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DEVELOPMENT OF MANTA RAY INSPIRED FISH ROBOT WITH EMBODIED SENSING FOR EFFICIENT UNDERWATER ENVIRONMENT MONITORING

Taha Rehman Aali
Department of Electrical Engineering, Sukkur IBA University, Pakistan

Hammad Adnan
Department of Electrical Engineering, Sukkur IBA University, Pakistan

Dr. Afaque Manzoor Soomro
Department of Electrical Engineering, Sukkur IBA University, Pakistan

Abstract
This study aims to design and develop a bio-inspired soft robotic fish for underwater environment monitoring. The ocean is vast, covering more than 70% of earth's surface and largely unexplored frontier having diverse ecosystems and vital resources. Monitoring underwater environment is important for understanding marine life and studying impacts of climate change. While traditional robots such as AUVs are precise and durable but due to their bulky structure struggle in complex conditions in ocean. Due to disadvantages such as less adaptable and potentially harmful to marine ecosystem of hard robots, the increasing demand for effective underwater environment monitoring has sparked interest in bio-inspired soft robotics. Soft robots are ideal for underwater monitoring due to their flexible and adaptable structure. They can navigate complex environments more easily, reducing the risk of damaging marine life and robot itself. This study presents the design and implementation of soft robotic fish inspired by manta rays known for their unique swimming pattern, efficient and agile locomotion. Our robot mimics real manta rays' movements patterns by utilizing pectoral fins made from soft materials which generate thrusts using pneumatic actuation. The robot fins were designed by studying manta ray fin propulsion and simulating in ANSYS software where we observed same pattern of movement of real manta ray fish. The fins were fabricated using ecoflex0030 which is flexible soft material. The prototype was tested to observe the movement of fins and evaluate its performance which was close to real fish movements. This study helps in advancement of bio-inspired underwater robotics field by improving efficiency and capability of underwater monitoring systems. Future work will focus on refining the design, improving performance of robot, developing communication system and embodied sensing for data collection such as pressure, temperature of underwater environments.

Keywords Traditional robots, bio-inspired, Soft robotic, Eco flux 0030, Naca airfoil, Fin propulsion, Soft Materials, Underwater Robotics.

INTRODUCTION

The ocean covers more than 70% of the earth's surface making it very vast and large but remains one of the least explored [1]. The ocean contains diverse ecosystems and vital resources important for planet's health and human survival. To understand marine life, studying impacts of climate change, monitoring underwater environment is crucial [3]. In the past ocean exploration was done by direct human involvement through diving and manned submersibles. However, these methods were limited by depth, duration and safety concerns. The advancement in technology introduced new advanced methods for underwater exploration, the methods include underwater vehicles used for studying underwater environments without direct human involvement.

These technologies opened new ways for scientific research and environment monitoring.

Underwater robots have become very important tools for ocean exploration. Underwater robots such as ROVs and AUVs are heavily used for environment monitoring, and they help in gathering data from the ocean. These robots are equipped with sensors, cameras and sonar systems to perform various ocean tasks and collect critical information about underwater environment autonomously. These traditional robots are precise and durable but due to their bulky structure they face challenges in complex conditions of the ocean. The disadvantages of these robots such as less adaptability and rigid parts can potentially harm marine ecosystem.

Soft bio-inspired robots are now used over traditional

robots for underwater monitoring due to their flexibility and adaptability [4]. They can navigate through complex and confined environments and can interact with diverse marine environments more safely and effectively [2].

These robots also draw less power and produce less noise than traditional robots. Soft bio-inspired robots take inspiration from real-life aquatic animals and mimic their movements such as swimming pattern, design and ae made of soft and compliant materials. These materials are analogous to ones found in living sea creatures [2]. By using such materials, robot's flexibility adaptability and degree of freedom increases. Soft robots are designed to move, crawl, swim and get used to surrounding the way natural sea livings are doing.

Traditional hard robots such as AUVs and ROVs have limitations in underwater monitoring due to their rigid structure, less degree of freedom, high power requirements and are less adaptable and poses harm for marine ecosystem [19]. To address these challenges flexible and adaptable soft robots are required which can easily navigate through confined and complex environments due to their efficiency and maneuverability. Manta rays belong to the family Myliobatidae and are among the largest species of sea. Manta rays are characterized by their rigid, compressed and flat bodies from top to bottom, and large, expanded pectoral fins which can reach spans of over 9 meters [5]. Manta ray's structure is like designed hydrofoil, and it helps them to generate lift [10]. The fins of Manta rays are flexible and allow them to produce thrust efficiently. Manta rays swimming pattern is analogous to flight of birds, which involves oscillation of fins and generate lift through upstroke and down stroke motion. Manta rays swim by flapping their large pectoral fins and these fins move in a wave-like motion, with a wave extending from base of the fin to tip. Research shows that initiation of both upstroke and down stroke happens at front base of fin and produces waves that travel through fin to the wing [21].

Swimming mechanics of manta ray is very complex and highly efficient. Manta ray swim by flapping their fins in vertical plane through upstroke and down stroke. The flexibility in their pectoral fins plays an important role in swimming mechanics of manta rays. Manta rays are known as one of the efficient swimmers in ocean due to their unique swimming pattern and large pectoral fins. Research shows that propulsive efficiency of manta rays can as be high as 89% [21].

Manta rays have efficient swimming mechanics and unique structural features that make them a good model for biomimicry. Bio-inspiration can be taken, and their wave-like motion of fins can be replicated to design bio-inspired soft robots for underwater monitoring. Studying and understanding about swimming patterns and fin movements of manta rays can lead to innovative solutions in developments of new technologies for underwater monitoring and soft robotics.

Soft robots are not made from hard rigid parts unlike traditional hard robots, and they are made from soft, compliant and flexible materials such as flexible polymers, silicones and elastomers to ensure flexibility of robots. For the actuation motors are not used instead soft robots are actuated by using pneumatic, hydraulic, dielectric elastomers and shape-memory alloys (SMAs). Each actuation method offers unique advantages and has limitations and choice of actuation method and materials used influences robot's flexibility, adaptability and performance to various tasks and applications.

METHODOLOGY

The first phase is to conduct literature review on Manta rays and study their movements, swimming patterns, design and related work that is done on soft robots inspired by Manta ray's. After conducting study, we analyzed a graph that we extracted from a research paper which helps in studying Manta ray's swimming movements. Using TRACKING software, we studied movements of Manta ray and ensured the graph matched our results from the software.

After extracting features, our next step involved designing our soft robot based on the study and analysis of different research papers. Building on this knowledge, we proceeded to the design phase, where SOLIDWORKS software is used to create a 3D model of our proposed soft robot. The design was based on a study conducted on manta rays and aiming to mimic their swimming movements as closely as possible.

For validation of our design, simulation was done on ANSYS software. Simulation helped us in ensuring our design accuracy before moving to fabrication and helped us in saving material in hardware. The final phase involved practical implementation of our design. Molds were prepared on SOLIDWORKS software and printed in FabLab. The fabrication process included fabricating fins of our robot by pouring material in molds and testing was done to ensure that final design worked properly and accordingly to simulation. Additionally, we designed a pressure kit with a microcontroller so that we can control our robot using laptop.

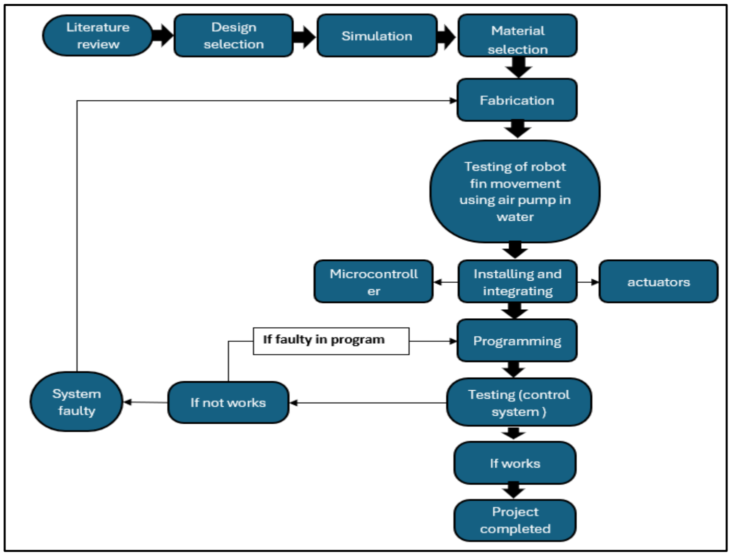


Fig. 2.1. flow chart of project.

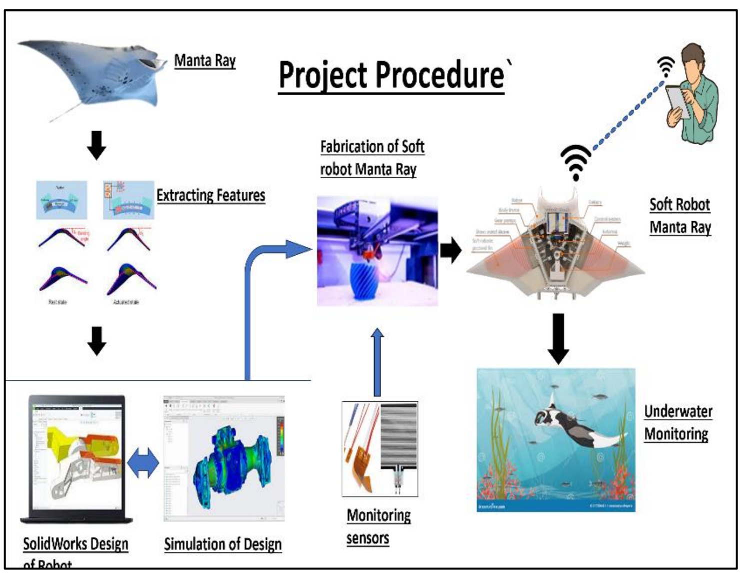
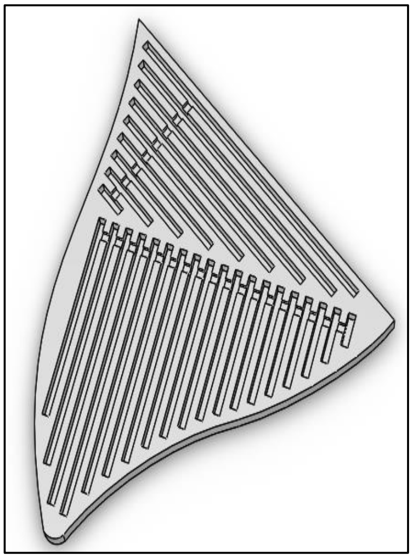


Fig. 2.2. Block Diagram of proposed Project Procedure

Design of Soft Robot

Analysis of shape design of Manta Ray

We extracted the data from a research paper [12] that includes the fin shape and size ratio. The image below shows the size ration (fin and body) and fin shape of Manta Ray. Furthermore, the image also had a Fig. of air foil that shows the aerodynamic profile of manta Ray. Another paper [5] that shows the fin movement in a certain pattern. We used these parameters to design the soft fins to achieve that pattern and rigid hard center part inspired from airfoil to get an aerodynamic center of robot.



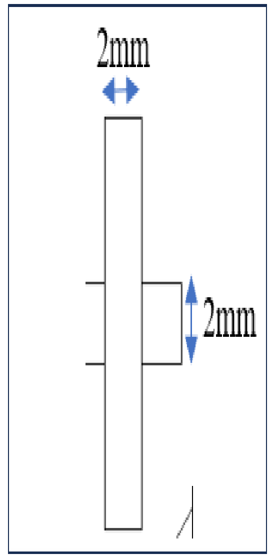
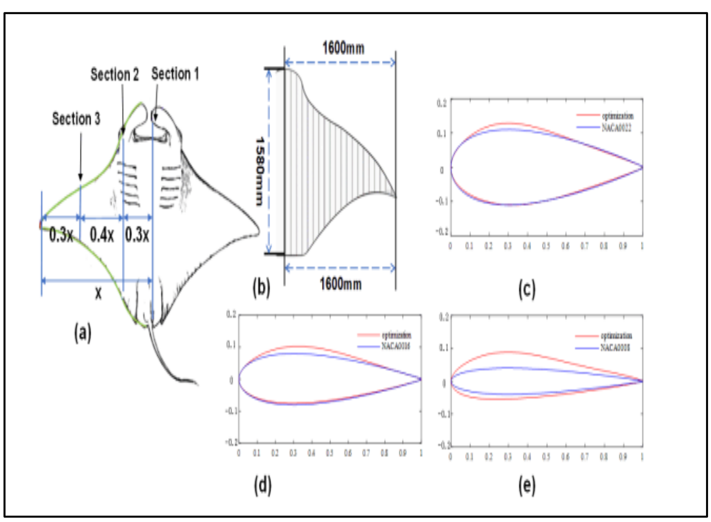


Fig. 2.3. (a) The schematic diagram of a real manta ray. (b) the scale of the robot (c) the NACA0022 and its optimized airfoil (d) NACA0016 and its optimized airfoil (e) NACA0008 and its optimized [12].

CAD Design of 3D Soft Fin

We needed to make a fin design that has flapping motion like a real-life Manta ray (mimicking as much as possible). Initially, we started designing the fins using SOLIDWORKS, several designs were made to achieve the required fin movement. We started with a single cavity and observed its actuation in the simulation software ANSYS, but it did not achieve the required results. After further literature review, we changed to a new design of fin that has two air cavities, one for transitional and other for rotational movement of the fin. The fin contains the upper cavity, the lower cavity and tilt cavity these parts help soft robot Manta Ray to create upward and forward thrust.



The fin design with single air cavity in fig's can only actuate in a straight vertical motion not in the desired curve path as mentioned in the chapter 1. The design was changed to double air cavity for straight and vertical actuation. Fig 8.b shows an initial fin design of double air cavity that failed to achieve the required curve path movement. After many hits and trails of various two cavity designs, we reached a design that became the base design for soft fin with which we can proceed to simulation. The upper half part of the fin that has one cavity for downward motion of fin, the increase of pressure in this cavity actuates the fin in straight downward direction. The lower half part of the fin has two cavities, that actuates the fin in upward straight and curved path. Increasing the pressure in the three cavities will result in the desired curve path. The width and height size of these cavities is 2mm.

Similar was the design of the right fin, which is like a mirror image of the left fin. These two fins were then simulated using ANSYS workbench to observe their movement before fabrication.

CAD design of Center part

The center body of manta ray was designed using SolidWorks. The design is inspired from the air foil for higher aerodynamic efficiency e.g. less drag and lift. The size of the center part is made by considering the size ratio, of 0.3x, obtained from the above-mentioned research paper. The total width of the center part is 60mm. The design is shown below,

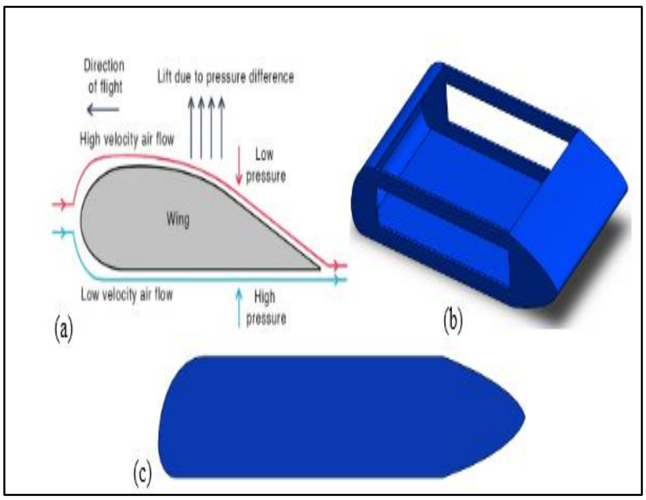


Fig. 2.4. (a) Airfoil Diagram has low drag and high lift as it passes through the air [13] (b) The isometric view of center part, the part has space in the center for placing pipes and the side openings for attaching the fin. (c) This is side view of center part; the design is similar to airfoil.

Simulation of Soft Robot

Material Defining

The first step is to define the material properties of Eco flex 30 for the simulation software. The ecoflex has nonlinear response of stress vs strain [14] [15] graph making it difficult to simulate, unlike linear materials that exhibit linear response which are easier for simulation software to understand. To understand nonlinear materials response to pressure, Ansys use two model Ogden and Yeoh. These models understand the behaviour of nonlinear material like ecoflex, dragon skin and so on. The Yeoh was selected as it is preferable for simple simulations, and it require low computational power.

To start with the material defining, an analysis type is to be selected first, the static structural is used to observe the actuation of the fin by applying pressure in the cavities. In the static structural block, shown below, the engineering data is selected to define the material.

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	1.105	g cm^-3		
4	Uniaxial Test Data	Tabular			

Fig. 2.5. Defining Material's Density Property.

15	Yeoh 2nd Order			
16	Material Constant C10	17000	Pa	
17	Material Constant C20	-200	Pa	
18	Incompressibility Parameter D1	0	MPa^-1	
19	Incompressibility Parameter D2	0	MPa^-1	

Fig. 2.6. Defining the constant values for model Yeoh of 2nd order.

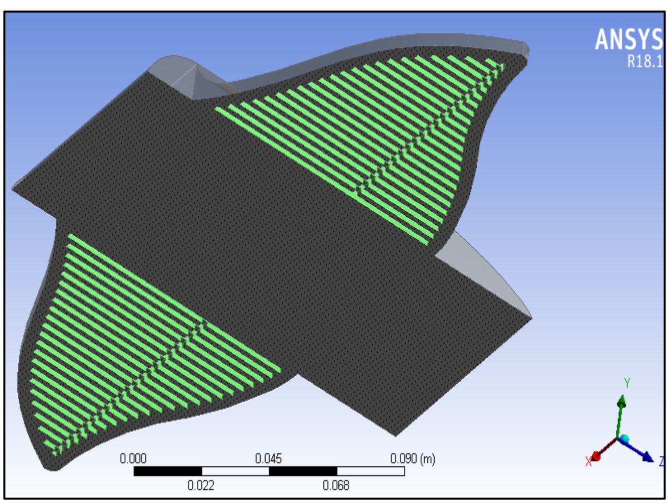


Fig. 2.7. Cut image of geometry using section planes to select upper cavity's walls.

Uploading geometry and selecting pressure areas

In the geometry step we imported our design to select the inner walls of each cavity to define the area where the pressure is to be applied to the software. After selecting we named each cavity and put them in named selection (tilt cavity, lower cavity, upper cavity). The purpose of using named selection is to use these areas multiple time without reselecting them again and again

because the total number of walls of all cavities are 696 which we selected one by one.

Static Structural Analysis

Static structural is the simplest simulation which is not time dependent like transient structural [16]. The static only needs fix surface, gravity, pressure and few analyses setting. After selection of cavities, we moved to the next phase of simulation which is model. In the model we selected the defined material and give it to it the geometry. We also defined parameters like pressure, fixed structure, standard earth gravity and desired result parameters like deformation, stress and strain. The pressure to each cavity was applied and solved separately. Furthermore, we adjusted the analysis setting before proceeding to solving the simulation.

In the outline there is a fixed support for the part which is not meant to be moving in the simulation. Moreover, there is pressure parameter for each cavity and desired results parameter like deformation and elastic strain.

Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	On
Define By	Time
Initial Time Step	1. s
Minimum Time Step	1.e-004 s
Maximum Time Step	1. s
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Off
Solver Pivot Checking	Program Controlled
Large Deflection	On
Inertia Relief	Off

Fig. 2.7. Analysis setting for Static Structural.

For static structural we just need to increase time stepping and as we are using elastic material, we need to turn on large deflection. The simulations results are as follows,

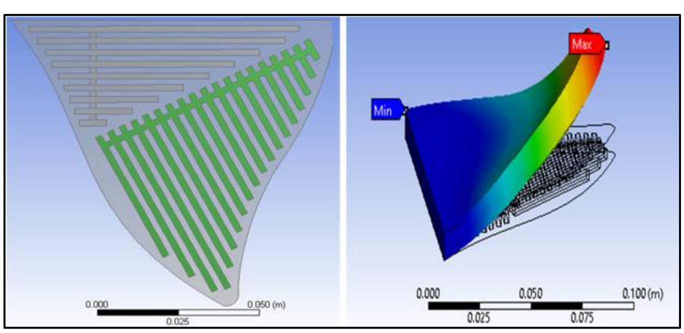


Fig. 2.8. (a) Selection of tilt cavity to apply pressure. (b) Result of applying pressure in the tilt cavity.

The image shows the result of applying pressure on the tilt cavity that bends the fin in the desired curved path. These are the separate results of the of each cavity. To see the combined result and to observe the motion path of the fin's tip we need to do Transient Structural Analysis.

Transient Structural Analysis

The Transient Structural Analysis is complex than Static Structural Analysis, as this analysis is time dependent [16]. In this analysis we need to two things. The sequence of increasing and decreasing pressures of each cavity using tabular data to get the desired curve path. And adding a greater number of steps and their sub time steps to increase pressure slowly avoiding any simulation error. The analysis settings for transient structural analysis are shown below,

Step Controls	
Number Of Steps	6.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	On
Define By	Time
Initial Time Step	0.5 s
Minimum Time Step	5.e-002 s
Maximum Time Step	0.5 s
Time Integration	On
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Off
Large Deflection	On

Fig. 2.9. Analysis setting of Transient Structural for adding steps and their sub time steps.

Also to turn on large deflection because the material is of elastic nature. In the analysis setting we added a greater number of steps, and their sub time steps and turned-on large deflection.

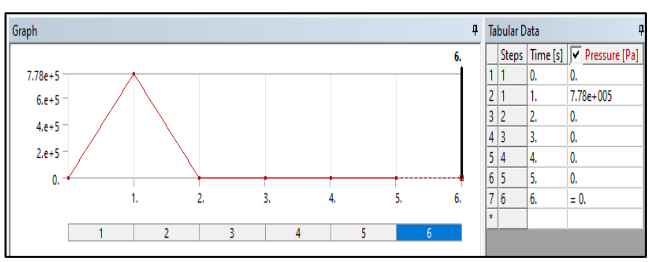
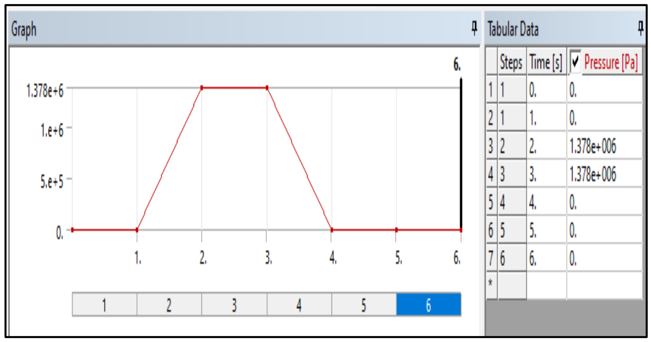


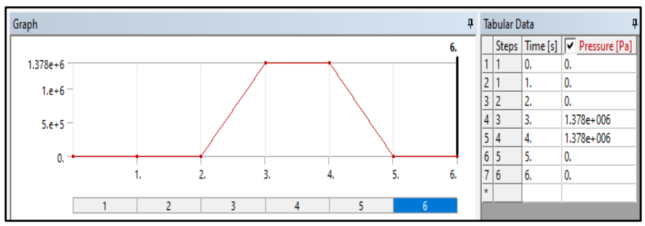
Fig. 2.10. Pressure graph of Upper cavity.

This pressure graph is of upper cavity that will increase and decrease with certain time.



	Steps	Time [s]	Pressure [Pa]
1	1	0.	0.
2	1	1.	0.
3	2	2.	1.378e+006
4	3	3.	1.378e+006
5	4	4.	0.
6	5	5.	0.
7	6	6.	0.

Fig. 2.11. Pressure graph of Lower cavity.



	Steps	Time [s]	Pressure [Pa]
1	1	0.	0.
2	1	1.	0.
3	2	2.	0.
4	3	3.	1.378e+006
5	4	4.	1.378e+006
6	5	5.	0.
7	6	6.	0.

Fig. 2.12. Pressure graph of Tilt cavity.

To check the path of fin's tip, we placed a deformation probe on the tip of the fin. The results of Transient Structural are as follows,

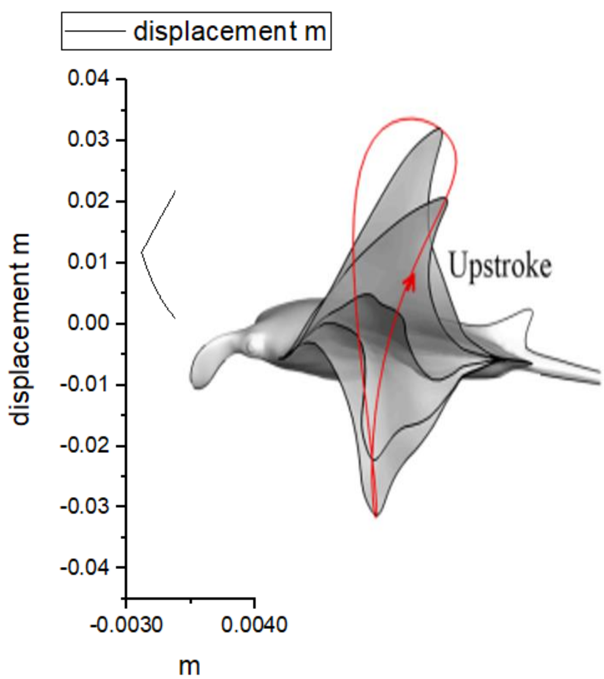


Fig. 2.13. (a) Graph of simulated Fin's tip motion path in ANSYS workbench. (b) Fin's tip motion path Real Manta Ray fish [5].

The result of simulated graph shows linearity rather than curve path it is because the pressure is increased or decreased in linear manner. If pressure is changed exponentially the resultant graph will have curve path.

Fabrication of Soft Robot

Design of Fin molds

The molds were designed by swapping the extrude cut with boss extrude and vice versa. So that the material will be poured in the fin except cavity areas. It has additional side parts to place pipes before pouring the material. This mold is just for the lower part of the fin, and it will be open at the bottom when the lower fin is fabricated, it needs a base mold to close the cavities from top and bottom. Same is for the upper part of the fin. So, in total we need four molds for left fin and four more for right fin.

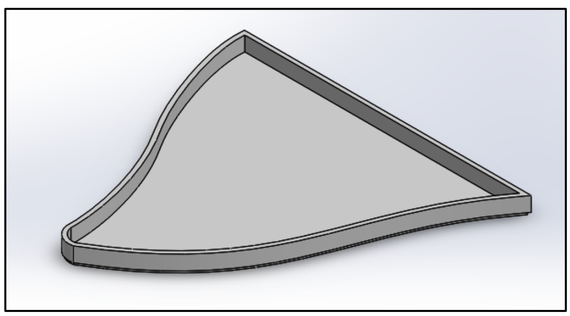


Figure 2.14. Base mold to close the cavities of lower part of the right fin.

3d printing Molds

After completely creating the molds design and center part of the robot which is discussed in chapter 4. The design is transferred as a g-code file to a 3d printer to print the molds. As mentioned before these are four molds for right fin and four additional will be made for the left fin.

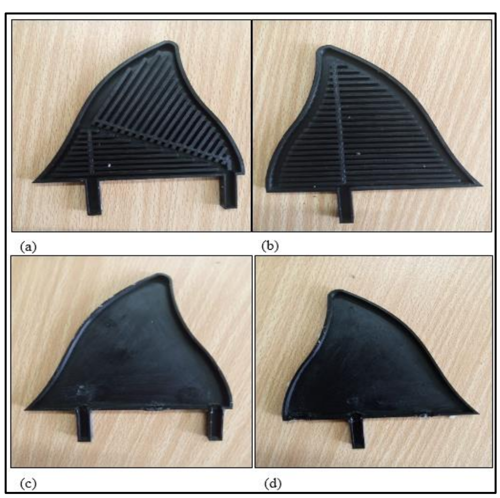


Fig. 2.15. (a) Printed right lower Mold. (b) Printed right upper Mold. (c) Printed right upper base

Mold. (d) Printed right lower base Mold.

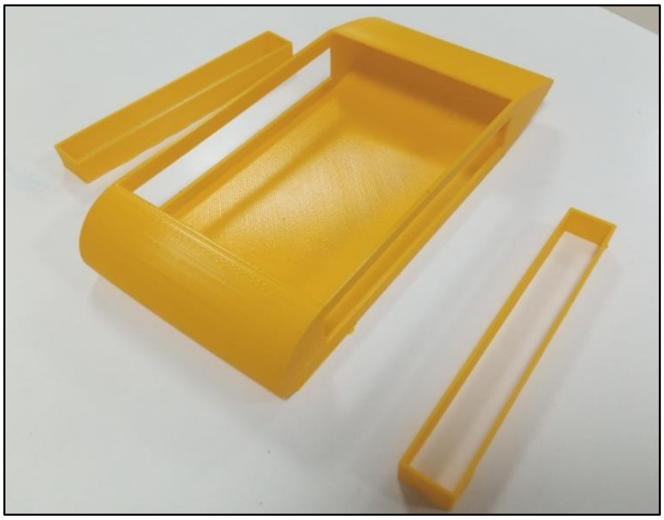


Fig. 2.16. Printed Center part of Soft Robot.

Fabricating Fins

The material ecoflex 30 is used for fabrication of the fins, the material comes in two parts one of them is hardner which changes it from liquid to solid flexible rubber. The two parts are used in equal amounts. The moment these two parts come in contact with each other their pot life starts (which is of 45 minutes). During this time the parts are to be mixed thoroughly, any traped bubbles are to be removed and the mixture is to be poured in the molds. Because after the pot time the mixture is already in curing phase it becomes more viscous its flowrate is decreased making it difficult to pour in the mold, also the more air gets trapped and manually removing it is very difficult.

After mixing the mixture it is poured on the molds and base mold simultanoeusly. Then we put them on the side to get cured completely. The cure time is of 4 hours after this another small mixture is made to combine the half fins and base part together, it takes another 4 hours to cure. Lastly another small mixture is made to finally combine both halfs of one fins. The whole process of making one fin takes 12-14 hours, if we had a thermal microven the process would take less time.

Fig. 2.16. Complete fabricated fin, gluing half cured fins together.

Combining Parts

After fabrication of both fins and printing of center part they are combined as shown in the image below. The top is open to connect it to the pressure pipes which are operated with the pressure kit.

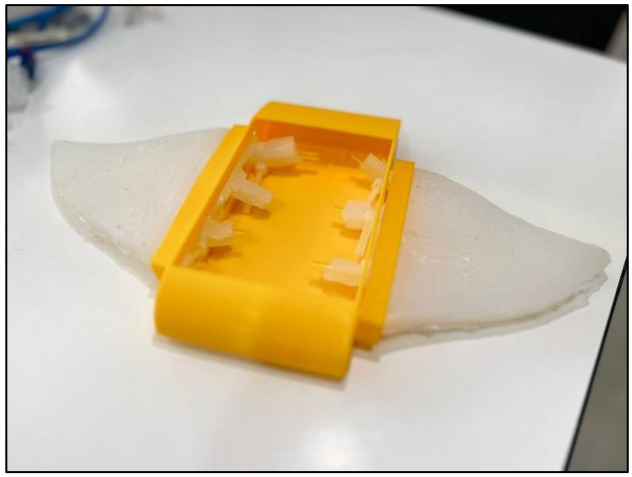


Fig. 2.16. Fabricated Soft Robot with rigid center part and attached soft fins with extruding pipe for pressure insertion.

Designing Hardware

To facilitate the movement of our exploration device, we developed a pressure kit consisting of solenoids, pumps, MOSFETs, and an Arduino controller. This kit has four modes of operation forward, left, right and stop. The pumps work in a sequence similar to what we defined in the simulation and the working of these modes is as follows,

1- For forward mode both fins solenoid valves will remain open, so that both fins start moving.

2- For stop mode the pumps stop operating.

3- For right mode the right fins solenoid valves will close, only left fin moves making the robot turn right.

4- For left mode the left fins solenoid valves will close, only fight fin moves making the robot turn left.

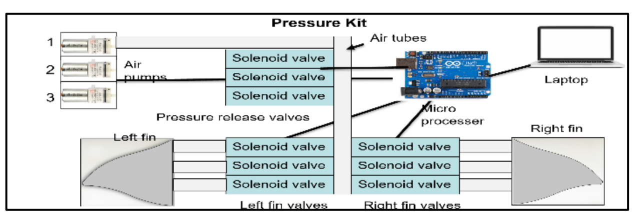


Fig.2.17.Block Diagram of Pressure Kit Diagram.

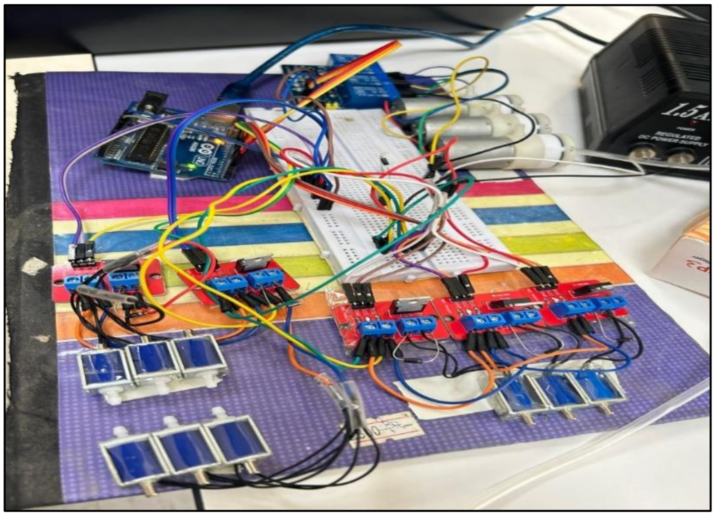


Fig. 2.18. Hardware circuitry of Pressure kit.

Arduino Program

The Arduino program controls the movements of the manta ray robot by applying pressure in both fins. The programming contains Five modes of movement forward, reverse, left, right and stop. The working of these modes is as follows,

For forward mode both fins solenoid valves will remain open, so that both fins start moving. For stop mode the pumps stop operating. For right mode the right fins solenoid valves will close, only left fin moves making the robot turn right. For left mode the left fins solenoid valves will close, only fight fin moves making the robot turn left.

Arduino Code

```
// Define the pins for the pumps
const int pump1 = 2;   // Digital pin 2
const int pump2 = 4;   // Digital pin 4
const int pump3 = 5;   // Digital pin 5

// Define the pins for the solenoid valves
const int valve1 = 6;  // Digital pin 6
const int valve2 = 7;  // Digital pin 7
const int valve3 = 8;  // Digital pin 8
const int rightvalve4 = 9;  // Digital pin 9 (additional valve for mode 'd')
const int leftvalve5 = 10;  // Digital pin 10 (additional valve for mode 'a')

// Variable to store the running state and mode
bool running = false;
char mode = 's';

void setup() {
  // Initialize the pump pins as outputs
  pinMode(pump1, OUTPUT);
  pinMode(pump2, OUTPUT);
  pinMode(pump3, OUTPUT);

  // Initialize the solenoid valve pins as outputs
  pinMode(valve1, OUTPUT);
  pinMode(valve2, OUTPUT);
  pinMode(valve3, OUTPUT);
  pinMode(rightvalve4, OUTPUT);
  pinMode(leftvalve5, OUTPUT);
```

```
  // Initialize the Serial Monitor
  Serial.begin(115200);
}

void checkSerial() {
  // Check if data is available on the Serial Monitor
  if (Serial.available() > 0) {
    // Read the incoming byte
    char incomingByte = Serial.read();

    // Check if the incoming byte is 'w', 'd', 'a', or 's'
    if (incomingByte == 'w') {
      running = true;
      mode = 'w';
    } else if (incomingByte == 'd') {
      running = true;
      mode = 'd';
    } else if (incomingByte == 'a') {
      running = true;
      mode = 'a';
    } else if (incomingByte == 's') {
      running = false;
      mode = 's';
      // Turn off all pumps and solenoid valves
      digitalWrite(pump1, HIGH);
      digitalWrite(pump2, HIGH);
      digitalWrite(pump3, HIGH);
      digitalWrite(valve1, LOW);
      digitalWrite(valve2, LOW);
      digitalWrite(valve3, LOW);
      digitalWrite(rightvalve4, LOW);
```

```
      digitalWrite(leftvalve5, LOW);
    }
  }
}

void checkDelay(unsigned long ms) {
  unsigned long start = millis();
  while (millis() - start < ms) {
    checkSerial();
    if (!running) return;
    delay(10);  // Check every 10 milliseconds
  }
}

void runModeW() {
  while (running && mode == 'w') {
    digitalWrite(rightvalve4, LOW);
    digitalWrite(leftvalve5, LOW);

    // Turn on pump1 and valve1, then wait for 1 second
    digitalWrite(valve1, HIGH);
    digitalWrite(pump1, LOW);
    checkDelay(1000);  // 1 second
    digitalWrite(pump1, HIGH);
    digitalWrite(valve1, LOW);
    if (!running) return;

    // Turn on pump2 and valve2, then wait for 1 second
    digitalWrite(valve2, HIGH);
    digitalWrite(pump2, LOW);
    checkDelay(1000);  // 1 second
    digitalWrite(pump2, HIGH);
```

RESULTS

The performance of our soft robot was assessed through a series of tests to mimic the swimming pattern of a manta ray. A 12v Dc Mini-Air pump is provided with 6v power to create a pressure of 375mmHG/50,000 Pa. This pressure displaces the tip of the fin 0.035m in vertical axis and 0.004m in horizontal axis with reference to origin. The two-axis displacement indicates that the fin generates forward and upward thrust, the total displacement is 0.039m and the percentage of horizontal thrust is approximately 10%. Which indicates that 90% of generated force is used to create upward thrust and remaining 10% force creates forward thrust.

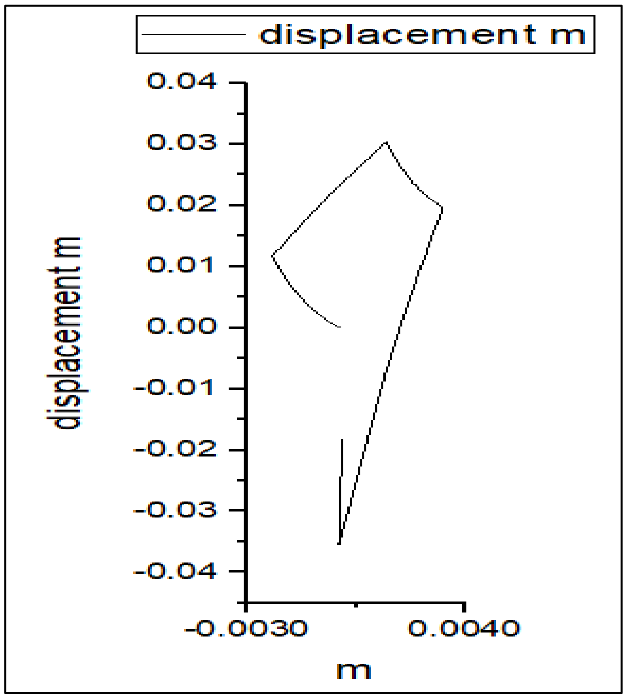


Fig. 3.1. Fin's tip displacement at applied pressure of 375mmHg.

This work successfully designed and fabricated a bio-inspired soft robotic fish, inspired by the real manta ray's swimming pattern and fin movements. The robot's design, developed using SolidWorks and simulated in ANSYS, accurately captured complex motion of manta fins. The mold was printed, and the robot fins were fabricated using Ecoflex0030. Despite achieving the desired fin movements, the robot's performance in water was limited by fabrication issues, such as leakages and uneven surface thickness. The practical implementation highlighted several areas that require further refinement.

The primary aim of mimicking real manta ray fin movements was achieved to a significant extent, demonstrating the feasibility of the design and its future applications. The use of Ecoflex0030 provided necessary flexibility, but fabrication process needs to be optimized to reduce surface irregularities and improve water tightness. The integration of fins with central rigid part and overall assembly must be refined to enhance the robot's in-water performance. The project provides the foundation for several future enhancements aimed at improving robot's adaptability and functionality for practical use.

Sensing in soft robotics is challenging due to inherent deformability and flexibility of these systems.

Unlike rigid robots in which traditional sensors can be easily mounted, soft robots require flexible sensors and flexible electronics. To interact in complex environments, particularly in underwater robot's ability to navigate with flexibility is crucial [23].

For underwater monitoring sensing capability of robot is vital as it enables the robot to measure and respond to environmental conditions such as pressure, flow, temperature and humidity and presence of different mixture of chemicals present in water. robot must be capable of measuring temperature, humidity, pressure, flow and other mixture of chemicals in water. By integrating these sensors, the robot's ability to sense is increased and the robot becomes able to give real-time environmental feedback, which leads to more accurate and efficient monitoring [27]. This capability is very important for applications such as marine life observation, underwater exploration and pollution detection.

In future developments, the robot embodied sensing capabilities can significantly enhance the functionality of soft robots in underwater environments. This approach can develop novel flexible sensors and their integration with soft robots so that robot's flexibility and mobility is not compromised [30].

Underwater communication is a growing field, and different developments and research are conducted to ensure that underwater robots are capable of transmitting real-time data and to control the robot remotely. Communication can be tethered, or wireless, tethered communication is limited to the length of wire used and wireless communication such as acoustic, optical and RF are developed each with certain limitations. For instance, acoustic communication is limited by short distance and requires line-of-sight, and RF communications have disadvantage of significant attenuation in underwater [33] [35]. Integrating communication modules with sensors and actuators will allow the robots to be controlled remotely and exchange data effectively, despite the challenges posed by underwater environment [37].

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