Designing a controllable miniature fish-like robot with enhanced maneuverability

Brian Goodluck Mmari

5th May 2024

Prof. Radhika Nagpal, Dr. Hungtang Ko

Submitted in partial fulfillment
of the requirements for the degree of
Bachelor of Science in Engineering
Department of Electrical and Computer Engineering

Princeton University

I hereby declare that this Independent Work report

represents my own work in accordance with

University regulations.

Your Signature

Brian Goodluck Mmari

Designing a controllable miniature
fish-like robot with enhanced maneuverability

Brian Goodluck Mmari

Abstract

Swarms is a collection of decentralized homogenous simple agents which interact locally to achieve a certain task. These local interactions can give rise to complex behaviors such as self-organization and adaptation, efficiency and robustness to failures, as well as scalability. Classical models of swarms often ignore the physical environment. However, it should be clear that mechanical interaction alone can give rise to collective behaviors. Multiple studies involving miniature robots have been done to study collective behaviors such as the Kilobot, HEXBUGS, smarticles etc. However, to understand mechanical intelligence in fish-schools, we require fish-like swimming robots. Many of the fish-like robots built in the field struggle in different metrics such as efficient maneuverability. As a result, my project aims to design a miniature-fish like robot with enhanced maneuverability so as to better understand the field of emergent collective behaviors in fish schools. This independent work details a brief analysis of the field of emergent collective behaviors, other low-cost robots with various navigation strategies, the hardware behind our robot and future implementations with flow-sensors.

ACKNOWLEDGMENTS

I would like to first thank Professor Radhika Nagpal for welcoming me into her research group. She has been truly inspirational especially through her mentoring and unwavering commitment to answer questions whenever I had them. I am also thankful for she has introduced me to the field of swarm robotics through her extensive research experience and insights. Furthermore, I have had the privilege of presenting this research project during the lab meetings where I gained critical feedback, which I'm grateful for. I'm incredibly fortunate to be working with her and I hope to keep learning from her and her research group.

I would also like to thank my direct supervisor, Dr. Hungtang Ko for his exceptional mentoring and teaching. Most of what I have learnt in research is because of his exemplary enthusiasm in the topic. I have also been fortunate to attend the Society of Integrative and Comparative Biology(SICB) conference because of the research that I have conducted with him. This conference opened doors for the various kinds of research opportunities available and how to best leverage them. Thank you for providing feedback on this report, poster and the overall project. Working with him has always been wonderful and I consider myself fortunate for the experience to learn from him.

Thank you to my second reader, Dr. Hossein Valavi, for his willingness to act as my second reader for this project.

Table of Contents

1. Background

1.1 Collective Behaviors

Collective behaviors are actions and movements that arise due to local interactions from multiple individuals in a group without any central control. These behaviors are usually observed among groups of organisms such as ants, birds, and fish. For instance a flock of birds sweeps through the sky, a group of ants forage for food, and a school of fish swims, turns and flees together because of collective behaviors[1]. The agents use simple local rules to govern their actions and via the interactions of the entire group, the swarm achieves its objectives[2]. A comprehensive example of this occurs in birds where a single bird in a flock simply tries to stay close to its neighbors, without taking any commands from a leader bird(because there's no lead bird) and collectively the flock is able to protect itself from predators as well as efficiently search for food.

Figure 1: Collaborative leadership: a lesson from birds

The field of collective behaviors has diverse applications in different fields such as robotics, computer science, and network systems. Collective behaviors leads rise to swarm intelligence which ultimately can be applied to different fields such as robotics, network optimization systems, traffic patterns in transportation systems, and military applications.

1.2 The Bluebot

Towards understanding collective behaviors in fish schools, different researchers have replicated autonomous fish-like swimming behaviors. The Bluebot was designed to offer higher degrees of autonomy, maneuverability, and biomimicry while still maintaining a miniature size($160cm^3$)[3]. Fish-like robots which are often used in laboratory studies are often tethered because it is challenging to integrate power and sensing autonomy in a small enough and maneuverable design[3]. Accordingly there's a gap between fish and fish-like robots in terms of designing fish-like robots with guaranteed self-propulsion, ability to control their body position in 3D, low-cost effective cruising and maneuverability[3]. As such, researchers designed the Bluebot which achieves mainly 2 goals: fish-like locomotion by careful selec- tion of flexible caudal fins which can produce reverse Kármán wake structures; (ii) to achieve self-propelled and controlled motions in 3D space, whose performance metrics such as speed and Cost of Transport(CoT) are reminiscent of fish[3]. According to their results, Bluebot was the first small enough autonomous multi-fin platform with closed-loop control that could be used for laboratory experiments for 3D fish-like swimming[3].

1.2.1. Design

The Bluebot was designed to be low-cost($100), easily manufacturable and highly maneuverable[4]. However, Bluebot has been significantly upgraded from its initial design with an exchangeable caudal fin, onboard power monitor and a more streamlined and biomimetic body shape[3]. The major components of the Bluebot are discussed as follows:

1. A single-cell (3.7 V, 320 mAh) Li-Ion battery.
2. Arduino Pro Mini microcontroller from the initial design[4]
3. Pressure sensors(TE Connectivity MS5803-02BA) mounted on the side of the robot, can provide pressure readings up to a depth of 10 m with a resolution of up to 0.25 mm to

control depth [5].

4. Inertial Measurement Unit(IMU) to control heading
5. Magnet-in-coil(MIC) propulsors which offer the following advantages: (i) they are easy to miniaturize; (ii) they have no moving components that penetrate the body of the robot, which makes for easier waterproofing; (iii) they are low-cost, with a current cost of around $ 1/unit.[4]
6. Caudal, Pectoral and Dorsal fin to achieve navigation in 3D space
7. A blue light photodiode (Excelitas Technologies VTP1112H), mounted at the front of the robot with a viewing angle of ±15°, measures light intensity.

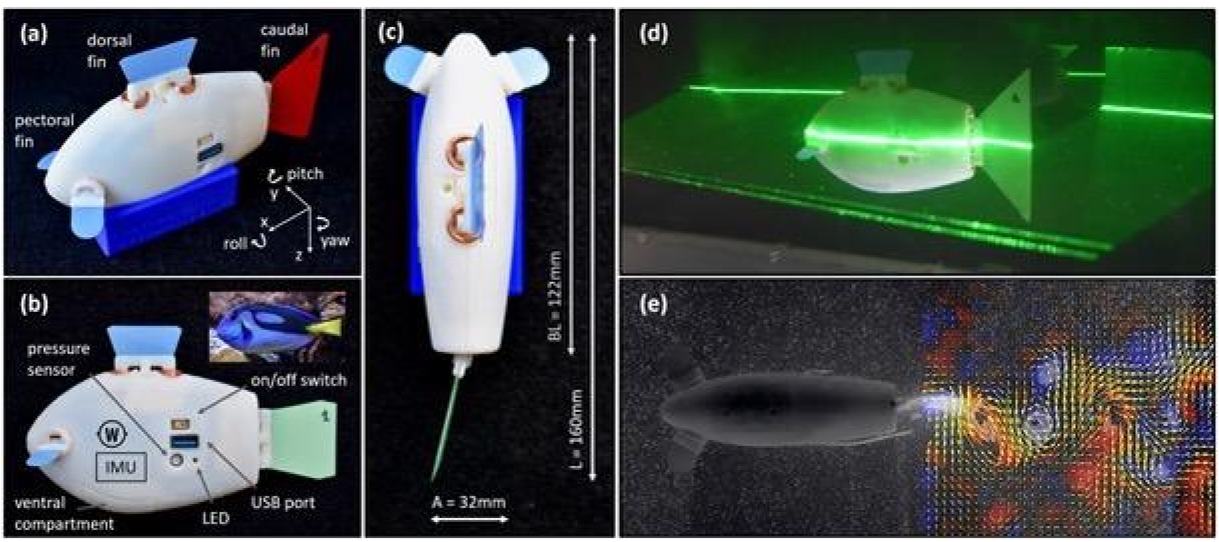


Figure 2: The Bluebot: an autonomous and biomimetic platform after the design upgrades

1.2.2. Applications

Design of the Bluebot enabled the reduction of mechanical complexities which came about with the usage of a mechanical rotary shaft actuator[4]. This extensively enabled the ability for 3D navigation underwater while still being relatively small sized and lower cost. In addition, the Bluebot

1.3. The Caltech Autonomous Reinforcement Learning Robot(CARL)

Inspired by understanding navigation strategies using sensory feedback and Reinforcement learning(RL), researchers at Caltech designed a low-cost off-the-shelf palm-sized underwater robot. Onboard sensor measurements are critical for autonomous ocean vehicles navigation so as to locate oceanic features with relevant scientific data in limited time. This is essential because most of the current Autonomous Underwater Vehicles(AUV's) are limited in area and speed of coverage[5]. As a result the alternative has been targeted sampling, where underwater vehicles locate areas of interest to increase their effectiveness under water. This inspiration also comes from nature e.g sea lions and catfish can hunt by seeking the wakes left behind by their prey[6][7]. Aquatic animals use flow sensing for a variety of other tasks, including following walls [14] and station keeping in the wake behind obstacles[15]. Each of the mentioned biological tasks could inspire similar practical applications in autonomous vehicles e.g autonomous navigation along the seafloor and detecting wake signatures from physical obstacles or hydrothermal vents[16].

1.3.1. Design

The CARL's hull and structural components were 3D printed using PLA (polylactic acid) and made watertight with a coating of two-part epoxy[17]. The major components of the CARL are discussed as follows:A single-cell (3.7 V, 320 mAh) Li-Ion battery.

1. 12-watt-hour lithium-ion battery (Samsung 35E 18650) provided power to the robot
2. Teensy 4.1 microcontroller for onboard control and computation[17]
3. 8 pressure sensors (MS5803-02BA, TE Connectivity) at four locations around CARL[17]
4. A wireless communication module (Songhe NRF24l01+ mini) to send and receive commands and data from CARL while on the surface[17]
5. Inertial measurement unit (IMU, MPU-6050, TDK InvenSense) measured acceleration and angular rotation rate for wall impact detection and active rotational stabilization[17]
6. Ten brushed DC motors (Crazepony 615 17500KV) with corresponding propellers
7. H-bridge motor drivers (Texas Instruments DRV8833)

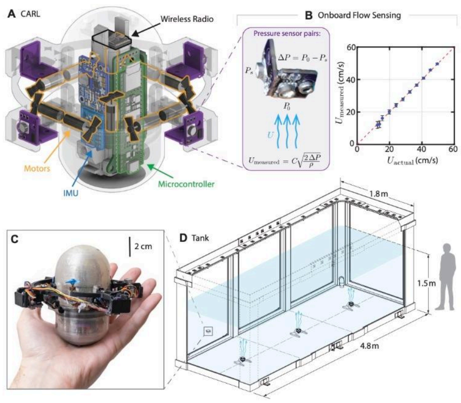


Figure 3: The CARL robot and a tank facility

1.3.2. Applications

The success of CARL in locating turbulent plumes demonstrates the potential for targeted sampling of real-world flow features with onboard flow sensing[17]. Onboard distributed pressure sensing offers a convenient, low-cost, and low-power method for measuring flow gradients[17]. In addition this can also be applied to bio-inspired robots which swim using undulatory motion and also generate confounding flow signals from body motion. If sensor readings are coupled with the swimmer's motion, pre-calculated models such as those used in[18] could be implemented to disentangle pressure signals from self-motion and external stimuli[17].

2. System Description

The current Blue Guppy fish robot is about 10 cm long, comparable to an actual Guppy fish (~6.35cm long). The structural components are 3D printed using PLA material. The design has been significantly upgraded from the last iteration. The current design combines inspiration from the Bluebot in terms of its actuation mechanism. In addition, we hope to design a PCB circuit for attaching flow sensors like the CARL robot so as to also perform flow sensing. Our setup will offer an additional advantage from the CARL robot, one in particular being the small and simple design.

2.1 Components & Design

2.1.1 Components

(1) **Arduino Nano-ESP32.** All the onboard computation and processing is done by this microcontroller. Arduino Nano-ESP32 was chosen because of its miniature size and Wi-Fi capabilities. This microcontroller can also be programmed using both Micropython and C++ other than the contemporary C++. Micropython, although slower than C++, is easier to work with and allows you to immediately test changes to your program without the need to compile and upload. Even though the code for this project was implemented in C++, future implementations could require MicroPython.

(2) **3.7 V, 100mAh Li-Po Battery.** The Li-Po battery offers power to all the electronic components of our blue guppy fish robot.

(3) **Magnetic-in-coil Actuators.** These components were inspired from the design of the Bluebot because they have no moving parts that penetrate the body of the fish-robot. This made waterproofing much easier to accomplish.

(4) **DRV8833 Board.** A H-bridge motor driver that was used for bidirectional control of the actuators.

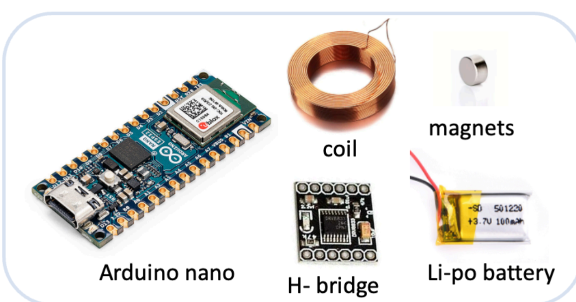
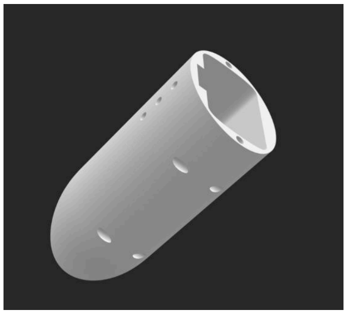


Figure 4: Components of the design

2.1.2 Hardware Design



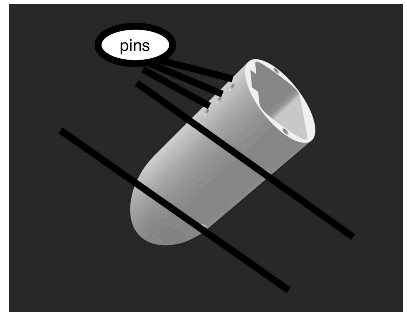


Figure 5: The body of the fish-robot

Figure 6: Black fish lines for synchronization with other fish

The body of the fish was designed so as to ensure that it is neutrally buoyant. This was achieved through multiple iterations of the design as well as gluing in metal plates, for increased weight, whenever necessary.

2.1.3 Circuit Schematic

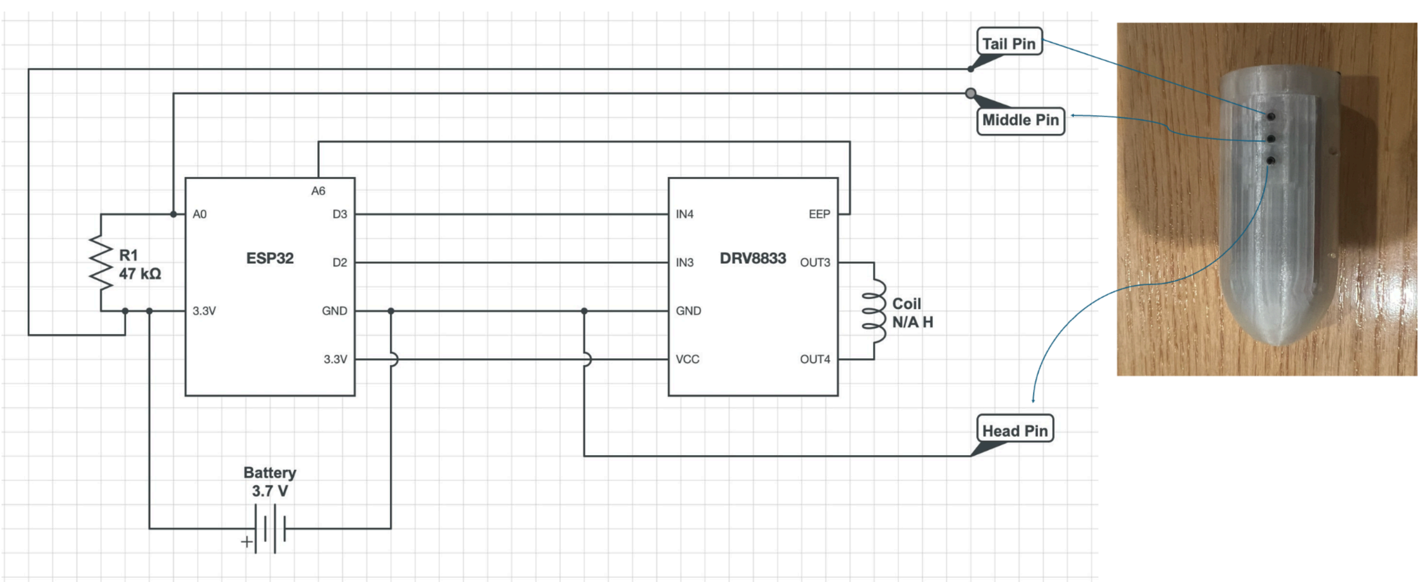


Figure 7: The circuit schematic for the design.

The three pins provide direct access to the circuit by allowing us to measure voltage without opening the fish. The pull-up resistor R1 pulls up voltage at A0 to 3.3V. Hence measuring the voltage difference between “Middle Pin” and “Head Pin” or “Tail Pin” and “Head Pin” should give you the voltage of the battery. In addition another area of interest is the DRV8833. The two inputs IN3 & IN4 receive PWM signals from the ESP32, whereas the two outputs OUT3 & OUT4 send polarized current to the coils. Switching the direction of currents causes switching of the flapping mechanism.

Figure 8: Proof of concept

2.2 Driving Mechanism

As mentioned before, the driving mechanism of our miniature robotic fish is inspired from the Bluebot. The current setup uses a small magnet placed inside the coils, where the coils are connected to the outputs of the H-bridge. The electrified coil then produces a magnetic field which exerts a force on the small magnet. Switching the direction of current changes the polarity of the small magnet which in turns determines the direction of rotation. Because the small magnet is not constrained but rather attached to the flapper, it moves. This concept is similar to how most electric motors work where they also have permanent magnets mounted in such a way that it produces a rotational force.

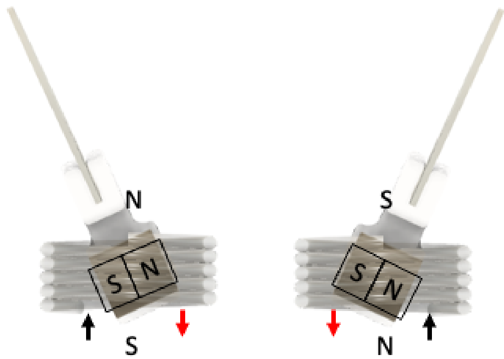
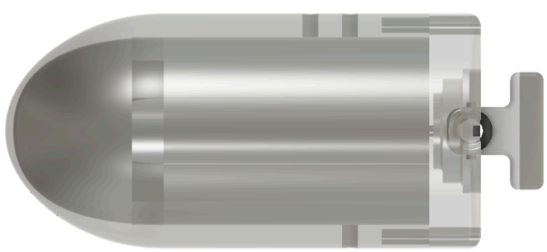


Figure 9: The driving mechanism

As mentioned previously this mechanism offers various advantages. One being that we no longer have a pocket of airspace which would bring about challenges for buoyancy. The fact that everything is compact means that the tail region can be regarded as dense as the body region.



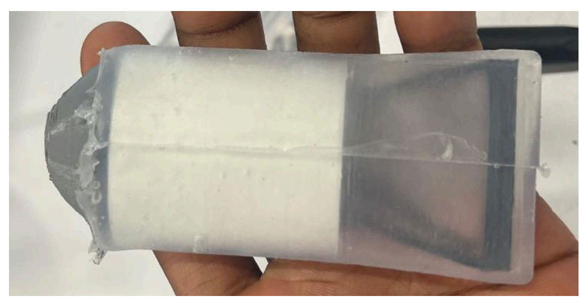


Figure 10: Current design with no pocket of airspace

Figure 11: Previous design with pocket of airspace

3. Remote Control

Once the hardware and electronics were tested and worked, the next challenge was achieving remote control. Once the fish-robot is inside the water, hwo do we command it to move how we want it to?

Different attempts were made to achieve this using the ESP32 microcontroller. The initial attempt was trying to use the WebServer protocol. The WebServer works by first entering the URL into a browser, then the browser uses the URL to send a HTTP request to ESP32. The ESP32 WebServer then sends some response to the HTML code to build the web page. The user is then left to enter an argument to send the client, which in this case could be for example to send a PWM signal to the fish-robot. However the biggest challenge with this setup was the fact that it required strong internet connection and even then the response time was very slow. This then required us to explore a different approach

3.1 ESP_NOW protocol

ESP_NOW is a wireless communication protocol developed by Espressif that features short message transmission enabling multiple ESP-devices to talk to each other in an easy way. ESP_NOW uses underlying Wi-Fi system hardware to offer a relay network for the two or multiple devices to communicate. ESP_NOW allows different network setup such as one-way, one leader-multiple follower, one follower-multiple leader, as well as multi-device - communication. Some of the major advantages of this protocol that greatly fitted the needs for our project were: quick response time, multiple modes of communications and ability to cover long distances. Even though the protocol can only send 250 bytes per message this was not a concern because we would only be sending command signals via numbers, not strings.

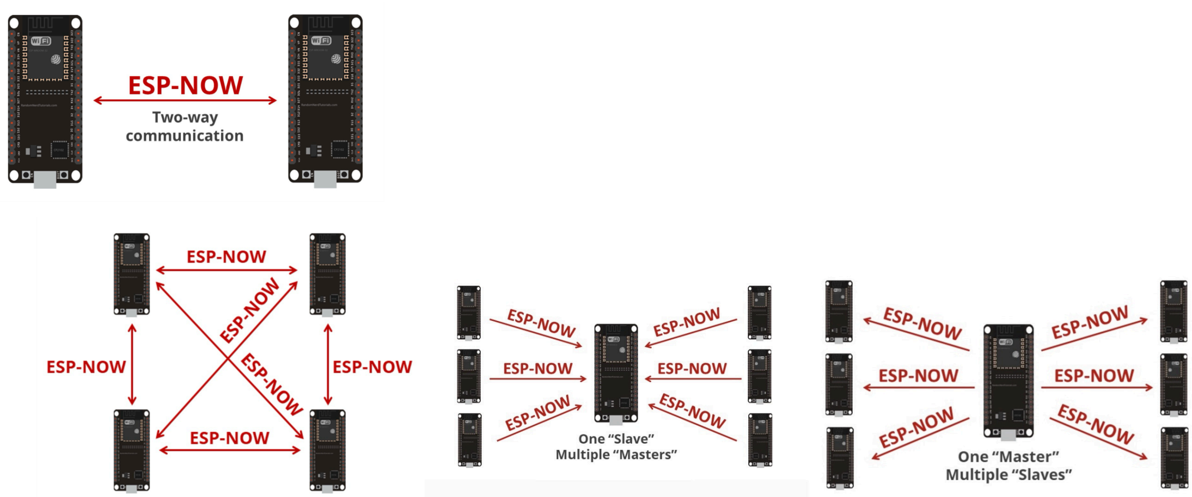
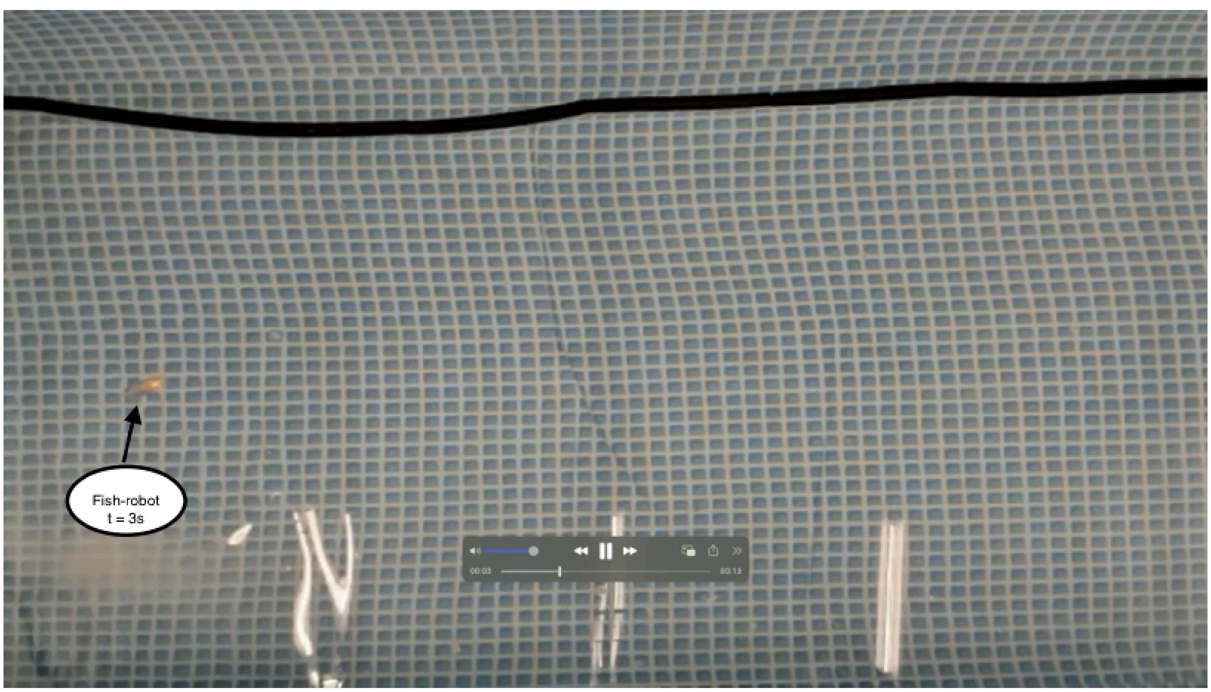


Figure 11: Different modes of communication by ESP32

For this semester, the focus was on two-way communication between the PC and the fish-robot. This is how the setup was involved:

(1) Connect one ESP32-transmitter to the PC, and the other-”receiver”- connected to the fish-robot
(2) Compile both sketches and open the Serial Monitor for the transmitter. Once the sketch for the receiver is uploaded, the Serial Monitor doesn’t appear because this ESP32 is now connected to WiFi.
(3) Type in commands in the Serial Monitor of the transmitter. The following was the chosen methodology:
    (a) 1 = to start the fish
    (b) 0 = to stop the fish
    (c) 0_0 to 9_9 to maneuver the fish using delay time. For example 1_9 means:
        (i) 1 = delay 50ms one side
        (ii) 9 = delay 450ms opposite side, hence fish-robot turns towards “1” side.



Based on these biological observations, one can define the following three key criteria for robots to exhibit fish-like swimming: (i) vortices are shed from the flapping caudal fin such that a reverse Kármán wake forms; (ii) the tail beat frequency is linearly correlated with the swimming speed; and (iii) CoT is U-shaped with a minimum at intermediate swimming speeds.[3]

[1] E. Shaw, \The scho oling of shes," Sci. Am., vol. 206, pp. 128{138, 1962.

[2] http://www2.ece.ohio-state.edu/~passino/swarms.pdf

[3] Berlinger, Gauci, Nagpal. January 20, 2021. Implicit coordination for 3D underwater collective behaviors in a fish- inspired robot swarm.

https://www.science.org/doi/10.1126/scirobotics.abd8668

[4] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8000334

[5] Y. Zhang, J. P. Ryan, B. Kieft, B. W. Hobson, R. S. McEwen, M. A. Godin, J. B. Harvey, B. Barone, J. G. Bellingham, J. M. Birch, C. A. Scholin, F. P. Chavez, Targeted sampling by autonomous underwater vehicles. *Front. Mar. Sci.* 6, 415 (2019).

[6] G. Dehnhardt, B. Mauck, W. Hanke, H. Bleckmann, Hydrodynamic trail-following in harbor seals (Phoca vitulina). *Science.* 293, 102–104 (2001).

arXiv:2206.01364

[7] P. Patton, S. Windsor, S. Coombs, Active wall following by Mexican blind cavefish (Astyanax mexicanus). *J. Comp. Physiol. A.* 196, 853–867 (2010).

[14] J. C. Liao, A review of fish swimming mechanics and behaviour in altered flows. *Philos. Trans. R. Soc. B.* 362, 1973–1993 (2007).

[15] L. N. Germanovich, R. S. Hurt, J. E. Smith, G. Genc, R. P. Lowell, Measuring fluid flow and heat output in seafloor hydrothermal environments. *J. Geophys. Res. Solid Earth.* 120, 8031–8055 (2015)

[16] H. Ko, G. Lauder, R. Nagpal, The role of hydrodynamics in collective motions of fish schools and bioinspired underwater robots. *J. R. Soc.* 20, 20230357 (2023).

[17] Gunnarson, Peter & Dabiri, John. Fish-inspired tracking of underwater turbulent plumes

https://arxiv.org/abs/2403.06091

[18] Renn, Peter & Morteza Gharib. Machine learning for flow-informed aerodynamic control in turbulent wind conditions

https://www.nature.com/articles/s44172-022-00046-z