Bangladesh University of Engineering & Technology (BUET)

Department of Mechanical Engineering

ME366: Electro-Mechanical System Design and Practice

Project Report: BactoBot

A Low-Cost, Bacteria-Inspired Soft Underwater Robot for Marine Exploration

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Abstract

Traditional rigid underwater vehicles pose risks to delicate marine ecosystems, such as coral reefs, due to their inflexible structures and high-speed propellers. This project, "BactoBot," addresses this challenge by developing a soft underwater robot designed for safe and gentle marine exploration. Inspired by the highly efficient flagellar propulsion of bacteria, BactoBot features 12 flexible, silicone-based arms arranged on a dodecahedral frame. This design provides inherent compliance, redundancy against single-point failures, and the potential for omnidirectional movement. Utilizing readily available components, 3D printing, and accessible microcontrollers, we successfully designed, fabricated, and tested a low-cost prototype capable of basic underwater navigation, including forward motion and turning, in a controlled environment. The project demonstrates the feasibility of replicating complex biological locomotion principles using DIY methods, paving the way for more affordable and environmentally-conscious robotic tools for marine science.

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1. Introduction

1.1 The Challenge of Underwater Exploration

The world's oceans are vast ecosystems teeming with life, much of which remains unexplored. Exploring delicate environments like coral reefs, underwater caves, and cluttered seabeds presents a significant challenge for robotics. Conventional Remotely Operated Vehicles (ROVs) are often rigid and powered by fast-spinning propellers, which can inadvertently damage fragile marine life and their habitats. The need for a safer, more adaptable, and accessible robotic platform is paramount for non-invasive marine research. The paradigm of soft robotics offers a compelling solution, enabling robots to interact with their environment in a safer, simpler, and more cost-effective manner.

1.2 Project Inspiration: Bacterial Flagella

This project draws its primary inspiration from one of nature's most efficient and unlikely swimmers: bacteria. The bacterial flagellum is the only known example of a true biological "wheel," a simple rotational motor that propels the organism. This project aims to replicate this unique locomotion strategy at a macro scale.

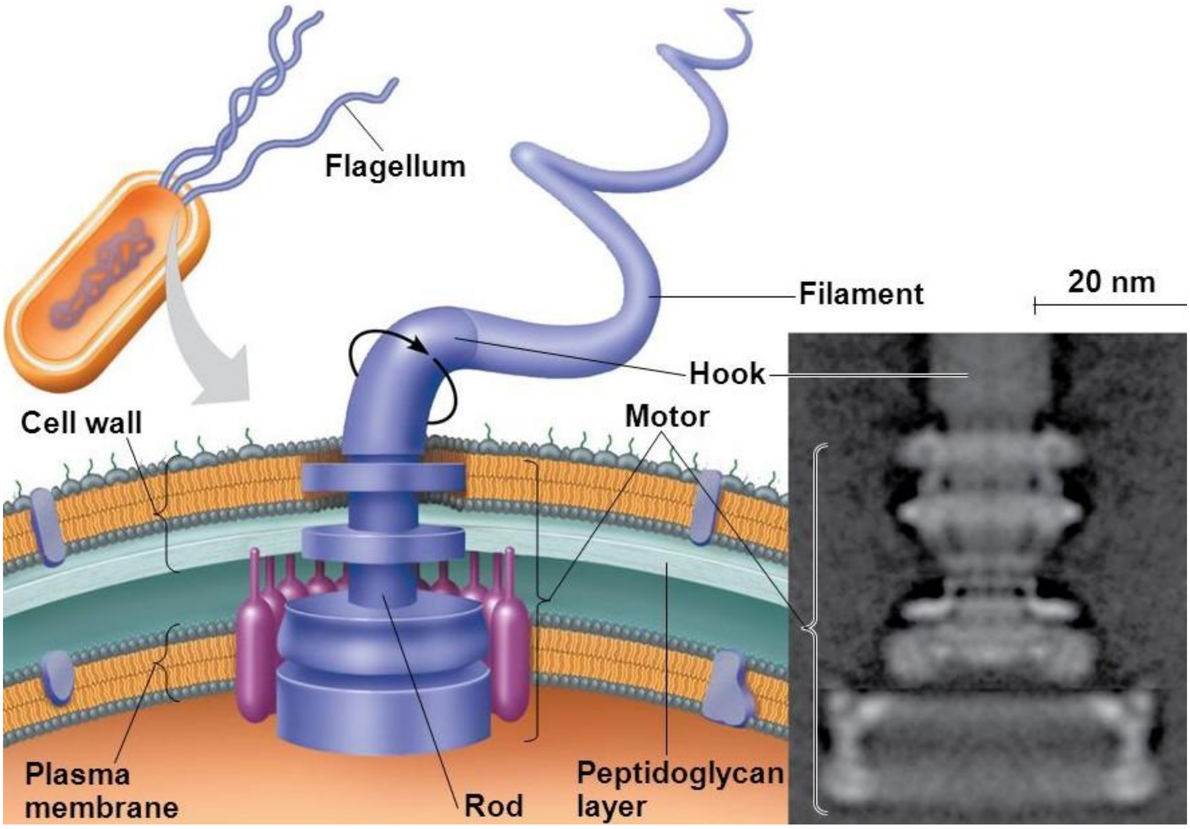


Figure 1: Structure of a Prokaryotic Flagellum, with motor, rigid hook and flexible filament.

1.3 Project Objectives

The primary goal of the BactoBot project was to design and build a budget-friendly, soft underwater robot based on the flagellar propulsion concept. Key objectives included:

- To design a redundant and robust mechanical structure using accessible materials.
- To replicate the passive deformation principle of flagellar propulsion.
- To implement a control system for basic underwater maneuvers (forward motion and turning).
- To overcome the practical engineering challenges of waterproofing and buoyancy on a limited budget.

2. Design and Fabrication

2.1 Mechanical Design

The mechanical structure of BactoBot was designed for robustness, redundancy, and ease of fabrication.

Body Frame: The core structure is a **dodecahedron** (a 12-faced shape) fabricated from 3D-printed PETG. This geometry was chosen because it allows for the symmetric placement of 12 arms, providing inherent design redundancy and the potential for omnidirectional movement.

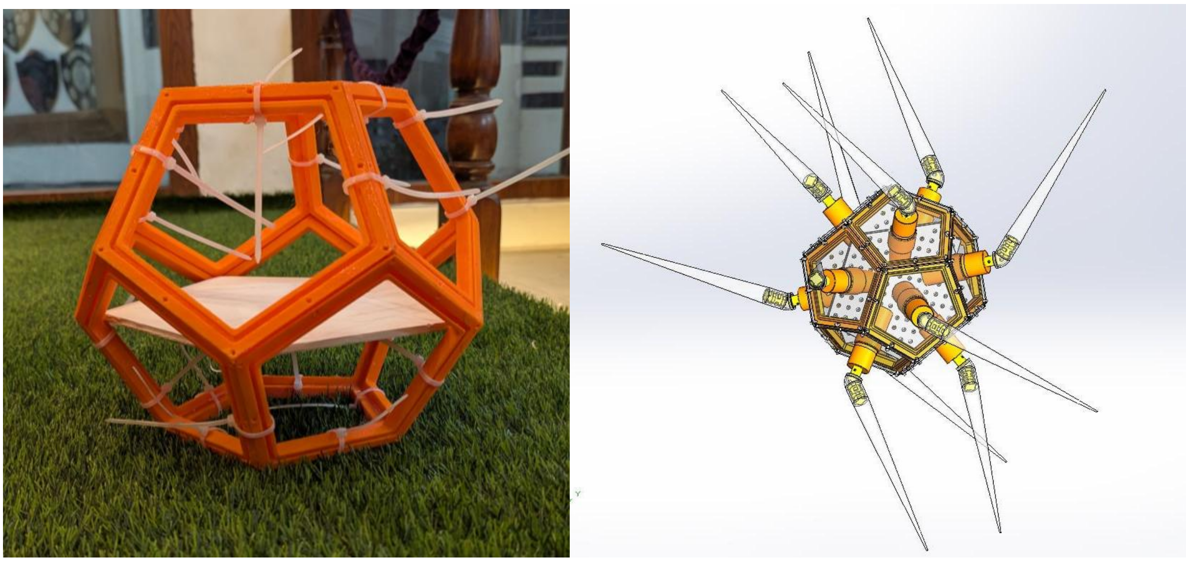


Figure 2: (Left) The 3D-printed dodecahedron frame. (Right) CAD model showing the full assembly.

Flagella: The 12 propulsive arms were molded from food-grade silicone rubber. This material makes the flagella highly flexible and safe for potential environmental interaction.

Each flagellum is designed as a straight, tapered arm that deforms passively into a propulsive shape in water.

Figure 3: (Left) Flagellum inside its mold. (Right) Flagellum with hook and motor shaft attached.

Waterproofing: Sealing the main body and 12 rotating motor shafts was a primary challenge. A multi-layered approach was used:

- Acrylic faceplates for each of the 12 faces.
- Specially designed, 3D-printed canisters to house the motors.
- O-rings to create a primary seal.
- Waterproof sealants (silicone, thread tape, grease) applied to all joints and potential points of ingress.

2.2 Electrical System and Actuation

The electrical system was designed with widely available and robust components suitable for a DIY project.

- **The Brain:** An **Arduino Mega 2560** serves as the central microcontroller, chosen for its large number of I/O pins and strong community support.
- **Actuation:** Propulsion is driven by **12 high-torque DC geared motors**, one for each flagellum.

- **Motor Control:** Each motor is controlled by a dedicated **BTS7960 high-current motor driver**, allowing for precise control of speed and direction.
- **Power:** The entire system is powered by a high-discharge **11.1V (3S) LiPo battery**.

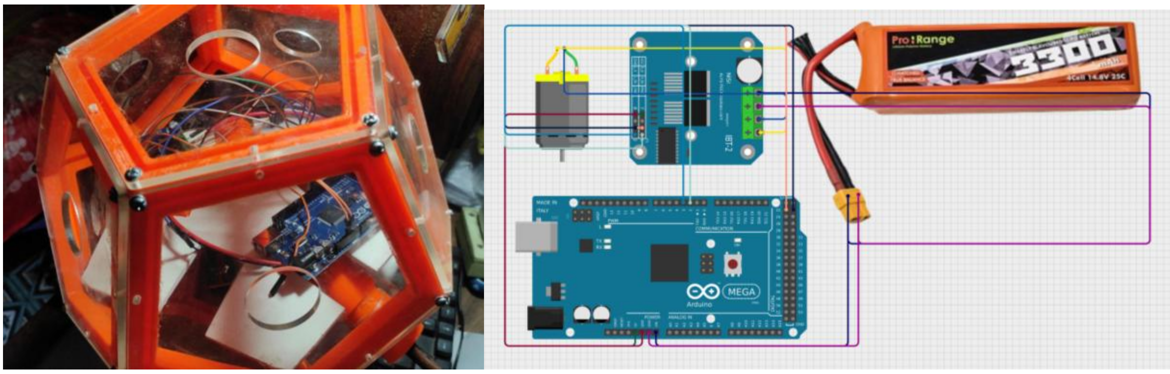


Figure 4: (Left) The assembled electronics inside the frame. (Right) The basic circuit diagram for a single motor.

3. Flagellar Locomotion Principle

3.1 Passive Deformation for Propulsion

Unlike a conventional propeller, BactoBot's locomotion is not based on a pre-formed rigid blade. Instead, it relies on the principle of passive deformation, a core concept in soft robotics.

1. A simple rotational torque is applied at the base of each straight, flexible arm by the DC motor.
2. As the arm rotates in the water, hydrodynamic forces cause it to bend and twist.
3. The arm passively deforms into a stable, helical (corkscrew) shape.
4. This rotating helical shape acts as a propeller, generating thrust by pushing against the water.

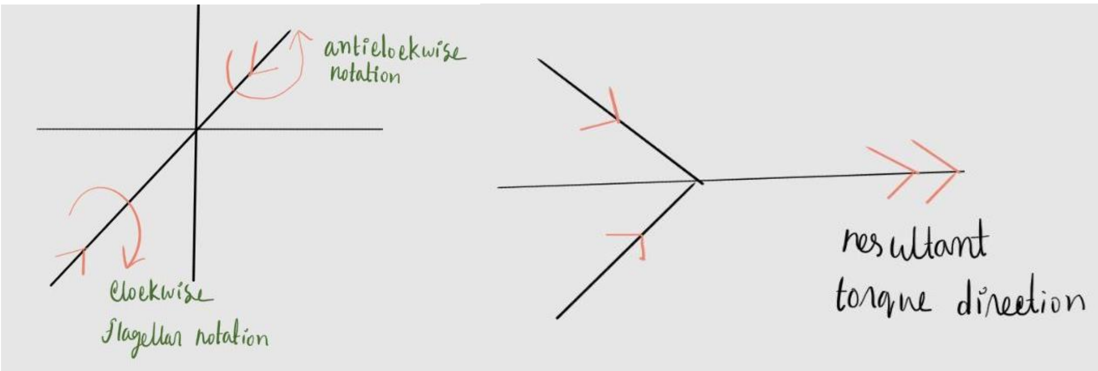
This method allows for complex propulsive motion to be generated from a very simple input (rotation), with the physics of the soft material and fluid interaction handling the complexity.

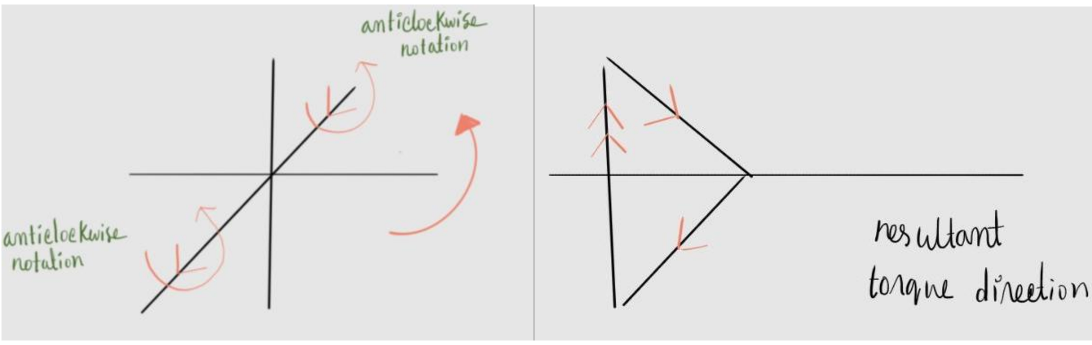
3.2 Control Strategy for Movement

By coordinating the rotation of the 12 arms, different maneuvers can be achieved. Our current implementation is open-loop.

- **Forward Motion:** To move in a straight line, opposing pairs of motors are activated. By rotating in directions that cancel out their rotational torques on the main body, a net thrust is generated, pushing the robot forward.

- **Turning Motion:** To turn, motors on one side are activated more strongly than on the other, or in a different combination. This creates an unbalanced torque, causing the robot to rotate around its central axis.





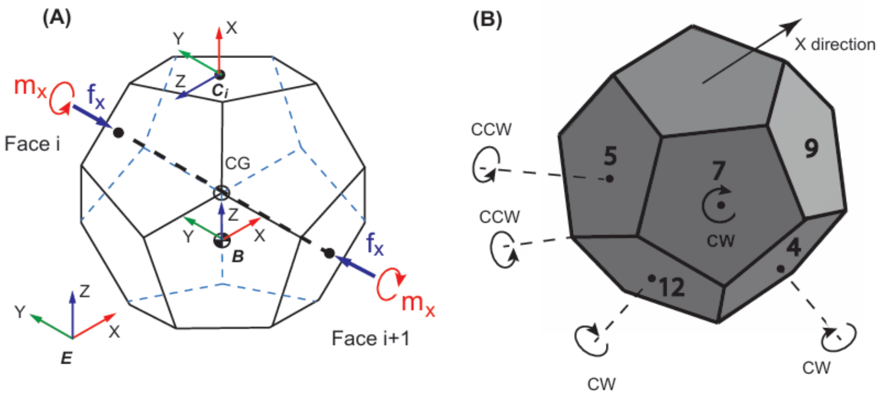


Figure 5: Diagrams illustrating how symmetrical actuation creates forward thrust (top) and asymmetrical actuation creates a turning torque (bottom). Inspired by the control scheme in [1].

4. Implementation and Testing

4.1 Key Engineering Challenges

- **Waterproofing:** Achieving a reliable, dynamic seal for 12 rotating shafts on a budget was our primary engineering challenge. Our strategy involved multiple layers of protection, from O-rings to liberal use of silicone sealant and poly-wrapping the entire robot during initial tests. This iterative process of sealing, testing, and re-sealing was critical to the project's success.
- **Buoyancy and Ballast:** Precisely balancing the robot to be neutrally buoyant was a tedious process of trial and error. Small ballast weights had to be carefully added and positioned inside the frame to counteract the weight of the components and achieve a stable orientation in the water.

4.2 Testing Environment and Results

BactoBot was successfully tested in a controlled tank environment. The tests validated the core design and functionality of the prototype.
The key results were:

1. **No Water Leaks:** The multi-layered waterproofing strategy proved effective during the testing period.
2. **Achieved Locomotion:** The robot successfully demonstrated both forward motion and turning maneuvers based on the open-loop commands sent to the motors.
3. **Stable Operation:** The robot maintained a stable orientation and depth during basic maneuvers, confirming the success of the buoyancy and ballast balancing.

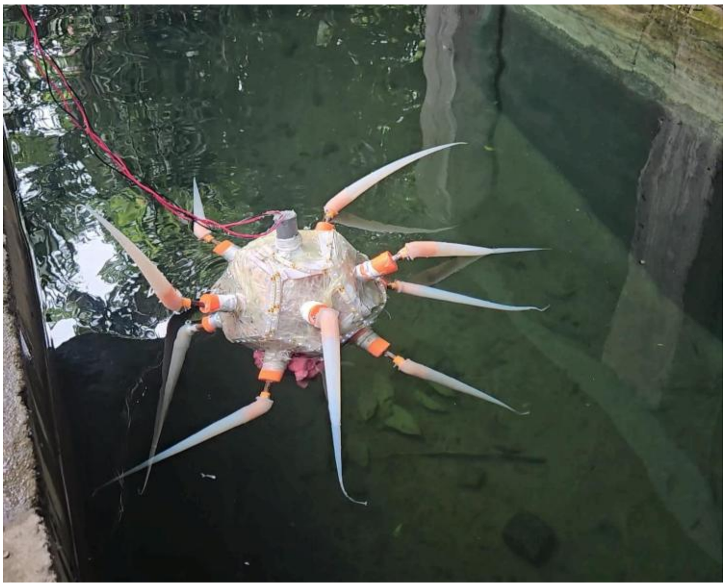


Figure 6: BactoBot submerged and operating in the test tank.

Watch here:
https://youtube.com/playlist?list=PLP1MpXDFlhkGGiaM0PEvsT2b7slWMGMUH&si=1uSfNwjm8kVEyjde

5. Conclusion and Future Work

5.1 Conclusion

This project successfully met its objectives to design, build, and test a low-cost, bacteria-inspired soft underwater robot. We proved that the advanced concept of flagellar propulsion can be replicated using accessible DIY methods and materials. BactoBot stands as a functional proof-of-concept, demonstrating a promising path towards creating safer, more affordable, and more accessible robots for the critical task of marine exploration.

5.2 Recommendations for Future Work

BactoBot provides a solid foundation for further development. Future work should focus on:

- **Implementing Closed-Loop Control:** Integrating an Inertial Measurement Unit (IMU) to provide feedback on the robot's orientation. This would allow for a closed-loop control system for precise navigation and station-keeping.
- **Enhanced Perception:** Integrating sensors like waterproof cameras to provide a visual feed, transforming the robot from a purely locomotive platform to a true exploration tool.
- **Improved Waterproofing and Durability:** Refining the mechanical design for more robust and long-term waterproofing to allow for deeper and more extended operation.
- **Autonomous Navigation:** Developing algorithms for autonomous navigation to allow the robot to perform exploration tasks with minimal human intervention.

6. Acknowledgements

We would like to express our sincere gratitude to our project supervisors—Dr. Kazi Arafat Rahman, Priom Das, Sadia Tasnim, and Md. Moyeenul Hossain Ratul—for their invaluable guidance, support, and encouragement throughout this project.

7. References

[1] Mathew, A. T., Feliu-Talegon, D., Abdullahi Adamu, Y., et al. (2025). "ZodiAq: An Isotropic Flagella-Inspired Soft Underwater Drone for Safe Marine Exploration." *Soft Robotics*. Published at: https://doi.org/10.1089/soro.2024.0036. (Preprint available at: https://arxiv.org/abs/2403.19556)