A Novel Underwater Biomimetic Propulsion System Derived from Zebrafish Neurological Analysis

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Background

Literature Review

Undulatory swimming, characterized by wave-like movements propagating along the body, is a prevalent mode of locomotion in aquatic organisms, including fish and marine mammals. This form of propulsion aalows aquatic organisms to navigate through water with **minimal energy expenditure** and maintain homeostasis. This is accomplished through the use of complex synaptic transmission pathways, which coordinate muscle contractions that generate the propulsive forces they need to swim. Previous studies have shown that the number of fired neurons is directly correlated to the current flow through these synaptic channels that are responsible for sending electrical signals for muscle movement. One such case study is the **Zebrafish**, a creature with highly specialized neurotransmitters along its spine to spur dorsal muscles and generate torque. Additionally, Zebrafish generate rheumatic swimming without sensory input due to central pattern generators in their brains. This makes them ideal to study for locomotion because outside stimuli will *not* pose a confounding effect on their movement. Because of these unique properties, Zebrafish ECG data can serve as a framework to optimize undulatory propulsion systems.

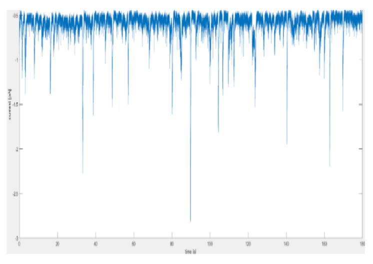

Figure 1: Sample Zebrafish ECG data

Figure 2: Picture of a Zebrafish Sourced from www.bcs.mit.edu

Scientists and engineers alike have determined that it is theoretically possible to design propulsion systems that mimic the neuromuscular pathways of aquatic organisms in the Zebrafish. These aptly-called **biomimetic propulsion systems** have the potential to be more efficient than traditional propulsion systems because they are **self-regulating** in respose to environmental stimuli. Additionally, fluid dynamics and mesh topology are critical in enhancing a biomimetic-powered submersible's energy efficiency even further. Modern oceanic topological models are generated using either queues or parallelization, as implementing both simultaneously causes a mismatch in object size initialization, leading to excessive computational overload.

Problem Statement

A comprehensive model that integrates neuromuscular control mechanisms and fluid dynamics into a unified design has yet to be realized. Current submersibles do not fully utilize **biological locomotion** or implement **priority queues** in generating their topological models. This limitation hinders their ability to navigate complex underwater terrain and adapt to changing environmental conditions. Moreover, as climate change impacts ocean conditions, there is a growing need for improved ecosystem monitoring and mapping of the ocean floor for deep-sea exploration.

This leads us to the fundamental problem we wanted to solve: *How can we develop a propulsion system that integrates the complex neuromuscular control mechanisms of Zebrafish with fluid dynamics to mimic natural propulsion more efficiently than traditional systems?* Such a system could not only enhance the maneuverability and efficiency of underwater vehicles but also **revolutionize ecosystem monitoring, mapping of the ocean floor, and deep-sea exploration**.

Target Planning

Engineering Goal

Our engineering goal is to create an **optimized submersible** powered by a novel biomimetic propulsion system and topological model to help scientists conduct climate research and map the ocean. Specifically, the submersible should:

- Have a functional 3D structure that minimizes water forces
- Utilize Zebrafish neurology as a feedback mechanism for energy-effficent locomotion

Evaluation Hypotheses

We needed to come up with a way to evaluate our project on completion. Ultimately, we decided to **combine** *the Scientific Method* and *the Engineering Design Process* to create evaluation hypotheses that would gauge the effectiveness of our final product:

- **Null Hypothesis:** Both the biomimetic propulsion system and topological model do not differ in energy efficiency compared to a traditional propulsion system.
- **Experimental Hypothesis:** The biomimetic propulsion system and topological model will both exhibit *statistically significant* [a] differences in energy efficiency compared to a traditional propulsion system.

[a] *We will use the standard convention for statistical significance ($p < 0.05$) in this project.*

Engineering Methodology

Preplanning

Constraints

- Restricted in 3D printing techniques
- Testing outside of a lab environment
- Unoptimal motor driver and power sensor specs
- Time frame of 4 weeks
- Limited budget of $100

Materials

Distilled Water 1 gallon	Mini Breadboard 1	INA219 Sensor 1
Arduino Nano 1	Raspberry PI 4B 1	TPU resin 400 grams
Meter-long water container 1	Stepper motors 2	Duct tape 1
Breadboard Jumper Cables	USB 3.0 Hub 1	Stop watch 1
L985 Motor 1	Ovonic LiPo battery 1	Electrical cables 20

Experimental Setup

Topological Model

1. Fill a 1-meter bucket with water
2. Place the control model at one end of the bucket
3. Place the optimized model next to the control
4. Connect both models to the open feedback loop, with the optimized propulsion system not in effect
5. Start a timer when both models are connected to the propulsion system
6. Record time for each model to reach the other end
7. Record power draw when each model reaches the other end

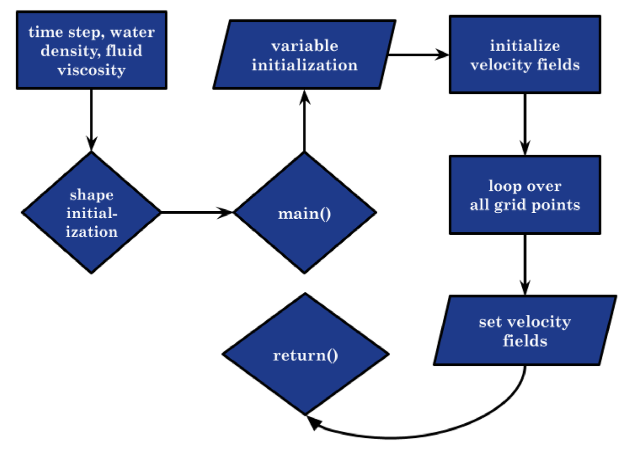

Figure 3: A flowchart of the topological processing

Neurological Model

1. Same as step one for the topological model
2. Place the model into the larger container
3. Connect to the closed loop system with ROS using PuTTY
4. Call the command to start the model
5. Stop the model after it traverses one meter
6. Record the power draw from the INA219 sensor
7. Repeat for fifty iterations
8. Repeat the same procedure, instead calling open loop control through the motor directly with SSH

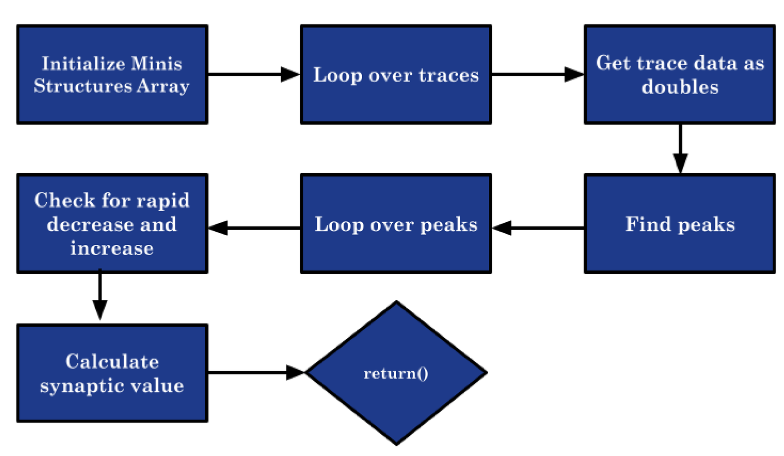

Figure 4: Neurological model framework

System Architecture

Beta I

Beta I was the initial prototype of our submersible, which utilized Navier-Stokes equations to construct optimized vector field graphs based on parameters such as water viscosity, time step, and water density.

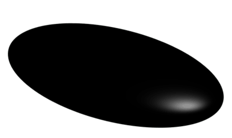

Figure 5: Beta I Picture

To optimize hydrodynamic efficiency:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f},$$

$$\nabla \cdot \mathbf{u} = 0.$$

To minimize drag force:

$$F_{\text{drag}} = \int_{\partial\Omega} \left(-p\mathbf{n} + \nu \frac{\partial \mathbf{u}}{\partial \mathbf{n}} \right) \cdot \mathbf{n} \, dA.$$

The hull design was refined iteratively through topology optimization:

$$\mathbf{F}\text{net} = \int \partial\Omega\mathbf{T} \cdot \mathbf{n} \, dA,$$

$$\mathbf{T} = -p\mathbf{I} + \mu \left(\nabla \mathbf{u} + \nabla \mathbf{u}^T \right).$$

To convert the vector fields into a printable CAD model, we used MATLAB's Simulink tool to convert the field graphs into a vtb file and imported it into OnShape.

Beta II

Beta II of our model incorporates **octree indexing**, which offers several advantages over traditional XYZ graphing methods. It partitions 3D space into hierarchical, smaller sections, providing a more organized and compact representation of spatial data. This indexing allows for logarithmic time complexity in search operations, making it highly scalable.

It also enables efficient updates, typically involving only modifying a small part of the tree, unlike XYZ graphing, which may require reprocessing and reindexing an entire data set. Additionally, octree indexing significantly reduces the number of calculations needed to determine visible surfaces, enhancing overall efficiency. We have since **printed and tested** Beta II, making it our final product.

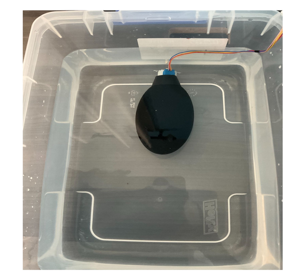

Figure 6: Beta II Picture

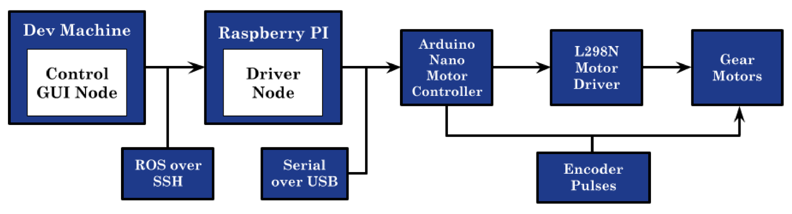

Figure 7: A flowchart of the circuitry

Statistical Analysis

We conducted a **left-tailed z-test**, utilizing known values of standard mean and deviation, across all 15 trials for each model.

Data Collection

Test #2	Control	Modified Design
Trial 1	0.06167	0.0516
Trial 2	0.05667	0.05508
Trial 3	0.06015	0.05035
Trial 4	0.05969	0.05138
Trial 5	0.05688	0.05016
Trial 6	0.05733	0.05421
Trial 7	0.05904	0.05245
Trial 8	0.06092	0.05315
Trial 9	0.06092	0.05411
Trial 10	0.06044	0.05411
Trial 11	0.05752	0.05462
Trial 12	0.05902	0.05113
Trial 13	0.05789	0.05385
Trial 14	0.06173	0.05262
Trial 15	0.05554	0.05051
Average	0.0590273	0.05296
Standard	0.0019626	0.001620789
Z-score		-3.09151425
P-Value	<0.01	

Figure 8: Propulsion model

Test #1	Control	Modified Design
Trial 1	3.56	3.44
Trial 2	3.53	3.49
Trial 3	3.5	3.42
Trial 4	3.54	3.46
Trial 5	3.55	3.47
Trial 6	3.53	3.47
Trial 7	3.5	3.49
Trial 8	3.58	3.46
Trial 9	3.51	3.48
Trial 10	3.59	3.47
Trial 11	3.56	3.47
Trial 12	3.57	3.42
Trial 13	3.58	3.45
Trial 14	3.53	3.5
Trial 15	3.59	3.47
Average	3.548	3.464
Standard Deviation	0.0309839	0.023543273
Z-score		-2.711088342
P-Value		0.034

Figure 9: Topological model

Benchmarks

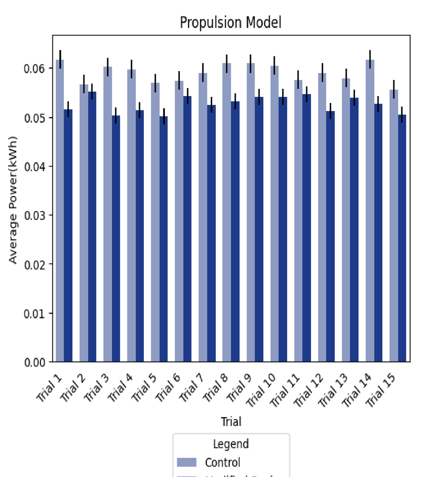

Figure 10: Propulsion model

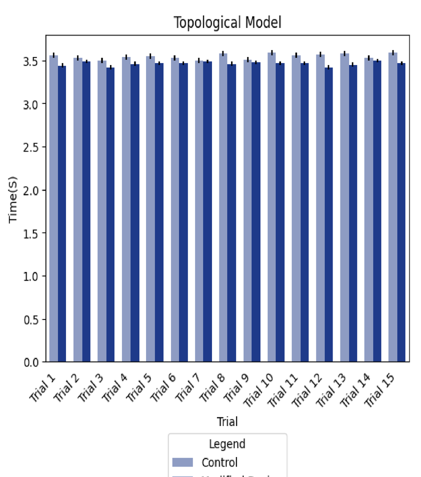

Figure 11: Topological model

Research Summary

Abstract

We propose a biomimetic propulsion system inspired by the spinal motor control mechanisms of zebrafish, allowing the submersible to adapt its propulsion strategy in real time based on real-time feedback from the environment. The design consists of two components: a neurological model and a topological model. The topological model is derived from Navier-Stokes equations to simulate fluid dynamics, coupled with topology optimization. We tested the system under two control conditions: open-loop configurations and closed configurations. The experimental results demonstrated that the topology and topological models achieved significant improvements in energy efficiency and traversal time, compared to a control set-up. This technology has far-reaching implications for ocean exploration, climate research, and underwater robotics. Moreover, our design is easily scalable for applications in larger underwater vehicles and multi-agent UAV systems.

Key Words

biomimetic submersible, undulatory swimming, computational fluid dynamics, neurological control model

Conclusions

Interpretation of Results

The topological and propulsion model z-scores of -2.71 and -3.09 correspond to p-values of 0.003 and 0.001, respectively. Since neither p-value is above 0.05, **we can reject the null hypothesis** that neither the biomimetic propulsion system nor topological model would differ in energy efficiency compared to a traditional propulsion system.

Implications

The implications of our work are far-reaching. By utilizing an innovative design and novel approach for locomotion, we were able to create **a highly efficient propulsion system** and **novel topological model** without the need for expensive components or complex manufacturing processes. This technology, coupled with the **scalable nature** of biomimetic propulsion systems, could alter how humans explore the ocean moving forward. Google is exploring the use of submersibles and LIDAR to automate ocean topography mapping rather than satellite imagery capturing the ocean surface, which is too reflective/too difficult for light to penetrate. Other companies could potentially send out multiple unmanned vehicles simultaneously, efficiently covering large areas of the ocean floor for research and exploration purposes.

Figure 12: Picture of Google's "Street View" boat Sourced from www.gcaptain.com

Future Work

- LIDAR Technology Our ROS driver pairs well with existing LIDAR technology.
- Camera Visioning JeVois camera microprocessors with a Generic Object Detection Tensor are a cheap solution for automated movement/collision detection.
- FPGA Chips Reduces communication latency down to *microseconds*.

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