Design of a Large-Scale Robotic Swarm

A Design Project Report

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Abstract

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Abstract

Nature offers many examples of complex collective behavior emerging from simple local interactions. In these systems a group of organisms appears to display an intelligence distinct from that of the individuals composing the group. Swarm robotics aims to build multi-agent robotic systems that emulate these emergent behaviors. These systems consist of a group of individual agents that can reach agreements without the need for a controlling authority through its distribution actions. This field leverages the strength of numbers to achieve complex tasks and emergent behaviors that are beyond the capability of individual agents. The reliance on simple, distributed coordination means that the swarm size can be seamlessly regulated without concern for single points of failure or bandwidth.

The primary objective was to develop a scalable and efficient swarm of robots capable of executing collective tasks that surpass the capabilities of individual units, drawing inspiration from the natural systems described above. By designing a simple hardware platform that is complete with onboard power, processing, actuation, sensing, and communication, these individual agents can be replicated and used to perform these collective tasks. In addition to the design, a communication protocol was designed to allow two robots to communicate and synchronize with each other while operating simultaneously.

Executive Summary

Swarm robots are a collection of robots designed to work collaboratively by mimicking emergent behaviors seen in nature, observable in many groups of organisms including insects, birds, and fish. Each robot in the swarm performs simple tasks, but together, they achieve complex objectives through coordinated behavior. The most common applications of swarm robotics include environmental monitoring, where they can collect data over large areas; disaster response, where they can search and navigate through rubble without risking human lives; and precision agriculture, where they contribute to crop management and pest control by operating in large numbers, covering vast fields efficiently.

This project describes the design, construction, and testing of a swarm-capable robot. This process begins with component selection and trade-off for size, energy efficiency, and scalability. With components selected, the project evolved toward robot prototyping, assembly, and test.

After going through various revisions and discussions, the hardware was set, with the next steps being testing each component and verifying its purpose. This project successfully verified the functionality of a single robot in real life, including its ability to communicate with itself. Additionally, it demonstrated communication between this robot and another robot through simulation. The next steps for this project involve ensuring multiple robots can operate independently and then applying the designed communication protocol to all of them.

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1 Relevance

Swarm robotics has become extremely relevant in today's world, transforming industries and daily life. The integration of swarm robotics in various sectors has revolutionized operations, enhancing efficiency, precision, and safety while reducing costs and human error. In applications such as environmental monitoring, disaster response, and space exploration, swarm robots excel due to their scalability, flexibility, and redundancy.

As advancements in artificial intelligence and machine learning continue, swarm robots are becoming more capable of performing complex tasks, driving innovation and economic growth. Their ability to operate autonomously and coordinate efficiently makes them ideal for tasks that are too dangerous, tedious, or vast for humans. This collaborative approach allows swarm robots to achieve complex objectives collectively, solidifying their pivotal role in future technological progress.

1.1 Acknowledgements

I would like to thank Professor Petersen and Professor Adams for being incredible mentors during this entire project. Beyond providing feedback and suggestions, both of their passions about this field were wonderful to see and got me excited about the project as well. This project would not have been possible without either of them.

2 Design Requirements

When designing to a number of requirements, there are many software and hardware considerations to take into account. Software is a little more malleable as it can be more fluid in its organization, but hardware had to be designed first as it takes time to make the schematic and layout as well as ordering the PCB once completed. At a high level, the design objectives were to achieve autonomous power and processing capability in each robot, have effective communication, and be able to adapt to different environments. I will first go into the designs previously considered for each requirement and then explain why it was not chosen and then how we landed on the final design that was eventually implemented. When designing a large-scale robotic swarm, several key considerations in both hardware and software are crucial to ensure that the system meets its functional requirements efficiently.

2.1 Design Tradeoffs

In designing a swarm-capable robot, balancing size, complexity, and organization is crucial. Smaller robots are ideal as they can navigate tight spaces and are less costly, allowing for deployment in large numbers. However, reducing size often complicates design because essential components like sensors, communication modules, and power sources must fit into a compact space. This increase in complexity can raise costs and maintenance challenges. Additionally, effective organization within the swarm—through streamlined communication protocols and intelligent decision-making—is essential to manage this complexity and ensure the swarm operates smoothly. Therefore, achieving an optimal balance between these elements is key to enhancing both individual robot performance and overall swarm functionality. The requirements that I focused on achieving are detailed in the following three sections.

2.2 Autonomous Power & Processing

The robots were going to be based upon the RP2040 microcontroller, chosen for many reasons. IT features a dual-core ARM Cortex-M0+ processor running at up to 133 MHz, providing ample processing power for many applications. It also has 264 KB of SRAM and is designed to be power efficient, allowing for more complex programs and data handling and making sure that memory would not end up being an issue in the future. However, the key advantage was that the RP2040 has 30 GPIO pins that can be used for analog and digital functions, especially with some being Analog-to-digital converter pins already. On the software side, it is able to be easily interfaced with different communication protocols and supports development using MicroPython, C, and C++. The flexibility of the number of GPIO pins allows for many different sensors and peripherals to be connected, enabling a wide range of functionalities.

Since each robot must operate independently without relying on external power sources, autonomous processing capabilities allow each robot to make decisions based on their own local sensory data without needing to communicate with a central processor. This also ensures that when adding more robots, adding more resources does not increase the demand on any shared resources, allowing the system to scale smoothly.

For power, we considered having a wireless charging module that would rest underneath the board and allow robots to recharge their batteries by simply being in proximity to a charging station, eliminating the need for physical connections. The other option was to attach a lithium battery underneath the board itself, making it simple and reliable. Using standard batteries with JST connectors simplifies the overall design, as batteries can be quickly swapped out, ensuring minimal downtime and extended operational periods for the swarm. A wireless charging module would be ideal but was not chosen because of the challenges associated with its implementation as well as timing constraints. It needed multiple charging stations across an area as well as precise alignment over distance. However, this would be the next step on another iteration of the hardware design.

2.3 Effective Communication

Communication is the backbone of this project. Robots need to be able to coordinate their actions, share data, and eventually be able to collectively make decisions. When performing tasks that have strict timing requirements, robots need to be able to synchronize. In scenarios like environmental monitoring or search and rescue, sharing sensor data among the swarm can significantly enhance the collective understanding of the environment, allowing them to reach a consensus faster. This requires a suite of sensors and a peer-to-peer communication mechanism.

The alternatives considered for this were using a buzzer, an IMU (Inertial Measurement Unit) , IR sensors, speakers, and microphones. A buzzer would be used as simple signals for basic communication tasks, such as alerts or status updated. However, these are limited to non-specific signals which would not be ideal for multiple robots. It would be hard to synchronize upon a basic signal. An IMU is composed of an accelerometer and a gyroscope and is valuable for navigation and orientation. I chose to only use an accelerometer, because I was primarily measuring linear acceleration and it would be sufficient enough for detecting collisions, movements, and general orientation relative to gravity. Accelerometers also have less drift compared to the additional sensors, like the gyroscope, in an IMU. In addition, integrating data from an IMU includes accelerometer, gyroscope, and magnetometer data which could require lots of computational power as well as sensor integration algorithms.

IR (Infrared) sensors were chosen because of its proximity detection, distance measurement, and communication aspects. IR sensors are ideal for short range sensing when identifying objects that are near the robot as well as being able to measure the distance to these objects without a need for contact. IR sensors generally consume less power compared to other types of sensors, making them suitable for battery-operated robots. Lastly, audio was chosen alongside IR to provide long range and two way communication by incorporating microphones and speakers. In scenarios where visual signals might be obstructed or in noisy environments where IR could fail, audio remains reliable. Speakers can emit specific sounds or tones that are used to synchronize activities or signal status updates across the swarm. Similarly, microphones can detect these audio signals and respond accordingly.

2.4 Adapt to Different Environments

Lastly, the ability of the swarm to be able to adapt to different environments is essential for it to be applied across a range of scenarios. Environmental adaptability ensures that the robots can function effectively in diverse settings, from indoor facilities with controlled conditions to rugged outdoor landscapes with variable weather and terrain.

The selection of the Pololu motors was largely influenced by its size compatibility with the PCB design (100x100 mm), ensuring that the motors could be integrated without compromising on space. These motors provide a good balance of power, control, and energy efficiency, making them well-suited for a variety of tasks. They are low power 6V brushed DC metal motors with a gearbox cross section of 10×12 mm and a 9 mm long, along with a gearbox output shaft. The decision was also supported by the availability and the established reliability of Pololu products.

2.5 Requirement Summary

In each requirement, the chosen alternatives were those that best aligned with the overall objectives of simplicity, cost efficiency, operational flexibility and scalability. Spending time on this selection process ensured that the swarm robots were not only capable of performing their intended functions but were also versatile enough to adapt to a range of operational scenarios.

3 Hardware Design

After going through many iterations as described in the earlier sections, we ended up deciding on the following block diagram. As illustrated in Figure 1, we chose to have 8 IR sensors, 2 microphones (CMA-4544PF-W), 1 speaker (AST-03208MR-R), 1 accelerometer (ADXL335BCPZ-RL), the necessary hardware setup for the RP2040, and the motor drivers (DRV8835DSSR), along with a few debug test points.

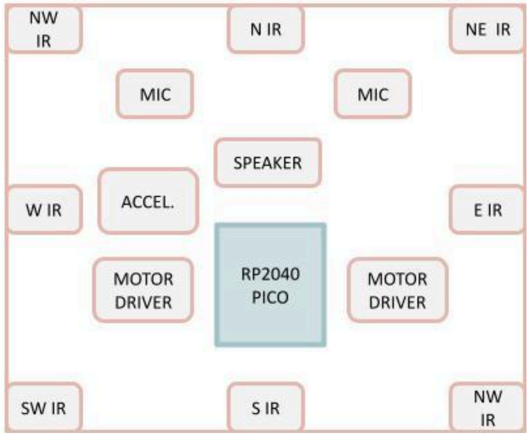

Figure 1: Final Block Diagram

3.1 Schematic Design

The full schematic diagram is shown in Figure 9. When designing a PCB using the RP2040 Pico, there are an abundance of resources available. I specifically used the “Hardware Design with the RP2040” manual which offers a minimal design example that this initial design was based off of that I will also further refer to in the following sections.

The schematic is organized into several sections, with each serving a particular purpose which will be detailed below. The power section includes voltage regulators, capacitors, and a USBC-Board connector for programming and power to ensure stable power supply to the other components on the board. The input power connection for this design is via the 5V VBUS pin of a Micro-USB connector which is regulated down to 3.3V that is then relayed to the rest of the components on the board. Various decoupling capacitors are necessary for the RP2040 as well to filter out power supply noise. The next section is the Flash storage section. In order to be able to store program code which RP2040 can boot and run from, we need to use a flash memory, specifically, a quad SPI flash memory. A crystal oscillator is also necessary to be able to have a well defined frequency source. But even though the RP2040 does not actually require an external clock source, it is good practice to have a stable source for other applications. Both the flash and crystal oscillator designs were directly taken from the Minimal design example.

It also includes 8 IR LED emitters and receivers, as indicated in Figure 2, in which each pair is arranged to maximize coverage. The emitters emit infrared light when powered, and are connected through current limiting resistors. For the receivers, photodiodes are used to detect the light and generate a small current when the light hits the photodiode that is then amplified using a transistor to then be read by the microcontroller.

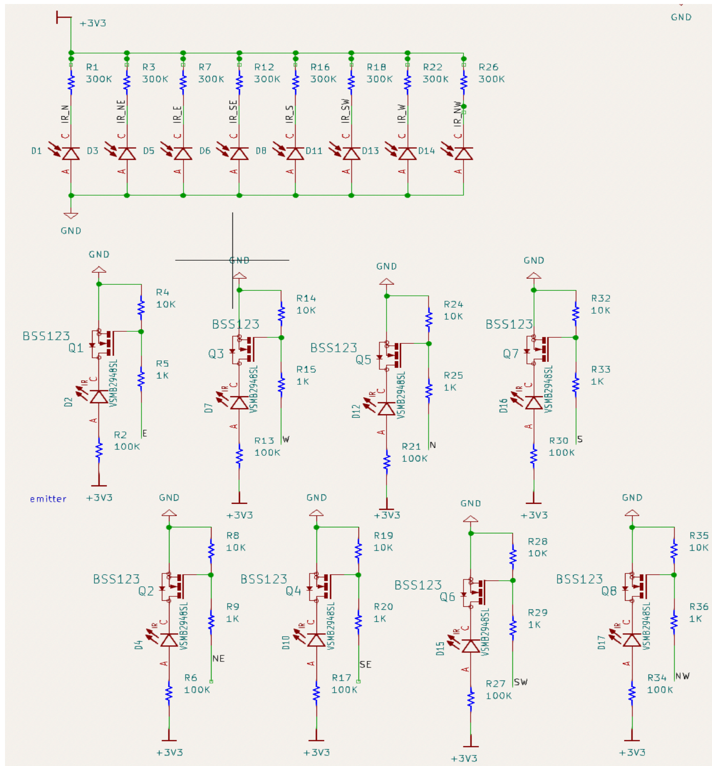

Figure 2: IR Emitter & Receiver Design

Since the robot was a battery powered device, a boost converter is necessary when the desired output voltage can be higher or lower than the input voltage, shown in Figure 3. The particular motor drivers being used for the motors operate at 6V. In the design of this, a Schottky diode was used, because it has a low forward voltage drop and fast switching speed. It allows current to flow to the output when the switch is off and blocks it when the switch is on. When the internal switch of the MC34063 is closed, current flows through the inductor L2, storing energy in its magnetic field. When the switch opens, the stored energy in the inductor is transferred to the load via the diode D18. The inductor's voltage reverses to maintain current flow, stepping up or down the voltage as required.The output voltage is fed back to the MC34063 through the voltage divider (R45, R46). The MC34063 compares this feedback voltage to its internal reference and adjusts the duty cycle of the switch to maintain a constant output voltage, which is 6V in this case.

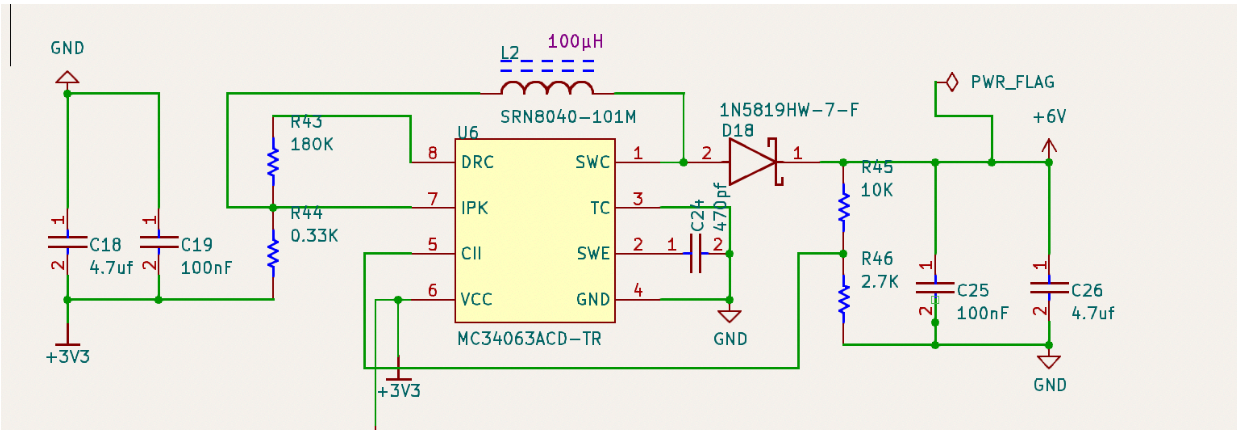

Figure 3: Boost Converter

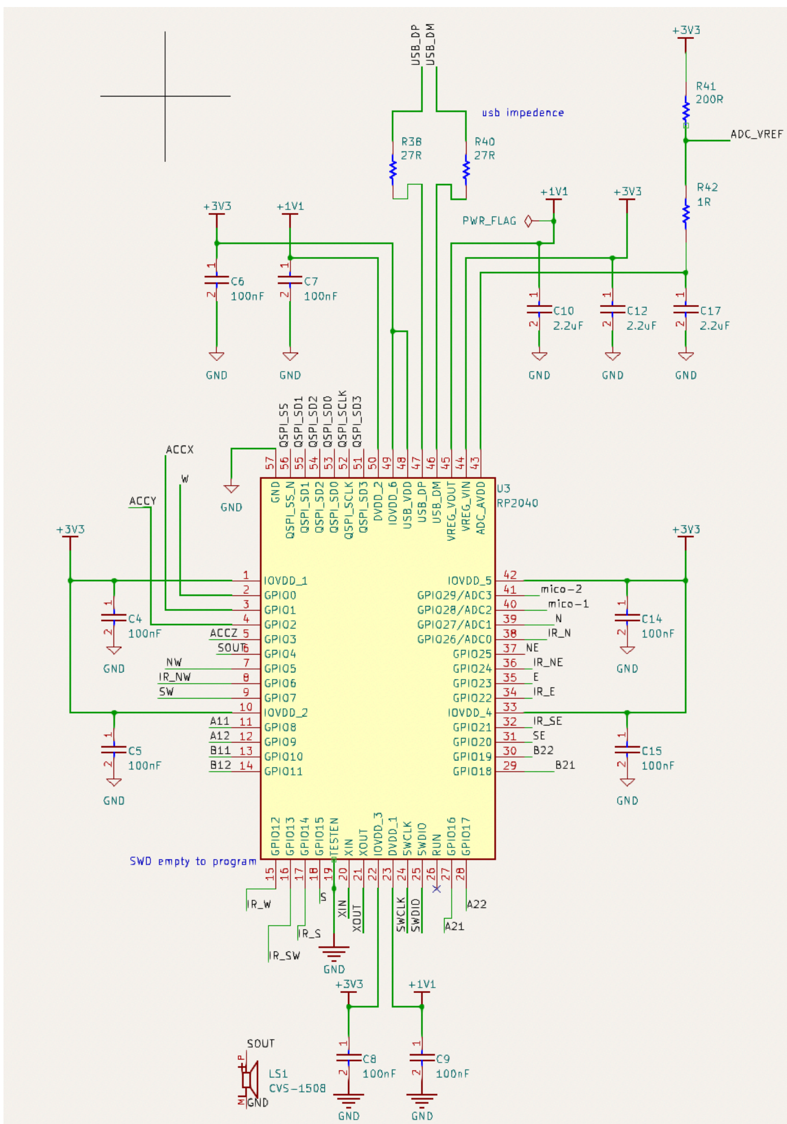

Figure 4: RP2040 Design

With the RP2040 being the base microcontroller for this project, described in the earlier section, various decoupling capacitors are placed close to the power pins to filter out noise and stabilize the voltage. This design is shown in Figure 4. All of the GPIO pins were used for the different peripherals and sensors of the robot, which required a tradeoff between the number of decoupling capacitors while still having enough space for chip pins. The different peripherals connected to the GPIO pins include X,Y,Z of accelerometer, each emitter and receiver pin for all 8 IR sensors, the two microphones connected to the ADC pins, and the speaker. The SWDIO and SWCLK pins are for Serial Wire Debug (SWD) which is used to program and debug the microcontroller.

3.2 Layout Design

The layout of the components is extremely important as each robot needs to be able to completely function by itself while maintaining the most accurate sensing information, with the final layout seen in Figure 10. The eight IR sensors are strategically positioned around the edges of the robot, with emitters on the top layer of the PCB and receivers on the bottom layer. The layout of the components is crucial, as each robot must operate independently while ensuring the highest accuracy in sensing information. This design minimizes noise during data reception. The sensors are arranged clockwise to cover the directions: north, northeast, east, southeast, south, southwest, west, and northwest. Since these IR sensors function as distance sensors, placing them as so allows for full 360 degree communication range. The two microphones were also placed towards the top symmetric with each other with the speaker in the middle of them, but slightly lower. This arrangement was chosen to ensure balanced audio capture from both sides, improving the robot's ability to detect the direction of sounds. The central placement of the speaker ensures that the audio output is evenly distributed.

4 Software design

The software architecture of the robotic swarm is designed to manage and facilitate inter-robot communication and coordination. I designed two communication protocols that leverage both infrared (IR) and audio signals, allowing the robots to interact seamlessly and respond dynamically.

4.1 IR Communication

The software architecture for the IR communication in the swarm robotics system is designed to handle short, high-intensity bursts of infrared light, which are crucial for rapid and effective robot-to-robot interactions. Each robot in the swarm is equipped with IR emitters and receivers that operate synchronously to transmit and receive signals. The emitters send out coded pulses of infrared light, which are captured by the receivers on nearby robots. The emitters use PWM signals from the microcontroller to generate these pulses of light. The choice of high-intensity bursts helps in minimizing the interference from ambient light and increases the communication range and reliability. On the receiver side, they detect these bursts via a pin on the microcontroller as well. I chose to only record the bursts if it was within a specific frequency range to allow them to be tuned to the specific frequency of the IR LEDs while accounting for error.

The received IR signals are then passed through a bandpass filter that eliminates the unwanted frequencies while waiting 3 timesteps for the signal to come through. It is then converted into electrical signals, which are decoded through demodulation. The software logs this decoded data and uses it to adjust the robot's actions accordingly. This might include changing direction, altering speed, or executing specific tasks, based on the collective behavior of the swarm. The system is capable of handling a high volume of signals efficiently, which is essential for maintaining the integrity and synchrony of the swarm's operations.

4.2 Audio Communication

In addition to IR, the swarm robots utilize audio communication to enhance their interaction capabilities, especially over longer distances or in environments where IR signals might be obstructed. The software is designed to generate specific audio signals, which are synthesized frequencies emitted through speakers and captured by microphones equipped on each robot. These audio signals are used for more complex commands or status updates that require a broader communication range. Upon reception, these signals are processed by filtering and demodulating the audio into digital data. The software continuously monitors and logs these communications, decoding them to retrieve meaningful information that influences the swarm's decision-making processes. The decoded data can prompt the robots to perform synchronized tasks or to relay important information back to a central controller or leader robot. This dual-mode communication system—integrating both IR and audio—ensures robustness and flexibility, allowing the swarm to operate effectively in a variety of environmental conditions and scenarios.

5 Evaluation

5.1 Single Robot Testing

The testing phase of this project was crucial to ensure the functionality and reliability of the designed robotic swarm. The primary objectives were to verify the correct operation of individual sensors and communication modules, before beginning to solder additional robots. To begin, I conducted a series of electrical tests to confirm the integrity of power and ground connections. The voltage regulators and decoupling capacitors were checked to ensure stable 3.3V and 1.1V outputs as the 1.1 is what powers the RP2040 Pico itself. The functionality of the boost converter was verified by measuring the output voltage and confirming it maintained a consistent 6V supply for the motor drivers. The individual components on the board were tested using a multimeter and oscilloscope to ensure that no parts had shorted or burnt out. The RP2040 microcontroller was then programmed with test firmware to interact with all connected peripherals by testing each GPIO pin to verify proper connection and functionality. The top and side view of the robot is seen in Figure 11 and 12.

Each IR sensor's signal strength was measured at various distances to create a calibration curve, validating their accuracy in proximity detection and distance measurement. Figure 4 and 5 illustrate the relationship between IR signal strength and distance. The blue line represents the raw data collected from the IR sensors, while the red dashed line indicates the fitted data. As the distance increases from 0 to 50 cm, the IR signal strength decreases exponentially. This predictable decay pattern confirms that the IR sensors effectively measure distance, as the signal attenuation follows the expected behavior of IR waves. This is critical for proximity detection and short-range communication within the swarm, ensuring that robots can detect and avoid obstacles or other robots accurately. I also wanted to verify that the use of 8 IR sensors does allow for 360 distance ranging, shown in Figure 5. Figure 6 provides a polar plot of the IR sensor distance measurements, showing the coverage and detection range of the sensors. Each sector represents a direction (e.g., north, northeast, etc.), with the distance measurements extending outward. The plot demonstrates that the IR sensors can detect objects in all directions, providing a full 360-degree coverage. This comprehensive sensing capability is vital for the swarm's situational awareness, allowing robots to navigate complex environments and maintain spatial relationships with other swarm members.

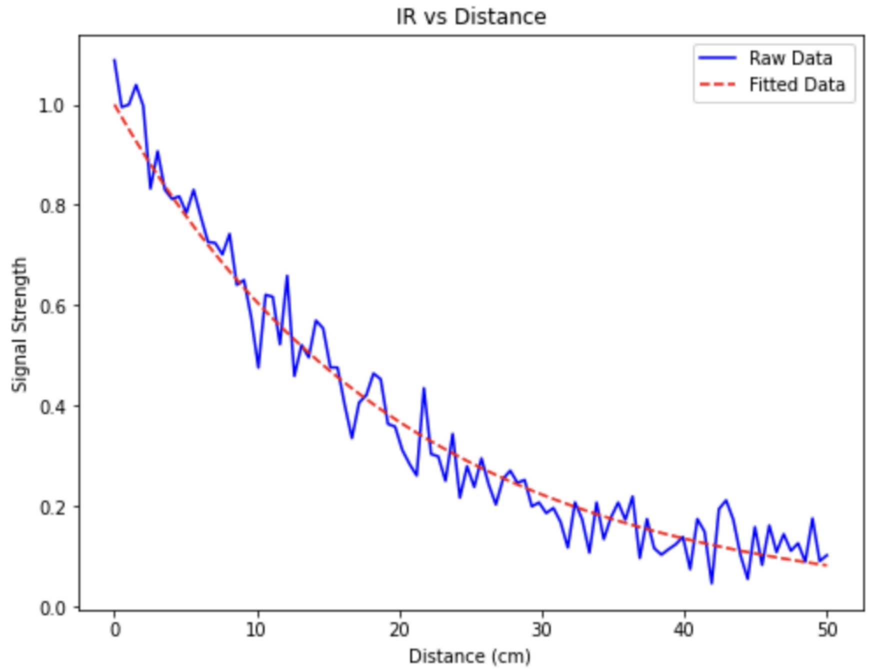

Figure 4: IR vs Distance

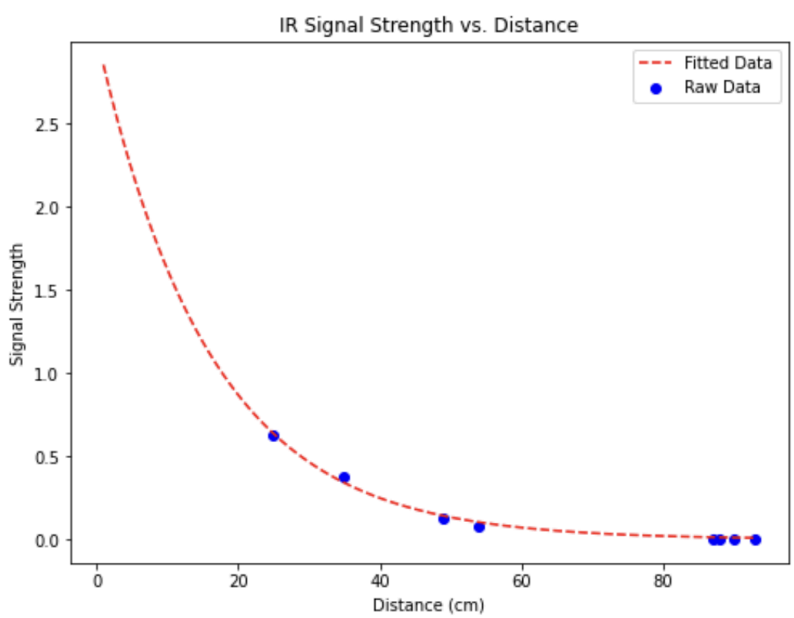

Figure 5: 8 IR Sensors Strength vs Distance

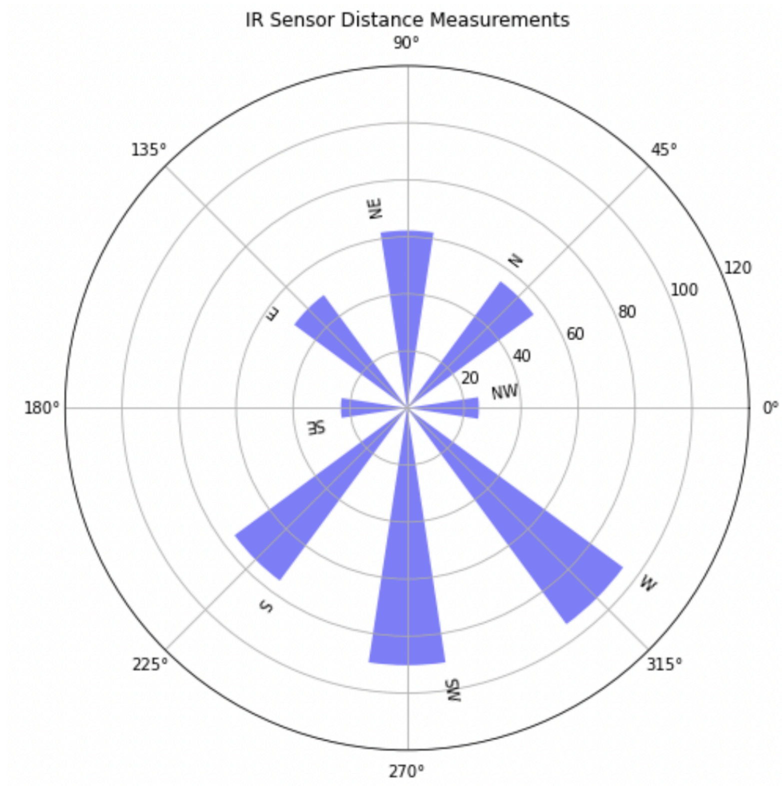

Figure 6: Polar Plot Comparison

The accelerometer was tested by subjecting the PCB to controlled movements and comparing the raw and filtered data to expected motion profiles. Figure 7 shows the accelerometer data along the X, Y, and Z axes. Each subplot compares raw data (blue) with filtered data (red). The filtered data closely follows the raw data, indicating that the accelerometer is accurately capturing the robot's movements and orientations. The X and Y axes display smooth periodic signals, which may correspond to the robot's motion patterns. The Z-axis shows more significant peaks, possibly due to vertical movements or impacts.

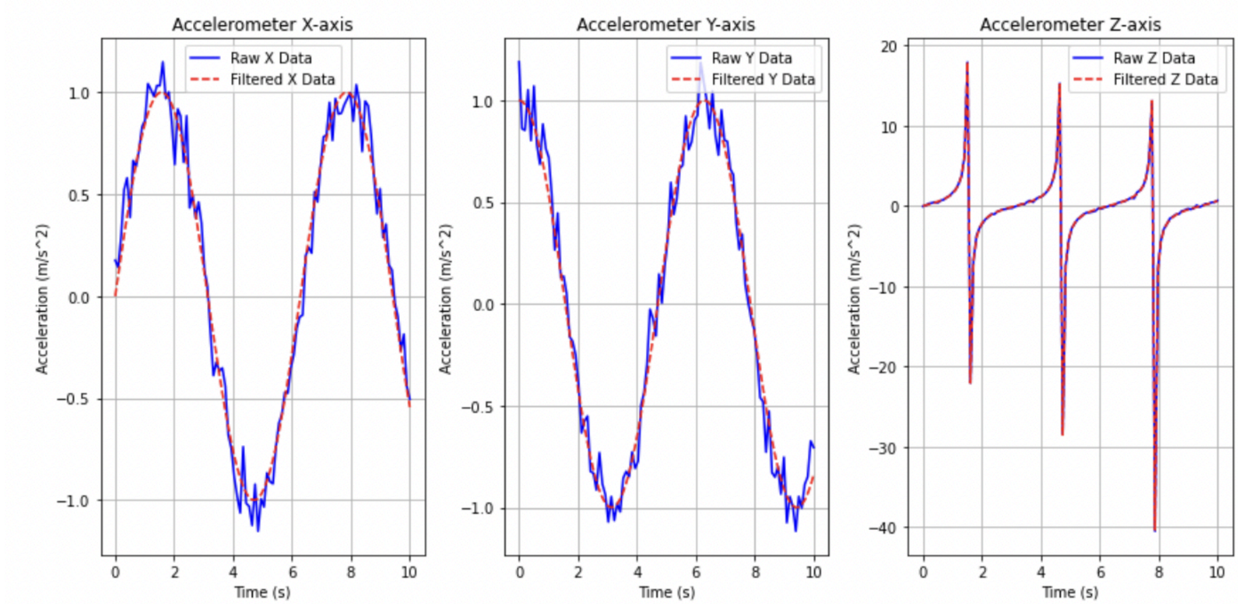

Figure 7: Accelerometer Data

The speaker and microphone were tested by emitting and capturing audio signals, ensuring clear transmission and reception. Figure 8 compares the emitted and received audio signals. The top plot shows the original tone emitted by the speaker, a consistent signal intended for communication. The middle plot displays the unfiltered signal captured by the microphone, which includes some noise. The bottom plot shows the processed signal after filtering, closely resembling the original emitted tone. This demonstrates that the audio communication system can effectively transmit and receive audio signals, filtering out noise to maintain clarity.

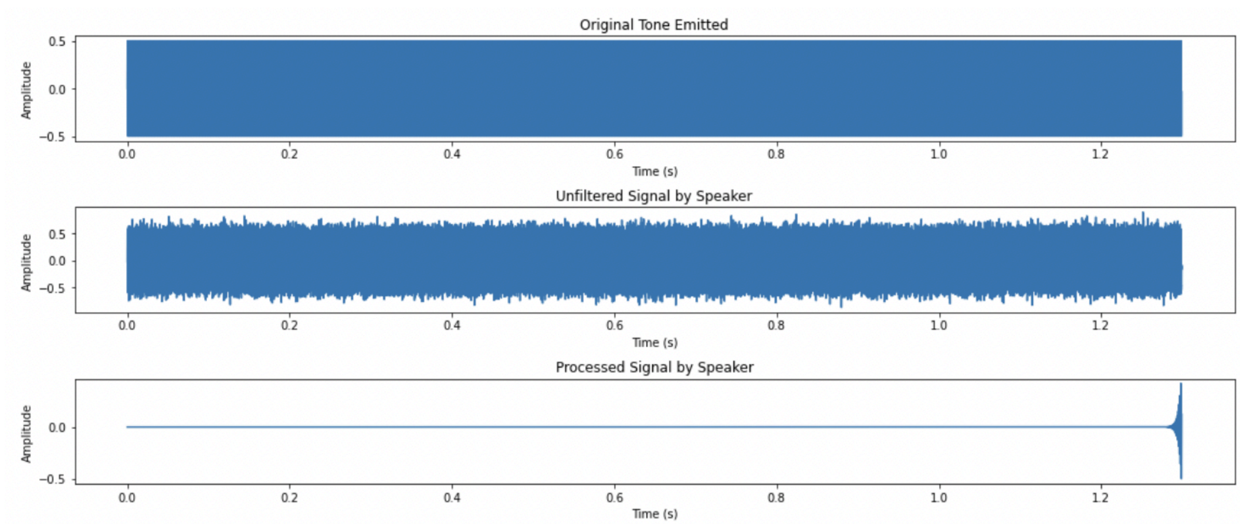

Figure 8: Speaker vs Microphone

6 Conclusion

In conclusion, the design and implementation of a large-scale robotic swarm, as presented in this project report, underscore the potential of swarm robotics to revolutionize various industries through enhanced efficiency, precision, and scalability. The results described in the evaluation section validate the design and implementation of the sensory and communication systems in the robotic swarm. Together, these systems enable the robots to perform coordinated tasks, avoid obstacles, and communicate effectively, ensuring robust and efficient swarm behavior. The successful validation of these components lays a solid foundation for scaling up the swarm and deploying it in various real-world applications, from environmental monitoring to disaster response.

7 Appendix

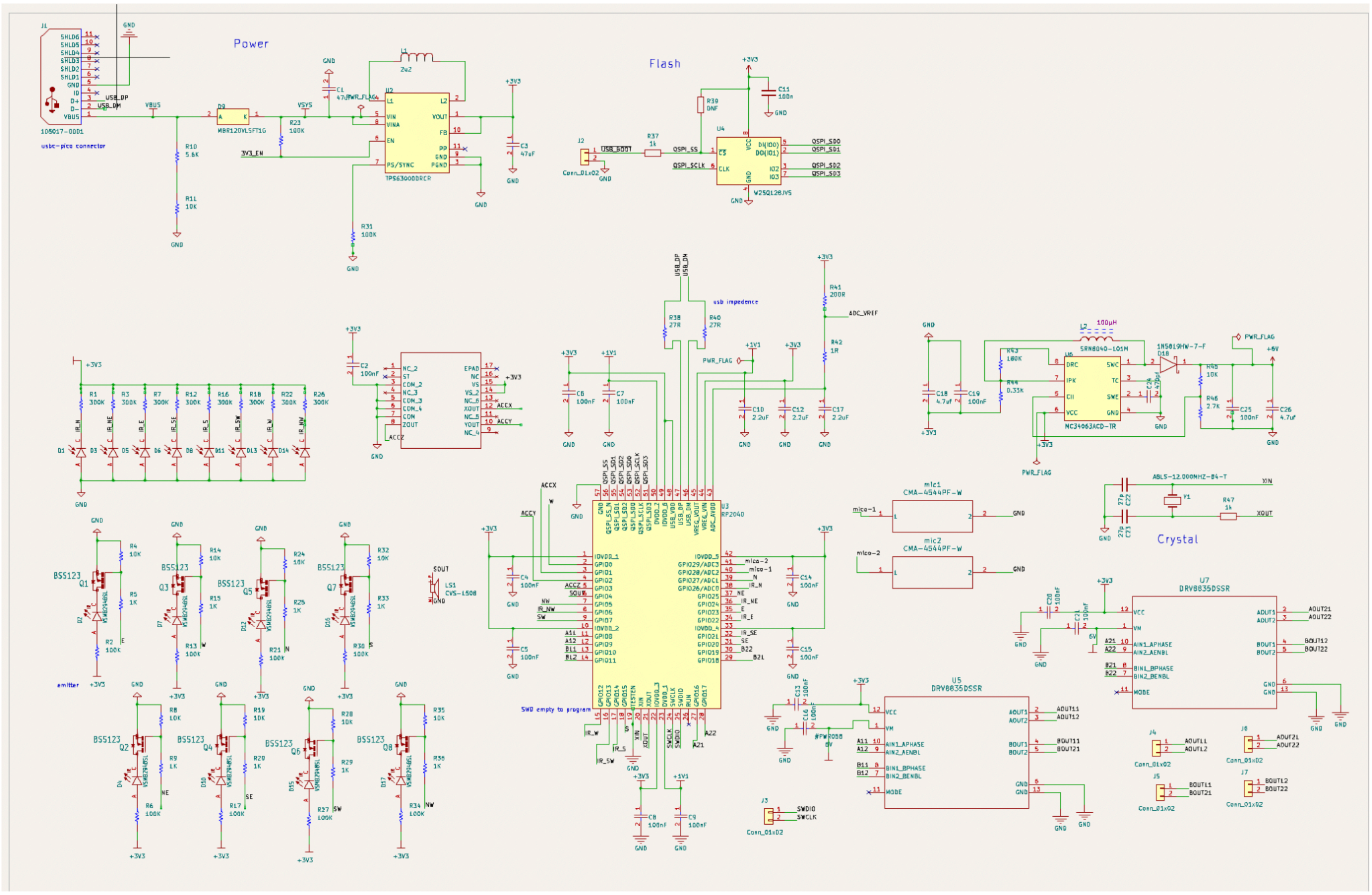

Figure 9: Schematic Design

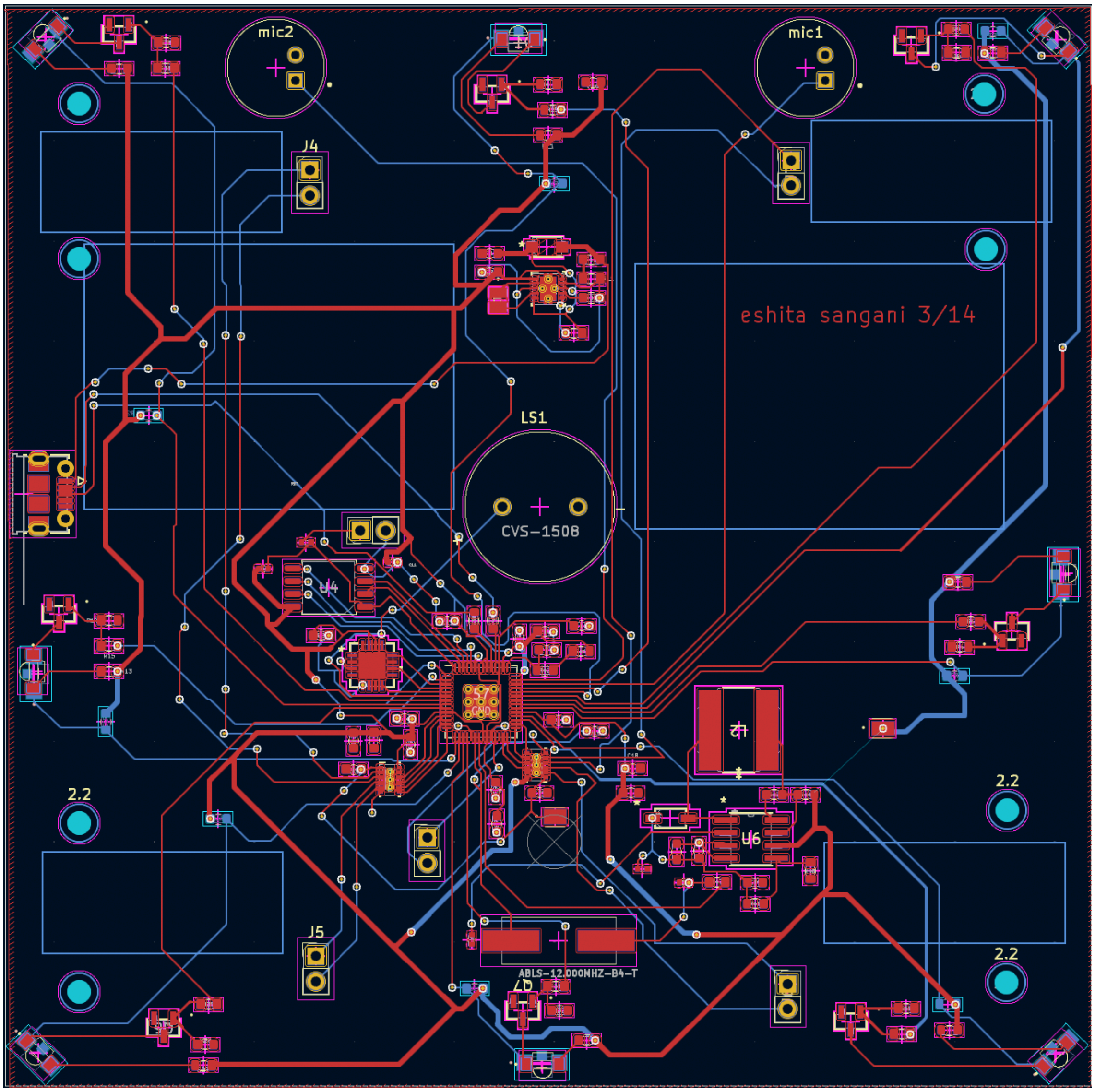

Figure 10: Layout Design

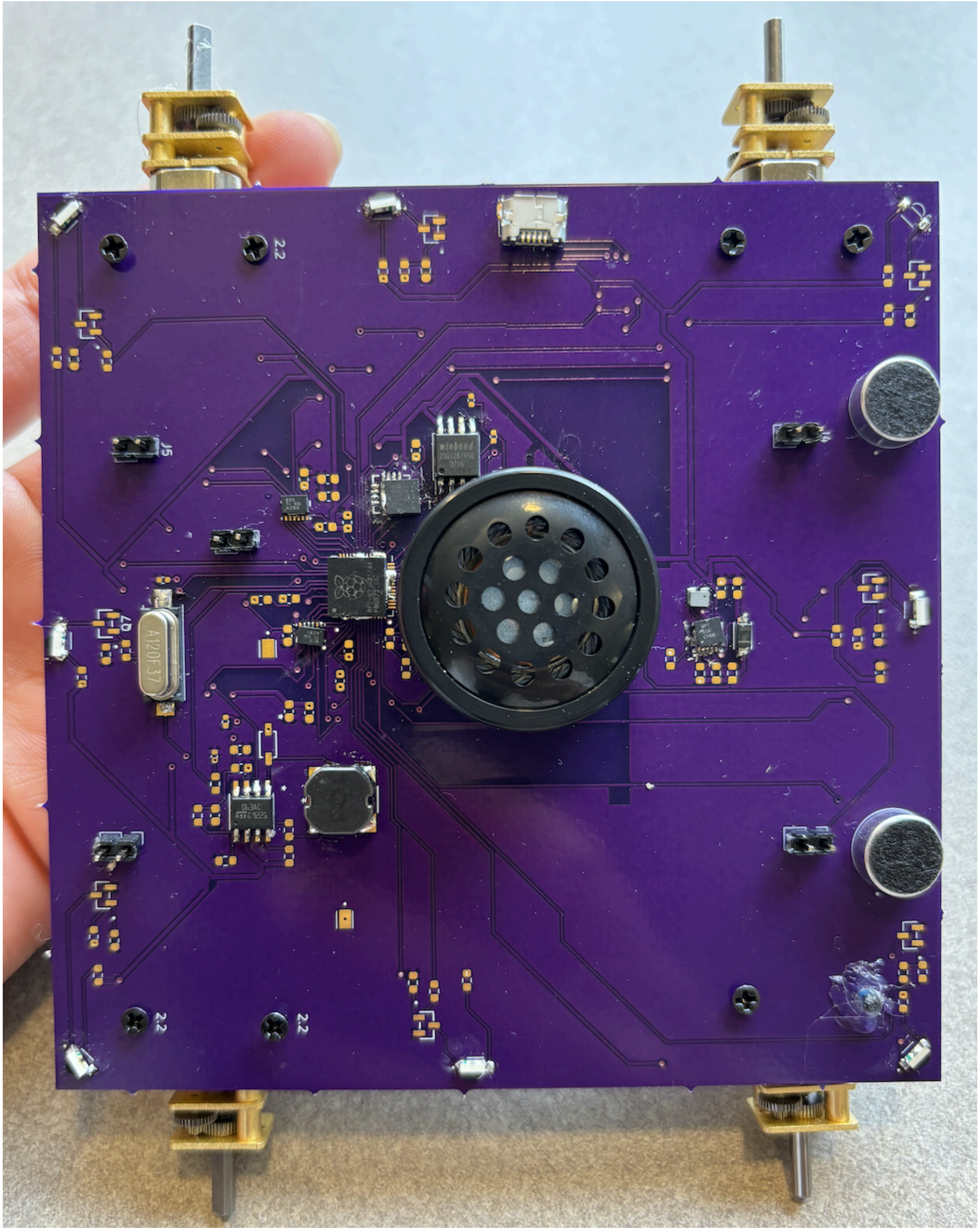

Figure 11: Top View of Single Robot

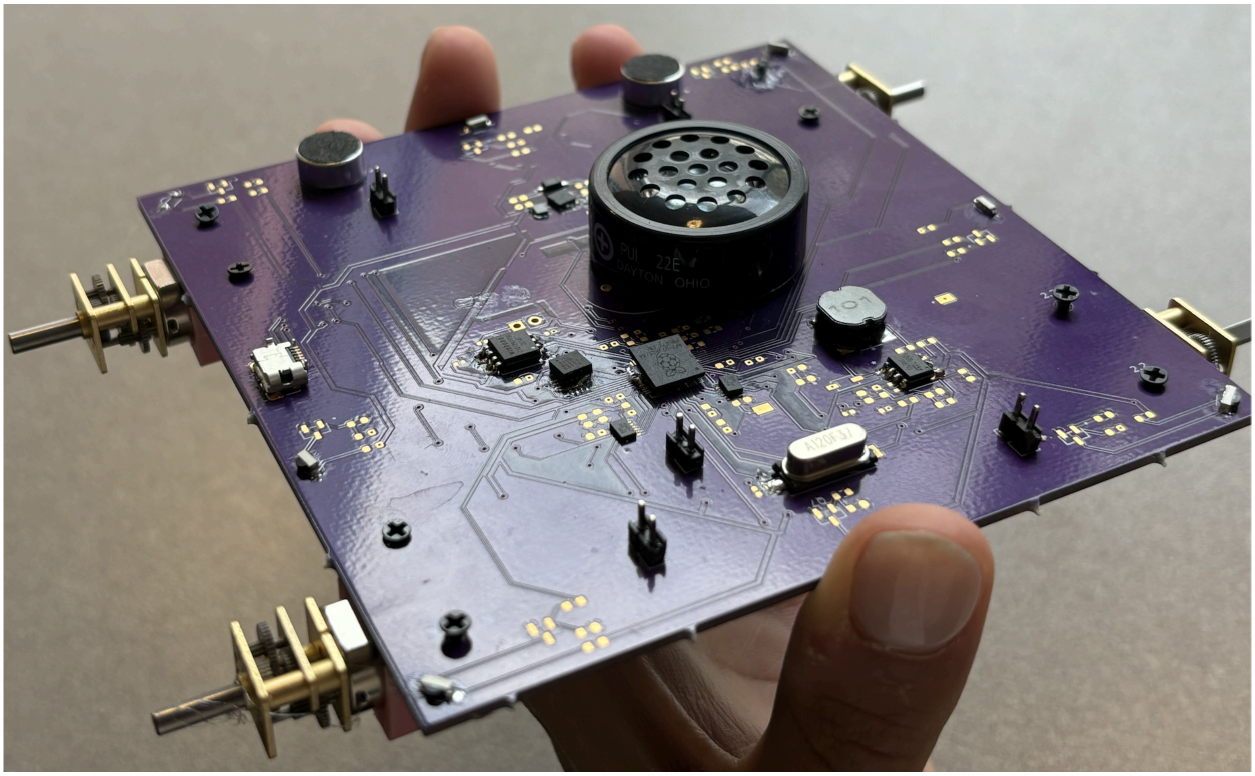

Figure 12: Side View of Single Robot