor vibration.

![Figure 44 - Wired Control System](image)

![Figure 32 – Propulsion Mech. Assembly](image)
4.3 Project Costing

The overall project cost has been estimated to be £78. This cost adheres to the cost budget constraint of £100 set at the start of the project. The overall cost is inclusive of all the component costs that were purchased for development purposes, but does not include the manufacturing costs and materials provided by The University of Manchester. A detailed table with all the project costs can be found in Appendix D.
Chapter 5: Testing

The final phase of the project consists in testing the robotic fish in its aquatic environment. To be able to do so, preliminary waterproof and buoyancy tests were carried out first. The following section portrays the various undertaken experiments, design improvements and obtained results.

5.1 Preliminary Testing

5.1.1 Waterproof Test

Avoiding water leakage inside the model’s housing is critical to the success of the project; hence various methods to ensure the robotic fish’s waterproofness were tested. All the experiments involved filling the interior of the housing with tissue and submerging it underwater for three minutes. Once the time was up, the model was opened and the tissue inspected. The first waterproofing method involved the use of aluminium tape and water resistant tape (duct tape) to seal the gaps between the housing parts. The obtained results were unsatisfactory as the majority of the tissue was wet. This can be attributed to the surface finish of the robotic fish, which is comparable of that of wood. The uneven surface combined with water degraded the adhesive properties of both tapes, leading to water leaking inside the model.

The second waterproofing method involved the addition of a silicone gasket. Gaskets for both the front and rear sections of the housing were manufactured by laser cutting a 2mm thick silicone sheet. The gaskets were located in between the left hand side and right hand side parts of the housing. In theory, as the parts are bolted together they will compress the silicone gasket, creating a watertight seal. Unfortunately in practice the seal did not work as expected and water still leaked in. This failure could be attributed to the stiffness of the gasket and the complex shape of the housing.
Finally, the last method tested was adding silicone sealant to the gaps in between the housing parts. The method proved to be only successful one, however it involves a long (24hr) curing time. This represented a complication to the overall prototype design as the control system electronics needed to be on inside the housing for 24 hours plus testing time. The control system batteries are not capable of performing such task and hence a switch had to be implemented. By adding a switch to prototype it was possible to turn off the control system while the silicone sealant cured, thus saving power. Due to the project’s time constraints waiting for the availability of a completely waterproof switch was not a viable option and therefore a common switch with a water resistant cover was employed. The switch was added to the top of the front left hand side part of the housing, by drilling a hole and sealing it with silicone sealant. Following Figure 46 portrays the added switch.

![Added Switch](image)

*Figure 46 - Added Switch (a) Outside View, (b) Inside View*

### 5.1.2 Buoyancy Test

Once it was determined that the model could be waterproofed the buoyancy test was carried out. As the newly added switch is only water resistant and not waterproof, having the prototype completely submerged underwater was hazardous. In light of this, it was decided that only enough weights will be added to make the model submerge just above its fins. The electric components were wrapped in plastic and tape to avoid any water damage and then placed inside the housing, as shown in Figure 47. Copper and steel pieces were used to add weight to the model. It was empirically determined that 0.225 kg
should be added to the left hand side and 0.244 kg should be added to the right hand side of the housing.

What is more, as the switch was added at the top of the housing, the location of the prototype’s centre of gravity was modified. This meant that the model was no longer stable when swimming. To correct this issue further 0.1 kg were added underneath of the model, as depicted in Figure 48. The added weight help move the robotic fish’s centre of gravity downwards and therefore improve the model’s stability. Overall the total weight of the prototype including weights is 1.693 kg.
5.2 Swimming Testing

To test the robotic fish in its aquatic environment, two experiments were designed. These experiments aim to evaluate the model’s performance against the proposed project’s objectives. To recapitulate, the robotic fish must be able to:

1. Be controlled by user-input and swim in a horizontal trajectory
2. Be able to swim at a variety of speeds controlled by the user

To evaluate the robotic fish compliance with the performance objectives, two tests were devised. The first test aims to assess the model’s ability to swim in a straight horizontal path. This was done by placing the model in a (1.00 × 1.50 × 0.50) water tank and evaluating its swimming path by the use of two cameras situated at different viewing angles. Although the test is not scientifically accurate, it provides conclusive results. On the other hand, the second test was designed to determine if the model could swim at variable speeds controlled by the user. The test involved timing the swimming model over a specified distance of 0.9m at a variety of caudal amplitudes and oscillation frequencies. To verify the accuracy of the obtained results, the swimming prototype was also recorded by a camera. All experimental tests were completed at least three times in order to obtain reliable results, and identify any possible anomalies. A complete detail of the tests and the obtained experimental results can be found in Appendix F.

5.2.1 Straight Horizontal Swimming Evaluation

Test evidenced the fact that the robotic fish could swim in a straight horizontal path for the selected caudal fin amplitudes and oscillating frequencies. The frequency domain was elected to be in between 0.5Hz and 1.5Hz in order to comply with the Strouhal number values for efficient flapping propulsion. Three sample points at 0.5Hz, 1Hz and 1.5Hz and corresponding caudal amplitudes at 30°, 50° and 70° were chosen. It is important to note that as the amplitude and flapping frequency increased it was
increasingly difficult for the model to swim in a completely straight path and minimal deviation was observed. Additionally, deviations may have been caused by induced water currents within the tank. *Figure 49* portrays snapshots of a video taken of the swimming robotic fish.

5.2.2 Variable Swimming Speed Evaluation

This test was used to assess the prototype’s capabilities of swimming at variable speeds and establishing a relationship between the swimming velocity, and the tail’s oscillating amplitude and frequency. During the test, the robotic fish swam at different flapping frequencies and amplitudes controlled by the user. Flapping amplitudes were set in between 30° and 70° at 10° intervals, while the frequencies were selected to be in the range of 0.5 Hz to 1.5 Hz, every 0.25 Hz. The test was divided into two parts; one at constant swimming frequency of 1 Hz and varying amplitude and another one with fixed oscillating amplitude of 60° and varying frequency.

From observation and video reviewing it is possible to say that the swimming behaviour of the prototype varied noticeable with different parameters. When the oscillation amplitude was small, the rolling moment became apparent and the swimming model wasn’t able to attain high velocities or keep a straight path easily. The same behaviour was observed at low frequencies. Moreover, at high frequencies the model was affected by the water turbulence and hence it was difficult to maintain a straight swimming path.
The test results were recorded and analysed in order to obtain the average swimming velocity for each set of parameters. Additionally, theoretical calculations based on the Elongated Body Theory (EBT) were performed to determine the average swimming velocity for the same parameters (Appendix F). Theoretical and experimental results are compared in following Figures 50 and 51.

![Figure 37 - Swimming Speed of Prototype against Flapping Amplitude at Constant Frequency 1Hz](image)

**Figure 50** shows the swimming speed of the robotic fish as function of the oscillating amplitude when the frequency is constant at 1Hz. Note that the amplitude is the total angle between the two final positions of the prototype’s tail. The red line represents the predicted results and the blue line depicts the experimental results. From the plot it is seen that the cruising speed increases as the amplitude increases. The theoretical rate of change in velocity decreases with increasing flapping amplitude. However, the experimental rate of change in velocity shows a similar value in between 30° – 40° and 60° – 70°, with a decrease during median amplitude angles. Additionally, it is possible to say that the experimental values match the theoretical values reasonably.
well, with a similar trend with increasing oscillating amplitude. Overall the average percentage error between theoretical and experimental values is 41%.

![Swimming Speed of Prototype against Flapping Frequency at Constant Amplitude 60°](image)

Figure 38 - Swimming Speed of Prototype against Flapping Frequency at Constant Amplitude 60°

Figure 51 portrays the swimming speed of the robotic fish as function of the oscillating frequency at constant amplitude 60°. From the plot it is seen that the cruising speed increases as the oscillating frequency increases. The theoretical acceleration of the model remains constant throughout all the data points. On the other hand, the experimental acceleration decreases from 0.75Hz to 1Hz and increases dramatically from 1Hz to 1.25Hz. Both experimental and theoretical data sets show the same trend with an average percentage error of 20%.

The difference between the errors of the constant frequency and constant amplitude tests may be attributed to the parameters chosen. For instance having a frequency higher than 1Hz will result more efficient and the overall testing error may be reduced. Nevertheless, there are errors inherent with the testing procedure and the prototype that can be associated to several reasons. First, the tank used was small and
when the oscillatory motions were fast there water became turbulent, which influenced the swimming performance. Second, due to its single joint configuration the prototype has a low propulsive efficiency that is significantly lower than that of actual fish. Third, EBT considers the swimming fish to be completely submerged in water, which unfortunately was not the case for the robotic fish prototype. Finally, the dynamic behaviour of the model was altered by a hanging weight attached to the model.

Overall, among all tests the maximum cruising speed was 0.15 m/s at an amplitude of 60° and a frequency of 1.5 Hz. It was also determined that the cruising velocity increases as the oscillation frequency and amplitude increase in the range of 30° to 70° and 0.5 Hz to 1.5 Hz, respectively. Unfortunately, the objective of producing a neutrally buoyant model was not achieved. However, the tests showed that the robotic fish is capable of swimming in a straight horizontal path at a variety of velocities controlled by the user, hence complying with the project’s objective.
Chapter 6: Conclusion

The project was planned, managed and developed according to a timeline documented by Appendix A Gant Chart. The overall competition was greatly delayed after the building phase, due to an unexpected lag in the manufacture of the mechanical system. Nevertheless, the project produced a fully functioning low cost biomimetic robotic fish.

The robotic fish prototype was designed to mimic Carangiform locomotion achieved by having flapping aerofoil layout driven by a servo motor. The 0.44m long robotic fish comprises a waterproof outer 3D printed structure that houses all electronic components. The biomimetic appearance was achieved by a bio-inspired streamlined lined geometry of the housing and a forked flexible caudal fin. The weight of the prototype is 1.2 kg (without added weights) and its maximum width is 0.15m. The control system was developed to meet the performance objectives set at the start of the task, through a clear control interface. The control system components include a microcontroller board, a Bluetooth module, and a power supply.

Due to the manufacturing technique of the housing, its waterproofing was complicated and required a change to the initial design. A switch was added to the housing; however, due to unavailability a completely waterproof one couldn’t be employed. This change in design meant that the model couldn’t be neutrally buoyant anymore. Hence, the neutral buoyancy objective was sacrificed in favour of achieving a fully functioning model.

The robotic fish prototype was then tested by a variety of experiments designed to assess its swimming performance. From them, it was determined that the model was able to confidently swim in a straight horizontal path and achieve at variety of speeds controlled by user input. A comparison with theoretical results showed that the swimming velocity
increases as the oscillation amplitude and frequency increase in the range of 30° to 70° and 0.5Hz to 1.5Hz, respectively.

To conclude, this project has proven a successful application of theory into practice by designing, building and testing a £78 robotic fish capable attaining a maximum velocity of 0.15 m/s whilst displaying dynamic behaviour similar to actual fish’s one. Nevertheless, is important to note that in order to achieve the ultimate goal of producing an autonomous robotic fish for underwater conservation, further design iterations are needed. The following Chapter 7 highlights possible future work an improvements to the current prototype.

**Chapter 7: Future Work and Improvements**

The finalised biomimetic robotic fish prototype is controlled by user input and is capable of swimming in a straight horizontal path at a variety of speeds; however it is not neutrally buoyant. The project’s time and budget constraints limited further development of the prototype at a late stage, however the following subsections detail additional work and development processes to achieve the ultimate project’s goal of producing an autonomous robotic fish to be used for underwater nature conservation. These improvements had been suggested with the finality of enhancing the prototype’s performance without completely changing its overall design.

**7.1 Mechanical Design**

To improve the performance of the robotic fish, its housing needs to be slightly redesigned. A major issue in the project was the difficulty encountered when trying to waterproof the housing, which lead to the addition of a switch which in turn affected the stability of the prototype. The housing seal can be improved by having the O-ring groove
situated only on one side of the housing, hence preventing the necessity to glue the O-ring. Additionally, a series of bolts may be added to the outer perimeter of the housing to help fully compress the seal. A redundant waterproof seal may be added in the form of a silicone skin as seen in the RoboTuna. The silicone skin could include a detailed work of art and the addition of pigments to further increase the biomimetic appearance of the prototype. Furthermore, whilst keeping the same single joint design configuration is possible to increase the propulsive efficiency of the model by having a flexible tail. The flexible tail will also aid imitate the dynamic behaviour of real fish. Another way of further increasing the propulsive efficiency of the model will include using modelling and simulation advanced packages such as ANSYS Fluent to refine the housing geometry and model the prototype’s behaviour whilst swimming. Modelling and simulation methods could also be used to determine the model’s drag coefficient and reduce errors in calculations.

7.2 Neutral Buoyancy

During this project, what limited the neutral buoyancy of the model was the control system’s switch. The switch should be replaced for a completely waterproof one, capable of being submerged underwater without any risk of hazard. What is more, in theory a stable neutrally buoyant model can be produced by simply increasing the overall height of the model’s housing and keeping the weights and components in the same location. This is due to the fact that as the height of the model increases, its centre of gravity will move downwards in relationship with the centre of buoyancy. However, further analysis and testing should be made to ensure this is applicable to the actual prototype. Finally the needed additional weights to achieve neutral buoyancy could be calculated empirically.
7.3 Control System

The prototype’s operating underwater range can be improved by changing the Bluetooth module for a lower frequency transceiver such as a GW100B duplex wireless communication module. Additionally, to incorporate capabilities to perform marine reconnaissance to the robotic fish, a series of sensors may be added. There are many sensors compatible with the model’s microcontroller development board, whose data is able to be feed-backed into the user interface for further processing. An ultrasonic distance sensor may be added to aid obstacle avoidance. A GPS position module can also be integrated to provide the user position information when the prototype is needed to operate at long distances. Other relevant sensors that could be included are a waterproof temperature sensor and an ultrasound and live video camera.

7.4 Manoeuvrability

By controlling the oscillation amplitude and frequency of the caudal peduncle and fin, it is possible for the robotic fish to turn without the need to add another actuator. Further tests need to be conducted in order to determine optimal amplitudes and frequencies for the model to perform such turns. By using this method and the addition of an ultrasonic distance sensor, the prototype will be able to avoid obstacles. Nevertheless, the manoeuvrability of the robotic fish will be limited. Note that if small turning radiiuses are required it is advisable to change the design configuration to a multiple jointed one.
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Appendix A - Project Management

The project must be completed within two semesters (22 weeks) and it comprises three main submission components. The project has been divided into four main stages in order to distribute the work evenly and balance the work load with other modules. These four phases were divided through the whole academic year as follows:

<table>
<thead>
<tr>
<th>Semester One</th>
<th>Semester Two</th>
</tr>
</thead>
<tbody>
<tr>
<td>Literature Review: 6 Weeks (Week 1-6)</td>
<td>Building: 3 Weeks (Week 14-16)</td>
</tr>
<tr>
<td>Design: 8 Weeks (Week 7-14)</td>
<td>Testing &amp; Evaluation: 5 Weeks (Week 17-22)</td>
</tr>
</tbody>
</table>

A Gantt chart was utilised to effectively plan the project and avoid overlooking any aspects, and is portrayed at the end of this section. It shall be noted that this project has been undertaken whilst completing a highly demanding academic programme and hence some delays did occur. A summary of the work done corresponding of each stage of the project is detailed below.

1. **Phase 1: Literature Review**

   This stage focused on the research and gathering of applicable literature to the project. This included background information on fish locomotion, oscillatory propulsion and the approximation to a flapping aerofoil and the work that has already been accomplished on biomimetic fish robots. This study provided in depth understanding of the matter at hand and facilitated the development direction of the model.
2. Phase 2: Design

With the gained knowledge from phase 1, the design of the model propulsion mechanism, control system, configuration and housing was initiated. The propulsive system included the design of the robotic fish driving components torque and frequency calculations for the selection of an appropriate electric actuator. The configuration and housing design included an extensive use of SolidWorks 2014 software to produce CAD drawings of the preliminary design, and to calculate the position of the model’s centres of buoyancy and gravity. The control system was designed based on a previous model created for a similar project and the chosen control platform was LabVIEW, software provided by National Instruments. Unfortunately, this stage took longer than expected as the initial design had to be refined a number of times in order to produce a viable final design. Additionally, as limited knowledge on electronics was available before the project, familiarisation and improvement of the functioning control system was done simultaneously with the mechanical system design.

3. Phase 3: Building

The model was built with simplicity and low cost in mind as a budget of £100 was designated for the project. The majority of components were procured once the final design was decided upon. The main time delay for this project was due to the low availability of the 3D printer on campus. The whole project itself was delayed by 2 weeks due to this problem. Unfortunately, the 3D printed parts did not coincide with each other as expected and further improvements had to be done to the model to ensure waterproofness.
4. **Phase 4: Testing & Evaluation**

Testing included waterproofness tests, buoyancy tests and finally swimming velocity testing. The prototype failed initial waterproofness testing and the control system had to be modified so that it was possible to switch the model off from outside. Buoyancy tests were carried out and some weights were added to the model to achieve a partially submerged robotic fish. Next, the control system was sealed inside the housing using silicone seal and varying velocity tests were performed to identify a relationship between the oscillating frequency and amplitude of the tail with the robotic fish’s swimming velocity. Finally, results and possible improvements were identified.
Figure A - Project Gantt Chart
Appendix B – Frequency and Torque Calculations

Chen’s (2008) has been used for the purpose of calculating the frequency and torque need to drive the oscillating caudal peduncle and fin. Chen’s (2008) model is illustrated in the following Figure B, where $G$ represents the centre of gravity of the caudal fin and peduncle, $S_A$ the area of the caudal fin and peduncle, $r$ the distance between the centre of gravity and the pivoting point and $c$ the length of oscillating arm.

For the proposed initial model the following parameters have been set.

$S_A = 0.015 \text{ m}^2$, $r = 0.045 \text{ m}$, $c = 0.265 \text{ m}$, $U = 0.5 \text{ m/s}$, $\theta_{\text{max}} = 45^\circ$

From observation of Figure B,

$A = 2\pi c \frac{\theta}{360} = 0.208m$

$A_{\text{max}} = \sqrt{c^2 + c^2} = 0.37m$

To obtain the maximum oscillating frequency and hence the maximum torque for the electric actuator, the largest allowable value for the Strouhal number was be selected. $St$ was taken to be 0.35, which lies in the upper range previously identified for flapping efficient propulsion.
Design, Building and Testing of a Robotic Fish

\[
St = \frac{f A_{max}}{U}
\]  

\[
f = \frac{St \ U}{A_{max}} = \frac{0.35 \times 0.50}{0.37} = 0.47 \text{ Hz}
\]

From previous Figure B it is possible to observe the angle \( \theta \), is:

\[
\theta = A \sin(2 \pi f t)
\]

Therefore angular velocity of \( G \) is given by:

\[
\dot{\theta} = \omega = 2\pi f A \cos(2\pi f t)
\]

The speed of the tail at \( G \) is:

\[
v_G = r \times \dot{\theta} = r \times 2\pi f A \cos(2\pi f t)
\]

The hydrodynamic drag force \( F \) at \( G \), acts in the opposite direction to \( v_G \) and is defined

\[
F = \frac{C_D}{2} \rho_w S_A v_G^2 = \frac{C_D}{2} \rho_w S_A \times (r \times 2\pi f A \cos(2\pi f t))^2
\]

Thus the torque needed by the actuator is:

\[
T = F \times r = \frac{C_D}{2} \rho_w S_A \times (r \times 2\pi f A \cos(2\pi f t))^2 \times r
\]

\[
T = 2\pi^2 C_D \rho_w S_A r^3 f^2 A^2 \cos^2(2\pi f t)
\]

The Torque is at its maximum when \( \cos^2(2\pi f t) = 1 \), hence:

\[
T_{\text{max}} = 2\pi^2 C_D \rho_w S_A r^3 f^2 A^2
\]

Using the same parameters as previously and \( \rho_w = 1000 \frac{kg}{m^3} \), \( C_D = 1.1 \)

\[
T_{\text{max}} = 2\pi^2 \times 1.1 \times 1000 \times 1.25 \times 0.045^3 \times 0.47^2 \times 0.208^2
\]

\[
T_{\text{max}} = 0.02363 \text{ Nm} = 0.2409 \text{ kg} \cdot \text{cm}
\]
Appendix C - Components Dimensions and Weights

The following Table C portrays all the components dimensions and weights used to produce simplified CAD drawings. The CAD drawings were utilised to determine the location of the centre of mass of the final assembly representing the robotic fish prototype.

Table C - Components Dimensions and Weights

<table>
<thead>
<tr>
<th>Component</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>Weight (g)</th>
</tr>
</thead>
<tbody>
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<td>12.30</td>
<td>51.82</td>
<td>53.40</td>
</tr>
<tr>
<td>9V battery</td>
<td>25.82</td>
<td>16.75</td>
<td>45.14</td>
<td>54.22</td>
</tr>
<tr>
<td>Arduino Nano Board</td>
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<td>34.60</td>
<td>13.97</td>
<td>25.51</td>
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<td>16.62</td>
<td>1.64</td>
<td>3.81</td>
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<tr>
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<td>20.09</td>
<td>39.56</td>
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<tr>
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<td>10.00</td>
<td>30.00</td>
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<td>Bearing</td>
<td>ID:5</td>
<td>OD:11</td>
<td>3.00</td>
<td>1.2</td>
</tr>
<tr>
<td>Shaft Seal</td>
<td>ID: 5</td>
<td>OD:16</td>
<td>6.00</td>
<td>0.01</td>
</tr>
<tr>
<td>Caudal Fin</td>
<td></td>
<td></td>
<td>Modelled in SolidWorks</td>
<td>N/A</td>
</tr>
<tr>
<td>Shaft and Adapter</td>
<td></td>
<td></td>
<td>Modelled in SolidWorks</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Appendix D – Project Costing

The overall cost is inclusive of all the component costs that were purchased for development purposes, but does not include the manufacturing costs and materials provided by The University of Manchester. Note that a very high cost will be associated with the 3D printing of the housing, however as this was done within the University facilities it is not accounted for. Detailed costing of the project is exhibited in Table D.

Table D - Project Costing

<table>
<thead>
<tr>
<th>Components</th>
<th>Cost (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4M Screw Provided</td>
<td></td>
</tr>
<tr>
<td>4AAA Enclosed Battery Case Provided</td>
<td></td>
</tr>
<tr>
<td>5M Rivets x 4</td>
<td>2.30</td>
</tr>
<tr>
<td>5M Screws x 4</td>
<td>1.90</td>
</tr>
<tr>
<td>9V Battery</td>
<td>3.50</td>
</tr>
<tr>
<td>9V Battery Clip Case Provided</td>
<td></td>
</tr>
<tr>
<td>AAA Battery x 4</td>
<td>3.50</td>
</tr>
<tr>
<td>Arduino Nano Micro Controller Board Provided</td>
<td></td>
</tr>
<tr>
<td>Ball bearing</td>
<td>2.13</td>
</tr>
<tr>
<td>BlueSMIRF RN-42</td>
<td>18.75</td>
</tr>
<tr>
<td>Duct Tape</td>
<td>1.00</td>
</tr>
<tr>
<td>LabView Software</td>
<td>Free</td>
</tr>
<tr>
<td>Futaba S3003 Servo Motor</td>
<td>12.37</td>
</tr>
<tr>
<td>Moulding silicone</td>
<td>Provided</td>
</tr>
<tr>
<td>O-ring splicing kit</td>
<td>19.90</td>
</tr>
<tr>
<td>Plug-in Breadboard</td>
<td>Provided</td>
</tr>
<tr>
<td>Shaft Seal</td>
<td>1.60</td>
</tr>
<tr>
<td>Silicone Sealant</td>
<td>2.40</td>
</tr>
<tr>
<td>SolidWorks 2014</td>
<td>Free</td>
</tr>
<tr>
<td>Superglue</td>
<td>3.36</td>
</tr>
<tr>
<td>Switch</td>
<td>3.05</td>
</tr>
<tr>
<td>Varnish Provided</td>
<td></td>
</tr>
<tr>
<td>Water Resistant Switch Cover</td>
<td>2.26</td>
</tr>
<tr>
<td>Weights Provided</td>
<td></td>
</tr>
<tr>
<td>Wires Provided</td>
<td></td>
</tr>
<tr>
<td><strong>Total Cost:</strong> £ 78.02</td>
<td></td>
</tr>
</tbody>
</table>
Appendix E – Testing Procedure

Test Date: 21-04-2016
Location: Pariser Building, Hydro Lab A8
Attending: Estefania Vega, Haiping

Aims and Objectives

The aim of this testing session is to validate the prototypes dynamic behaviour with the project’s performance objectives. In order to do so, two experiments have been devised.

Required Equipment

- Laptop with Bluetooth capabilities and LabVIEW 2015 software
- 1.00 × 1.50 × 0.50 Water Tank
- Stopwatch
- 2 Video Cameras
- Measuring Tape
- String
- Pen and Paper

Pre-testing Requirements

Before the test could be carried out, a risk assessment of the potential dangers during testing was completed (seen end of section). Next, all the required equipment was evaluated to ensure correct functioning. Then, the prototype was visually inspected to establish that it was assembled in an appropriate manner.
Additionally, the model was submerged in the water tank to check the existence of any leakages (bubbling). Finally, the testing area was cleared for testing to begin.

**Testing procedure**

Both tests were video recorded to further analyse the test results, ensure there were no anomalies within the experiment results and finally review the undertaken tests.

Furthermore both tests require two people; Person A and Person B.

**Test 1: Straight Horizontal Swimming Evaluation**

A video camera mounted to a tripod was set to be facing the side of the clear water tank. Additionally, another camera was set to have an unobstructed view along the length of the water tank. Both cameras will be controlled by Person A. Once both cameras are recording, Person B will be instructed to place and release the robotic fish prototype into the water tank. Following *Figure E.1* shows a view of the partial testing facilities and arrangement.

![Testing Facilities](image)

*Figure E.1 - Testing Facilities*

For this test the model is allowed to swim across the entire length of the water tank, and in each trial it starts from the same departure point. The test was carried out at
three different oscillation amplitudes and frequencies, chosen to suitably cover the allowed domain. The results are shown in Tables E.1 to E.3

Table E.1 - Results Straight Horizontal Swimming Evaluation, Amplitude 30° Frequency 0.5Hz

<table>
<thead>
<tr>
<th>Trial Number</th>
<th>Straight Horizontal Trajectory (Yes/No)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>Straight</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Minimal deviation to left</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>Minimal deviation to left</td>
</tr>
</tbody>
</table>

Table E.2 - Results Straight Horizontal Swimming Evaluation, Amplitude 50° Frequency 1.25Hz

<table>
<thead>
<tr>
<th>Trial Number</th>
<th>Straight Horizontal Trajectory (Yes/No)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>Straight</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Straight</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>Straight</td>
</tr>
</tbody>
</table>

Table E.3 - Results Straight Horizontal Swimming Evaluation, Amplitude 70° Frequency 1.5Hz

<table>
<thead>
<tr>
<th>Trial Number</th>
<th>Straight Horizontal Trajectory (Yes/No)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>Straight</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Minimal deviation to right</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>Straight</td>
</tr>
</tbody>
</table>

Test 2: Variable Swimming Speed Evaluation

For this test ultra-high density polystyrene (UHDP) was taped to one end of the tank. Additionally, 0.9 m were measured from that end of the tank and a string was used to mark the position. Another string was used to mark the centre of the tank in the perpendicular direction. The place where both strings intersected was marked as the prototypes’ starting point, as shown in Figure E.2.

![Figure F.2 - Test Starting Point](image)
Person B released the model from the starting point, while Person A timed how long it took to reach the UHDP wall. If there was any deviation from the centre line, Person B measured the distance and recorded it. The test was carried out two times, one keeping the oscillatory frequency constant and varying the amplitude and the other one vice versa. Each test was repeated three times in order to ensure results accuracy. The following Tables E.4 and E.5 portray the obtained results.

Table E.4 - Test 2 Results at Constant Frequency 1Hz

<table>
<thead>
<tr>
<th>Oscillatory Amplitude (°)</th>
<th>Trial 1</th>
<th></th>
<th>Trial 2</th>
<th></th>
<th>Trial 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time (s)</td>
<td>Deviation (m)</td>
<td>Time (s)</td>
<td>Deviation (m)</td>
<td>Time (s)</td>
<td>Deviation (m)</td>
</tr>
<tr>
<td>30</td>
<td>18.57</td>
<td>0.13</td>
<td>19.66</td>
<td>0.35</td>
<td>18.67</td>
<td>0.37</td>
</tr>
<tr>
<td>40</td>
<td>14.01</td>
<td>0.28</td>
<td>15.10</td>
<td>0.30</td>
<td>14.67</td>
<td>0.26</td>
</tr>
<tr>
<td>50</td>
<td>14.50</td>
<td>0.40</td>
<td>12.27</td>
<td>0.09</td>
<td>13.40</td>
<td>0.23</td>
</tr>
<tr>
<td>60</td>
<td>12.13</td>
<td>0.30</td>
<td>11.67</td>
<td>0.37</td>
<td>11.09</td>
<td>0.32</td>
</tr>
<tr>
<td>70</td>
<td>8.98</td>
<td>-</td>
<td>8.72</td>
<td>0.20</td>
<td>8.8</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table E.5 - Test 2 Results at Constant Amplitude 50°

<table>
<thead>
<tr>
<th>Oscillatory Frequency (Hz)</th>
<th>Trial 1</th>
<th></th>
<th>Trial 2</th>
<th></th>
<th>Trial 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time (s)</td>
<td>Deviation (m)</td>
<td>Time (s)</td>
<td>Deviation (m)</td>
<td>Time (s)</td>
<td>Deviation (m)</td>
</tr>
<tr>
<td>0.50</td>
<td>28.58</td>
<td>-</td>
<td>17.73</td>
<td>0.17</td>
<td>17.72</td>
<td>-</td>
</tr>
<tr>
<td>0.75</td>
<td>14.20</td>
<td>-</td>
<td>11.44</td>
<td>0.45</td>
<td>11.15</td>
<td>0.20</td>
</tr>
<tr>
<td>1.00</td>
<td>9.98</td>
<td>0.16</td>
<td>11.15</td>
<td>0.16</td>
<td>10.45</td>
<td>-</td>
</tr>
<tr>
<td>1.25</td>
<td>6.92</td>
<td>0.16</td>
<td>6.53</td>
<td>0.34</td>
<td>7.16</td>
<td>0.22</td>
</tr>
<tr>
<td>1.50</td>
<td>6.20</td>
<td>0.13</td>
<td>6.15</td>
<td>0.45</td>
<td>6.43</td>
<td>0.245</td>
</tr>
</tbody>
</table>

By using Pythagoras theorem and the reasoning shown in Figure F.3, the actual swimming distance of the prototype was calculated for all the data points experimentally obtained. Using the actual swimming distance the cruising velocity for each data point was calculated, and then averaged. Results for constant frequency and constant amplitude are shown in Table F.6 and Table F.7 respectively.
Table E.6 - Test 2 Velocity Results at Constant Frequency 1Hz

<table>
<thead>
<tr>
<th>Oscillatory Amplitude (°)</th>
<th>Trial 1 Velocity (m/s)</th>
<th>Trial 2 Velocity (m/s)</th>
<th>Trial 3 Velocity (m/s)</th>
<th>Average Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>40</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>50</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>60</td>
<td>0.08</td>
<td>0.08</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>70</td>
<td>0.10</td>
<td>0.11</td>
<td>0.10</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table E.7 - Test 2 Velocity Results at Constant Amplitude 60°

<table>
<thead>
<tr>
<th>Oscillatory Frequency (Hz)</th>
<th>Trial 1 Velocity (m/s)</th>
<th>Trial 2 Velocity (m/s)</th>
<th>Trial 3 Velocity (m/s)</th>
<th>Average Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.03</td>
<td>0.05</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>0.75</td>
<td>0.06</td>
<td>0.09</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>1.00</td>
<td>0.09</td>
<td>0.08</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>1.25</td>
<td>0.13</td>
<td>0.15</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>1.50</td>
<td>0.15</td>
<td>0.16</td>
<td>0.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Testing videos are available at:

https://www.dropbox.com/sh/72rbdp85acv8f/AAChv36awLrPqLCnYe8qcAw8a?dl=0
## Risk Assessment

<table>
<thead>
<tr>
<th>Activity/Category/Area</th>
<th>Risk Assesments</th>
<th>Equipment:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk Level</td>
<td>Risk Rating (L/M/H)</td>
<td>COSHH</td>
</tr>
<tr>
<td>Hazard</td>
<td>Description</td>
<td>Electrical Shock</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The robotic fish is connected to two batteries that can be connected at once, and hence avoid having a live circuit near water.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Care should be taken when near the testing tank in order to avoid tripping into it. Two feet must always be grounded.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If the surface is large, signs must be put up indicating the wet areas. However, for small areas each individual must take care and avoid any sudden motions within the testing area.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Activity/Category/Area</th>
<th>Risk Assesments</th>
<th>Equipment:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk Level</td>
<td>Risk Rating (L/M/H)</td>
<td>COSHH</td>
</tr>
<tr>
<td>Hazard</td>
<td>Description</td>
<td>Electrical Shock</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The robotic fish is connected to two batteries that can be connected at once, and hence avoid having a live circuit near water.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Care should be taken when near the testing tank in order to avoid tripping into it. Two feet must always be grounded.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If the surface is large, signs must be put up indicating the wet areas. However, for small areas each individual must take care and avoid any sudden motions within the testing area.</td>
</tr>
</tbody>
</table>
Appendix F – Theoretical Results Calculation

Using Lighthill’s Elongated Body Theory it is possible to calculate the swimming velocity of the robotic fish to be:

\[ U = \sqrt{\frac{m \left( \frac{\partial y(x, t)}{\partial t} \right)^2}{C_D \rho_w S + m \left( \frac{\partial y(x, t)}{\partial x} \right)^2}} \bigg|_{x=l} \quad (12) \]

Using same reasoning as Chen’s (2008) model:

\[ y = Ax \sin(\omega t) \]

\[ \left( \frac{\partial y(x, t)}{\partial t} \right)^2 = (Ax \omega \cos \omega t)^2 \]

\[ \left( \frac{\partial y(x, t)}{\partial t} \right)^2 = \frac{A^2 \omega}{2} \int_0^1 \frac{x^2}{l} \, dx = \frac{A^2 \omega l^2}{6} \]

Where, \( Al = A_{max}/2 \)

Substituting back to Eq. (12):

\[ U = \sqrt{\frac{m \omega}{6} \frac{A_{max}}{2}} \]

\[ \omega = 2\pi f \]

\[ \frac{A_{max}}{2} = \sin(\theta) \times c \]

\[ \therefore U = \sqrt{\frac{m \frac{2\pi f}{6}}{C_D \rho_w S + m \frac{2\pi f}{6} \times (\sin(\theta) \times c)^2}} \quad (F.1) \]

where, \( \theta \) is the oscillating amplitude and \( f \) the oscillating frequency.
The following parameters have been calculated for the final robotic fish prototype, with exception of the drag coefficient which was approximated to be slightly less than a cylinder’s one.

\[ m = 1.6926 \text{ kg} \quad c = 0.267m \quad C_D = 0.7 \quad \rho_w = 1000 \text{ kg/m}^3 \quad S = 9.62 \times 10^{-3} \text{m}^2 \]

Substituting these parameters into Eq.(1):

\[
U \approx \frac{0.3555f \times \sin(\theta)}{\sqrt{\frac{3367}{500} + (0.1236f \times \sin^2(\theta))}} \quad (F.2)
\]

All the theoretical values were calculated in basis of Eq.(2) substituting the appropriate \( \theta \) and \( f \). Obtained results are shown in the following Table F.1 and F.2.

Table F.1– Theoretical Velocity Results at Constant Frequency 1Hz

<table>
<thead>
<tr>
<th>Oscillatory Amplitude (°)</th>
<th>Cruising Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.069</td>
</tr>
<tr>
<td>40</td>
<td>0.088</td>
</tr>
<tr>
<td>50</td>
<td>0.104</td>
</tr>
<tr>
<td>60</td>
<td>0.118</td>
</tr>
<tr>
<td>70</td>
<td>0.127</td>
</tr>
</tbody>
</table>

Table F.2 - Theoretical Velocity Results at Constant Amplitude 60°

<table>
<thead>
<tr>
<th>Oscillatory Frequency (Hz)</th>
<th>Cruising Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.059</td>
</tr>
<tr>
<td>0.75</td>
<td>0.089</td>
</tr>
<tr>
<td>1.00</td>
<td>0.118</td>
</tr>
<tr>
<td>1.25</td>
<td>0.147</td>
</tr>
<tr>
<td>1.50</td>
<td>0.176</td>
</tr>
</tbody>
</table>