Design and Control Strategy of Bio-inspired Underwater Vehicle with Flexible Propulsor

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Abstract: Biomimetics aims to take inspiration from nature and develop new models and efficient systems for a sustainable future. Bioinspired underwater robotics help develop future submarines that will navigate through the water using flexible propulsor. This research has focused on the Manta Ray species as batoid has a unique advantage over other species. This study also aims to improve AUV (Autonomous Underwater Vehicle) efficiency through biomimetic design, the purpose of which is to observe and study the marine environment, be it for sea exploration or navigation. The design and prototyping process of bioinspired AUVs have been mentioned in this study, along with testing a propulsive mechanism for efficient swimming and turning capabilities. The Robot was designed taking structural considerations from the actual Manta-Ray locomotion and body design. The propulsion mechanism and control circuit were then implemented on the developed systems. The prototype of the Manta Ray was able to generate a realistic swimming pattern and was tested in an acrylic tank. The experimental results obtained in the tank basin are very close to the results we observe in the real-world scenario in terms of the vehicle's forward and turning motion.

Keywords: Autonomous underwater vehicle, Biomimetic robotics, Maneuverability, Manta ray, Flexible propulsor.

Exploration of the oceans is a challenging task, requiring specialized technology. One such technology is AUVs, or Autonomous Underwater Vehicles which are robotic vehicles that, depending on their design, can drift, drive, or glide through the ocean environment without real-time control by human operators. While conventional AUV's are widely available, they generally are not able to travel large distances efficiently. Much of current technology draws inspiration from nature so that we can approach towards a sustainable future. Mimicking biology, especially in the case of animals, is beneficial, particularly in the cases where the animal performs better than existing technology. Batoid fishes (*e.g.*, Manta rays) are highly efficient swimmers, combining extreme strength and incredible maneuverability. Replicating these unique properties in synthetic autonomous underwater vehicles would have tremendous implications. The flapping motion of Manta ray is considered to be energy efficient as the propulsion involves lower fluid related energy losses. Its gliding motion would be highly significant in energy saving. An important design consideration for a biomimetic AUV is the propulsion mechanism's design, shape, location on the machine, movement patterns, and mechanical and material properties (*e.g.*, inertia and stiffness). The overall shape of the robot is another important consideration. As fish are impressive swimmers in many ways, it is hoped that biomimetic robots that swim like a fish might be superior to submarines, using propellers. The first experimental undulating-fin device was reported in 2001 [1]. The research group found a very interesting fact about the batoids locomotion mode that allowed them to move forward and backward. A mathematical analysis and a prototype proved their ability to generate reversible thrust. Later at University of British Columbia, a research group in 2002 was the first to build a biomimetic robot based on a batoid fish, a Gymnuramicrura[2]. The actuation was given by the use of Shape Memory Alloys (SMA), A shape - memory alloy is an alloy that "remembers" its original shape and that when deformed returns to its pre-deformed shape when heated. It was not able to propel itself in water, the robo-ray could emulate both undulatory and oscillatory locomotion strategies. Some robots were manufactured trying diverse technologies to actuate the wing [3]. The vortex flow pattern and high propulsive efficiency of 89% were associated with Strouhal numbers within the optimal range (0.2–0.4) for rays swimming at routine and high speeds [4]. These fishes are impressive swimmers in many ways, it is hoped that biomimetic robots that swim like a fish might be superior to submarines, using propellers. Analysis of the swimming pattern of the manta species provides a baseline for creating many bio-inspired underwater vehicles, which is briefly discussed in this paper. The first experimental undulating-fin device was reported in 2001 by Sfakiotakis [5]. The research group found a

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very interesting fact about the batoids locomotion mode that allowed them to move forward and backward. It was not able to propel itself in water, the robo-ray could emulate both undulatory and oscillatory locomotion strategies. Willy A. and K.H. Low developed stingray-like robots, which exhibit undulation type motion [6]. In order to create undulation motion, two flexible pectoral fins were designed which were controlled separately by using actuators and strategic control algorithms. For fin actuation, ten servo motors were used along with a crank mechanism at the end of each motor to replicate the motion of ray's fin. Two very interesting study were carried out in 2007 and 2009 on BHRay-I [7] and BHRay-II [8]. Researchers were developed underwater robot by taking inspiration from Manta Ray's oscillatory motion of fins [7]. The pectoral fins were made of carbon fibre pipe, a silicone rubber board and reinforcing aluminium controlled using servo motors [8]. Flexible silicone rubber passively generates phase difference, which is critical for an efficient thrust production in fins. In both the batoid robots (2005-2009) wide fins do not allow the robot to pass through narrow water areas. In 2010, The actuation was given using Shape Memory Alloys (SMA), A shape - memory alloy is an alloy that "remembers" its original shape and that can be deformed when cold but returns to its pre-deformed shape when heated [9]. In 2013, advanced techniques were performed and the latest robot release by a team lead by Hillary Bart-smith form the university of Virginia was the manta Bot [10]. The study included researchers from university of Virginia and three other universities who worked on "reverse engineering" the way stingrays and Manta rays move through water. The vehicle has two arms controlled by servo motors with 3D printed silicon body and various other sensors integrated with raspberry pi for its motion [10]. Later, in 2014 cownose ray inspired fish robot was developed by the robotics institute of Beijing university, Beijing, China [11]. Cownose ray-inspired robotic fish which can be propelled by oscillating and chord wise twisting pectoral fins. The bionic pectoral fin can produce effective angle of attack, and the thrust generated can propel robotic fish effectively. The oscillating and pitching motion can be obtained simultaneously by the active control of chord wise twisting motion of the bionic pectoral fin, which can better imitate the movement of cownose ray's pectoral fin [11]. Researchers from national university of Singapore built manta droid, an underwater robot that looks and swims like a Manta ray fish, using only single motors and flexible fins to propel through water in an uncanny manner using water like its natural counterpart [12]. A soft-bodied robot that can swim like a Manta ray has been created at China's Zhejiang university. With less than 20-centimetre length, this robot can swim as fast as 6 cm/sec and has been developed for information gathering in lakes and oceans. These are made of soft silicon without any motor. This artificial muscle contracts and relaxes when external stimulation is applied. It contains two layers and a conductive hydrogel in between them. When voltage is applied, two dielectric films are to be compressed to the centre. When released it gets back to its original shape. They use their own conductive properties to achieve one side of the charge. Therefore, they can control the motion of the bot using electrical impulses. This is an efficient method and very nature inspired, although its applications are currently limited and provides little range of motion [13]. Prof. Fish has studied the design evolution of flexible and tubercles in propulsor [14] and connect the thread with development of efficient unmanned underwater vehicles. Prof. Fish also jotted the limitations of Biomimetics and showed the way to overcome them. A simplified analytical model has been described by Moored and his co-workers for the swimming motions of batoid fishes [15]. He was able to quantify the hydrodynamic perfor-mance of the batoid fish robot by using artificial pectoral fin. For propelling the robot uses tensegrity structures to propel himself with an oscillating swimming style [15]. Moslemi and Krueger in 2010 studied the influence of the velocity program and duty cycle on the propulsive efficiency using an experimental approach [16]. In the previous year, Murphy and his research group studied bioinspired underwater vehicles and tried to improve the capabilities [17]. Subsequently Lock et. al. have made a great effort to understand the multimodal locomotion of animal and tried to apply in the real world situation [18]. Prof. Lauder and Tangorra have made significant progress in actuating and controlling robotic fish by integrating body and fin movements [19]. The next follow-up study is designing and fabricating of an ostraciiform swimming robot and its navigation and control and guidance systems. The lead researcher Costa D has compared with other biomimetic vahicles and found that the strategic architecture has much higher efficiencies [20]. Cui *et al.* have come up with the techniques [21] to assess the unmeasured velocities, unknown disturbances and uncertainty in hydrodynamics using the strategic control design. In 2006 Mittal and his research group studied pectoral fin hydrodynamics using CFD techniques. They have found out wake vortices topologies and hydrodynamic forces [22]. A very recent study [23] carried out the design and development of state-of-the-art Anguilliform robot MAR with modular systems and driven by a single, speed-controlled brushless DC motor to create smooth forward thrust and maneuvering. Deway in 2013 studied underwater flight of Manta Ray as a part of his doctoral research [24]. A research team pursued another very relevant study at Worcester Polytechnique Institute on Manta Ray Robot as a part of UG dissertation in 2016 [25].

Brower 2006 studied the design of Manta ray-inspired UUVs for long-range and low power operation [26]. Wang, Yu and Zhang have evaluated hydrodynamic performance parameters of bioinspired Manta Ray robot and made significant progress in the biomimetics domain [27]. A very interesting study by Prof. Frank A Fish in 2009 described that artificial systems should get inspiration from nature to make them efficient and environmentally friendly [28]. He primarily focused on whale flippers' tubercles, which is a great source of inspiration to optimize hydrodynamics of flexible propulsors. He further did in detailed study on whale flippers and showed the potential of application in the marine environment for propulsion [28]. Bioinspired Unmanned Underwater Vehicle (UUVs) are manufactured using diverse technologies to actuate the wing [30]. For certain groups conductive polymers, electroactive polymers (EAP), or Ionic Polymer-Metal Composite (IPMC) played the role of the muscles. Other groups chose an external actuation of the wing with a rotational motor, planetary gear mechanism and spherical joint to effectuate all pectoral fin movements. However, the aim of all progress exposed was to generate thrust in an efficient way, but manoeuvrability and stability are a key factor in an unmanned underwater vehicle which often operates near the seabed.

In this paper, we will discuss the method of actuation for the bioinspired UUV with improved efficiency. A complex kinematics model is designed to imitate the 3-dimensional wave function attaining motion in both spanwise and chordwise direction of the pectoral fins, further the efficiency is increased with addition of tubercules which facilitates reduction in drag force, with increase in stability and maneuverer supported by the dorsal fin and the tail as shown in the Figure **1**.

DESIGN AND MANUFACTURING

The design methodology used to develop the present manta bot is presented in this section. Entire CAD design of the Manta ray has been well outlined using dimensionally accurate pictorial representations. The design has been further divided into four major parts, body to accommodate all the electronic components, pectoral fins to provide forward or upwards/downwards thrust, dorsal fin to increase the lateral surface area for stability and tail to increase the manoeuvrability.

A). Initial Design Considerations

The CAD model is shown in the Figure **2**. Initially, the size of the robot was roughly decided by matching the accurate scale of the adult oceanic Manta ray, but it was not an attainable goal since they generally possess a 240-inch wingspan. Therefore, a small-scale version with a wingspan of 16 inches was agreed upon as a test case. By considering anatomical ratios shown in Figure **3**, the actuating motors, the bot's weight, and a body length of 10 inch were decided. These dimensions led to a rigid body structure that is approximately 16 inches wide.

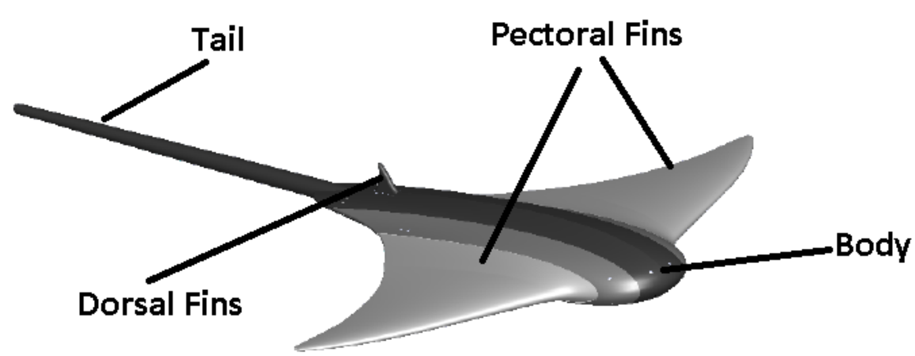

Figure 1: Design with different body parts.

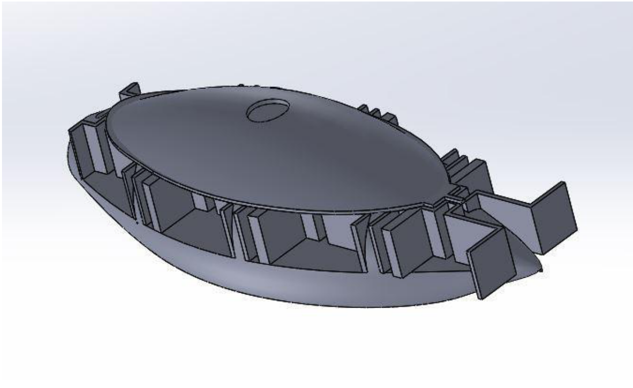

Figure 2: CAD model of the prototype on Solidworks.

The prototype was made based on the biological morphology of the Manta ray. The Bot's body and fins are 3-D printed of different materials based on the Manta ray's flexibility in this prototype. Fin being made flexible to make the swimming better while the body is made up of a PLA material to provide stiffness to the body as all the electrical components are present inside it. After the designing and printing of the body and fins were done, the actuation process is then implemented based on our observation of natural species. For this purpose, an Arduino Mega 2560 microcontroller was used, actuating dc motors through a H-bridge to provide them rotation in both directions programmed to span around 180 degrees. The dc motors used were having high torque to provide it adequate thrust against the hydrodynamic drag force.

The design of the body is made much more streamlined and hydrodynamic. To reduce drag force we have included the hydrofoil shape in the body. Drag force is generally due to contributions from fluid pressure and tangential (viscous) stress acting on the surface of the body. For streamlined bodies, pressure drag is negligible compared to the skin friction drag. The hydrofoil shape (long and thin with a rounded nose and sharp trailing) is a remarkable geometry that produces a large lift force and experiences considerably low drag force. The innovative hydrodynamic design of the prototype model, has proper slots for fitting motors hence can generate thrust and lift with minimum loss.

B). Actuation

Actuations of the fins are highly important for strategic locomotion. The desired actuation was derived based on the nature of the locomotion of actual Manta rays. In order to achieve a similar magnitude of fin oscillation, about 60 degrees would provide the closest representation of the Manta's motion. The actuation of the bot underwater to shown below in Figure **4**. For the prototype model, 8 high torque servo motors were incorporated for the actuation of the fin. Due to its better and precise control servo motor was preferred over DC motor in the final model. Several forces act on an underwater vehicle the requires consideration for better performances. Some of these factors are mass, environment, overall pressure. When a body moves underwater, both air and water apply external pressure on it; hence, pressure is a significant factor for underwater bots and cannot be ignored.

C). Byouncy of the Bot

In order to optimize the weight of the robot, several parameters like density and strength of the materials, thickness of the mechanical components are considered. In this study, we strategically used PLA

(**a**) (**b**)

Figure 3: (**a**) 3-D printed model of prototype Manta ray's body (**b**) Full assembly of the prototype.

Figure 4: Sinusoidal actuation of the fins in underwater condition.

(poly lactic acid) for the body due to its robust nature. At the same time, Ninjaflex material has been used for the fins due to its flexibility. The fin was made thin so it could mimic the actual Manta Ray's movement and reduce the mass of the robot as a whole. The new fin length was 1.5mm, which is 1mm thin than the other preliminary models due to which we were able to increase the fin span of the robot keeping the mass of the robot same. The size of the robot was made very compact in order to reduce the mass of the bot significantly. Environmental disturbances can affect the motion and stability of a vehicle. This is particularly true for an underwater vehicle where waves, currents and even wind can perturb the vehicle. When the vehicle is submerged, the effect of wind and waves can be largely ignored. The most significant disturbances then for underwater vehicles are currents. In a controlled environment such as a pool, the effect of these environmental forces is minimal. When considering underwater bodies, it’s not just the water that puts external pressure on the body but also the atmospheric air that adds on to the weight of the body and pushes the body further into the water. At sea level, pressure due to air is 14.7 psi or 1 atm. For every 10m of depth, pressure increases by about 1 atm and hence, the absolute pressure at 10m underwater is 2 atm. The increase in pressure as depth increases is significant, and underwater vehicles must be structurally capable of withstanding a relatively large amount of pressure to survive. The electrical equipment will also be mounted in the robot's body and the vehicle should be safe in the marine environment in all aspects, so the design is of utmost importance.

The prototype Bot’s body was designed to be streamlined to reduce the drag force experienced underwater as much as possible. Moreover, the fins have a larger span to displace large volumes of water while in motion. They were printed with lesser infill using FDM (Fused Deposition Modelling) having a width of 1.5mm, enough to reduce the overall weight and increase its flexibility. The body was carefully designed to fit in the microcontroller, circuitry, ultrasonic sensor for obstacle detection, camera module, and eight servo motors. This design methodology has the least volume possible and reduce the overall mass. The connecting rods were linked to the servo motors similarly to the prototype, creating a much stronger and direct mechanical link with the fin. Waterproofing is an essential objective to meet before the vehicle hits the testing basin to avoid any damage to the electrical components. Silicon sealant was used to seal the top lid, the hole at the bottom passing wires and any other open ends or holes which could cause trouble.

The electrical components of the robot depend heavily on requirements set by the other systems; motor voltage, current draw, sensors necessary for an intelligent control system, and size ,weight restrictions all factors are considered in the selection of parts. In order to mimic the undulating motion of the actual Manta Ray servo motors were used mainly because of their precise and controlled movements. On trial basis, the motors' frequency was set such that it mimics the undulating motion of the actual Manta Ray. Since, the main aim of the bot is to do surveillance underwater, Pi camera has been installed to do the task. To stay protected while moving underwater, the bot has been equipped with a waterproof ultrasonic sensor to avoid any obstacle which comes in its way that might damage the body of the bot.

RESULTS AND DISCUSSION

Experimental Results

From the actuation video for the forward movement of the developed vehicle, the following locomotion was captured, showing the fins' sinusoidal motion, which provides the robot the forward thrust.

Similarly, making certain iterations in the code structure and synchronised fins is now actuated oppositely, turning the bot in the left or right direction.

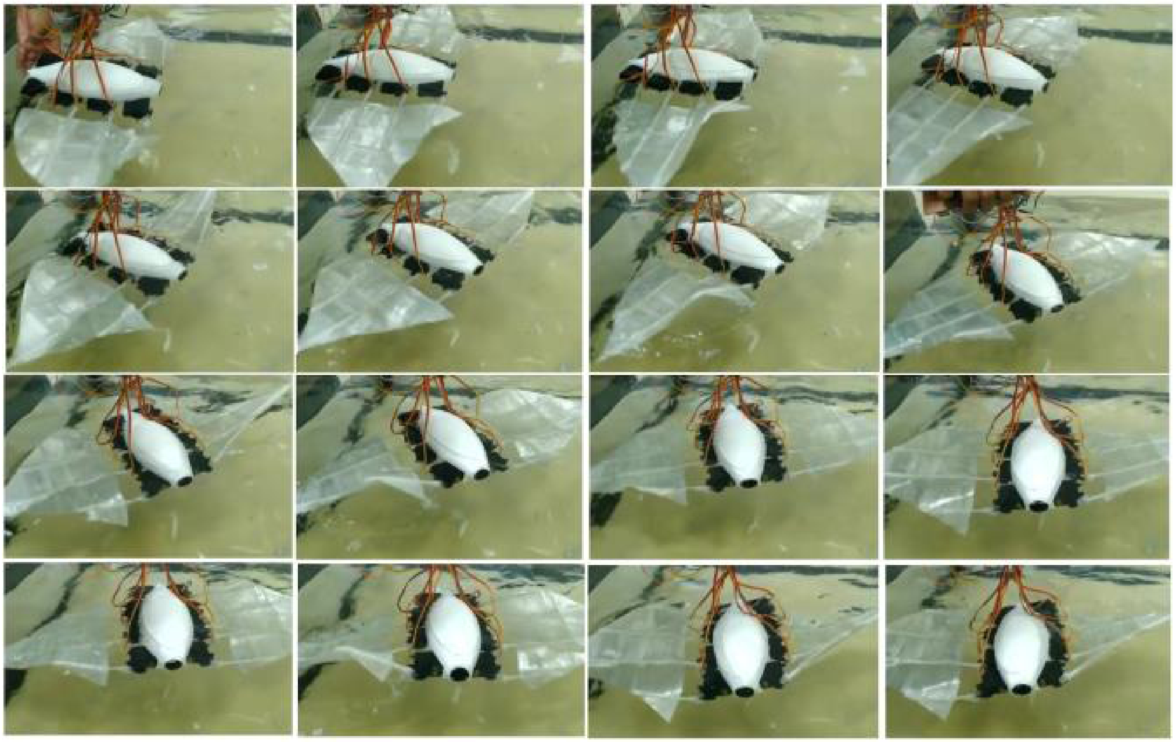

Figure 5: Turning of robot in the right direction based on unsymmetric actuation.

Unsymmetric actuations of pectoral fins gives the turning motion in the bot which is very intuitive and proves capability of our robotic system.

Simulation Results

Refering to Figure **1**, a CFD (Computational Fluid Dynamics) Tool was used to do simulation on the robot and its individual components to achieve the best possible design through several iterations. CFD can give some very important fluid parameters which help us to design the vehicle and select appropriate motors. During the analysis, the domain was considered as sea water with the properties listed in Table **1**. The Material property selected for robot body are mentioned in Table **2**. The properties for material of Pectoral Fin, Dorsal Fin and Tail are mentioned in Table **3**.

Table 1: Water Domain (sea) PROPERTIES

Molar mass	18 kg/kmol
Density	1030 kg/m^3
Specific heat capacity	4180 $Jkg^{-1}K^{-1}$
Reference temperature	15 ℃
Dynamic viscosity	0.0009 $kgm^{-1}s^{-1}$
Thermal Conductivity	0.6 $Wm^{-1}k^{-1}$

Table 2: Manta Bot Body Material (PLA)

Density	1.24 g cm 3
Tensile strength	50 MPa
Young's Modulus	2315 MPa
Thermal Expansion Coefficient	1.23e-3 strain/℃
Softening Temperature	65 °C

Table 3: Pectoral Fin, Dorsal Fin and Tail Material (TPE85A)

Density	0.84 g cm 3
Tensile strength	8 MPa
Flexural Modulus	0.03 GPa
Thermal Expansion Coefficient	15e-5strain/℃
Melting Temperature	210 °C

The manta bot design is analysed under static condition and fluid flowing over the body / part in the closed enclosure of water domain with a predefined velocity of water field as 3.5 m/s and the pressure set as 102KPa.The calculated velocity of 4.88cm/s has been provided to the robot in an opposite direction to the flow of water. A tetrahedral shaped mostly dominated with trigonal meshes with medium

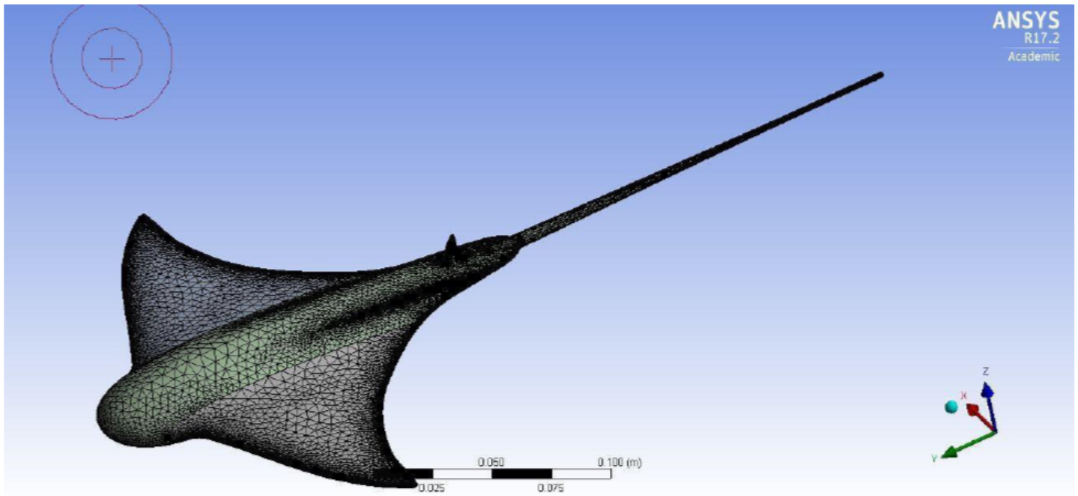

Figure 6: Manta Bot Meshing.

smoothing over the cured surface with a coarse mesh pattern was selected for optimized results as show in Figure **6**.

Having completed the simulation, the various iterations were carried out to come up with an efficient model. A laminar flow was observed under static condition of the Manta bot with the velocities of the fluid particles within the range from 1.513e-2 m/s to 4.922 m/s.

The next set of simulations are carried out for tubercled fins inspired by a humpback whale. From various iterations, the results of three fins, as shown in Figure **7**, have been discussed briefly to understand the ideology behind the addition of tubercules. Keeping in mind the objective of this paper, reduction in drag and lift force is required for overall performance boost. The drag force restricts the vehicle's forward motion, decreasing the efficiency. While the lift force adds on with the calculated buoyant force acting in the positive Y Direction, requiring more thrust to dip and propel under the water. To achieve a stable and efficient movement, decreased drag and lift force are required. On referring the comparison between the fins in Table **4**, fin 3 was selected for optimized results.

Table 4: Comparison of Drag and Lift Force in Fins

Model	Drag	Lift
Fin 1	16.5552 N	6.8342784 N
Fin 2	18.033632 N	0.57202231 N
Fin 3	12.42 N	1.30 N

It is obvious from the simulation results that the fin 3 with tubercles offers less drag compared to smooth fins. Consecutively, the lift force is also reducing, which affects forward thrust. Another importnant feature is that the developed robot that uses Ninjaflex and PLA is naturally buoyant so we are not much focusing on lift production but on forward thrust generation.

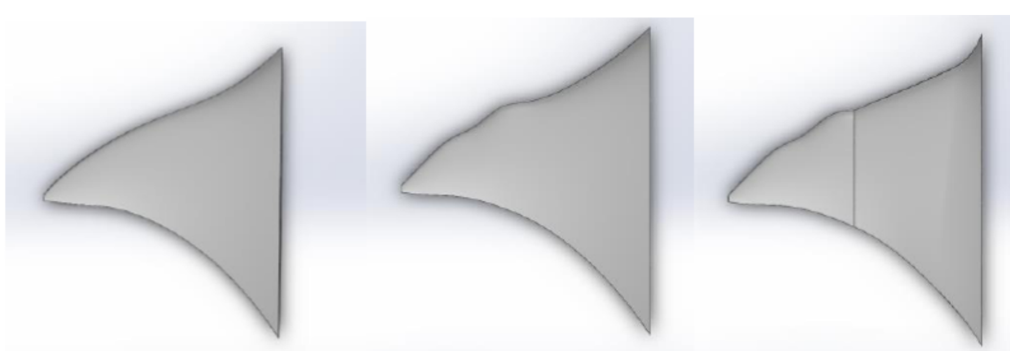

Figure 7: Fin **1**(Left), Fin **2**(Middle) and Fin **3**(Right).

CONCLUSION

Taking inspiration from nature has been a part of human life since ages. In this paper, a design as close to the nature has been adopted with servo-driven kinematics mechanism with use of flexible materials to provide movements identical to muscles and natural design of ray fishes. The authors were able to generate forward thrust and turning motion of the underwater vehicle inspired by Manta Ray. The bot underwater despite being a little dense and heavy the body of the bot is naturally buoyant and hence is floating just on the water surface, mainly because of the wide span of the fins which are displacing a lot of water. The bot is able to generate enough thrust to successfully move forward and can also turn in either directions (left and right) underwater. In the simulation, additional modifications have been made in fins to reduce the drag force by up to 20%, increase the lateral thrust force, increase stability, improve hydrofoil shape on frontal and side impacts, and sharp manoeuvrability was observed.

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