Bioinspired Fish Locomotion Through Variable Undulation

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Mechanical Engineering

24-775 Bio-Inspired Robot Design & Experimentation

Abstract

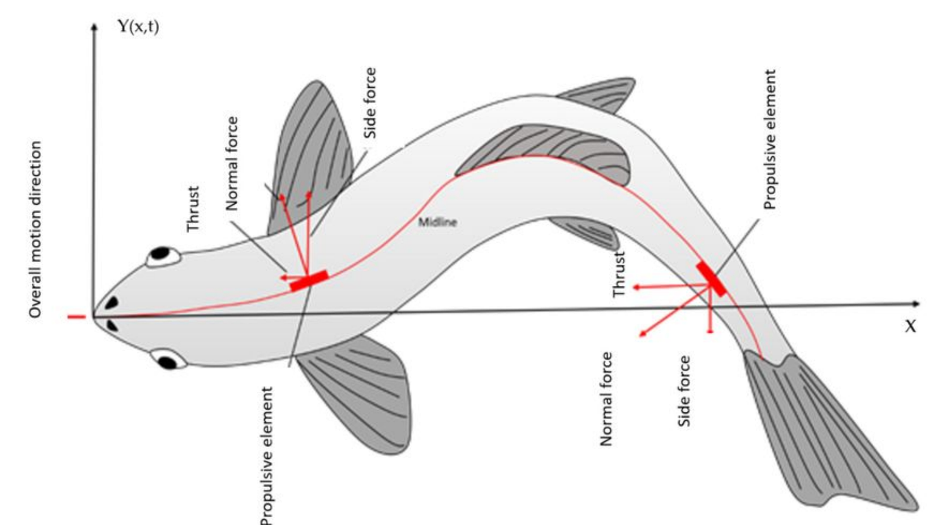
This research investigates the optimization of surface water robotic propulsion through a study of bio-inspired approaches to fishtail locomotion. We propose developing and evaluating multi-actuator system to understand the fundamentals of control complexity and propulsion efficiency. By systematically analyzing how different joint configurations, rigidity settings, and actuation methods affect thrust generation, we aim to bridge the gap between biological efficiency and robotic implementation. Our methodology includes comprehensive testing of designs under standardized conditions, measuring thrust generation, energy efficiency, and swimming pattern replication accuracy. The results will provide crucial insights for the development of more efficient robotic systems, with applications in marine exploration, environmental monitoring, and underwater infrastructure maintenance

Introduction

Currently, underwater robots lack the efficiency and maneuverability of aquatic creatures observed in nature, which would benefit defense and wildlife protection efforts that seek improved propulsion methods [1][2]. Inspired by fish, this project aims to develop a robot that locomotes using an undulating motion using an active tail design.

With this tail design, we seek to study how different swimming patterns affect the efficiency of swimming based on the time taken to travel a certain path. These swimming patterns are inspired from the different fish swimming patterns and depend on different regions of the tail being actuated as well as differing frequencies and amplitudes of oscillation.

Research Hypothesis: A high frequency, low amplitude tail motion will move the robot faster and in a more stable manner than a low frequency, high amplitude pattern.



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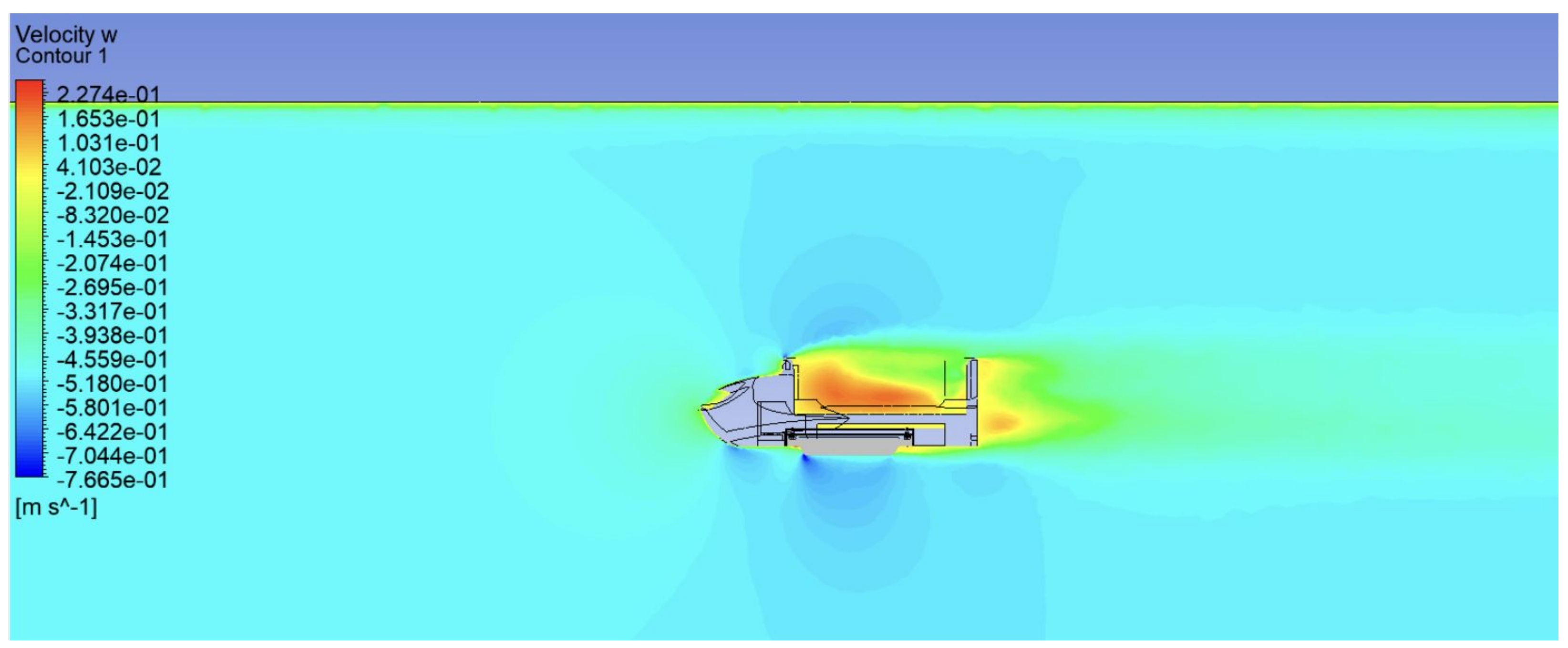
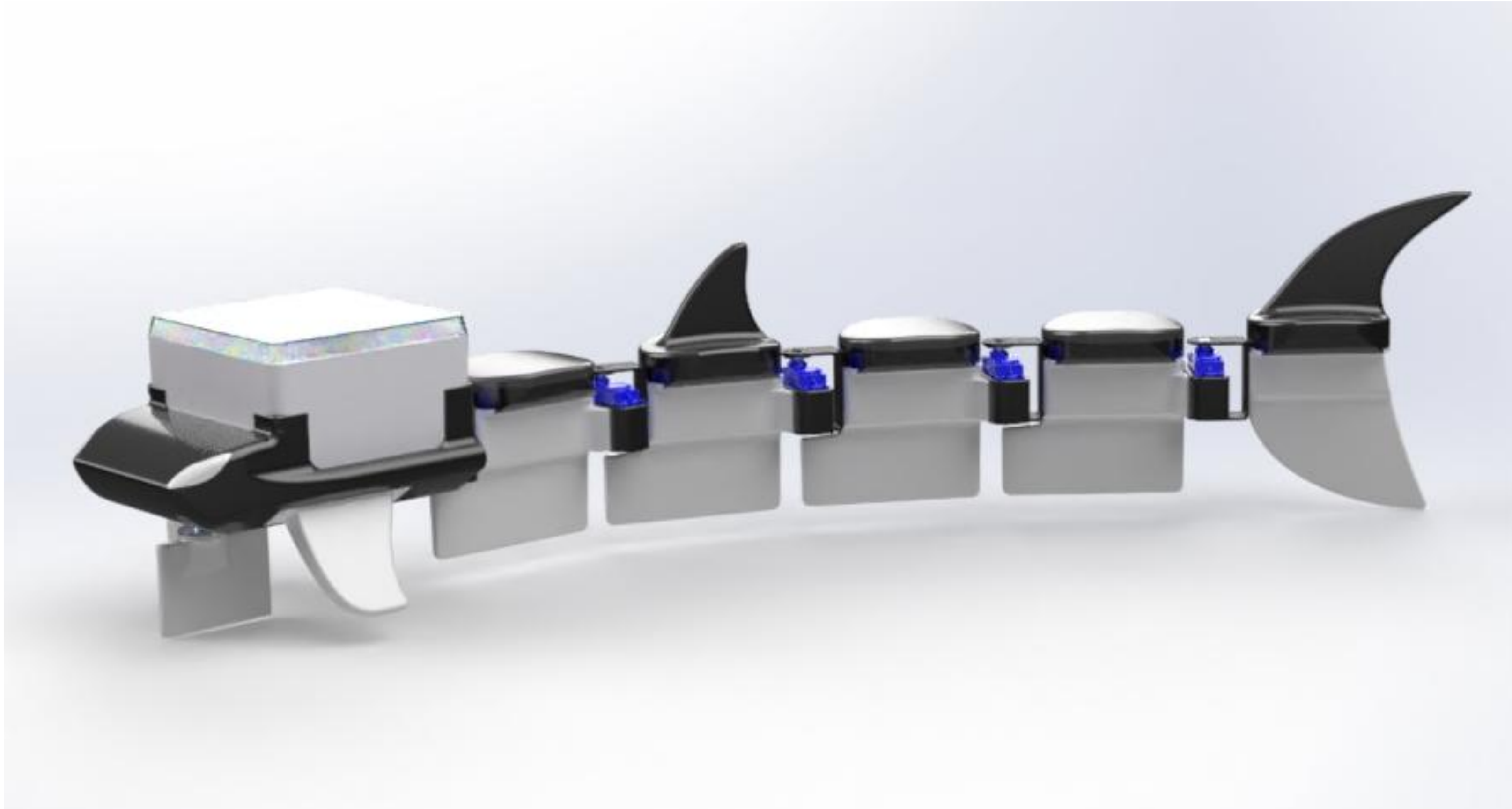
Methods



Design Optimization:

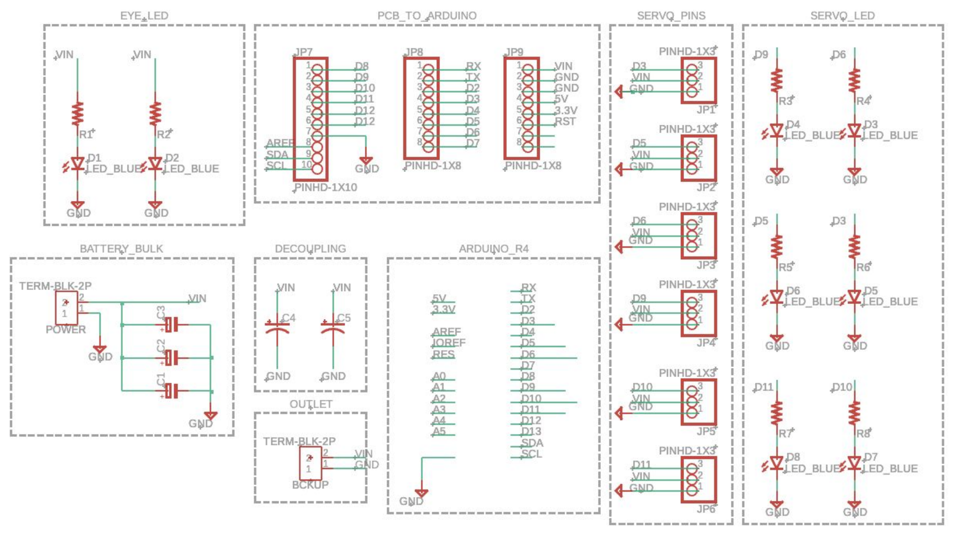
- Head design evaluated to optimize drag force as well as turbulent kinetic energy in the wake
- Components designed to optimize hydrodynamics and forward propulsion

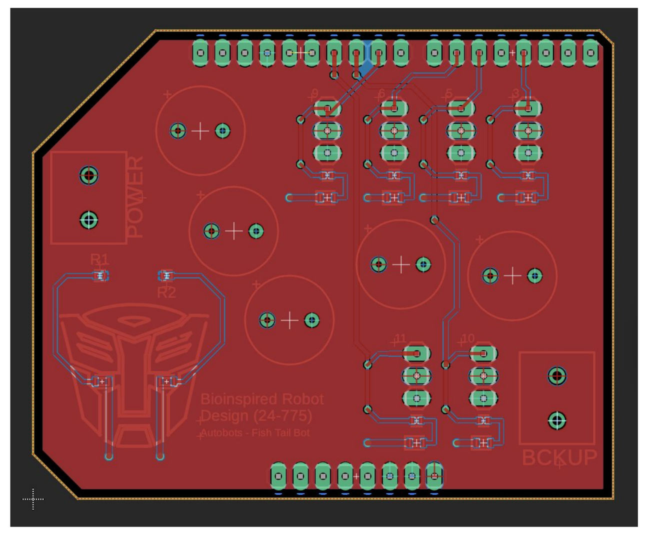
Methods



Design:

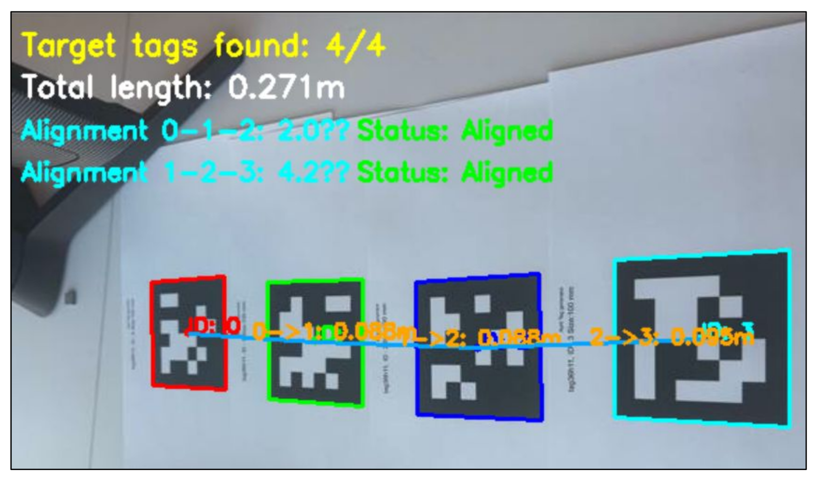
- **Head:** Streamlined hydrodynamic front with side fins for lateral fins for yaw rotation reduction. Snap fit raft design to hold the electronics enclosure above water
- **Body Joints:** Combination of horizontal buoy fins and vertical fins with maximized surface area for optimized thrust generation

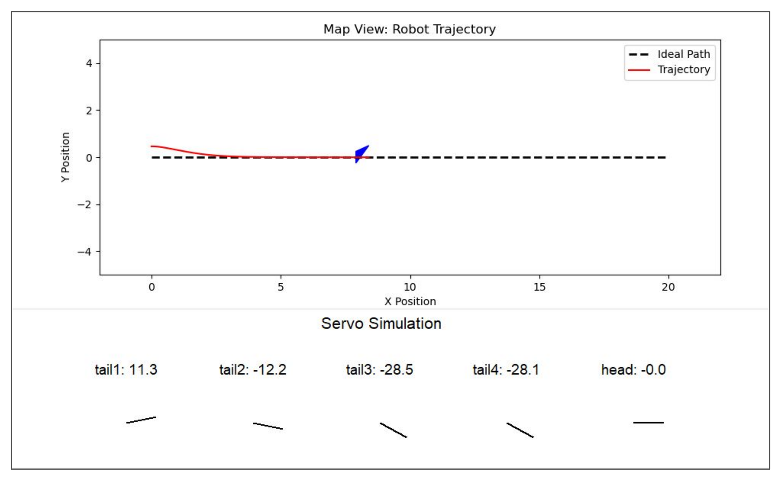




Electronics:

- **PCB**
  - Efficient power and space management
  - LEDs for debugging
- **Arduino Uno R4**
  - Servo motor control
- **Raspberry Pi**
  - Pose detection and joint angle calculation for PID control





- **Computer Vision**: Current pose estimation using AprilTags on the head, joints.
- **Controls**: PID controller that correct robot's state error by changing its speed and heading to achieve desired path.

Motion: The robot moves forward by moving its tail in sinusoidal wave motion. The motion can be modified by altering the frequency, amplitude, and phase shift parameters of the sine wave, affecting the robot's speed.

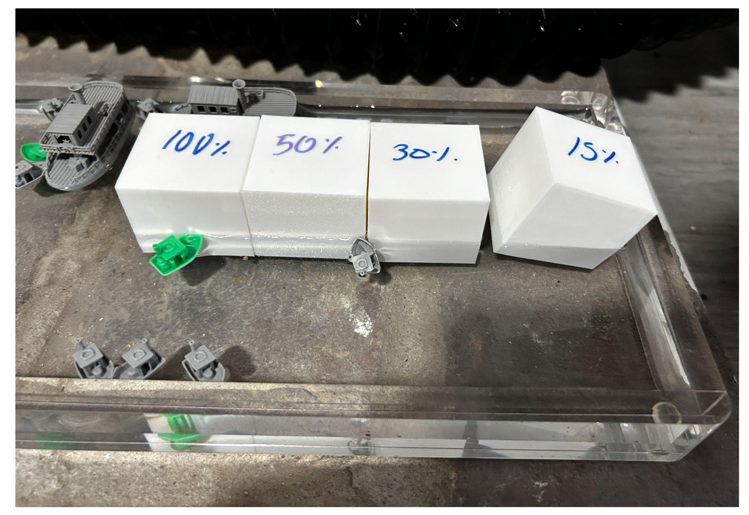
Results

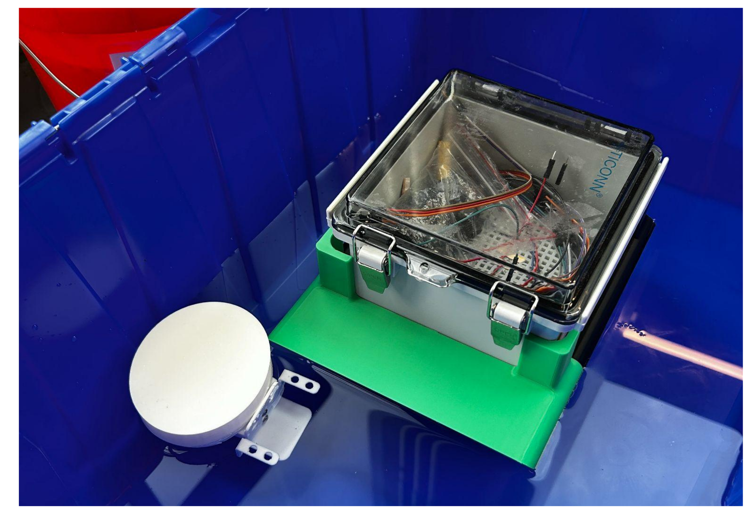
Our experimental validation demonstrates promising results across several key tests.

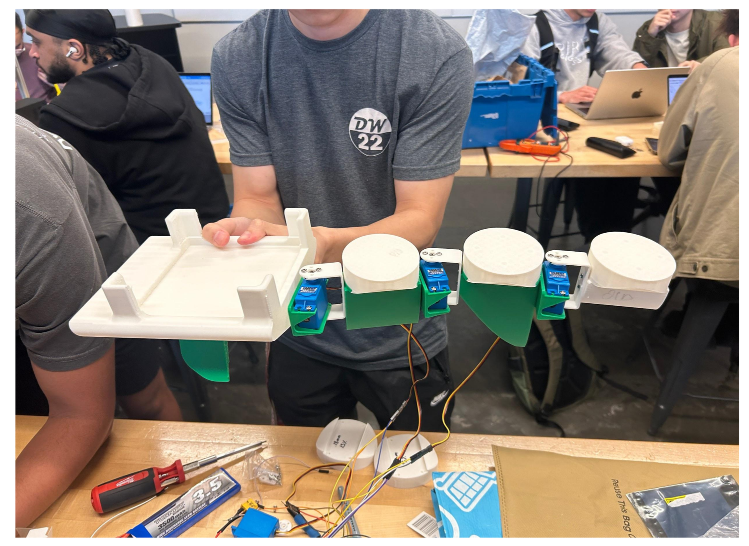
Float Tests: We successfully optimized buoyancy by adjusting 3D print infill percentages (from 20% to 15%) and strategically placing foam floats on the head, achieving neutral buoyancy with proper orientation.

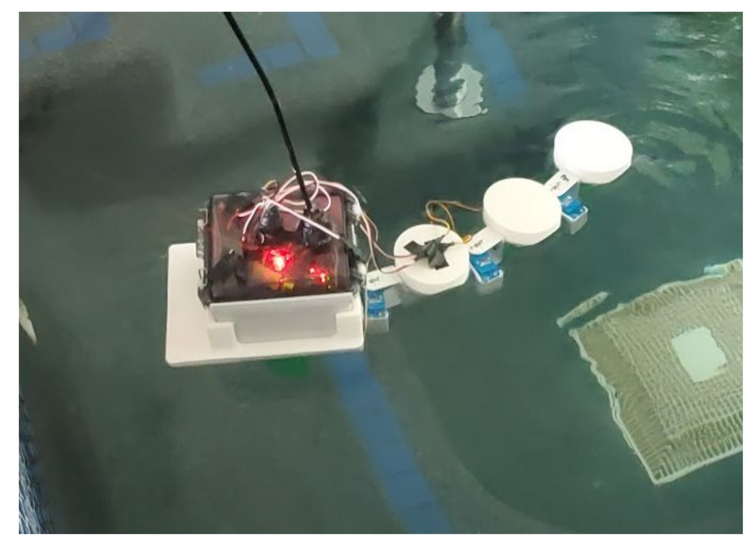
On-land Locomotion: Experiments with our articulated tail showed effective undulation patterns at 1Hz frequency and up to 20° amplitude, validating our joint design and controller algorithm.

Initial Swim Tests: revealed challenges - while the robot maintained buoyancy, forward propulsion was limited due to insufficient head mass relative to the tail, resulting in whole-body undulation rather than the desired concentrated tail movement. Unlike AgnathaX from EPFL, which uses force sensors to actively adjust to water conditions, our current design relies solely on visual feedback through AprilTag detection [4].









Discussion/Conclusions

At the time of writing, the robot has passed multiple tests including waterproofing, AprilTracking, land and water movement testing. Tests using variable amplitude, frequency, and phase shift parameters of the sinusoidal wave motion on the tails fins have been conducted; however, due to suboptimal weight distribution and design limitations, these tests showed no measurable propulsion. For the remainder of the semester, we plan to implement design modification, refine undulation parameters to yield measurable propulsion efficiency and enable responsive swimming behavior to address our research hypothesis.

References/Acknowledgements

References:

[1] "How To Protect Marine Animals From Boat Strikes," Clearwater Marine Aquarium, Jun. 30, 2017.

[2] "Submarine Detection and Monitoring: Open-Source Tools and Technologies," The Nuclear Threat Initiative, Mar. 02, 2021.

[3] Romano. Development of a Novel Underactuated Robotic Fish with Magnetic Transmission System, September 01, 2022.

[4] R. Thandiackal et al. "Emergence of robust self-organized undulatory swimming based on local hydrodynamic force sensing". Science Robotics, Aug. 11, 2021.

ChatGPT and Gemini were used when developing controllers and verifying circuit board design. Perplexity was used to troubleshoot servo Arduino code. Claude was used when tracking APRIL tags.