Design and Development of Propulsion System for an Underwater Drone

A report submitted

in partial fulfillment of the requirements

for the degree of

Bachelor of Technology

In

Aerospace Engineering

by

Kanishka Bhatt	**Kashish**
[R290221094]	[R290221035]
Rohan Sahu	**Punit Gandas**
[R290221096]	[R290221061]

Under the guidance of

Dr. Dhiraj Kumar

Mechanical Cluster

School of Advanced Engineering (SoAE)

UPES, Dehradun, India-248007

May 2025

Department of Mechanical Cluster

UPES

Certificate

It is certified that the work contained in the project titled "***Design and Development of Propulsion System for an Underwater Drone***" by following students has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

Student Name	*Roll Number*	*Signature*
1. Rohan Sahu	***R290221096***	
2. Punit Gandas	***R290221061***	
3. Kashish	***R290221035***	
4. Kanishka Bhatt	***R290221094***	

Signature	***Signature***	***Signature***
Dr. Dhiraj Kumar	**Dr. Ashish Karn**	**Dr. Ram Kunwar**
(Project Supervisor)	**(Head Of Department)**	**(Activity Coordinator)**
Aerospace Department,	Aerospace Department,	Aerospace Department,
Mechanical Cluster, UPES	Mechanical Cluster, UPES	Mechanical Cluster, UPES
Dehradun – 248007	Dehradun – 248007	Dehradun – 248007
Uttarakhand, India	Uttarakhand, India	Uttarakhand, India

Abstract

The exploration and inspection of underwater environments—whether for ecological monitoring, infrastructure assessment, or military intelligence—require advanced robotic platforms capable of navigating complex aquatic terrains with precision, agility, and energy efficiency. Traditional underwater drones, primarily driven by rotary propeller systems, often fall short in meeting these demands due to inherent limitations such as mechanical inefficiency in manoeuvring, excessive energy consumption, and disruptive noise generation. These shortcomings can hinder performance in sensitive ecosystems and stealth operations, where minimal environmental disturbance is critical.

This thesis introduces the conceptualization, design, and development of a novel propulsion system for underwater robots, one that draws inspiration directly from the biomechanics of aquatic life. By leveraging principles of biomimicry—specifically the fluid, efficient locomotion observed in marine animals like cuttlefish, fish, and sea turtles—this work proposes a transformative alternative to conventional propeller-based propulsion. The resulting system emphasizes hydrodynamic performance, silent operation, and modular design, establishing a new benchmark in underwater mobility.

The propulsion mechanism centers around fin-actuated structures that replicate natural swimming motions through the use of flexible linkages and waterproof actuators. These bio-inspired fins are engineered to generate both linear thrust and multidirectional control forces, enabling the underwater drone to perform intricate maneuvers such as hovering, agile turning, and station-keeping with minimal latency. The incorporation of different fin geometries and configurations—each tailored to specific operational profiles—further enhances the system's adaptability. For instance, larger caudal-like fins are optimized for high-speed traversal, while smaller, undulating fins support stable inspection and fine control.

A significant focus of this project is placed on achieving superior energy efficiency and reduced acoustic signature—two critical parameters for long-duration missions. Through a rigorous cycle of iterative prototyping and experimental validation in controlled aquatic environments, key performance metrics were measured, including thrust-to-power ratios, hydrodynamic drag coefficients, response latency, and directional stability. The experimental results consistently demonstrated a marked reduction in noise levels and turbulence compared to traditional propeller

systems. Additionally, smoother acceleration curves and lower power draw reinforced the propulsion system's suitability for applications where energy conservation is paramount.

Beyond its performance advantages, the system is designed with practical usability in mind. The entire propulsion assembly is housed within a streamlined, waterproof casing that ensures robustness against pressure variations and corrosion. Its modular construction allows for quick swapping of fin components and straightforward maintenance, thereby supporting a wide range of drone platforms and mission requirements. This ease of integration opens up opportunities for deployment in various domains, from academic marine biology studies to commercial infrastructure inspections and strategic reconnaissance missions.

In conclusion, this thesis substantiates the feasibility and effectiveness of a biomimetic propulsion approach in revolutionizing underwater drone mobility. By imitating nature's time-tested aquatic locomotion strategies, the proposed system delivers enhanced agility, lower energy consumption, and a quieter operational footprint. These advancements not only represent a substantial contribution to the field of bio-inspired robotics but also pave the way for the next generation of intelligent, environmentally conscious underwater vehicles. Future research will build upon this foundation, exploring more sophisticated control algorithms, material innovations, and multi-modal propulsion integrations to further refine the capabilities of such systems.

Acknowledgements

We take this opportunity to express our sincere thanks to our supervisor **Dr. Dhiraj Kumar** for their guidance and unwavering support and insightful feedback throughout the entire process of researching and writing this thesis. We would also like to express our gratitude towards them for showing confidence in us. It was a privilege to have a great experience working under him in a cordial environment.

We are very much thankful to the University of Petroleum and Energy Studies, for providing us the opportunity of pursuing Bachelor of Technology in Aerospace Engineering in a peaceful environment with ample resources.

We are thankful to **our classmates**, for their constant support throughout the project. We would also like to give a special mention to the Aerospace Lab staffs **Mr. Vikrant Rana, Mr. Anuj Rana, and Mr. Sri Om Pundir and Mr. Narendra Singh Rawat (workshop lab) and our classmate Mr. Lakshya Saxena** for their constant support and guidance during the manufacturing process. Further we would like to mention about design block lab staff for helping us to manufacture the ornithopter.

In the end, I would like to acknowledge my parents, family members. Without their support, this work would not have been possible.

Kanishka Bhatt

Punit Gandas

Rohan Sahu

Kashish

Declaration

We hereby declare that this submission is our own and that, to the best of our knowledge and belief, it contains no material previously published or written by another person, nor material which has been accepted for the award of another degree or diploma by a university or other higher learning institute. All the material in the report is our own and we are solely responsible for any plagiarism.

Punit Gandas

(500095607 & R290221061)

Kashish

(500093026 & R290221035)

Rohan Sahu

(500097958 & R290221096)

Kanishka Bhatt

(500097845 & R290221094)

Contents

List of Figures

Chapter -1: Introduction

The propulsion system of an underwater drone is a critical component that enables it to navigate through water effectively and carry out various tasks. Unlike aerial or land-based vehicles, underwater drones face unique challenges such as higher fluid density, greater drag forces, and the need for maneuverability in three dimensions (forward/backward, upward/downward, lateral movement).

1.1 Key Aspects of an Underwater Drone System

1.1.1 Types of Propulsion Mechanisms.

- Thrusters (Propellers): The most popular type of underwater drone propulsion, thrusters create thrust by pushing water in the opposite direction with the help of revolving propellers. These may move both horizontally and vertically and are usually driven by electric motors.
- Jet Propulsion: To provide propulsion, certain drones employ water jets that pull in water and shoot it out quickly. Modern drones employ jet propulsion, which is more efficient at greater speeds.
- Buoyancy Control: To adjust depth, certain underwater drones, particularly those intended for deep-sea or long-term observation missions, employ buoyancy control devices like to those found in submarines. By adjusting the volume of air or ballast within the drone, it can sink or float without using energy for continuous propulsion.

1.1.2 Power Sources for Propulsion

- Battery Types: Rechargeable batteries power the majority of underwater drones. Lithium-ion and lithium-polymer batteries are the most often used because of their lightweight design and high energy density. The drone's durability and operational range are determined by its battery capacity.
- Fuel cells: Compared to conventional batteries, fuel cells have a better energy density and a longer operating period, making them an attractive option for long duration underwater drone missions.
- Hybrid Systems: To improve durability and guarantee continuous operation, underwater drones occasionally make use of a battery and fuel cell combination of power sources.

1.1.3 Control of Propulsion

- Thrust Vectoring: numerous thrusters that may function independently are frequently used by underwater drones to control movement in numerous directions. The drone can accomplish fine control over its movements, such as turning, rising, falling, and hovering in one spot, by adjusting the speed and direction of each thruster.

- Propeller Design: Thrust generation, efficiency, and noise reduction are all balanced in the propeller's design, which includes size, pitch, and number of blades. In stealth applications, propeller noise reduction is critical, particularly for military or research drones.

1.1.4 **Advanced Propulsion System**

- Magnetohydrodynamic (MHD) propulsion: Using an electromagnetic field to move saltwater instead of moving elements like propellers, magnetohydrodynamic propulsion is used by certain experimental underwater drones. For military and scientific reasons, this device may offer stealth benefits due to its lowest noise levels.
- Bio-inspired Propulsion: Scientists are investigating propulsion mechanisms that replicate the swimming movements of fish or other marine life. These technologies provide better efficiency and maneuverability, especially in small spaces or areas with plenty of obstacles.

1.2 Applications:

Unmanned underwater vehicles (UUVs), also referred to as underwater drones, have become more important in a variety of industries. because of their adaptability and capacity to function in hazardous and difficult underwater conditions. Below is a summary of their main significance:

1.2.1 Exploration and Research in the Marine Environment

- Oceanography & Marine Biology: Underwater drones allow researchers to study marine ecosystems, monitor species, and explore deep-sea regions that are typically inaccessible to humans.
- Archaeology: Underwater drones help find and examine shipwrecks, underwater ruins, and other historical treasures without upsetting sensitive locations.

1.2.2 Environmental Surveillance

- Pollution Detection: Underwater drones monitor water quality, instantly detecting oil spills, chemical leaks, and pollutants to enable prompt environmental action.
- Research on Climate Change: Data collected by underwater drones on ocean currents, salinity, and temperature is used to estimate the impact of global warming on marine habitats.
- Figure [1] illustrates a environment monitoring drone.

Figure 1: Environmental Monitoring[1]

1.2.3 Defense and Security

- Naval Surveillance: Underwater drones are used by military organisations for mine detection, reconnaissance, and surveillance.
- Countermeasure Systems: Without endangering human life, drones may be utilised to neutralise underwater mines and other dangerous objects.
- Figure [2] presents a underwater surveillance drone for defense purpose.

Figure 2: Underwater surveillance for defense purposes [2]

1.2.4 Oil and Gas industry

- Inspection and Maintenance: Pipelines, undersea infrastructure, and offshore oil rigs are routinely inspected by underwater drones. Because of their ability to find damage, corrosion, and leaks in deep water, maintenance procedures are safer and more effective.
- Exploration: To find possible drilling locations for the production of oil and gas, UUVs are utilised for mapping and exploring the seabed.

1.2.5 Business Use

- Underwater Infrastructure: Underwater wind farms, pipes, cables, and other renewable energy facilities are maintained and inspected by UUVs. This helps to guarantee the reliability of the infrastructure that underpins modern economies.
- Aquaculture: They are also used in fish farms to monitor fish health, inspect underwater nets, and ensure the safety of the aquatic environment.

Figure 3: Aquaculture Drone [3]

1.2.6 Mission of Search and Rescue

- Disaster Recovery: During marine disasters, underwater drones can find casualties, wreckage, and other objects, helping investigators and rescue teams without putting divers in danger.

- Accident Investigation: They assist in the investigation of calamities such as shipwrecks and aircraft crashes since they can enter deep oceans that are inaccessible to manned vehicles. Figure [3] depicts a cable drone used for underwater exploration.

- Figure [4] depicts a cable drone used for underwater exploration.

Figure 4: Underwater Exploration drone[4]

1.2.7 Educational Uses

- Amateur Exploration: Thanks to technological developments, amateurs and educational institutions may now affordably use underwater drones to study underwater ecosystems and marine species.

- Documentary Filmmaking: To obtain distinctive video of marine life, underwater drones are being utilised more and more in nature documentaries and other films.

- Figure [5] shows a digital documentary Filmmaking Drone.

Figure 5: Digital Filmmaking Drone[5]

1.2.8 Scientific Data Collection

- Deep-Sea Studies: They are engineered to operate at extreme ocean depths—often exceeding 6,000 meters—using pressure-resistant hulls and advanced navigation systems such as Inertial Navigation Systems (INS), Doppler Velocity Logs (DVL), and Ultra-Short Baseline (USBL) acoustic positioning. These AUVs are equipped with high-resolution multi-beam sonar, sub-bottom profilers, magnetometers, and CTD (Conductivity, Temperature, Depth) sensors to map the seafloor and gather critical geophysical and geochemical data. They can autonomously conduct long-duration missions to monitor undersea volcanic activity, detect tectonic plate shifts, and analyze hydrothermal vent ecosystems by measuring parameters like temperature gradients, pH levels, and mineral concentrations. This data is crucial for advancing our understanding of seafloor spreading, plate tectonics, and the dynamic processes shaping Earth's crust beneath the oceans.[6]
- Autonomous Data Collection: Advanced drones equipped with AI and onboard sensors are capable of independently collecting, processing, and transmitting data over long durations without requiring direct human control. These drones can be pre-programmed to follow specific flight paths, adapt to changing environmental conditions, and make real-time decisions to optimize data acquisition. This capability is especially valuable in remote or hazardous environments—such as disaster zones, deep forests, oceans, or industrial sites—where continuous human operation is impractical.

1.2.9 Underwater Cable Layering and Maintenance

- Seafloor Mapping for Cable Routes: Underwater drones equipped with high-resolution multi-beam sonar, side-scan sonar, and sub-bottom profilers are used to create detailed 3D maps of the ocean floor. These maps help engineers determine the most stable and obstacle-free paths for laying submarine communication and power cables. The drones can detect underwater ridges, trenches, and sediment types, which is crucial for avoiding hazards like underwater landslides or volcanic activity that could damage cables in the long term.

- Environment and Geo-Technical Assessment: Before cable deployment, drones also perform environmental assessments to ensure minimal disruption to sensitive marine ecosystems. They collect data on seafloor composition, currents, and biological activity, helping planners select routes that avoid marine protected areas and reduce environmental impact.
- Routine Maintenance and Fault Detection**:** Once cables are deployed, underwater drones perform regular inspection missions to assess the physical condition of the cables. Using HD cameras, sonar, and sometimes non-destructive testing tools, they can detect signs of wear, marine growth, sediment burial, or external damage caused by fishing equipment or ship anchors.

1.2.10 Underwater UXO (Unexploded Ordnance) Detection

- High-Resolution Sonar and Magnetometer Scanning: Underwater drones use side-scan sonar, synthetic aperture sonar (SAS), and magnetometers to detect metallic objects buried in sediment or resting on the seafloor. These systems allow them to scan large areas quickly and identify anomalies that match the signature of UXOs such as bombs, mines, or torpedoes.
- Precise Geolocation and Mapping: Equipped with advanced positioning systems like USBL (Ultra-Short Baseline) and DVL (Doppler Velocity Log), the drones can precisely mark the GPS coordinates of potential UXO locations. This geo-referenced mapping is critical for safe navigation, future clearance operations, and long-term monitoring.
- Figure [6] shows an unexploded ordnance detection drone.

Figure 6: Unexploded Ordnance Detection Drone[7]

Chapter-2: Literature Review

2.1 Introduction to Underwater Drone Propulsion

The evolution of underwater propulsion systems has been heavily influenced by the unique challenges of operating in a dense and dynamic aquatic environment. Underwater drones, also known as Unmanned Underwater Vehicles (UUVs), face increased fluid resistance, turbulence, and navigational constraints due to the nature of water compared to air. Consequently, the design and development of propulsion systems for these vehicles require a nuanced understanding of hydrodynamics, energy efficiency, material science, and bioinspired mechanics. This literature survey explores various propulsion technologies that have emerged over the decades, from conventional propellers to modern biomimetic approaches, while identifying current research gaps and design challenges.

Propulsion in underwater drones can be classified into five major categories: traditional propeller-based systems, jet propulsion, magnetohydrodynamic (MHD) drives, biomimetic propulsion, and hybrid systems. Each of these systems has its own domain of efficiency, maneuverability, acoustic signature, and suitability based on mission profile. [8]Traditional propellers, though dominant in commercial applications, struggle with noise, cavitation, and limited maneuverability. Jet propulsion offers better speed but consumes excessive energy at low speeds. MHD systems are silent and ideal for stealth operations but remain impractical for large-scale adoption due to their low thrust and high-power requirements. Biomimetic propulsion, on the other hand, emulates the movement of aquatic life, offering a balance of efficiency, silence, and agility, making it a focus area for current and future research.

As underwater drone missions become more diverse—ranging from deep-sea exploration and military reconnaissance to environmental monitoring and aquaculture support—the need for optimized, adaptive, and stealthy propulsion solutions becomes increasingly evident. The literature indicates that while many propulsion concepts are technologically feasible, the practical implementation, especially in challenging real-world ocean environments, remains constrained by limitations in materials, energy systems, and dynamic control. This survey investigates the breadth of current technologies, and the cutting-edge research aimed at overcoming these challenges.

2.2 Conventional Propeller-Based Propulsion

2.2.1 Operating Principle

Traditional underwater drones have long relied on electrically driven propellers or thrusters for movement. These systems work on Newton's Third Law—water is displaced in one direction using rotating blades, and a reactive force propels the drone in the opposite direction. The simplicity, availability of components, and established design guidelines make propeller-based systems the default choice in commercial and academic prototypes.

2.2.2 Applications and Advantages

Propeller propulsion is suited for:

- Long-distance transit where consistent speed is required.
- Industrial inspections (e.g., pipelines, hulls, and offshore platforms).
- General-purpose exploration where complex maneuvering is secondary

Benefits include:

- High mechanical reliability
- Easily scalable power output
- Compatibility with off-the-shelf controllers and batteries

2.2.3 Design Parameters

Efficiency in such systems depends on the following:

- Blade diameter and pitch
- Rotational speed (RPM)
- Number of blades
- Motor torque
- Ducting or shrouding around propellers

Adjusting these parameters can alter thrust, torque, and acoustic signatures. However, fine-tuning them for a specific mission or environment often requires extensive CFD simulations and water tunnel testing.

2.2.4 Limitations and Challenges

Despite their popularity, propeller systems are constrained by:

- **Cavitation**: At high RPMs, the drop in local pressure on the blade surface causes vapor bubbles to form. These collapse violently, causing noise, vibration, and eventual erosion.
- **Noise Signature**: Propeller turbulence and cavitation make them acoustically loud, which is undesirable for wildlife observation or military reconnaissance.
- **Limited Agility**: Traditional systems cannot perform lateral or hovering maneuvers effectively unless supported by multiple thrusters at various orientations.
- **Efficiency Drop at Low Speeds**: These systems struggle to maintain high thrust-to-power ratios at low velocity or in dense waters with strong currents.

2.3 Jet Propulsion Systems

2.3.1 Mechanism of Operation

Underwater jet propulsion operates by rapidly drawing in water and expelling it through a convergent nozzle. The momentum change results in a forward thrust. It is commonly found in torpedoes and specialized underwater vehicles requiring rapid motion and low mechanical complexity.

2.3.2 Performance Characteristics

Jet propulsion systems are effective at:

- High-speed operation with a streamlined body
- Situations demanding minimal rotating parts
- Simple internal configurations with enclosed flow channels

Jet nozzles can be integrated with directional control systems, allowing limited vector thrust capabilities. Moreover, their compact internal design offers fewer protrusions, making them better suited for confined or debris-filled environments.

2.3.3 Disadvantages and Operational Limits

Despite their merits, jet systems suffer from:

- **Inefficiency at low speed**: High-speed operation is required to create effective suction and jet ejection.
- **Higher power consumption**: Due to continuous pumping and lack of passive gliding.
- **Limited maneuverability**: Unless assisted by multiple vector nozzles, the control is restricted to linear motion.

While used in military-grade systems or special-purpose robotics, jet propulsion’s high energy demand makes it less ideal for endurance missions or long-duration autonomous tasks.

2.4 Magnetohydrodynamic (MHD) Propulsion

2.4.1 Working Principle

MHD propulsion relies on the interaction between electrically conductive seawater, magnetic fields, and applied current. A strong magnetic field is aligned perpendicular to an electric current passed through the water, generating a Lorentz force that propels the fluid—and thus the vehicle—in a perpendicular direction.

2.4.2 Advantages

- **No moving parts**: This makes it extremely quiet—ideal for covert missions.
- **Stealth-oriented**: Absence of cavitation and vibrations renders MHD practically

undetectable by sonar.

- **Low maintenance**: Reduced wear-and-tear due to absence of mechanical parts.

2.4.3 Limitations

- **Extremely low thrust**: Unsuitable for most real-world underwater navigation.
- **High power consumption**: Strong magnetic fields and continuous electric input are energy-intensive.
- **Engineering challenges**: Requires superconducting magnets and sophisticated insulators.
- **Scalability issues**: The system doesn’t scale well with larger vehicle designs or high-thrust requirements.

MHD propulsion remains largely experimental, though significant research is underway in defense-oriented laboratories and advanced marine robotics projects.

2.5 Biomimetic Propulsion Systems

2.5.1 Conceptual Foundation

Biomimetic propulsion, derived from "bio" (life) and "mimesis" (to imitate), involves replicating the movement patterns of aquatic creatures to generate thrust. Marine animals like tuna, dolphins, rays, and squids exhibit unmatched agility, efficiency, and silence in underwater motion. These species have evolved over millions of years to maneuver through complex aquatic environments, and their locomotion methods are now being translated into mechanical systems for underwater drones.

Unlike propeller or jet-based systems that push fluid linearly, biomimetic propulsion uses undulatory or oscillatory movements to produce force through **vortex ring generation** and **momentum exchange** with the surrounding fluid. These propulsion modes offer low noise, high efficiency at low speeds, and exceptional maneuverability in constrained or obstacle-rich environments.

2.5.2 Classification of Bio-Inspired Locomotion

Biomimetic propulsion can be broadly classified into the following types:

- **Undulatory Locomotion**: Seen in eels, sea snakes, and lampreys. The entire body undergoes wave-like deformations that push water backward. It is ideal for maneuvering through tight spaces and cluttered environments.
- **Oscillatory Locomotion**: Observed in fish like tuna or sharks. Only the posterior part of the body, especially the tail, performs oscillations. This produces strong forward thrust with limited body deformation.[9]
- **Pectoral Fin-Based Locomotion**: Employed by rays and cuttlefish. Propulsion is

generated by oscillating or undulating large fins. These systems allow for hovering, reverse motion, and excellent yaw control.

- **Jet Propulsion through Contraction**: Found in jellyfish and squids. These animals contract their bodies to expel water through a siphon or aperture, propelling themselves forward. Mechanical implementations mimic this using bell-shaped actuators.

2.5.3 Mechanical Implementation

Recreating biological propulsion mechanically requires:

- **Flexible materials** like silicone or elastomers for fins
- **Precision actuators** such as servo motors or Shape Memory Alloys (SMAs)
- **Central control units** (e.g., Arduino, Raspberry Pi) for coordination
- **Feedback sensors** (IMUs, pressure sensors) to stabilize motion

Linkage-based systems are also used where rigid links emulate fin or tail motion, driven by rotary actuators and springs to imitate natural stiffness patterns.

2.5.4 Advantages

- **Reduced Acoustic Signature**: Movement through fluid is smoother, generating less noise and avoiding cavitation.
- **High Efficiency at Low Speeds**: Ideal for slow-moving drones like those used in marine biology or reef monitoring.
- **Superior Maneuverability**: Can perform turns, spirals, and hovering better than traditional propulsion.
- **Energy Conservation**: Some biomimetic systems, like undulatory propulsion, allow gliding phases with no active power draw.

2.5.5 Challenges

- **Mechanical Complexity**: Building flexible, dynamic fins requires advanced materials and design.
- **Control Complexity**: Nonlinear dynamics demand sophisticated control algorithms, often involving adaptive feedback systems.
- **Material Durability**: Repeated flexing in saline water can degrade soft materials over time.
- **Scale Limitations**: Efficient designs exist mostly in small-scale models; scaling them for larger drones is non-trivial.

2.6 Hybrid Propulsion Systems

2.6.1 Motivation for Hybridization

To overcome the limitations of individual propulsion types, researchers have developed **hybrid propulsion systems** that combine the strengths of two or more methods. These systems switch dynamically between propulsion modes depending on mission needs.

A typical example involves:

- **Propeller-based transit** for covering long distances quickly
- **Biomimetic fin or tail motion** for maneuvering in tight spaces or when stealth is necessary

2.6.2 Architecture and Control

Hybrid systems require:

- Modular body designs to integrate both propulsion systems
- Smart controllers (often AI-assisted) to determine when to switch propulsion modes
- Seamless integration of power management between subsystems

Controllers might assess parameters such as battery level, proximity to obstacles, or mission mode (e.g., exploration vs. inspection) to change propulsion styles mid-mission.

2.6.3 **Benefits**

- **Mission Flexibility**: Suitable for diverse underwater terrains and tasks
- **Energy Optimization**: Conserves battery by shifting to the most efficient mode.
- **Robustness**: If one propulsion type fails, the other can take over
- **Performance Enhancement**: Achieves a balance between speed and precision

2.6.4 Limitations

- **System Weight and Complexity**: Multiple propulsion modules increase payload and mechanical design load
- **High Control Overhead**: Requires advanced software for mode transitions
- **Integration Challenges**: Tuning two propulsion mechanisms to complement rather than interfere is non-trivial

Still, hybrid propulsion is considered a frontier in UUV development, especially for applications in military, disaster response, and marine archaeology.

2.7 Hydrodynamics and Fluid-Structure Interaction

2.7.1 Hydrodynamic Drag and Flow Resistance

One of the fundamental challenges for any underwater drone is overcoming hydrodynamic drag. Since water is over 800 times denser than air, even small velocity increases result in significantly higher resistance. Drag is categorized into:

- **Skin friction drag** – caused by water viscosity against the vehicle's surface
- **Pressure drag** – due to shape and flow separation
- **Induced drag** – from oscillatory motion or vortex interactions

Reducing drag directly improves propulsion efficiency and extends mission time.

2.7.2 Cavitation and Its Effects

Cavitation occurs when water pressure falls below vapor pressure, forming bubbles that implode, damaging surfaces and generating sound. It's a major issue in high-speed propeller systems.

Biomimetic systems are inherently **less prone to cavitation**, thanks to smoother motion and lower blade-tip speeds.

Mitigation strategies include:

- Blade re-design (e.g., larger, slower-rotating blades).
- Use of **ducted fans** and **nozzle shrouds**
- Advanced materials like carbon fiber composites

2.7.3 Vortex Control and Strouhal Number

In biomimetic propulsion, thrust is often generated by vortex rings. The key efficiency metric is the **Strouhal number (St)**:

$$St = \frac{fA}{V}$$

where
f: oscillation frequency
A: Amplitude of motion
V: forward velocity
St: Strauhal Number
Optimal Strauhal number lies between **0.25 and 0.35** for maximum propulsive efficiency. Maintaining this number requires **real-time adjustments** based on speed, tail motion, and flow feedback.

2.7.4 Fluid-Structure Interaction (FSI)

The mutual effect of water flow and fin/tail deformation is termed FSI. It's essential in designing:

- Flexible actuators
- Linkage systems
- Fin surfaces
- High-fidelity **CFD simulations** combined with **finite element modelling** help optimize

propulsion shapes and motions before physical prototyping.

2.8 Control Systems and Real-Time Feedback in Underwater Propulsion

2.8.1 Importance of Propulsion Control

In underwater environments, drones are subjected to dynamic, unpredictable conditions such as shifting currents, pressure changes, and obstacles. Effective propulsion control is essential to ensure:

Stability in turbulent waters

- Responsive manoeuvrability
- Efficient energy usage
- Real-time course correction
- Control systems must synchronize actuation, sensors, and feedback loops to ensure safe navigation.

2.8.2 Types of Control Systems

There is various control systems used in UUV propulsion:

- **PID Controllers**: Common in industry, Proportional-Integral-Derivative controllers offer basic control through error minimization but may struggle with nonlinear dynamics.
- **Model Predictive Control (MPC)**: Uses system models to predict future behavior and adjust input accordingly. Ideal for adaptive control in turbulent or unknown environments.
- **Fuzzy Logic Control**: Provides rule-based decision-making, useful when precise models of water interaction are difficult to define.
- **Neural Networks and Deep Learning**: Allow autonomous drones to learn patterns from prior missions or simulated data, adapting control parameters in real-time.

2.8.3 Sensor Integration

A wide range of sensors support control systems:

- **IMUs (Inertial Measurement Units)**: Measure roll, pitch, and yaw
- **Depth sensors**: Track vertical position
- **Pressure sensors**: Monitor structural integrity
- **Current meters**: Detect environmental forces
- **Vision systems**: Aid in visual navigation and obstacle detection

Control loops combine sensor data with control algorithms to stabilize motion. In biomimetic systems, additional feedback from **strain gauges** and **fin position encoders** help maintain optimal flapping frequency and amplitude.

2.9 Energy Efficiency and Power Management

2.9.1 Power Sources in Underwater Drones

Underwater drones mostly rely on:

- **Lithium-Ion (Li-ion) Batteries**: High energy density and rechargeability.

- **Lithium-Polymer (Li-Po) Batteries**: Lightweight and flexible but less safe under extreme pressure.
- **Fuel Cells**: Convert hydrogen or methane to electricity; higher endurance but complex integration.
- **Hybrid Systems**: Combine battery and fuel cells to balance performance and longevity.

Advanced missions are investigating:

- **Ocean Thermal Energy Conversion (OTEC)**
- **Solar-charged surface buoys** for refueling
- **Microbial fuel cells** that generate power from seawater microbes

2.9.2 Energy Consumption in Propulsion

Propulsion is the largest energy sink in underwater drones, consuming up to 80% of total power in most cases. To reduce consumption:

- Efficient fin designs reduce hydrodynamic drag
- Oscillatory propulsion can alternate between powered and passive motion
- Glide phases and smart trajectory planning reduce the need for continuous thrust

2.9.3 Energy-Aware Motion Planning

AI-driven planning allows drones to:

- Predict ocean currents and drift accordingly
- Minimize sharp turns or acceleration/deceleration
- Schedule sensor operation to balance power with mission goals

Bio-inspired control algorithms even allow motion profiles that mimic energy-saving behaviors of real fish—like swimming with currents, clustering behind obstacles to avoid flow resistance, and reducing tail oscillation in slow zones.

2.10 Research Gaps and Unresolved Challenges

Despite progress, several critical gaps persist in the field:

2.10.1 Limited Real-World Testing

Most biomimetic and advanced propulsion systems are still validated in controlled laboratory setups. Real ocean environments introduce variables like:

- Biofouling
- Sediment interference
- Variable salinity and temperature gradients
- Pressure-induced hardware failure

Long-term, real-world testing is needed to transition lab models to deployable systems.

2.10.2 Scalability Issues

Many biomimetic systems perform well at small scales but lose efficiency when scaled up. Challenges include:

- Structural integrity of flexible fins
- Increased drag with larger surface area
- Actuation delays in large mechanisms

Designing scalable, modular fin systems is a key challenge.

2.10.3 Material and Structural Fatigue

Soft materials like silicone or TPU degrade over time due to:

- Salinity
- Repeated mechanical flexing
- UV and microbial exposure

2.10.4 Cavitation Mitigation

Though biomimetic designs reduce cavitation, high-speed motion or mechanical errors can still trigger bubble formation. More advanced blade/flap geometries and predictive control algorithms are needed to keep operations within safe flow regimes.

2.10.5 Feedback-Based Vortex Optimization

Real-time feedback for vortex control is underdeveloped. Systems that can sense wake structures or Strouhal number shifts and adapt motion accordingly can boost efficiency significantly.

2.10.6 Integration of AI with Fluid Dynamics

While AI is advancing in control, there's a lack of integration with CFD models, making real-time prediction of thrust or drag behavior difficult. Hybrid AI-CFD systems could unlock more dynamic propulsion modeling.

2.11 Future Research Trends

2.11.1 Biohybrid Robots

Next-gen underwater drones are beginning to use living tissues or biologically derived actuators. Research into muscle-powered propulsion or genetically engineered fins could blur the lines between machine and organism.

2.11.2 Smart, Adaptive Materials

The integration of smart, adaptive materials into underwater drone propulsion systems represents a significant advancement in the development of efficient and responsive thrust mechanisms. Among these materials, smart polymers—also known as stimuli-responsive or intelligent polymers—stand out due to their ability to change physical properties such as stiffness, shape, size, or surface texture in response to external stimuli like temperature, pH, electric or magnetic fields, light, or water pressure.

In the context of underwater propulsion, smart polymers can be engineered to enable morphing fins and propellers, allowing them to dynamically adapt their geometry during operation.

2.11.3 Autonomous Swarm Coordination

In emerging frontier in underwater drone propulsion lies in the coordinated operation of drone swarms, where multiple autonomous vehicles work collectively to perform tasks more efficiently than a single unit could. Inspired by natural phenomena—such as the V-formations of migrating birds or the schooling behaviour of fish—hydrodynamic coupling between swarm members has the potential to significantly enhance propulsion efficiency and reduce energy consumption.

In aquatic environments, fish often swim in schools to exploit the wake vortices generated by those in front. These vortices create alternating zones of high and low pressure in the water, which trailing fish use to reduce drag and gain propulsion assistance. Underwater drones can mimic this behaviour through precisely controlled relative positioning, synchronized swimming patterns, and adaptive thrust modulation.

2.11.4 Energy Harvesting

UUVs of the future may recharge on the go via:

- Ocean wave energy harvesters
- Tethered surface buoys with solar panels
- Thermoelectric energy from hydrothermal vents

2.11.5 Integration with IoT and Satellites

As unmanned underwater vehicles (UUVs) become increasingly autonomous and capable, they are being integrated into multi-domain operational networks that include surface vessels, aerial drones, land-based control stations, and satellite systems. These interconnected networks form a cohesive real-time intelligence and control architecture, enabling dynamic mission updates, resource sharing, and collaborative behavior across different platforms.

In this context, UUV propulsion systems are no longer isolated subsystems but become adaptive components in a larger networked environment. Through real-time communication links—often established via acoustic modems underwater and relayed through surface buoys or tethered aerial relays—UUVs can receive dynamic mission directives and environmental updates from centralized or distributed cloud-based AI platforms.

These AI systems, often powered by edge-cloud hybrid computing, analyze massive streams of data—such as sonar readings, ocean currents, target movement patterns, and mission progress metrics—and send optimized propulsion commands back to the UUVs. This allows for on-the-fly adaptation of propulsion modes based on mission re-tasking, energy availability, tactical needs, or environmental constraints.

2.12 Objectives

The scope of the project primarily involves two of the objectives:

1. Design of propulsion system for underwater drone.
2. Fabrication of model, preparation of experimental setup and instrumentation of model.
3. Underwater testing for thrust generation and identification of suitable design parameters.

Chapter- 3.: Methodology

3.1 Conceptual Design of Propulsion System and CAD Modeling

After learning from the literature review, the second step was to create a conceptual design for the propulsion system of the underwater drone. The target was to design a propulsion system particularly built to achieve specific performance requirements in responding to common challenges enumerated in current systems. This phase focused on innovation, system integration, and feasibility.

The start of the conceptual design phase involved the delineation of the performance requirements that comprised required thrust, cruising and maximum speed, depth of operation, endurance, and maneuverability. The requirements were derived from the intended use of the underwater drone, which could differ from exploration to inspection or surveillance. Through these requirements, a number of propulsion configurations—like single compared to dual-thruster layouts, fixed compared to vectoring nozzles, and direct-drive compared to gear-based systems—were considered for applicability.

Key design considerations included:

- Thrust demands, which deliver adequate force to push and maneuver in peaceful and turbulent water conditions.
- Energy efficiency, with the objective of optimizing battery life and minimizing power losses through optimal motor selection and propeller design.
- Hydrodynamic compatibility, whereby the propulsion system is adapted to the drone's hull shape to reduce drag and prevent flow disturbances.
- Thermal control, particularly in enclosed underwater systems, to prevent motors and electronic components from overheating.
- Material selection, taking corrosion resistance, pressure, and durability in saltwater conditions into consideration.

To make these ideas into tangible forms, Fusion 360 was employed as the primary software for 3D modeling and visualization of the design. This software facilitated the development of detailed CAD models of the components of the propulsion system, including motor housings, propellers, mounting structures, and integrated cooling channels. Parametric modeling features of Fusion 360 enabled iterative refinement of the design as a reaction to performance simulations and design feedback.

Through the use of these models, spatial co-alignment of the propulsion system with the overall drone structure was assessed. Weight distribution, center of mass, and assembly and maintenance considerations were prioritized.

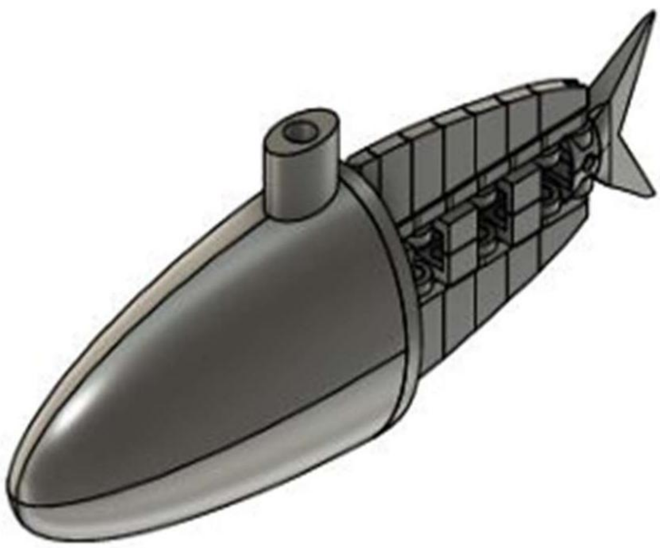
Several design options were examined and contrasted through the simulation capabilities of Fusion 360, enabling basic structural and motion analysis. The simulations provided early indications of the mechanical stresses endured by propellers, their vibration behavior, and the torque requirements under various operating conditions.

By the end of this phase, a finalized conceptual design was achieved—one that balanced innovation with practicality and was ready for prototyping and further validation through fabrication and testing. The design incorporated modular components to facilitate easy upgrades or repairs, ensuring long-term adaptability. Additionally, it was optimized for manufacturability using common materials and 3D printing techniques, accelerating the transition from digital model to physical prototype.[10]

3.2 Assembly of Model

Once all components were fabricated and prepared, the final assembly of the propulsion system and related instrumentation was undertaken with meticulous attention to detail. The assembly process began with a dry-fit procedure, where individual parts were initially positioned without permanent fastening to verify dimensional accuracy, alignment, and mechanical compatibility. Any minor inconsistencies detected during this stage were corrected through post-processing techniques such as sanding, re-drilling, or the application of precision epoxy fillers.

3.2.1 Overall Assembly and Dimensions for first model



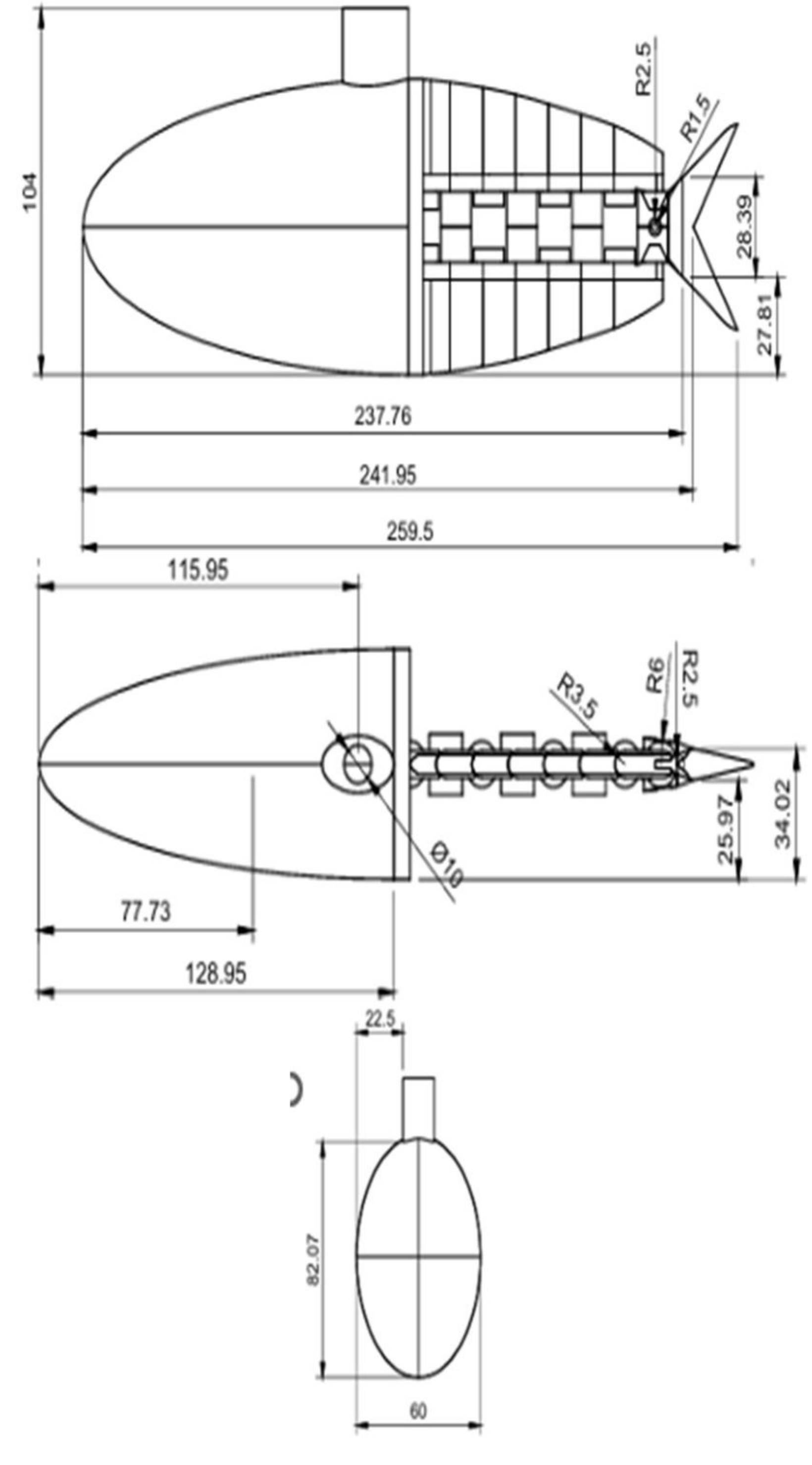


Figure 7: Cad model and Body dimensions of first fish model

3.2.2 Overall Assembly and Dimensions for second model

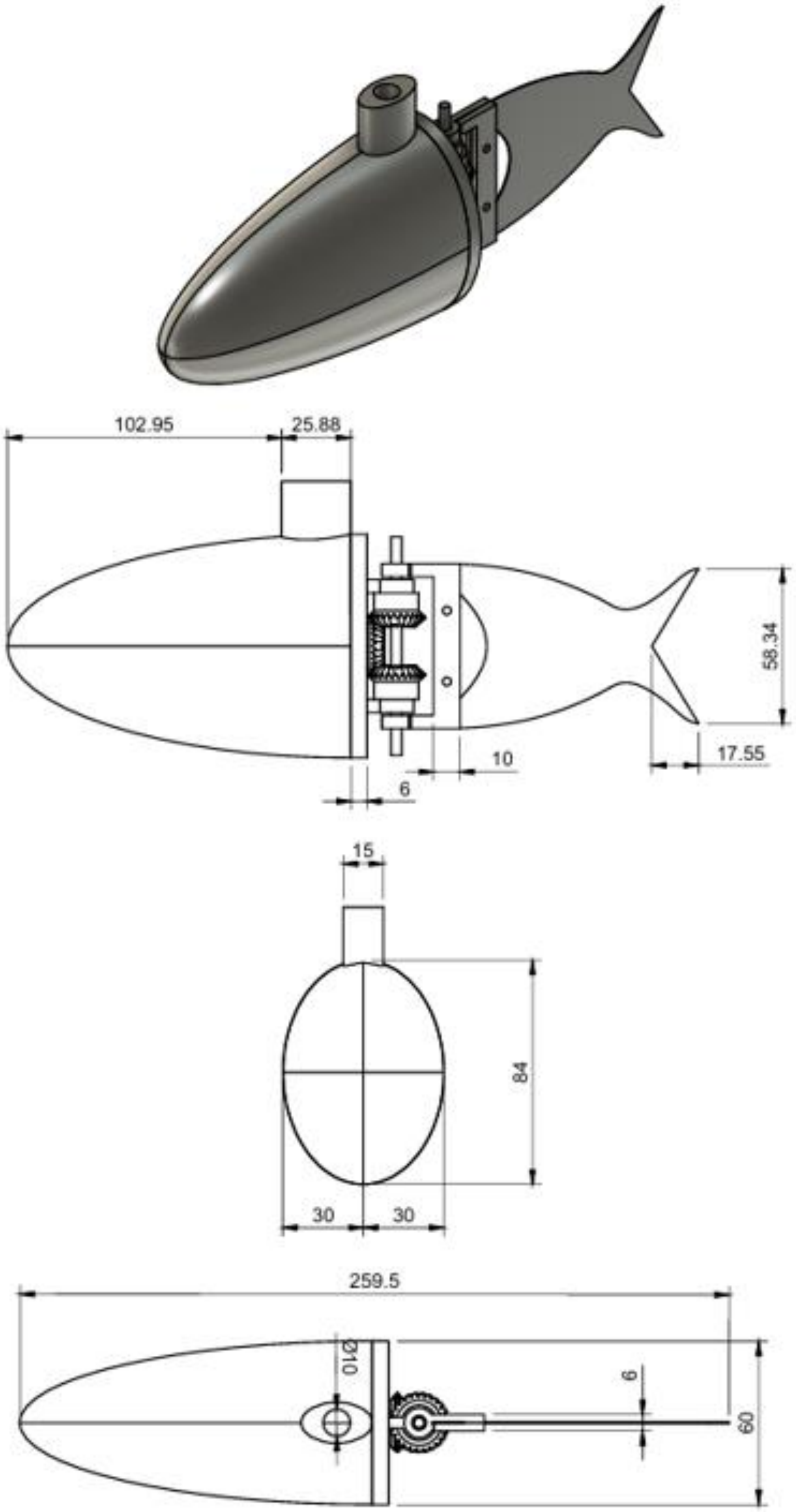


Figure 8: Cad model and dimensions of second fish model

3.3 Fabrication of Model

Following the conceptual design, the following step was to create a physical model by 3D printing technology. The additive manufacturing or the 3D printing technology consists of creating three-dimensional objects by the deposition of material layer by layer from a computer model. The technology suited the project well as it provided quick prototyping, easy changes to the design, and production of complex geometries that are hard or costly to produce using traditional manufacturing methods.

With the CAD models designed in Fusion 360, each component of the propulsion system—like the propeller, motor housing, mounting brackets, and structural enclosures—were exported in STL format and then processed using slicing software to make them print-ready.

The main material employed was PLA (Polylactic Acid) due to its ease of printing, accuracy in dimensions, and minimal environmental footprint. Where added strength or resistance to moisture was needed, PETG (Polyethylene Terephthalate Glycol) was employed because of its excellent mechanical properties and water-resistant characteristics.

There are the fabricated components of first model

3.3.1 Body and Disk

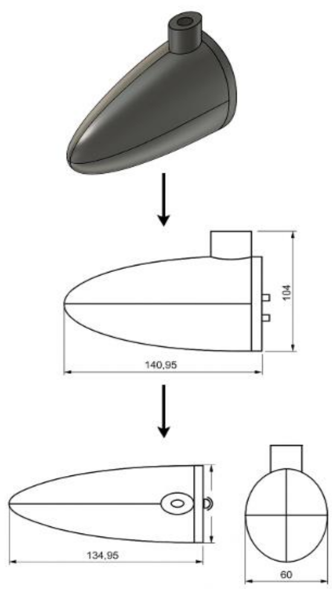


Figure 9: Cad model and body dimensions of front body

3.3.2 Tail

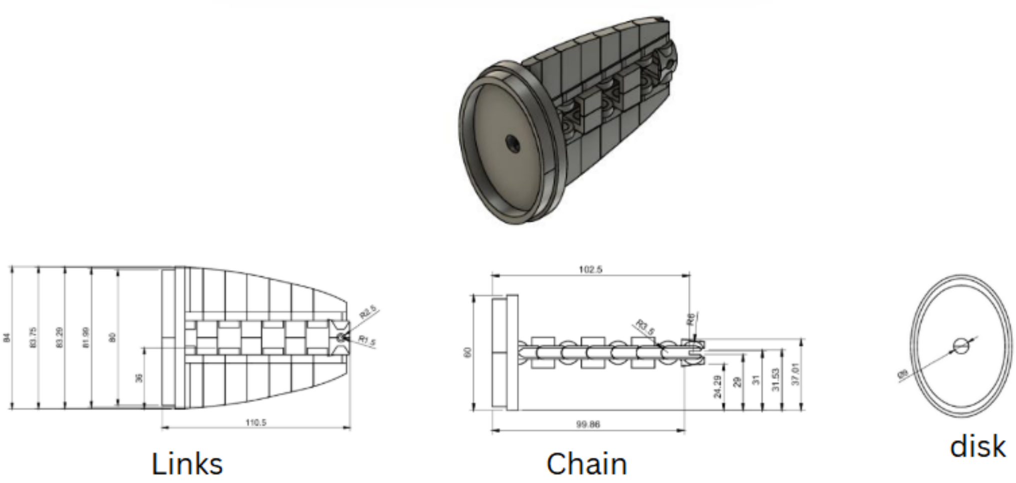


Figure 10: Cad model and dimensions of tail

3.3.2 Links and their mirror links

Currently, the tail is created by combining 14 links, which consists of 7 links of different dimensions and the remaining 7 links that are just mirror images of the first 7.

Link 1 and Link 8 (mirror images)

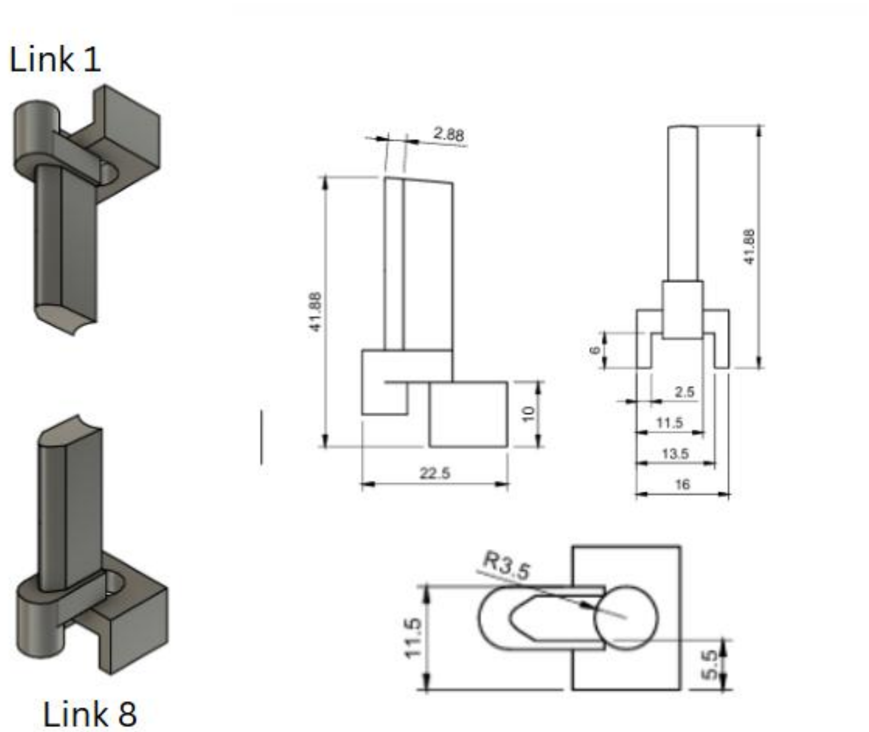


Figure 11: Cad model and dimensions of Link 1 and Link 8

Link 2 and Link 9 (mirror links)

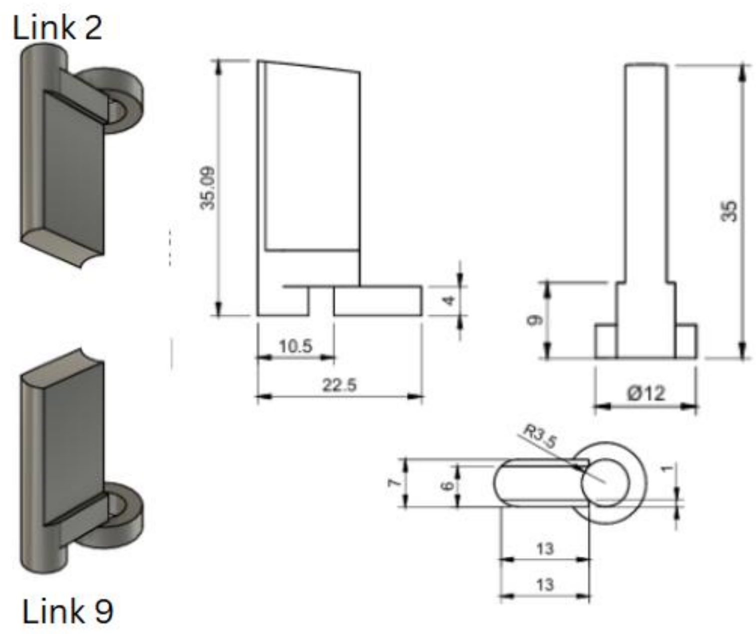


Figure 12: Cad model and dimensions of Link 2 and Link 9

Link 3 and Link 10 (mirror links)

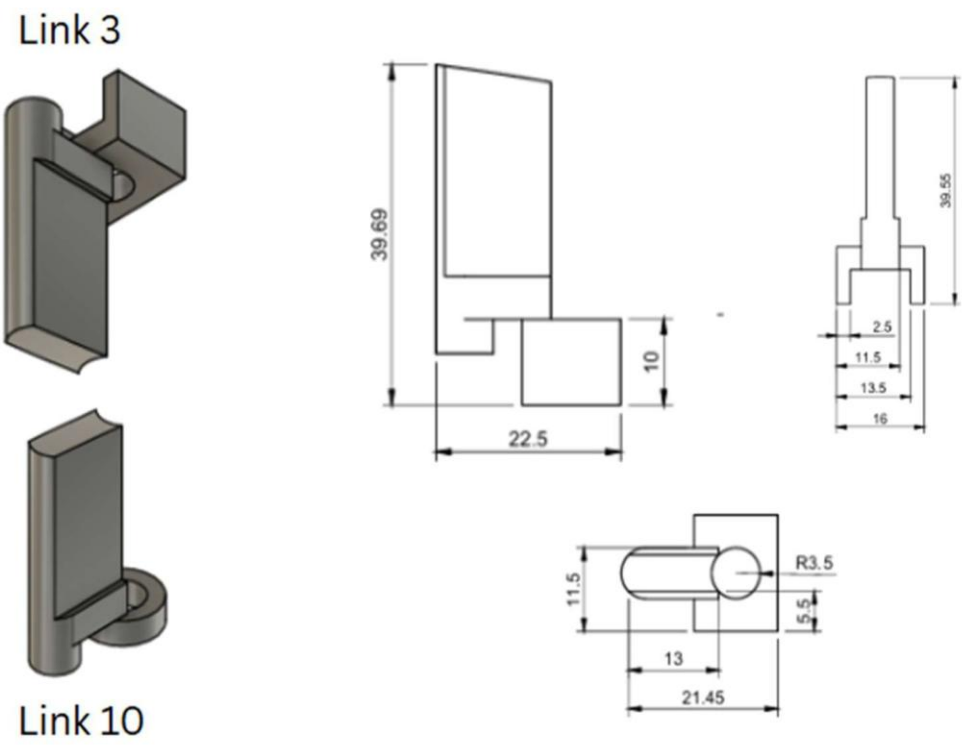


Figure 13: Cad model and dimensions of Link 3 and Link 10

Link 4 and Link 11 (mirror links)

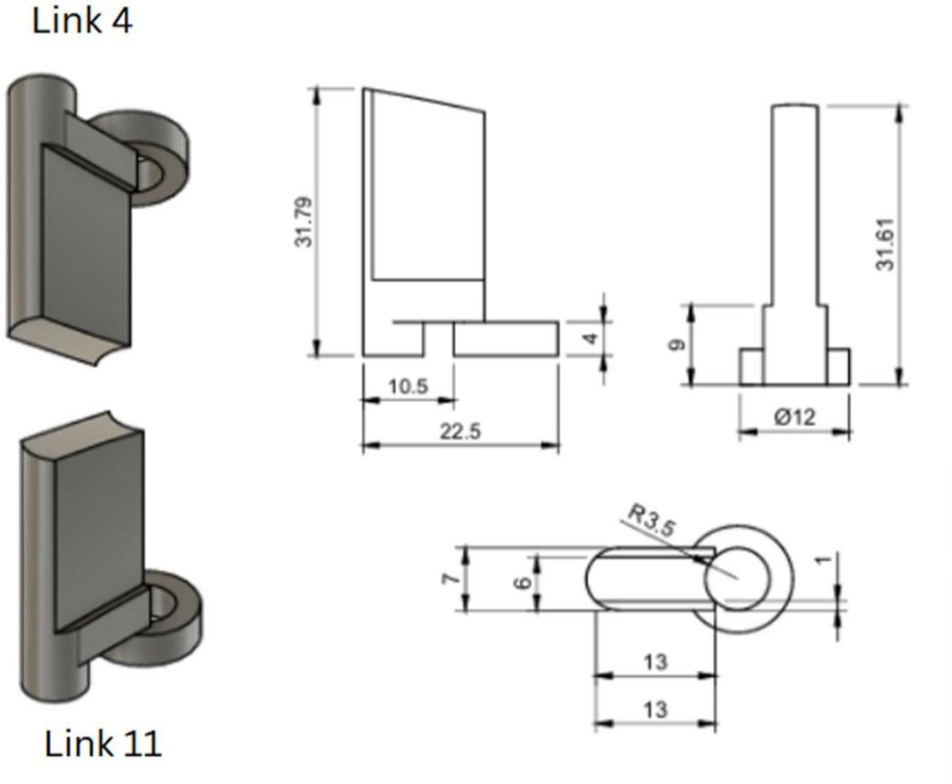


Figure 14: Cad model and dimensions of Link 4 and Link 11

Link 5 and Link 12 (mirror links)

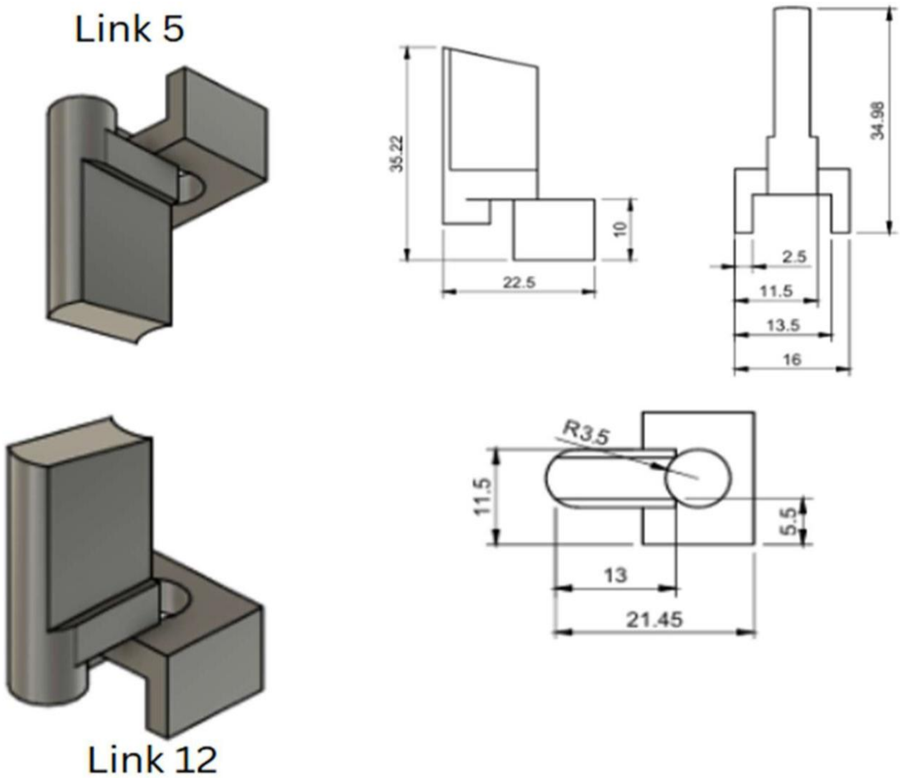


Figure 15: Cad model and dimensions of Link 5 and Link 12

Link 6 and Link 13 (mirror links)

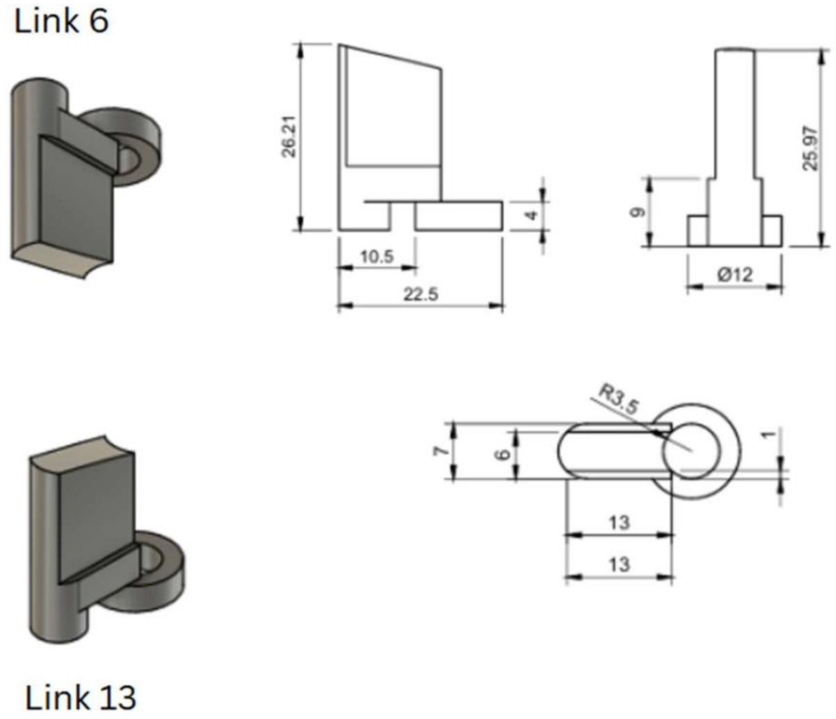


Figure 16: Cad model and dimensions of Link 6 and Link 13

Link 7 and Link 13 (mirror links)

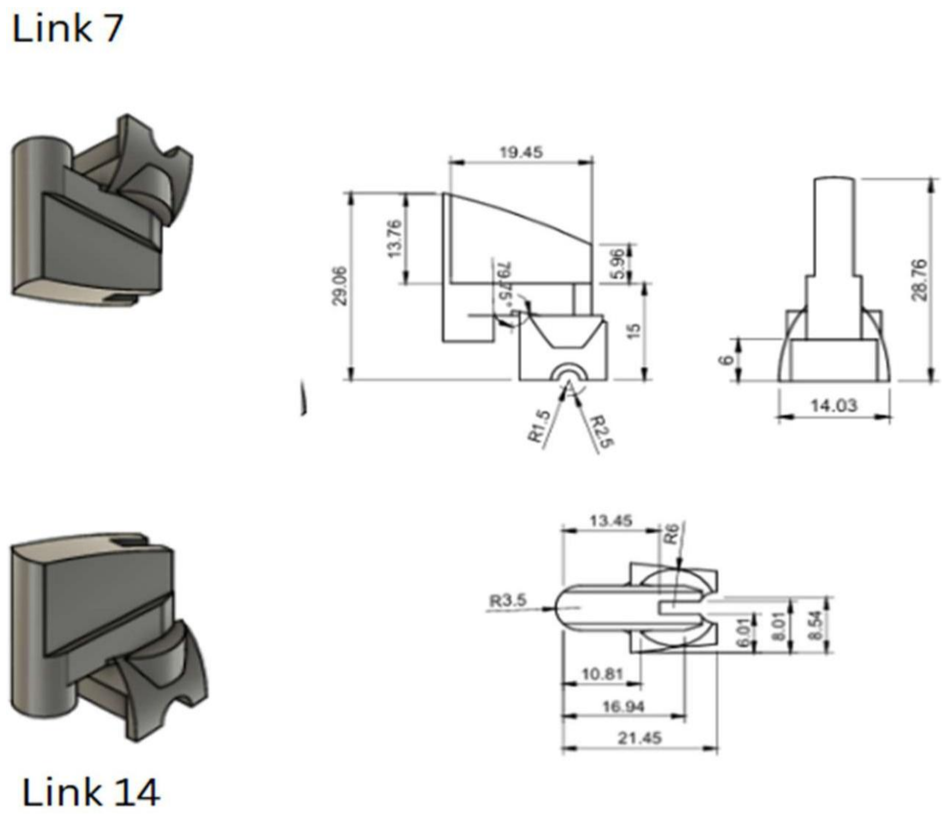


Figure 17: Cad model and dimensions of Link 7 and Link 14

Complete Link Profile

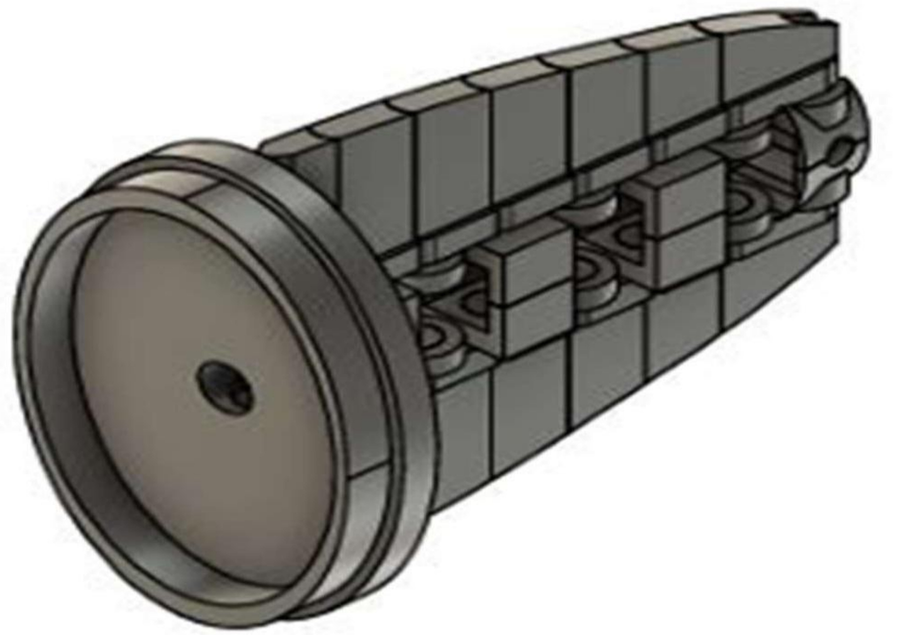


Figure 18: Cad model of complete Link Profile

Fabricated components of the second model consist of

3.3.4 Gears

•

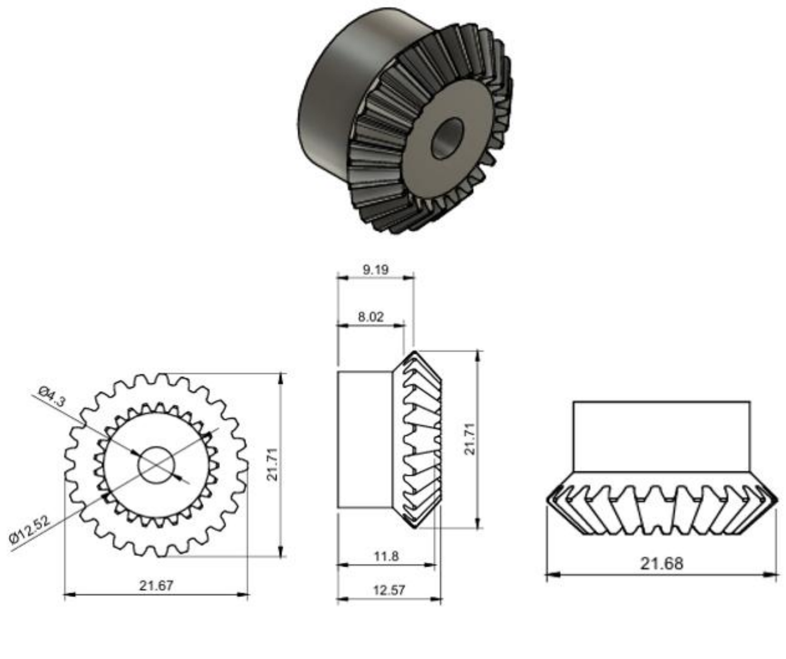


Figure 19: Cad model and dimensions of gears.

3.3.5 Shaft and Disc

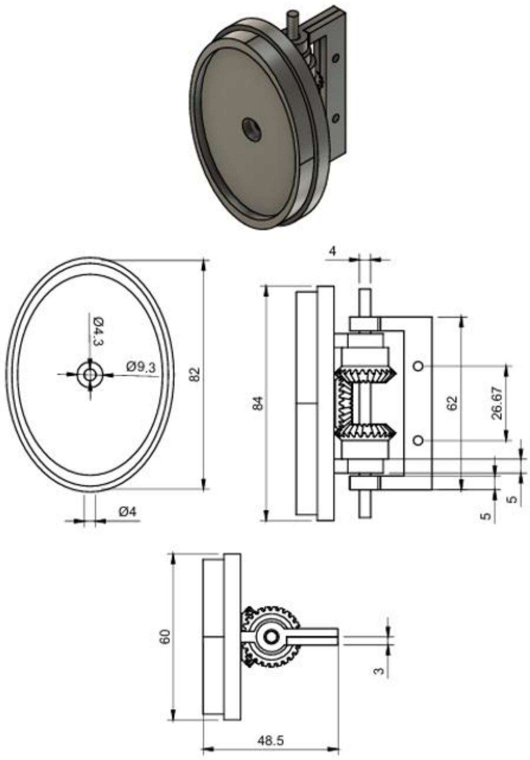


Figure 20: Cad model and dimensions of shaft and disc

3.3.6 Clip

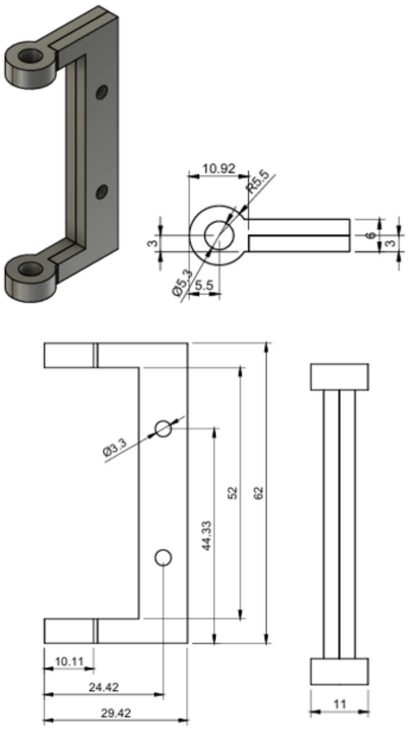


Figure 21: Cad model and dimensions of clip

3.3.7 Front Body

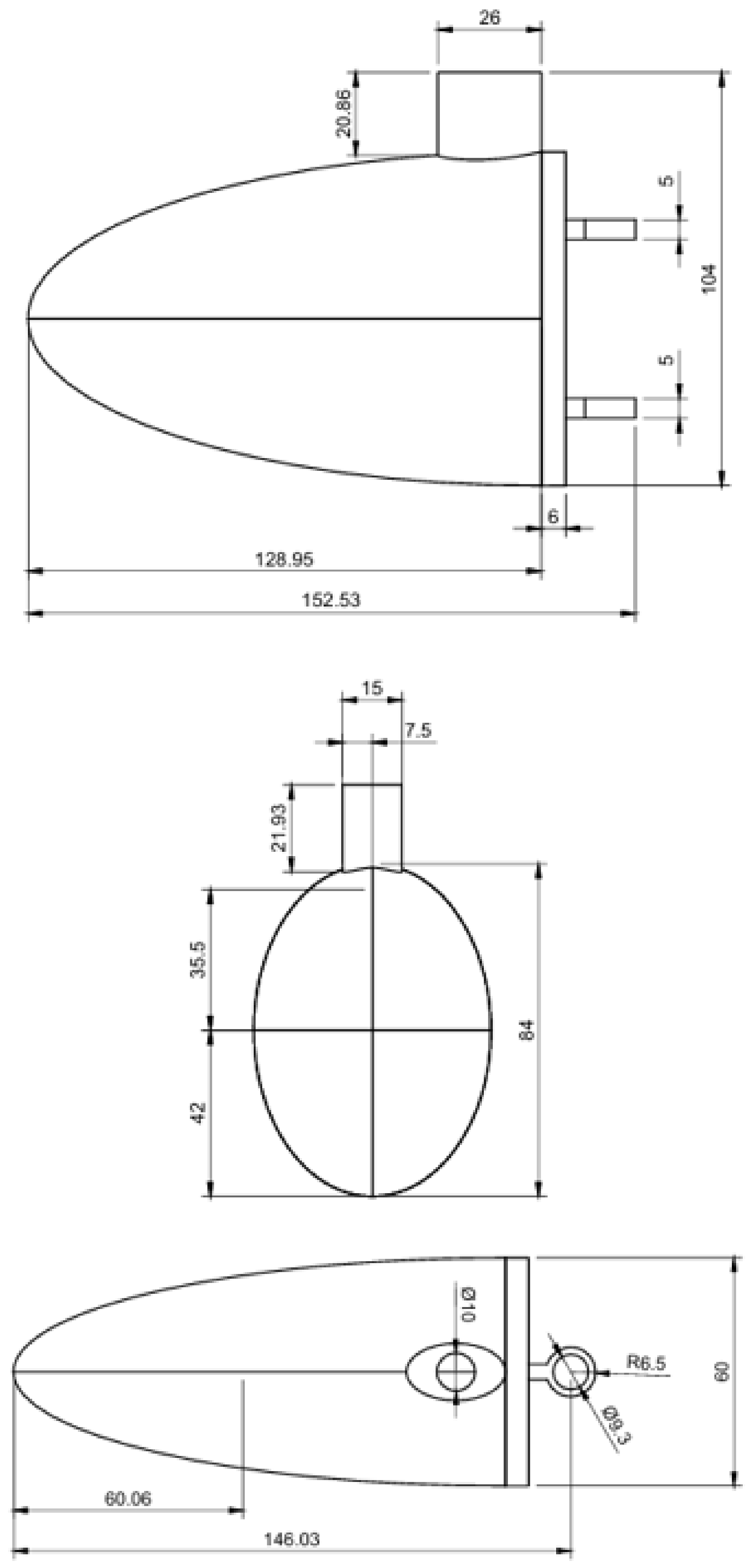


Figure 22: Cad model and dimensions of frontal body

3.4 Motion Mechanism

3.4.1 Motion Mechanism for first model

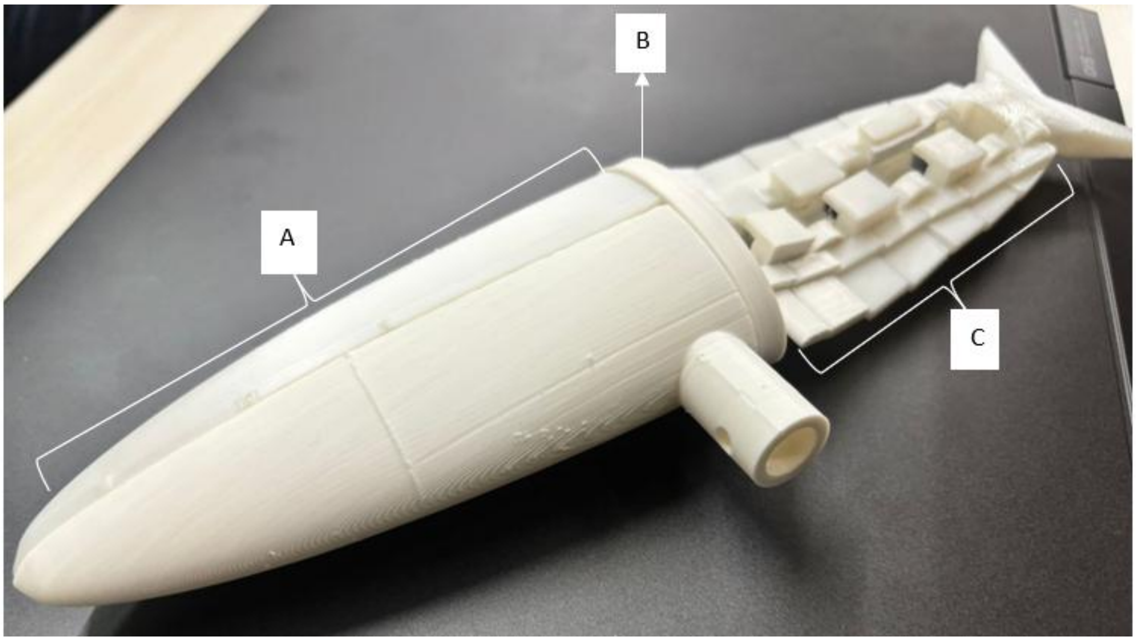


Figure 23: Assembled First Model

A- front body B- Disc C- Tail and fin

The propulsion mechanism of the underwater drone is based on a novel rotary-to-oscillatory motion conversion system, designed to mimic the undulatory movement of aquatic lifeforms. The system begins with a high-torque DC motor, whose rotational output is transferred through a precision-aligned shaft assembly supported by deep-groove ball bearings to ensure smooth and constrained axial rotation. This shaft is mechanically coupled to a helical spring structure, which functions as a flexible transmission element. The assembly is enclosed within a sealed housing, integrated with a dynamic shaft seal to prevent water ingress while maintaining mechanical freedom of rotation. As the motor rotates, the helical spring transmits torque along its axis, imparting a twisting deformation that is converted into lateral oscillatory motion at the distal end of the assembly. This distal end features a radial link mechanism—a series of articulated segments arranged around the outer diameter of the helical structure—which amplifies the torsional motion into a synchronized side-to-side oscillation. This design effectively transforms continuous rotary input into a biologically inspired, oscillating tail movement, enabling efficient thrust generation in water through lateral force propagation.[11]

The motor is precisely controlled using motor driver circuits governed by PWM (Pulse Width Modulation) signals, allowing dynamic adjustment of tail frequency and amplitude in response to navigation commands. This bioinspired actuation method offers advantages in manoeuvrability, energy efficiency, and silent operation compared to traditional propeller-based systems, making it highly suitable for stealth and exploration missions in underwater environments.

3.4.2 Motion Mechanism for Second model

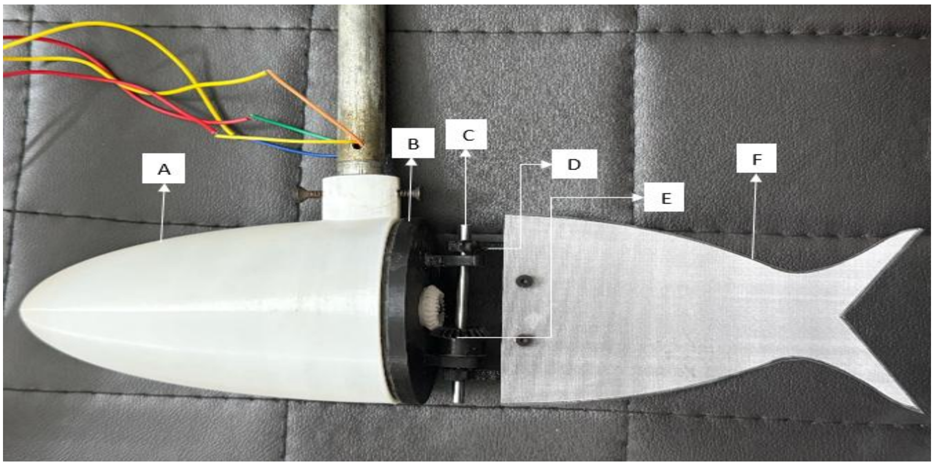


Figure 24: Assembled Second Model

A- Front Body B- Disc C- Shaft D- Clip E- Gear F- Tail

The underwater drone employs a gear-based mechanical transmission system to convert rotational motor input into oscillatory tail motion, mimicking biological swimming patterns. Housed within the main body of the drone is a compact DC motor, which provides the primary rotational actuation. The motor shaft is coupled to a pinion gear, which drives a larger secondary gear through direct meshing. This gear-pair configuration serves as a speed reducer and torque multiplier, enabling smooth and controlled actuation of the tail mechanism. Attached concentrically to the secondary gear is a crank-pin or eccentric cam, which acts as a motion converter. As the gear rotates, the offset pin translates continuous rotary motion into a reciprocating linear motion. This reciprocating input is transmitted to the tail fin via a rigid linkage arm or push-rod assembly. The tail fin itself is designed as a clip-on structure, allowing it to pivot about a central axis or flex at its base in response to the input oscillations.

As the linkage moves back and forth, the tail performs lateral oscillations, creating thrust by interacting with the surrounding water in a waveform similar to that of a fish's caudal fin. The gear-driven design ensures mechanical precision, repeatability, and robustness, while the use of enclosed bearings and sealing rings protects the internal drivetrain from water intrusion.

This mechanism is highly effective in generating forward propulsion with low acoustic signature and excellent maneuverability. The motion amplitude and frequency can be precisely tuned through motor speed modulation using motor drivers with PWM control, making the system adaptable to various operating conditions and swimming pattern.

3.5 Experimental Setup for Thrust Requirement

The experimental setup for the design and development of the underwater drone involves a systematic approach to evaluate the propulsion system, structural integrity, and overall performance of the drone in simulated underwater conditions. The setup includes a water tank, a load cell, and a container rod, with the drone prototype fully assembled and equipped with the necessary components. An enclosed space is created for testing by filling the water tank to a level where the drone may be fully immersed. The load cell, which is a part of the drone's propulsion system, gauges the thrust produced by the thrusters or propellers and provides vital information on propulsion efficiency. Accurate displacement and stability measurements are guaranteed by the regulated vertical and horizontal movement of the drone, which is attached to a container rod within the water tank. Figure [7] depicts the schematic diagram of the experimental setup, illustrating the fish model in a water tank connected to a load cell via a rod.

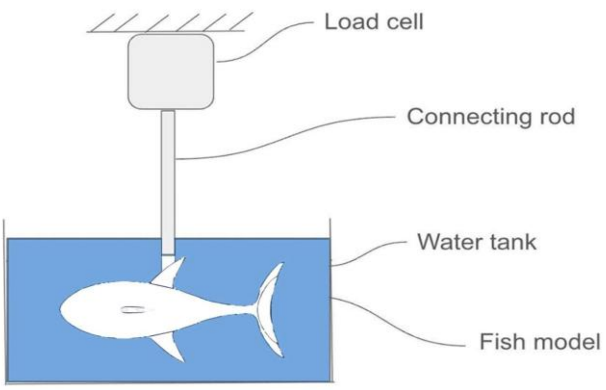


Figure 25: Experimental Setup for Thrust Requirement[12]

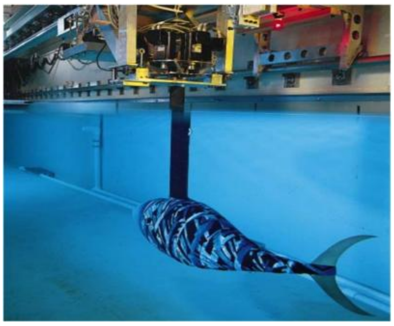


Figure 26: Robo tuna setup from – "An Efficient Swimming Machine[13]

Figure [7] shows the Robo Tuna experimental setup, demonstrating an efficient swimming machine for hydrodynamic analysis. The performance of the drone is evaluated by analyzing data gathered from the load cell and additional sensors, with an emphasis on pinpointing areas that require improvement. The study is used to determine what modifications to make to the drone's propulsion system, structural elements, or other design elements. To make sure these changes result in improved efficiency, stability, and reliability, retesting is done. This experimental configuration not only offers insightful information about the drone's capabilities but also establishes the foundation for future refinement and advancement of underwater drone technology.

Figure [7] illustrates the proposed model, depicting the interaction between the motor, spring, tail, Arduino, and laptop for control and actuation.[14]

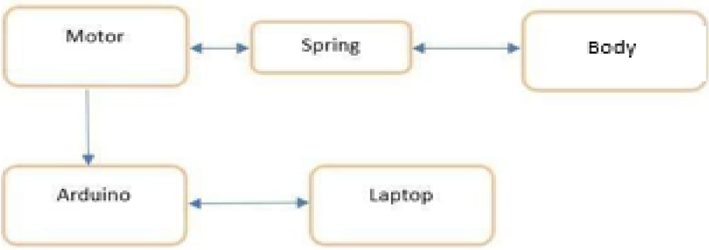


Figure 27: Proposed Model

The flowchart illustrates the working of a system involving a motor, spring, tail, Arduino, and laptop. The motor generates mechanical motion that is transferred to the spring, which acts as a medium to propagate this motion further to the tail. This could be part of a mechanism where the tail is driven by oscillatory or dynamic motion for specific functionality, such as propulsion or balancing.[15]The Arduino acts as the central control unit, interfacing with both the motor and the laptop. The laptop communicates with the Arduino, providing commands or processing data, while the Arduino ensures proper coordination and execution of the system's operations. This setup indicates a system designed for experimentation or control of dynamic mechanical movements.

3.6 Model Instrumentation

1. Arduino UNO (microcontroller)
2. Jumper wires
3. Stepper Motor – (NEMA17)
4. Stepper Motor Driver – (TB6600)

Designing an underwater drone requires a well-integrated system of mechanical, electrical, and electronic components. Electronics play a crucial role in controlling movement, collecting environmental data, and ensuring communication between subsystems. This section focuses on the primary electronic components used in the underwater drone project and discusses their specifications, roles, and integration methods in the overall system.

3.6.1 Arduino Uno – Microcontroller Unit

The Arduino Uno is a central processing unit in this project, responsible for controlling most of the underwater drone's operations. It is an open-source electronics platform based on the ATmega328P microcontroller and is well-known for its ease of use and extensive library support.

Key Specifications:

- Microcontroller: ATmega328P
- Operating Voltage: 5V
- Input Voltage (Recommended): 7V – 12V
- Digital I/O Pins: 14 (6 of which provide PWM output)
- Analog Input Pins: 6
- Flash Memory: 32 KB (0.5 KB used by bootloader)
- SRAM: 2 KB
- EEPROM: 1 KB
- Clock Speed: 16 MHz
- USB Interface: Type-B USB connector
- Communication Protocols Supported: UART, SPI, I2C

Figure 28: Arduino UNO

The Arduino Uno serves as the brain of the underwater drone. It performs essential tasks such as reading sensor data (like pressure, depth, and orientation), executing control algorithms, and generating output signals to actuators like motors and servos. It also handles serial communication with a PC or telemetry system for remote monitoring. Its moderate processing capabilities are sufficient for real-time tasks in small-scale robotics, and its compatibility with multiple shields and libraries makes integration easier.

3.6.2 Jumper Wires – Signal Interconnection

Jumper wires are essential but often overlooked components in any electronic system. They facilitate electrical connections between modules, components, and the controller.

Types Used:

- Male-to-Male: For breadboard and header pin connections
- Male-to-Female: Connecting Arduino headers to sensor modules
- Female-to-Female: For linking two male headers, such as between driver boards

Technical Details:

- Core Material: Copper with flexible silicone or PVC insulation
- Typical Lengths: 10 cm to 30 cm
- Wire Gauge: 22 AWG (standard)

Jumper wires connect the Arduino Uno to sensor modules, motor drivers, and power distribution boards. They provide the flexibility to modify or rewire components quickly during testing and debugging phases. Good wire management is crucial, especially in waterproof housings, to prevent signal interference and accidental disconnections.

Figure 29: Jumper Wires

3.6.3 Stepper Motor – NEMA 17

A stepper motor is an electromechanical device that converts electrical pulses into precise mechanical movements. NEMA 17 refers to a standardized frame size (1.7 × 1.7 inches) commonly used in robotics and 3D printers.

Technical Specifications:

- Step Angle: 1.8° (200 steps per full revolution)
- Holding Torque: ~0.45 Nm (varies with model)
- Rated Voltage: 12V
- Rated Current: 1.2 – 2.0 A per phase
- Coil Resistance: ~1.5 – 3 ohms
- No. of Leads: 4 (bipolar)
- Rotor Inertia: ~68 g·cm^2
- Insulation Class: B (130°C maximum operating temperature)

Figure 30: Stepper Motor – NEMA 17

The NEMA 17 stepper motor is used for applications that require controlled linear or rotary motion, such as adjusting rudder angles, rotating cameras, or operating fins. Since stepper motors operate in discrete steps, they allow for accurate positioning without needing feedback sensors, simplifying the control system. In this underwater application, it provides smooth, vibration-free motion and can hold its position when powered, which is crucial for maintaining orientation or depth stability.[17]

3.6.4 Stepper Motor Driver – TB6600

The TB6600 is a micro stepping stepper motor driver module capable of powering high-current bipolar stepper motors. It serves as the interface between the low-power logic signals from the Arduino Uno and the high-current requirements of the stepper motor.

Technical Specifications:

- Input Voltage Range: 9V – 42V DC
- Output Current Range: 0.5A to 4.5A (adjustable)
- Supported Micro stepping: 1, 1/2, 1/4, 1/8, 1/16, 1/32
- Input Signal Logic: Compatible with 3.3V and 5V systems
- Protection Features:
    - Overcurrent protection
    - Overtemperature shutdown
    - Short circuit protection
    - Undervoltage lockout
- Cooling: Aluminum heatsink with optional fan support
- Control Inputs: STEP, DIR, and EN (Enable) pins

Figure 31: Stepper Motor Driver – TB6600

In the underwater drone, the TB6600 receives control signals (step pulses and direction) from the Arduino and translates them into high-power outputs for the stepper motor. The driver also allows micro stepping, which results in smoother and quieter motor operation, essential for sensitive underwater tasks. Furthermore, its robust protection features prevent component failure due to overloads, which is especially important in sealed environments where heat dissipation is limited.

3.6.5 Reliability Considerations

Electronics in underwater applications face specific environmental challenges:

- Corrosion from saltwater (even in freshwater, humidity is a concern)
- Pressure differentials at depth
- Electromagnetic interference (EMI) from motors and power conversion
- Heat dissipation within waterproof enclosures

To address these:

- All PCB joints are conformal-coated or potted.
- Shielded wires are used for sensitive signal lines.
- The stepper motor is mounted with rubber dampers to absorb mechanical vibration.
- The entire control system is tested in a dry run with simulated loads before underwater deployment.

The integration of the Arduino Uno, jumper wires, stepper motor (NEMA 17), and TB6600 motor driver represents a compact, cost-effective, and reliable electronic control system for an underwater drone. Each component has been selected based on its compatibility, ease of programming, mechanical resilience, and availability. Together, these electronics form a solid foundation for real-time control, environmental sensing, and actuation required in underwater robotics.

Future improvements could include the use of more powerful microcontrollers (like STM32 or Raspberry Pi Pico), waterproofed industrial connectors for long-term deployment, and feedback systems using encoders for closed-loop motor control.

All of these parts are arranged to produce the necessary torque and operate the model.

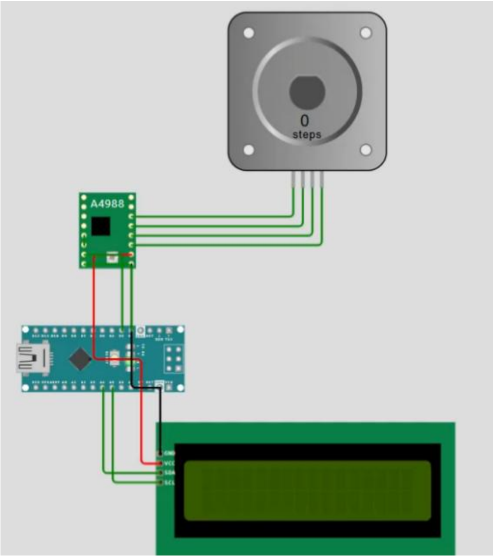


Figure 32: Electronics assembly [18]

3.7 Manufacturing Challenges and Solutions

The fabrication phase of the underwater drone project heavily relied on 3D printing technology due to its cost-effectiveness, rapid prototyping capability, and ease of iteration. Initial fabrication was carried out using the in-house 3D printer available in the Design Block Lab of our college, utilizing PLA (Polylactic Acid) filament due to its ease of printing and biodegradability.

3.7.1 Limitations on In-House Printing

Even while on-campus facilities were easily accessible, the on-campus 3D printer offered a number of significant obstacles:

Lack of Dimensional Accuracy: In intricate geometries such as the links and curved tail portions, the printer showed inconsistent resolution. Misalignment and play in mechanical joints resulted from the frequent ±0.7 mm deviation in tolerances between mating components.

Surface Finish Problems: There were visible layer lines, under-extrusion in some corners, and stringing artefacts in the printed parts, particularly in the shaft connections and gear profiles. This was unsuitable for dynamic parts in a fluid environment because it caused friction during mechanical motion.

Warping and Bed Adhesion: Because of the inconsistent bed temperatures and absence of enclosure in the cooling process, larger components, like the front body enclosure, warped considerably at the corners.

Warping and Bed Adhesion: Because to the printer's lack of enclosure and inconsistent bed temperatures, larger components, like the front body enclosure, bent considerably at the corners during cooling. The waterproof sealing edges were impacted by this distortion of the desired shape.

Support Removal Difficulty: Many overhang areas formed blobs or drooping, particularly in hollow portions, as a result of inadequate slicer optimisation and excessive usage of thick supports. Manually removing the supports caused surface scarring and sporadic thin-walled section breaking.

Only a basic prototype was produced utilising college resources due to these problems. We chose to contract with a specialised 3D printing vendor to handle the fabrication of crucial assemblies that required high dimensional accuracy, strength, and smooth motion.

3.7.2 Outsourced Printing and Improvements

The external service provider used an industrial-grade FDM printer with dual extrusion capability, allowing for better control of support materials, print resolution (100 microns), and temperature regulation. Key benefits included:

High Dimensional Precision: Tolerances improved to within ±0.2 mm, enabling interference fits and snug placements of electronics within housings.

Superior Surface Finish: The prints were visibly smoother, reducing drag and eliminating the need for extensive post-processing. Parts like the fin links and motor mounts functioned more reliably in oscillatory motion.

Waterproof Compatibility: The external vendor printed parts using PETG and ASA, which offer superior resistance to water absorption, enabling better sealing during underwater testing.

3.7.3 Waterproofing Techniques

Ensuring watertight integrity in the propulsion system was crucial. We employed the following techniques:

O-Ring Channels: CAD modifications added grooves for rubber O-rings around shaft outputs and access ports. These were sealed using silicone-based grease to prevent micro-leakage.

Epoxy Encapsulation: All motor terminals and PCB joints were potted with marine-grade epoxy to prevent corrosion and short circuits.

Conformal Coating: Sensitive electronics, including the Arduino Uno and motor driver, were sprayed with acrylic conformal coating to resist humidity and condensation.

Threaded Seals and Gaskets: Enclosures were designed with integrated screw threads and flat sealing surfaces where custom rubber gaskets were added. This allowed for easy disassembly and reassembly during testing without compromising waterproofing.

3.7.4 Dimensional Tolerances for Assembly

Challenge: Inaccuracies in printed part dimensions can make it hard to assemble tight-fitting components like motor mounts, bearings, or seals.

Solution:

- Design with tolerances in mind (+/-0.2 mm or as per printer specs).
- Post-process with CNC machining or sanding for precision fits.
- Use threaded inserts or bushings rather than relying on printed threads.

3.7.5 Strength and Pressure Resistance

Challenge: Layered construction leads to anisotropic strength — weak points between layers can fail under hydrostatic pressure, especially at depth.

Solution:

- Orient parts in the printer to minimize stress across layers.
- Use higher infill percentages (≥80%) or solid parts for structural elements.
- Post-process critical parts with annealing or composite reinforcement (e.g., carbon-fibre infused filament).

3.7.6 Warping and Print Failures on Larger Parts

Challenge: Larger body parts tend to warp or delaminate, especially with high-temperature materials like ABS.

Solution:

- Use heated enclosures, bed adhesives, and brim/raft settings.
- Print in sections and assemble using adhesives or interlocking joints.

3.8 Calculations

3.8.1 Torque Required

Designing an effective propulsion system for an underwater drone requires careful application of fluid dynamics and mechanical engineering principles. The following theoretical foundations were used to estimate key parameters such as thrust, torque, buoyancy, and drag.

Thrust Generation and Tail Dynamics

In a biomimetic propulsion system, thrust is generated by oscillatory motion of a fin or tail that displaces water in a rhythmic pattern. The tail's motion mimics aquatic life such as fish, where lateral displacement creates reaction forces from the surrounding fluid. The generated thrust depends on the velocity of tail movement, the surface area interacting with water, and the resistance of water (drag).

Total Area of Tail, A = 6134.6 x 10^-6 m^2

Let Dynamic Pressure = q

Density of water, rho = 1000 kg/m^3

Velocity of tail's COM = v

Coefficient of Drag, Cd = 0.5

(From Cd vs Re graph at this Reynolds Number)

Distance from tail joint to COM of Tail,

L = 55.54 mm (approx. = 56 mm)

Frequency of Tail, f = 5 Hz

The velocity v of the tail tip can be modeled as a simple harmonic motion, with the formula:

$v = 2 \times \pi \times f \times L$

$v = 2 \times \pi \times 5 \times 56 \times 10^{-3}$

v = 1.759 m/s (Approx, v = 1.76 m/s)

Where:
f is the frequency of oscillation (in Hz)
L is the distance from the joint to the tail's center of mass

This velocity determines the dynamic pressure experienced by the surface, given by Bernoulli's principle:

$q = 0.5 \times rho \times v^2$

$q = 0.5 \times 1000 \times 1.76^2$

q = 1548.8 pascal

Where:
rho is the density of water (~1000 kg/m^3).
The drag force exerted on the tail can be calculated using:

Force F:

F = 0.5 x rho x v^2 x A x Cd

F = q x A x Cd

F = 1548.8 x 6134.6 x 10^-6 x 0.5

F = 4.75 N

Where:

Cd is the drag coefficient depends on the shape and the Reynolds number
A is the tail projected surface area

q is the dynamic pressure

This force represents the effective thrust that the tail can produce per cycle of oscillation. The torque required to drive the tail from the actuator is obtained by:

Torque T:

T = F x L

T = 4.75 x 56 x 10^-3

T = 0.266 N-m

This torque helps determine motor selection, gear ratios, and structural loading at joints.

3.8.2 Estimated Weight of Model

Mass of Front body = 59 gram

Mass of Tail link = 37 gram

Mass of Disc joining Fish Body and Tail = 29 gram

Mass of Motor = 256 gram

Miscellaneous Mass = 17 gram

Total Mass of Fish Model = 400 gram.

3.8.3 Estimated Buoyancy Force

Buoyancy is a critical factor in underwater drones, as it determines whether the system will float, sink, or hover neutrally. The principle of buoyancy is governed by Archimedes' law, which states:

"Any object submerged in a fluid experience an upward force equal to the weight of the fluid displaced."

For a body with volume V submerged in water, the buoyant force is given by:

$$Fb = rho * V * g$$

Where:

V is the displaced volume (approximated as a half-ellipsoid in this design)

g is gravitational acceleration (~9.81 m/s^2)

In this project, the drone's body shape was approximated as a half-ellipsoid. The volume V of a full ellipsoid is:

$$V = \frac{4 * \pi * a * b^2}{3}$$

Where:

a and b are the semi-major and semi-minor axes, respectively. Halving this gives the actual submerged volume of the drone. When compared to the drone's weight, this buoyant force determines stability, flotation, and vertical maneuvering capabilities

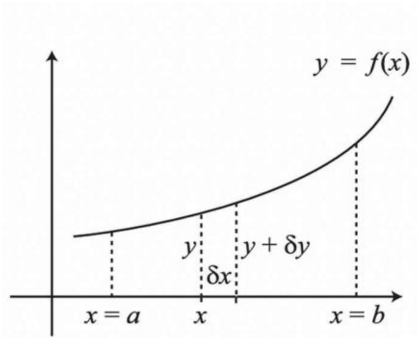


Figure 33: Force Calculation [19]

If we rotate a curve y about x-axis, we will get a closed shape which will have some volume. Figure [20] represents the buoyancy force calculation, illustrating the function y=f(x) with incremental changes in x and y. Now if we take a cross-section of the solid, parallel to the y-axis, this cross-section will be a circle. But rather than take a cross-section, let us take a thin disc of thickness δx, with the face of the disc nearest the y-axis at a distance x from the origin. The radius of this circular face will then be y.

The radius of the other circular face will be y +δy, where δy is the change in y caused by the small positive increase in x, δx. The disc is not a cylinder, but it is very close to one. It will become even closer to one as δx, and hence δy, tends to zero. Thus, we approximate the disc with a cylinder of thickness, or height, δx, and radius y. The volume δV of the disc is then given by the volume of a cylinder, $\pi\, r$ h, so that

δV = $\pi\, y$ δx V= $\int \pi\, y$ δx.

Equation of ellipse:

$(\frac{x}{a}) + \frac{y}{b} = 1$ substituting $y = b\,(1 - (\frac{x}{a}))$,

we get V = $\int \pi\, b\,(1 - (\frac{x}{a}))\,\delta x$

Integrating from -a to a we get,

V = (4/3) πa b

Semi major axis = 270 mm = 0.27 m

Semi minor axis = 84 mm = 0.084 m

V = 0.095001761 m

Volume of our fish model = V/2 = 0.047500880 m

Buoyancy mass = rho x V/2

Buoyancy mass = 1000 x 0.047500880

Buoyancy mass = 475 gram

By summing all resistive forces acting on the drone—including drag, gravitational pull in negative buoyancy conditions, and thrust misalignments—engineers calculated the minimum required thrust. This was then matched with the thrust curves of selected propeller-motor combinations obtained from test data or manufacturer datasheets. The system was tuned to provide a thrust-to-drag ratio greater than 1.2, allowing effective maneuverability while maintaining control authority under loaded and unloaded conditions.

These calculations formed the foundation for tailoring the propulsion system to operate efficiently under underwater constraints. By balancing power output, hydrodynamic performance, and mechanical stability, the final design achieved reliable navigation, energy-efficient movement, and structural resilience in varied aquatic environments. The theoretical groundwork ensured that experimental iterations were minimized, saving time and resources in the development cycle.

3.9 Limitation

During the development and prototyping of our underwater drone, we faced multiple technical and mechanical issues that significantly affected the performance of the model. The initial design included a tail mechanism composed of linked segments connected through a helical spring, with motion driven by a motor and shaft system. This setup was aimed at producing oscillatory motion, imitating fish-like swimming. However, the model failed to generate sufficient motion or amplitude. The primary issues included poor transmission of movement through the links, which resulted in irregular and limited tail motion. The spring also did not function as intended—either due to improper preload, misalignment, or inadequate flexibility—causing energy loss instead of aiding motion. Furthermore, the 3D-printed components suffered from dimensional inaccuracies, which affected the assembly and introduced friction and instability in the moving parts.

To overcome these challenges, we redesigned the model with a simplified yet more effective mechanism. The new design features a gear and shaft system to replace the problematic links and spring. This modification allows better torque transmission from the motor to the tail section, ensuring controlled and repeatable oscillations. The gear mechanism improves mechanical coupling, reduces backlash, and provides higher amplitude motion, enhancing the overall efficiency and performance of the underwater drone. This iteration lays a stronger foundation for future improvements and testing.

Chapter-4: Results and Discussions

4.1 Prototype Development

The prototype development phase marked the first tangible realization of the drone's design. This involved transitioning from CAD models into a functioning physical system, with a strong focus on testing the biomimetic propulsion concept. The initial prototype consisted of the 3D printed body and tail assembly, powered by a stepper motor-driven linkage system. The CAD models were designed in Fusion 360 and printed using college lab facilities. Key components integrated at this stage included:

IMU (Inertial Measurement Unit) for orientation tracking
Pressure sensors for depth measurement
NEMA 17 stepper motor for tail actuation
Arduino Uno microcontroller for control logic
The prototype was assembled and submerged in a controlled water tank to observe initial performance parameters like thrust response, oscillation stability, and sealing integrity. However, several challenges were observed:

- Irregular tail motion due to backlash in spring-based transmission
- Limited tail amplitude and frequency response
- Surface imperfections in 3D-printed links caused unwanted friction

Despite these issues, the prototype successfully demonstrated neutral buoyancy and basic actuation, validating the core concept. The system provided critical learning for improving torque transmission and mechanical stability.

SLA vs PLA in Prototype Development for Underwater Drone

In the prototype development phase of the underwater drone, both PLA-based FDM (Fused Deposition Modeling) and SLA (Stereolithography) 3D printing technologies were considered based on their material properties, print quality, and suitability for underwater applications. PLA, being affordable and easy to print, was initially used for rapid prototyping of large structural components. However, its porous nature and limited mechanical strength made it less suitable for water-sealed or pressure-bearing parts. Additional post-processing, such as epoxy coating or resin infiltration, was necessary to improve its waterproofing. In contrast, SLA printing offered superior dimensional accuracy and smooth surface finishes, making it ideal for components requiring tight tolerances, such as sensor housings, sealing interfaces, and electronic enclosures. SLA parts, especially when printed with tough or engineering-grade resins, demonstrated better water resistance and precision, although they were more expensive and required longer post-processing steps, including alcohol rinsing and UV curing. Ultimately, a hybrid approach was adopted—FDM with PLA was used for larger, non-critical structural elements, while SLA was preferred for detailed, watertight, and high-precision components critical to the drone's underwater performance.

SLA was preferred in our project as that gave us the desired output

4.2 Product Development

Following the discovery of the prototype's flaws, the following phase concentrated on improving the software and hardware subsystems. Durability, modularity, and environmental protection were prioritised. Among the main improvements were:

- IP68-rated waterproof enclosure redesign including twin O-ring shaft seals and integrated gaskets
- The spring-link assembly was replaced by a gear-based tail mechanism, which increased accuracy and decreased slippage.

With the help of the TB6600 motor driver for the stepper motor, the Arduino platform was used to construct the embedded control logic. For tail oscillation, the system was set up to run in a looping control pattern. An extra battery module and an emergency manual override mechanism were included for safety testing.

4.3 Optimisation

To enhance the propulsion system's performance and operational efficiency, several optimization techniques were applied:

Mechanical Optimization:

- CAD redesigns introduced streamlined curves and blended transitions to reduce hydrodynamic drag.
- Gear ratio optimization allowed higher tail amplitude with lower input torque.
- Weight distribution adjustments ensured the center of gravity aligned with the center of buoyancy, improving underwater stability.

Software Optimization:

- PID control algorithms were tuned in MATLAB/Simulink to achieve smooth motion transitions.

- Oscillation frequency, tail angle, and motor pulse timing were optimized to maximize thrust with minimum power.
- Efficient PWM tuning minimized heat buildup and reduced current spikes.

Energy Efficiency:

- Low-RPM high-torque motor control modes were adopted for energy conservation.
- Load balancing ensured minimal idle power drain from sensor modules.
- Tail movement cycles were programmed with coasting phases to mimic fish gliding behavior, reducing active power draw.

4.4 Load Factor Analysis

Load factor analysis played a fundamental role in verifying the structural robustness and dynamic stability of the underwater drone across a range of mission profiles. Given the complex and variable conditions of the underwater environment—such as flow turbulence, varying depth pressures, and manoeuvring loads—understanding how the structure responded to external forces was essential for reliable and safe operation.

The analysis began by identifying and quantifying all primary force components acting on the vehicle during static and dynamic states. These included:

Buoyant Force (F_b):

Calculated using Archimedes' Principle:

$$F_b = rho * Vdisplaced * g$$

where

rho is the density of water, Vdisplaced is the volume of water displaced by the drone, and g is the gravitational acceleration.

The design targeted neutral to slightly positive buoyancy to ensure energy-efficient hovering and controlled vertical movement.

Hydrodynamic Drag (F_d):

Evaluated using the equation:

$$F_d = 0.5 * Cd * A * v$$

where Cd is the drag coefficient (derived from CFD simulations),

A is the projected frontal area, and v is the velocity.

Drag forces were mapped over a range of forward and lateral velocities to determine propulsion power requirements and structural reinforcement needs.

Thrust Forces and Reactive Moments:

The propulsion system introduced forces along multiple axes depending on motor orientation (typically in an X or T configuration). Each motor produced a thrust vector and an associated reaction torque, both of which were integrated into the load model to assess torsional and bending stresses on the frame. Unbalanced thrust due to differential motor speeds was analysed for its effect on yaw and pitch stability.

Load Factors (n):

Dynamic load factors were estimated from manoeuvring conditions using:

$$n = \frac{anet}{g}$$

where anet is the net acceleration experienced during sharp turns, dives, or payload shifts. Peak load factors typically ranged between 1.2–1.6g during aggressive manoeuvres, which informed the safety margins for structural design.

Stress contours, von Mises stress plots, and deformation vectors helped identify high-stress concentration zones, particularly around motor mounts, joint interfaces, and payload attachment points. Based on these insights, reinforcement ribs, fillets, and higher strength materials (such as carbon-fibre reinforced composites) were introduced in critical regions. Additionally, ballast placement was fine-tuned using centre of mass and centre of buoyancy calculations to maintain stability and control authority under loaded conditions.[19]

By incorporating both simulation-based predictions and empirical data from test dives, the load factor analysis enabled a well-informed, robust structural design. It ensured that the drone could withstand both normal operational loads and unplanned dynamic events—such as current disturbances or sharp course corrections—without mechanical failure or control instability.

References

[1] L. Meng, T. Hirayama, and S. Oyanagi, "Underwater-Drone With Panoramic Camera for Automatic Fish Recognition Based on Deep Learning," *IEEE Access*, vol. PP, p. 1, Nov. 2018, doi: 10.1109/ACCESS.2018.2820326.

[2] S. C. van den Berg, R. B. N. Scharff, Z. Rusák, and J. Wu, "OpenFish: Biomimetic design of a soft robotic fish for high speed locomotion," *HardwareX*, vol. 12, p. e00320, Oct. 2022, doi: 10.1016/J.OHX.2022.E00320.

[3] V. D, T. Asokan, and V. R, "Performance analysis of a caudal fin in open water and its coupled interaction with a biomimetic AUV," *Ocean Engineering*, vol. 291, p. 116348, Jan. 2024, doi: 10.1016/J.OCEANENG.2023.116348.

[4] L. Paulsen, "Underwater drone for marine ecosystem applications: An alternative propulsion and control system."

[5] M. A. M. Afifi, A. El-Sadek, and K. M. El-Haddad, "First record of skipjack tuna (Katsuwonus pelamis) from Dahab in the Gulf of Aqaba, Red Sea, Egypt ARTICLE INFO ABSTRACT," 2022. [Online]. Available: www.ejabf.journals.ekb.eg

[6] A. Miller, B. Miller, and G. Miller, "Navigation of Underwater Drones and Integration of Acoustic Sensing with Onboard Inertial Navigation System," *Drones*, vol. 5, no. 3, 2021, doi: 10.3390/drones5030083.

[7] A. Naddi and A. Mazlan, "A Fully Actuated Tail Propulsion System for a Biomimetic Autonomous Underwater Vehicle," 2015.

[8] A. Lambertini *et al.*, "Underwater Drone Architecture for Marine Digital Twin: Lessons Learned from SUSHI DROP Project," *Sensors*, vol. 22, no. 3, 2022, doi: 10.3390/s22030744.

[9] A. Nishitani, R. Kawada, and J. Kojima, "Development of combined aerial and underwater drone system," in *OCEANS 2022, Hampton Roads*, 2022, pp. 1–5. doi: 10.1109/OCEANS47191.2022.9977370.

[10] J. Žaglinskis and E. Noreikaitė, "The Application of an Underwater Robot for the Creation of a Database for the Technical Inspection of the Underwater Components of Water Transport and Infrastructure," *Applied Scientific Research*, vol. 3, pp. 182–196, Apr. 2024, doi: 10.56131/tmt.2024.3.1.259.

[11] E. Diamanti, Ø. Ødegård, V. Mentogiannis, and G. Koutsouflakis, "Underwater Drones as a Low-Cost, yet Powerful Tool for Underwater Archaeological Mapping: Case Studies from the Mediterranean," *Journal of Computer Applications in Archaeology*, vol. 8, Apr. 2025, doi: 10.5334/jcaa.184.

[12] "FISH TANK".

[13] Y. Luo, Q. Xiao, G. Shi, G. Pan, and D. Chen, "The effect of variable stiffness of tuna-

like fish body and fin on swimming performance," *Bioinspir Biomim*, vol. 16, no. 1, Jan. 2021, doi: 10.1088/1748-3190/abb3b6.

[14] A. Kumar *et al.*, "Blockchain for unmanned underwater drones: Research issues, challenges, trends and future directions," *Journal of Network and Computer Applications*, vol. 215, p. 103649, Jun. 2023, doi: 10.1016/J.JNCA.2023.103649.

[15] V. D, T. Asokan, and V. R, "Performance analysis of a caudal fin in open water and its coupled interaction with a biomimetic AUV," *Ocean Engineering*, vol. 291, Jan. 2024, doi: 10.1016/j.oceaneng.2023.116348.

[16] L. Meng, T. Hirayama, and S. Oyanagi, "Underwater-Drone With Panoramic Camera for Automatic Fish Recognition Based on Deep Learning," *IEEE Access*, vol. PP, p. 1, Apr. 2018, doi: 10.1109/ACCESS.2018.2820326.

[17] T. Kodama, K. Tanaka, K. Kuwahara, A. Kariya, and S. Hayashida, "Depth-Adaptive Air and Underwater Invisible Light Communication System with Aerial Reflection Repeater Assistance," *Information*, vol. 16, p. 19, Apr. 2025, doi: 10.3390/info16010019.

[18] "Volumes of solids of revolution." [Online]. Available: www.mathcentre.ac.uk

[19] S. Kumar, R. Lal, A. Ali, N. Rollings, U. Mehta, and A. Mansour, "A Real-Time Fish Recognition Using Deep Learning Algorithms for Low-Quality Images on an Underwater Drone," 2024, pp. 67–79. doi: 10.1007/978-981-97-0327-2_6.

APPENDIX I- MATLAB CODES

1. CODE FOR SAME SIDE MOTION

The following is the code that runs this in the backend.

```
// Define stepper motor connections and steps per revolution:
#define dirPin 2
#define stepPin 3
#define stepsPerRevolution 1600

void setup() {
  // Declare pins as output:
  pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);
}

void loop() {
  // Set the spinning direction clockwise:
  digitalWrite(dirPin, HIGH);

  // Spin the stepper motor 1 revolution slowly:
  for (int i=0; i < stepsPerRevolution; i++) {
    // These four lines result in 1 step:
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(2000);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(2000);
  }

  delay(1000);

  // Set the spinning direction counterclockwise:

digitalWrite(dirPin, LOW);

  // Spin the stepper motor 1 revolution quickly:
  for (int i=0; i < stepsPerRevolution; i++) {
    // These four lines result in 1 step:
    digitalWrite(stepPin, HIGH);

 delayMicroseconds(1000);
```

```
    digitalWrite(stepPin, LOW);
    delayMicroseconds(1000);
  }

  delay(1000);

  // Set the spinning direction clockwise:
  digitalWrite(dirPin, HIGH);

  // Spin the stepper motor 5 revolutions fast:
  for (int i=0; i < 5 * stepsPerRevolution; i++) {
    // These four lines result in 1 step:
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(500);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(500);

delay(1000);

  // Set the spinning direction counterclockwise:
  digitalWrite(dirPin, LOW);

  // Spin the stepper motor 5 revolutions fast:
  for (int i=0; i < 5 * stepsPerRevolution; i++) {
    // These four lines result in 1 step:
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(500);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(500);

  delay(1000);
}
```

2. CODE FOR OSCILLATORY MOTION

```
// Define stepper motor connections and steps per revolution:
#define dirPin 2
#define stepPin 3
#define stepsPerRevolution 800

// Calculate steps for 120 degrees
```

```
#define stepsPer120Degrees (stepsPerRevolution / 3)  // 800 / 3 ≈ 266.67

void setup() {
  // Declare pins as output:
  pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);
}

void loop() {
  // Rotate 120 degrees clockwise
  digitalWrite(dirPin, HIGH);
  for (int i = 0; i < stepsPer120Degrees; i++) {
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(400);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(400);
  }

  delay(500);

  // Rotate 120 degrees counterclockwise
  digitalWrite(dirPin, LOW);
  for (int i = 0; i < stepsPer120Degrees; i++) {
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(400);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(400);
  }

  delay(500);
}
```