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# DESIGN AND CONSTRUCTION OF A ROBOTIC SURVEILLANCE FISH

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## *ABSTRACT*

*The use of robots has increased exponentially in the 21st century due to improvement in the design of drives, actuators and control electronics. Bio-inspired robots are robots which use electro-mechanical motion to achieve near natural movement of the animal they represent. Stealth and energy efficiency are amongst qualities obtainable from nature inspired movements.*

*The design and construction of a robot fish is an attempt into bio-mimicry. This project entails the use of conventional, cheap and off the shelf mechanical mechanisms to achieve the anguilliform motion of a typical African Catfish. A geared motor driven crank and telescopic connecting rod mechanism is used to achieve the undulating motion of the tail. This created the propulsion needed to achieve the surging motion. The pectoral (right and left) fins are controlled by two (2) independent geared DC (direct current) motors. Moving the right or the left fins to a position tangential to the fish body generates drag which steers (yaws) the fish to the right or left direction respectively. Plastic containers are used as the ballast tanks through which two (2) DC submersible water pumps vary the buoyancy of the robot for both surface and subsurface swimming thereby achieving the pitching motion. Light weight hollow Aluminium (aerosol can) is used for the rib cage (core) of the fish. This Aluminium core encloses the ballast containers, propulsion motor and the crank/connecting rod assemble. Light weight synthetic rubber is used to enclose the body of the fish making it water proof and flexible. The center of gravity of the fish was maintained just under the fish head and upper frame region using the weight of the battery and propulsion motor to maintain the fish stability.*

*The fish was able to achieve a speed of 0.1m/s and submerged in 4 secs during the tests. The test was done in non-flowing water. The fin movement, buoyancy variation and propulsion were achieved during the test.*

***KEYWORDS:*** *Design of Drives, Actuators and Control Electronics*, *To Achieve the Surging Motion*

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## INTRODUCTION

### 1.1 Background of Study

For the purpose of this design and construction, two aspects of a typical water based fish was considered:

- Fish anatomy and Hydrodynamics.
- Fish Locomotion.

The anatomy of a typical fish and the subject of fish locomotion were first understudied. Fish anatomy is relevant in this design as it will highlight the structural and physical build of a fish using the internal and external anatomy. This enabled us achieve the stealth intended in terms of the size ratio of one body part to another (fins, tail, head), weight distribution along the body. The hydrodynamics which deals with the motion of fluids and the forces acting on solid bodies immersed in fluids and in motion relative to them will also be analyzed.

Secondly, fish locomotion is the second aspect of the stealthy surveillance robotic fish requirement. The propulsion methodology and buoyancy of the fish will also be analyzed to efficiently mimic fish movement while considering the electronic and electromechanical payload it will carry.

With the knowledge of fish anatomy and requirements for fish locomotion, the appropriate mechanism, links using principles of mechanics of machines and the theory of buoyancy, the fish motion and stabilization can be achieved.

## STATEMENT OF PROBLEM

The problem of oil/gas pipeline vandalization and contraband smuggling of goods and weapons along the many rivers, coastline and creeks is critical and pose a major concern. These nefarious activities usually take place in the dead of the night, under the cover of darkness and the quietness is maximized. Human surveillance is often difficult and requires a lot of manpower, personnel integrity and real-time observation are difficult for the large number of oil/gas installations and river boarders which stretch across the nation.

The approach of this project is to use a domesticated fish species (catfish) as a bionic fish-form robot either as single or network of fishes to monitor oil installations and river borders, swimming from location to location and then transmitting the audio-video live status of such locations to the controlling operator. The data can then be used to deploy armed personnel, sound an alarm or trail perpetrators. This method of surveillance will leave no noticeable trace of surveillance as the robot fish can submerge itself underwater after any abnormal activity is recorded. The robot fish can then re-emerge for maintenance and battery recharging.

## 2.2 AIM AND OBJECTIVES

### Aim

The aim of this Project is to design and construct catfish-like robotic fish with video/audio equipment, wireless transmission electronics embedded into it with remotely controlled propulsion and GPS tracking capability for surveillance purposes.

### Objectives

This work has the following objectives:

- To design the Surveillance robotic fish with three (3) degrees of freedom: Surging, Pitching and Yawing motion.
- Construction of body frame, mechanism and motor actuators of the robotic catfish.
- To test the robot fish propulsion, buoyancy, hydrodynamic control and visual transmission capabilities.
- To document limitations of the robot design, energy efficiency, maneuverability and overall efficiency of the robot mechanism.

## SIGNIFICANCE OF RESEARCH

Bio-inspired robotic locomotion is a fairly new subcategory of bio-inspired design. It is about learning concepts from nature and applying them to the design of real-world engineered systems. More specifically, this field is about making robots that are inspired by biological systems. Biomimicry and bio-inspired design are sometimes confused. Biomimicry is copying the nature while bio-inspired design is learning from nature and making a mechanism that is simpler and more effective than the system observed in nature (10). Biomimicry has led to the development of a different branch of robotics called soft robotics.

The biological systems have been optimized for specific tasks according to their habitat. However, they are multifunctional and are not designed for only one specific functionality. Bio-inspired robotics is about studying biological systems, and look for the mechanisms that may solve a problem in the engineering field. The designer should then try to simplify and enhance that mechanism for the specific task of interest. Bio-inspired robotics are usually interested in biosensors (e.g. eye), bioactuators (e.g. muscle), or biomaterials (e.g. spider silk).

Animals have adapted over the years and are very well suited to the environments they inhabit. If we want to build a robot that can operate in a particular environment, like the ocean floor, why not copy a solution that nature has come up with? We want our robots to be able to overcome any challenges they face, and animals have already figured out how to do that. Rarely do we see animals stuck in the wild. If an animal were to get stuck, it would wiggle and squirm its way to freedom. Traditional autonomous robots can't really do this as their behaviors have to be programmed ahead of time [11].

While research into autonomous robots are ongoing, there exists a wide spectrum for remotely controlled robots which is yet to be fully explored. Furthermore, efficient biomimicry is still in its infancy due to the large number of varying animal species. The complexity and dynamism of animal locomotion and habitat adaption is yet to be fully explored with existing electromechanical controls and artificial intelligence [12][13]. Thus a research into the locomotion and behavior of a local fish species (African catfish) is a contribution to non-autonomous biomimicry.

## SCOPE

The scope of this work is limited to the following:

- The motion of the fish-like robot will be limited to three (3) degrees of motion. Typical underwater vessels such as ships, submarines and UUV's have six (6) of Freedom.
- The catfish will not be Autonomous thus its movement and behavioral pattern will be controlled by a human operator. This design and construction will focus on movement hydrodynamics, minimization of swimming turbulence, achievement of propulsion with minimal battery power consumption and the clarity of the audiovisual signals transmitted.
- The design will utilize links to simulate the vertebrae column. The design will also use of servomotors to generate the undulating movement of the caudal fin via the vertebrae column. Furthermore, the use of magnetic actuators to lift and drop either or both pectoral fins to cause drag and initiate a change of direction of swim.
- The design will utilize a flexible ballast container with small sized pumps. The pump will suck water in and push water out of the flexible ballast container necessary for the fish hydrostatics. This is because hydrostatic forces such as weight and buoyancy play crucial roles in the stability of fishes.

Here is how: The weight, W, is defined as the mass multiplied by the gravitational constant, $M_{f.}$ g. On the other hand, the buoyancy, B, is defined by Archimedes law as the displaced mass of water multiplied by the gravitational constant, $\rho_w V_{f.}$ g [14][15].

where $V_f$ is the fish volume and

$\rho_w$ is the density of water.

In order to keep the position of the robot stable underwater, W and B need to be equal. Additionally, the centers of mass and buoyancy must be vertically aligned, while the centre of buoyancy should be above that of the weight. This enumerates why the buoyancy ballasts will be used for this project.

## LIMITATIONS

This project is limited to only three (3) degrees of freedom for the fish. These are Surging, Pitching, and Yawing motions.

## METHODOLOGY

This chapter describes the procedure of designing and constructing the robotic fish. This entails selection of the motion mechanism for the Caudal fin (Tail fin), calculation of the speed requirement and torque requirement of the driver component. Furthermore, the inferred weight determination of the motion of the central enclosure, buoyancy calculations and buoyancy alterations to achieve surging motion were also documented. The overall power requirement of the assembly with the video capturing and transmission devices was also determined. The selection requirements of the material used for the central fish body, head region, pectoral fins and the highly flexible lower caudal fin region were also documented.

### Design of Robotic Fish

Using design terminology of water/air moving vehicles, the three (3) degrees of motion which this research achieved are:

- Surging
- Yawing
- Pitching
- **Surging:** This can be described as the linear longitudinal (front/back or bow/stern) motion imparted by maritime conditions that is moving forward and backward on the X-axis.
- **Yawing:** This can be described as he turning rotation of a vessel about its vertical Z axis, that is turning left and right on the Z-axis.
- **Pitching:** The up/down rotation of a vessel about its transverse/Y (side-to-side or port starboard) axis, that is tilting forward and backward on the Y-axis.

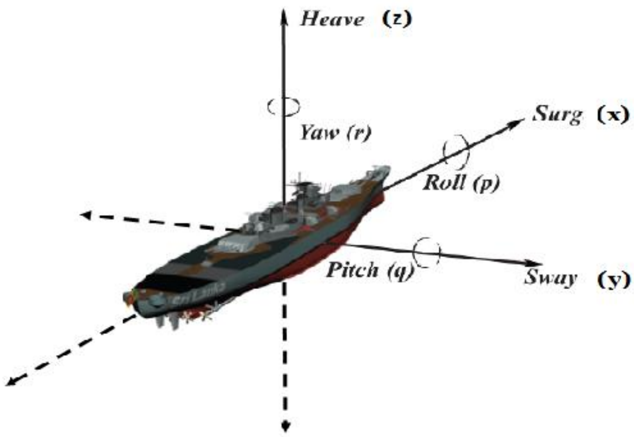



**Figure 1: Description of 6 Degrees of Freedom of a Ship.**

## Surging / Propulsion Motion Mechanism

The selected mechanism for propulsion which can produce the required swing for the caudal fin region of the fish is the Crank and connecting rod system.

Figure 2 shows,

The crank and connected rod can be related by the following expressions:

Given that

**L** = rod length

**r** = crank radius

**A** = Crank angle

**x** = Position of Piston pin from crank center.

**P** = Piston Pin

**N** = Crank Pin

**O** = Crank center

Thus:

Using Cosine law:

$$l^2 = r^2 + x^2 - 2.r.x.cosA$$

$$l^2 - r^2 = x^2 - 2.r.x.cosA$$

$$l^2 - r^2 = x^2 - 2.r.x.cosA + r^2[(cos^2 A + sin^2 A) - 1]$$

$$l^2 - r^2 + r^2 - r^2 sin^2 A = x^2 - 2.r.x.cosA + r^2 cos^2 A$$

$$l^2 - r^2 sin^2 A = (x - r.cosA)^2$$

$$x - r.cosA = \sqrt{l^2 - r^2 sin^2 A}$$

$$x = r.cosA + \sqrt{l^2 - r^2 sin^2 A}$$

Furthermore, velocity with respect to crank angle(take first derivative, using the chain rule)

$$x' = \frac{dx}{dA}$$

$$= -r\,sinA + \frac{\frac{1}{2}.(-2).r^2\,sinA\,cosA}{\sqrt{l^2 - r^2 sin^2 A}}$$

$$= -r\,sinA - \frac{r^2\,sinA\,cosA}{\sqrt{l^2 - r^2 sin^2 A}} \quad (1)$$

Figure 3 shows the modified Crank and connecting rod used to achieve the fish caudal fin swing.

The maximum tail rod position occurs at $A_1 = 90^o$

The expression becomes

$\mathbf{X_1} = r.\cos 90 + \sqrt{(l^2 - r^2 \sin^2 90)}$ (2)

$\mathbf{X_1} = \sqrt{(l^2 - r^2)}$

In this position, the maximum swing angle can be obtained as:

$\Theta = \mathrm{Sin}^{-1}(r/x_1)$ (3)

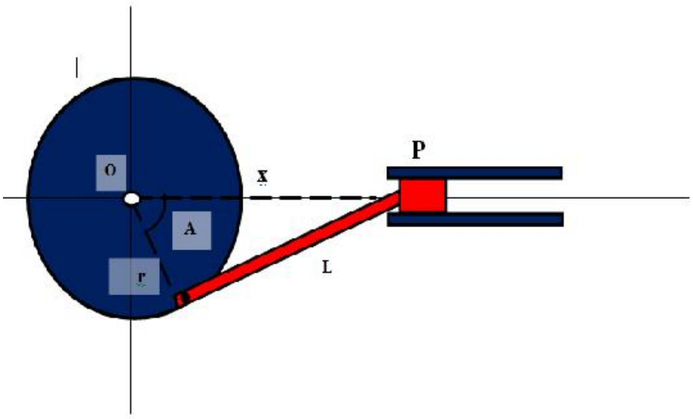



**Figure 2: Typical Crank, Connecting Rod, Piston Assembly**

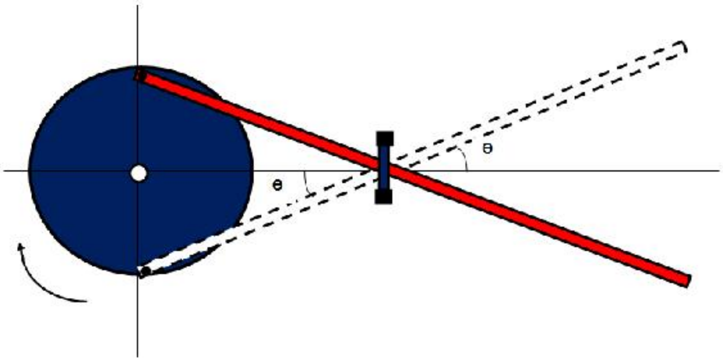



**Figure 3: Maximum Swing Angle of a Modified Crank and Connecting Rod Assemble**

## Drag Considerations

In order for the connecting rod/fish tail to create a swing through water, it must overcome the viscous drag of the medium.

Viscous drag is given as ;

$$F_d = -\frac{1}{2}\rho v^2 A C_d v \tag{4}$$

Where :

**$F_d$** = Drag force

**ρ** = Density of the Liquid

**v** = velocity of moving object

**A** = Surface Area of the object pushing through the Liquid

**$C_d$** = Coefficient of drag.

**V** = normalized unit velocity vector

**Negative sign** = Indicates the Drag force is in opposite direction to the velocity.

The force generated by the connecting rod swing

**$F_r$** = m.a (5)

Where:

**$F_r$** = Force exerted by connecting rod

**M** = mass of attached fish tail

**A** = acceleration of fish tail.

But

**ω** = 2π RPM/ 60 (6)

**a** = (ω. r /60)/(60Y rev/2) (7)

where :

**Yrev** = no. of revolutions the crank makes in 1 min

**ω. r** = Linear velocity

Therefore:

For the tail to push through water: $\mathbf{F_r >> F_d}$

## Locus of Motion of the Connecting Rod

If the locus of a point M on the connecting rod is plotted, it produces an ellipse (see below). For the purpose of achieving a swinging motion of the fish tail, the ellipse is not desirable. In order to convert the elliptical locus of this motion to a parabolic locus, a telescopic connecting rod was introduced. This disconnects the motion of the connecting rod from the second half of the elliptical locus during the crank motion.

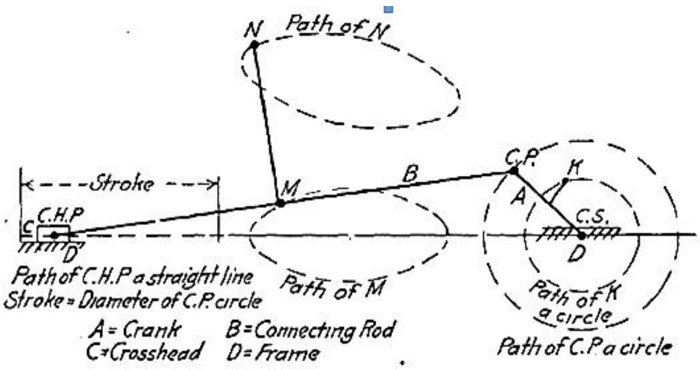



**Figure 4: Ellipse Produced by Point M on a Connecting Rod for a Typical Crank- Connecting Rod Mechanism.**

The equation of an Ellipse is given by :

$$(x-h)^2/a^2 + (y-k)^2/b^2 = 1 \quad (8)$$

Where (h,k) are respective x,y coordinates at the center of the ellipse and (a,b) are respective x,y coordinates of the vertex and co-vertex.

The equation of a Parabola is given by :

$$y= (x-h)^2 + k \quad (9)$$

where h = distance that the parabola has been translated along the x axis

k= distance the parabola has been shifted up and down the y-axis

The Locus of the motion of an imaginary point on a typical connecting rod of a crank/connecting rod mechanism is shown in red and green colour below. However, with the introduction of the telescopic section to the connecting rod, half of the elliptical path is not transmitted to the

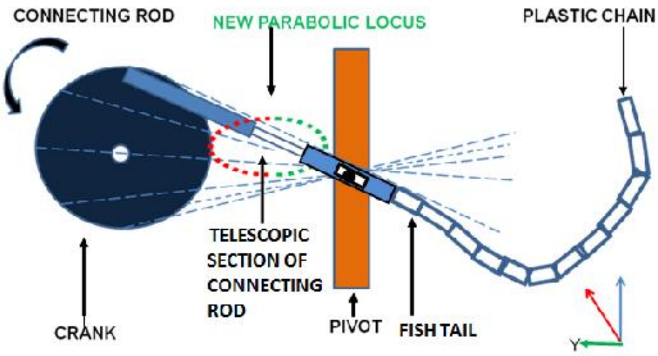



**Figure 5: Connecting ROD Showing Telescopic Section Attached to Crank.**

## Motor Torque Calculation

Torque can be defined as moment, or rotational force. It is expressed as :

$$\tau d = r \times Fr \quad (10)$$

where;

$\tau_d$ = Design Torque

r = Moment arm/Crank radius

$F_r$ = Force applied to arm.

For the crank driver (motor) to be able to drive the connecting rod via the crank :

$\tau_m >> \tau_r$

where:

$\tau_{m}$ = Motor torque

$\tau_{d}$ = Design torque

## Yawing / Turning Motion Mechanism

## Pectoral Fin Design

Pectoral fin can be defined as a pair of fins situated on either side just behind a fish's head, helping to control the direction of movement during locomotion

A DC motor was used to actualize the steering action of the Yawing motion. The robotic pectoral fin is designed to move through an angle of $90^o$.

Shown below is the swing motion from the robotic pectoral fin. To determine the time (secs) required for the fin to travel a quarter turn of one revolution is :

Let motor speed = K rpm

Time required to travel through 1 rev ($360^o$) =( 1/K) × 60 secs

Time required to travel through quarter turn ($\Theta/4 = 90^o$) = [(1/k) ×60] /4 secs

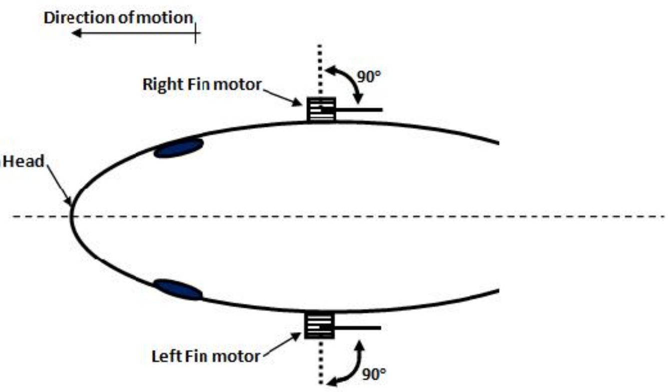



**Figure 6: Diagram of Fish Upper Head Region Showing Motion of the Pectoral fin DC Motors.**

## Pitching Motion / Buoyancy Motion Mechanism

Buoyancy is the force acting opposite the direction of gravity that affects all objects submerged in a fluid. When an object is placed in a fluid, the object's weight pushes down on the fluid (liquid or gas) while an upward buoyancy force pushes upward on the object, acting against gravity. In general terms, this buoyancy force can be calculated with the equation;

$$F_b = V_s \times \rho \times g \quad (11)$$

Where:

$F_b$ = buoyancy force,

$V_s$ = submerged volume,

$\rho$ = density of the fluid the object is submerged in, and

$g$ = force of gravity.

We first obtained the weight of the Fish assemble:

$m_f$ = mass of fish

$$W = m_{f.}\, g \quad (12)$$

From equation 3.11, the $V_s$ (submerged volume of fish) which is also the displaced volume of water can varied by varying the weight of the fish.

Given that **ρ=m/v**, with the volume of fish fixed, the mass can be varied which in turn alters the weight. In order to alter the mass, a ballast is introduced into the fish. The ballast is connected to two (2) water pumps. One of the pumps sucks in water while the other pumps out water.

The following steps were used to achieve the sinking and rising (Pitching) motion of the fish:

- The normal buoyancy force $\mathbf{F_{b1}}$ was determined by placing the fish in water, causing in to float due to the low mass to volume ratio. The natural volume of water displaced is $\mathbf{V_{s1.}}$ With $\mathbf{V_s}$ displaced, the fish was partially submerged in water. The normal buoyant force is expressed as:

  $$F_{b1} = V_{s1} \times \rho \times g$$

- The fish was then manually submerged completely in water and the value of $\mathbf{V_{s2}}$ was obtained. Now the submerged buoyancy force $\mathbf{F_{b2}}$ to keep the fish sub-surface is :

$$F_{b2} = V_{s2} \times \rho \times g$$

- The ratio of the normal buoyant force to weight of the normal fish without ballast is then determined. Since the Buoyant force is proportional to the mass of an object given the volume is held constant, we then have :

$$F_{b1} / m_{f1} = k$$

Where,

$m_{f1}$ = mass of fish without ballast and

K= constant of proportionality.

Thus the mass of the fish to produce the new buoyant force for the fish to be sub surface is :

$$[F_{b1} / m_{f1}] = [F_{b2} / (m_{f1}+m_{fb})]$$

Where

$m_{f1}$ = Mass of fish

$m_{fb}$ = Mass of filled ballast

Using the value of $m_{fb}$ obtained above**,** the volume of the ballast container is then obtained using:

$$V_{fb} = \rho .\ m_{fb}$$

Where:

ρ = Density of water which is the ballast filling fluid.

$m_{fb}$ = mass of Ballast and filling fluid

## Fish Body and Tail Construction

The Core of the fish which houses the Crank motor, Crank wheel and the Connecting rod designed with a cylindrical hollow Aluminium aerosol can. This is because the Aluminum aerosol can is light enough to float but though enough to rigidly hold the motor in place and prevent excessive vibrations.

Figure 7 shows the fish tail was designed using a combination o.5cm rubber tube, soft cadboard paper and molded silicone. The rubber tube represents the fish spine which transmits motion from the connecting rod through the entire tail up till the caudal fin. The cadboard/silicon rubber combinations gives the tail region the flexibility and muscle needed to swing through water in a gliding manner.

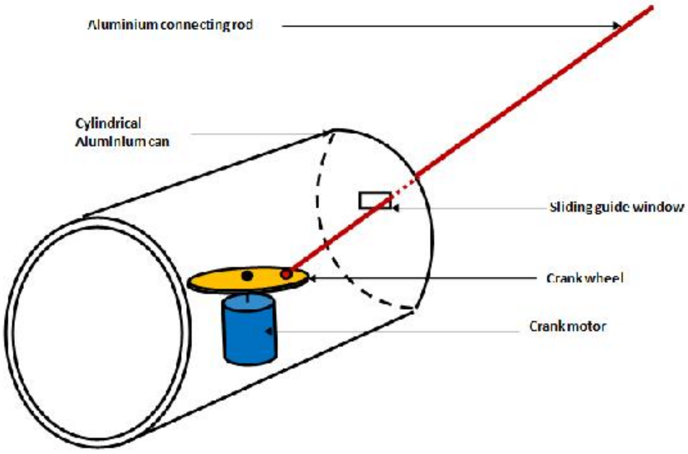



**Figure 7: Fish Core, Crank Motor, Crank Wheel and Connecting rod Assembly.**

## Construction Images of the Fish Core

The fish core was constructed using a 0.0762m light weight hollow Aluminium aerosol can covered with synthetic rubber used for car tyre tubes. The right and left pectoral fin motors are held rigidly to along the circumference of the frame using metal clips. Figures 3.6a, 3.6b and 3.6c show the assembled fish core.

**Figure 8: (a) Fish Core Construction, (b) Fish Core Construction & (c) Fish Core Construction.**

# RESULTS AND DISCUSSION

## Results

This chapter presents the results obtained from the preceding chapter showing the design. The parameters in this chapter include the design and operational parameters. Details of construction of the robotic fish have been described in the previous chapter.

## Fish Specifications

The Operational parameters were deduced using measurements obtained after the construction was completed while the design parameters were obtained from the calculations in Chapter 3.

**Table 1: Operational Parameters**

| | Parameter | Values |
|---|---|---|
| 1. | Total length | 0.03M |
| 2. | Fin to Fin length | 0.0508M |
| 3. | Fish Weight | 0.6kg |
| 4. | Fish Speed | 0.1M/S |
| 5. | Submersion time | 4secs |
| 6. | Current consumption | 1.2A |
| 7. | Voltage requirements | 6V DC |

### Fish Speed

The speed of the robotic fish was measured in a 1m long water bath, and the fish covered a distance of 0.65m in a period of 5 seconds, giving an average of 0.10 - 0.13m/s.

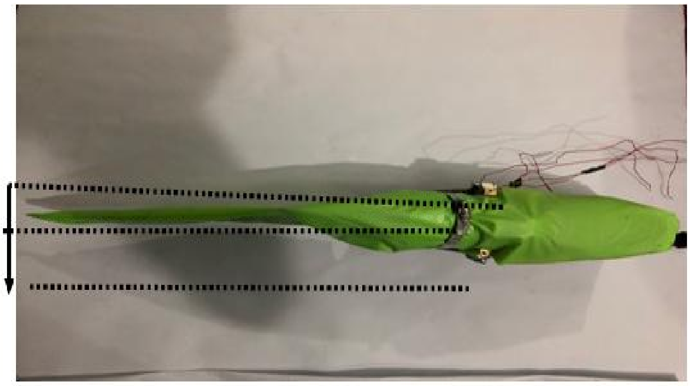
### Fish Weight

The weight of the fish is 0.6kg and it is a good result in that it will give the fish room for movement and aid floating.

**Table 2: Design Parameters**

| | Component | Length | Weight | Torque / Voltage | Speed | Material | Volume |
|---|---|---|---|---|---|---|---|
| 1. | Crank Driver Motor | - | - | 0.22N.m, 6V | 160 rpm | - | - |
| 2. | Connecting ROD | 0.0254m Length/ 0.03m diameter | - | - | - | - | - |
| 3. | Crank Diameter | 0.0508m | - | - | - | - | - |
| 4 | Ballast Capacity | - | - | - | - | Plastic | $0.1\times10^5 m^3$ |
| 5. | Fin Motor | - | - | 0.1N.m/6V | 55 rpm | - | - |
| 6. | Fish Body | 0.03m | - | - | - | Neoprene synthetic rubber | $5\times10^5$ $m^3$ |
| 7. | Fish Weight | - | 0.6kg | - | - | - | - |

### Images of Fish Motion



**(a) Fish in Neutral Position**
**Figure 9: Fish Tail in Neutral Position.**

## DISCUSSIONS

### Fish Volume

Due to the heterogeneous nature of the fish, the fish volume was determined using an inferred method. Using Archimedes principle, the volume of water displaced by the fish when placed in a filled water bucket was collected and measured. The volume obtained by Archimedes is equal to the volume of the fish assemble. The volume was used in the buoyancy calculation.

### Fish Speed

From the analysis of the speed of the robotic fish in water, the fish had a relatively good speed, and this was related directly to the high torque of the motor and the light weight of the material used for the body construction.

## CONCLUSION AND RECOMMENDATION

### Conclusion

The design, construction and assembly of robotic surveillance fish was successful. The robotic fish was tested and based on the results, the following conclusion were drawn:

- The robotic fish which was designed to achieve 3 degrees of freedom. This aim was successfully achieved in that the fish could move in all 3 directions intended.
- The combination of clothe fibre and synthetic rubber material used for the fish body construction is a gave the robotic fish a light weight and required flexibility.
- The robotic fish achieved propulsion and maneuverability, hence the main purpose of the research is achieved.
- The telescopic connecting rod was achieved using a solid Aluminium rod sliding in and out of a greased hollow rubber tube of slightly wider diameter.
- The low voltage, high torque unidirectional DC motors used in this research also enhanced the controlled movement of the fish.

### Recommendation

- The knowledge gained from this design can be further used to develop a robot with high maneuverability with 6 degrees of freedom.
- The surveillance capability of the fish can be enhanced by installing multiple directional cameras which will reduce the need for turning of the fish while in use.

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