FH04 Project Aves

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EXECUTIVE SUMMARY

The goal of the project is to create a device that will be placed in various environments for bird monitoring purposes. Through audio detection, the device will be able to identify what species of birds are in the area as well as localize the audio to determine the location of where the bird is calling from. This will allow for species monitoring, population monitoring, and migration tracking. The device will also host a variety of sensor inputs that can monitor environmental data such as soil moisture, humidity, and temperature.

The stakeholders of the project provided an existing prototype that handles most of these functions except for audio localization. The current prototype consists of a solar panel setup that feeds into an electronics box that hosts a Raspberry PI to run a machine learning database to determine bird species. In addition, several analog sensors are wired into a PI hat to collect environmental data.

For this project, the goal is to streamline their hardware system that allows for better thermal regulation, host more input/output ports, and be more user friendly. In addition, the project seeks to create a localization package that includes a microphone array to collect different vectors from an audio source and a program to calculate and determine the location of the source.

To implement this, the team created a main printed circuit board (PCB), denoted as “The Mainboard,” that hosts the Raspberry PI and has plenty of input/output ports to host environmental sensors and data storage. The PCB allows the user to easily swap out sensors, pull data from board, and regulate heat better as there are no PI hats stacked on top of each other. For the localization package, an array of microphone PCBs were designed, with each board having four microphones and a microcontroller to communicate with the Raspberry PI and process the vectors. Through the array, vectors can be collected to calculate the location of the source, and software was designed to ensure that all the vectors are time-synced and aligned with a single audio source at a time.

After manufacturing a first draft of The Mainboard it was discovered that due to wiring errors to the PI, none of the data collected by the microphones or sensors could be processed through the PI. In the second draft, manufacturing errors led to inconclusive results as the PI could not properly boot. The team settled with a pre-existing Raspberry PI board that could handle the necessary amount of inputs required for testing. Due to the difficulties with getting the Mainboard working, the localization package could not be tested in the field. However, using randomly generated vectors, the team successfully showed the capabilities of source localization through the program.

The project had many time constraints of finishing board designs quickly in order to allow for sufficient time for the board to be manufactured and shipped from China to the United States and still have time for testing. This meant that the required software to be tested also needed to be done by the time the boards came in. Delays in shipping for The Mainboard caused pushback in timelines and resulted in less test time than the team would have liked. As far as financial costs, the majority of costs came from buying the necessary components for The Mainboard and its manufacturing costs. The only other significant costs were buying pre-existing solutions to analyze their effectiveness and the costs to manufacture a physical mounting structure for the board and sensors.

As the device was not meant for regular use by humans, the only concerns about safety with the device was its impact to the environment. Throughout the project, the team had to keep in mind that this device would be in natural environments where it could disturb the natural environment and the species living there. In addition, the device had to be designed to withstand the natural environment to ensure that nothing would overheat or discharge any waste into the environment as the device is often left alone without human interaction for long periods of time.

The next step for the project is to design a new Mainboard that can easily be manufactured whilst still containing all the required components. After verifying the functionality of The Mainboard, further testing of localization in a real environment can be done.

1.0 INTRODUCTION

Project AVES is a joint project with the University of Texas at Austin's Robotics and Integrated Biology labs. The goal of the project is to record bird calls, identify species, localize bird positions[7], and collect environmental data, such as soil moisture and temperatures, in isolated environments with minimal maintenance.

The system design report provides the technical design, risk reduction strategies, testing plans, and project management plans required to build the device. The report is split into six parts, Design Problem, Design Solution, Design Implementation, Test and Evaluation, Time and Cost Considerations, Safety and Ethical Aspects, and Recommendations. The Design Problem, Solution, and Implementation describes the design problem, project specifications, implementation, and deliverables while providing context and motivation behind Project AVES. The Test and Evaluation section provides a breakdown of the system into its hardware and software components, including research, testing, and experimentation to refine the design. The Time and Cost Considerations section outlines the timeline of the project's development and details the allocation of financial resources throughout the design and testing phases. The Safety and Ethical Aspects section addresses the responsibilities associated with deploying a device in natural environments. It discusses potential risks to users, wildlife, and the environment, as well as the ethical implications of data collection, privacy, and long-term monitoring. Finally, the Recommendations section summarizes key insights gained during the project and offers guidance for future iterations. This report serves as a comprehensive guide for the development and implementation of Project Aves, ensuring an efficient workflow and reliable solution to environmental monitoring.

2.0 DESIGN PROBLEM

The design problem is to create a device whose main function is bird species monitoring. This will be done through audio detection. By listening to different bird calls in the area, the device should be able to identify what the bird is and the location it is calling from. This will help monitor species in the environment, identify migratory patterns, and monitor populations. The biggest challenge is implementing a method of audio localization that can accurately determine the distance the bird is from the device. The device will also need to run a machine-learning database that identifies the bird calls.

In addition to bird species monitoring, the device also needs to be capable of collecting environmental data such as soil and climate measurements. Since the device is left out in environments for long periods, often many years, the device also has to be robust enough to run its data collecting capabilities while also being self-sufficient in power. Due to the device being out in the environment, it needs to be unobtrusive, which will require making the physical electronics of the device small enough to be able to be stored within a product that it does not disturb the animals of the environment it is in. This will allow animals to behave naturally around the device, allowing our device to collect accurate data about the animals in the environment.

To be able to make this device successful, it will be important to learn the intricacies of bird calls[8] and how to detect them, audio detection methods, optimization of electronic design, and environmental protection methods. If these problems are correctly tackled, researchers, environmentalists, and bird enthusiasts can use the device to collect important bird species and environmental data.

2.1 Design Goal

Project AVES aims to design and implement a multifunctional, autonomous device capable of monitoring environmental conditions and bird populations in a variety of ecosystems. The core functions of the device include recording and analyzing bird calls while simultaneously collecting local data such as soil moisture, and temperature, as well as air temperature, moisture, and humidity.

The device will operate autonomously, powered by a solar panel and backed up by a battery system to ensure continuous functionality, even in less optimal weather conditions. The data will then be stored locally within the device while being able to wirelessly transmit processed data to researchers.

It is important to note that the device is designed solely for a passive monitoring system through non-intrusive measures and not for any real-time interaction with its environment. Its longevity and resilience are key design features, making it suitable for year-long or multi-year studies in various outdoor conditions. Additionally, the project will not include handling data security concerns, commercialization, or intellectual property management, as this is strictly an academic and research-focused effort.

2.2 Specifications

This section outlines the design specifications for the device, detailing the environmental factors, operation environment, system outputs, audio sensing inputs, user interfaces, and performance requirements. These specifications ensure the device is reliable, user-friendly, and capable of meeting deployment needs across diverse and challenging conditions.

2.2.1 Environmental Factor Input Bounds Specifications

The device incorporates capacitive soil moisture sensors for cost-effectiveness, soil and ambient temperature sensors designed for high-temperature environments requiring external ADCs, and a solar power bank system that may expand with project needs.

Table 1. Environmental Factor Input Bounds Specifications

Input	Bounds
Soil Moisture Sensor	Likely capacitive type, more advanced sensors quickly become expensive. Production deployments might be able to leverage better sensors depending on budget and application. [1] Usually have their ICs with ADCs, interfaced over I2C, SPI, UART, or other channels.
Soil and Ambient Temperature Sensors	Deployments are expected to be in forest and

	desert environments and will need to withstand relatively high maximum temperatures. Will need an external ADC for interfacing, as currently considered SOMs do not have onboard ADCs.
Ambient Temperature Sensor	See comments for the Soil Temperature Sensor above (Table 3.1, Soil Temperature Sensor)
Solar Power Bank	Stakeholders have created a system for this. It involves a solar panel connected to a backup battery and the main hardware system.

2.2.2 Operation Environment Specifications

The device is designed to function in extreme environmental conditions, managing heat in enclosed spaces and optimizing power consumption for solar-powered setups. It runs on a Debian-based OS with TensorFlow Lite compatibility for efficient bird call classification.

Table 2. External Environment Operation Specifications

Aspect	**Requirements**
Temperature	Devices must be deployable and remain completely functional across a nearly universal set of environments: deployments of similar devices have taken place in both temperate and extreme temperature conditions, ranging from tropical rainforests

	to deserts.
Rainfall and water	Devices must be deployable across a nearly universal set of environments: deployments of similar devices have taken place in environments where they will be prone to water ingress. If not designed for, water ingress will likely result in heavy damage to electronic components.

Table 3. Internal Design Constraint Specifications

Aspect	**Requirements**
Heat Generation	The mainboard will reside in an enclosed box, so thermal management is critical to prevent the Linux SoM from overheating (leading to premature failure or downtime).
Power Consumption	Power is provided by a lead-acid solar-cell charging solution[10]. Though the power provided is stable, there is limited capacity. Device specifications will need to be chosen to prevent excessive current draw and voltage drop (leading to downtime as the battery recharges).
Debian-Based Operating System	Stakeholders require a Debian-based operating system to maintain the portability of the current codebase.
TensorFlow Lite Compatibility/Optimization	Stakeholders would like to use BirdNET, a

	Tensorflow Lite neural network classifier for bird calls. [2]

2.2.3 Total System Outbounds Specifications

Outputs include a wireless communications module for remote management and versatile deployment and an SSD array for robust, low-power storage of bird call data, ensuring reliability and redundancy.

Table 4. Total System Output Bounds and Justifications

Input	**Bounds and Justification**
Wireless Communications Module	Enables remote management (via Secure Shell or management console), and PTP/PTMP communications for multi-device deployments[13]. A combination of both might be advantageous for short-range high-speed and reliable remote access.
SSD Array/Sensing Data	Meets requirements for redundant, reliable, robust, and replicable low-power high-capacity storage to store recorded bird calls/identifications.

2.2.4 Audio Sensing Input Bounds Specifications

The audio system uses an electret microphone capsule that is connected to an op-amp in a circuit board to facilitate accurate localization and high-quality bird call analysis. Multiple microphones will be placed around a focal point for more accurate vectorized localization, leveraging efficient and cost-effective sensing technologies.

Table 5. Audio Sensing Input Bounds and Justifications

Input	**Bounds and Justification**
MEMS/Parallel Polled Microphone Arrays	Localization is often performed using microphone arrays with data recorded virtually instantaneously. Using an MCU with fast internal switching ADCs on traditional omnidirectional microphones, or better yet, MEMS microphones (which have onboard ADC capabilities and digital communication, are inexpensive, and surface-mountable) would provide for this.
Recording/High-Resolution Microphone with 4+ Channel ADC	Provides high-quality audio of bird calls, enabling further analysis and identification. Using a single 4-channel ADC ensures signal synchronization.

2.2.5 User Interface Specifications

User interface specifications for this device are relatively simple: the hardware must be robust and easy to assemble (Table 2.6), and only standard basic communications are required on the software end (Table 2.7).

Table 6. Hardware User Interface Specifications

Aspect	**Requirements**
Mainboard Assembly	Users must be able to assemble the main device without extensive electronics

	experience. The main circuit board should necessitate no soldering for routine setup and repair: any add-on devices should be pluggable.
Device Connections	Users should be able to use standard consumer hardware interfaces for device interconnects, e.g. USB for digital devices and XLR for analog audio devices.

Table 7. Software User Interface Specifications

Aspect	**Requirements**
Shell Access	Users must be able to access Linux SoM using Secure Shell or a similar protocol for management.
Logged Files	Users must be able to access and parse logged audio/sensor data from the onboard SSD array.

2.2.6 Performance Specifications

The device must be able to perform the required tasks effectively, including detecting sources both close and far range, as well as being able to localize the aforementioned sources, both of which are described in Table 2.8.

Table 8. Internal Design Constraint Specifications

Aspect	Requirements
Sensing Range	Each deployment should be able to localize and identify bird sounds within reasonable near to far-field localization ranges, though exact distances will vary by deployment.
Specific-Source Localization	The system must be able to differentiate bird sounds from ambient noise for localization.

2.3 Deliverables

The task can be grouped into two large deliverables: a compact main printed circuit board (PCB) capable of hosting the various devices required to solve the task at hand, and if the development timeline allows, an integrated hardware/software package for source localization of bird sounds, keeping in mind the restrictions posed by the surrounding environment.

2.3.1 Mainboard

The PCB will integrate any sensors, microcontrollers, and communication modules requested by project stakeholders. The board should be user-friendly, power efficient, and fit into the stakeholders' solar power setup. In addition, the board should fit in a standard, environment-proof enclosure to maintain the thermal stability of onboard devices[9][10][12].

2.3.2 Audio Source Localization Package

The audio and source localization package will at a minimum allow for usage of the stakeholders' current microphones with an existing identification system, and ideally will consist of microphone modules, hardware for neural network acceleration, and software to calculate the relative locations of birds from their calls. All hardware must be resistant to water intrusion, overheating, and animal interference through the selection of robust enclosures, external facing hardware, and careful device selection [9].

3.0 DESIGN SOLUTION

The system is broken down into two main components: a hardware package including a main circuit-board device, microphones, and environmental sensors; and a software package including firmware for audio source localization on distributed microphone boards, software applications interfacing with the BirdNET library, and software concerned with logging capabilities.

3.1 Design Concept

The Design Concept section covers three key areas: the hardware system, the software system, and the previous iterations and designs of the current device. Each area has been thoroughly explored to provide an in-depth understanding of the device's design process.

3.1.1 Overview

The hardware package consists of sensors to measure environmental conditions around the device, audio localization units with their own microphones and microcontrollers, high-resolution microphones for enhanced identification capabilities, disks for data storage, modems for remote access, and an ARM-based SOM to tie the system together. These components are organized and connected using appropriate communications channels as listed in Figure 3.1 below. Sensors have been allocated for environmental sensing, and microphone boards have been designed as separate units to handle localization preprocessing and audio collection tasks. Hardware outputs include a cellular modem and a redundant m.2 SSD array for storage.

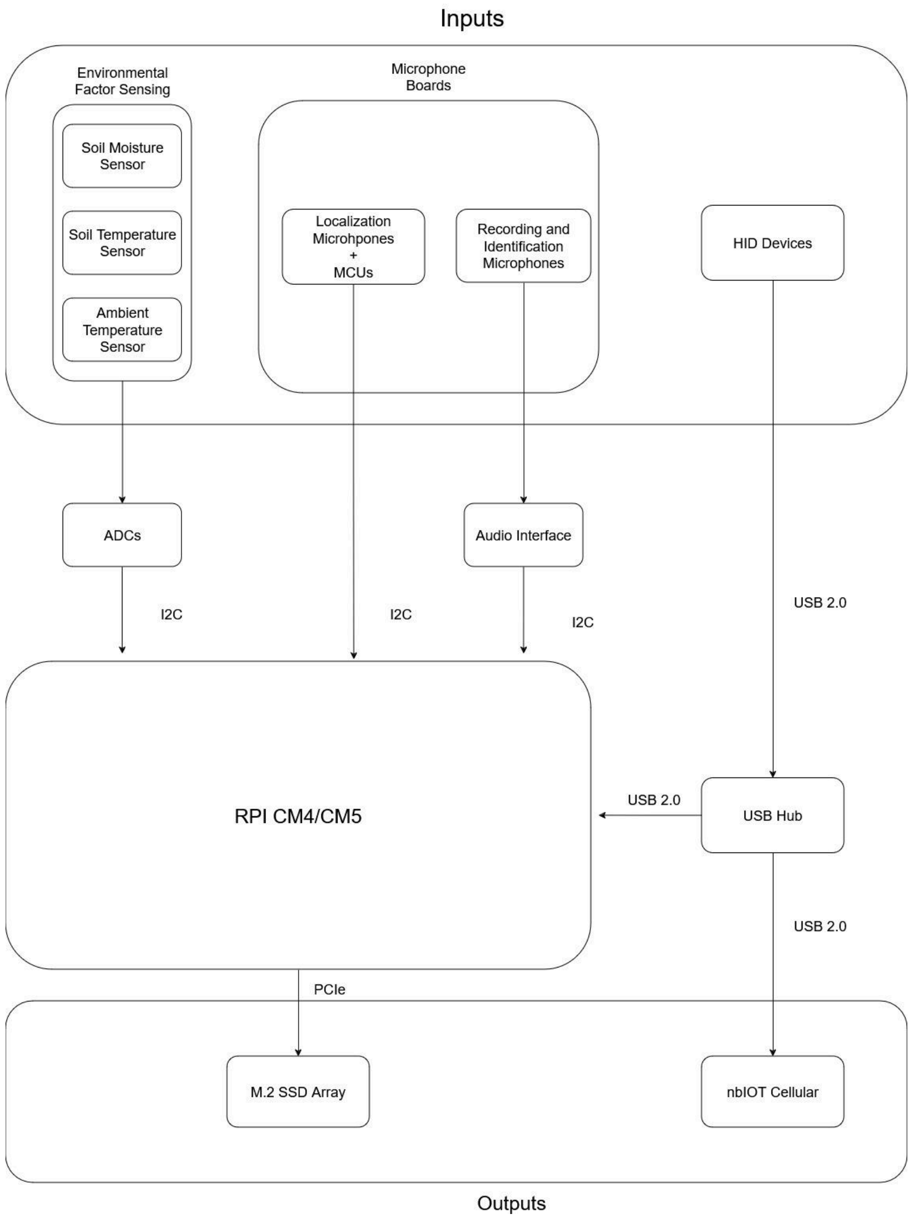


Fig. 3.1: Overall Hardware System Block Diagram

The software system is illustrated in Figure 3.2
below and consists of a firmware package to run on our proposed mic boards and a main software package that runs on the Raspberry Pi-based mainboard.

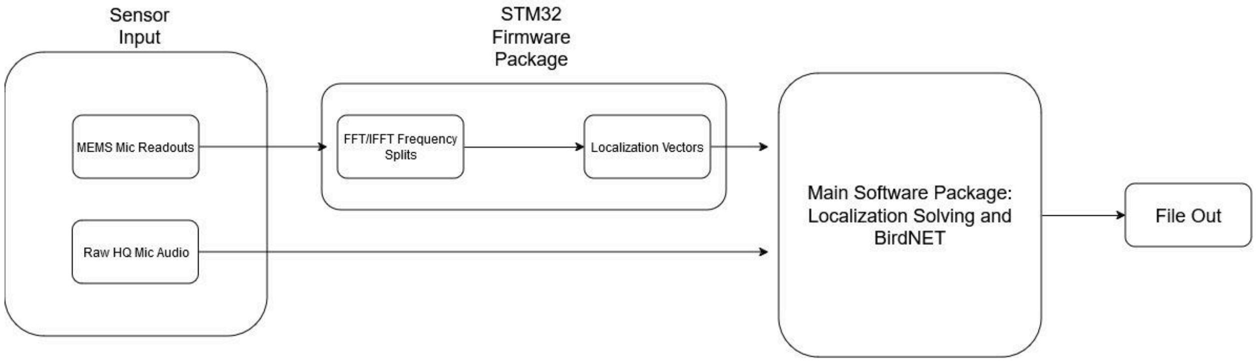


Fig. 3.1: Overall Software System Block Diagram

3.1.2 Hardware System Design

This section provides an in-depth explanation of the makeup of the hardware subsystem split into two sections. The two sections go into detail about the two main hardware subsystems. The first consists of a mainboard that houses main functions related to compute/data I/O. The second contains smaller mic boards to facilitate audio collection for localization and categorization.

3.1.2.1 Mainboard

The mainboard contains a Raspberry Pi Compute Module 4 along with various devices needed to facilitate communications with system inputs and outputs. Input peripherals include SparkFun Qwiic I2C interconnects for communication with the mic board subsystem and ADCs for reading data from environmental sensors (refer to Fig. 1) ensuring precise monitoring of climate and soil conditions. This system allows the device to handle all the different sensor inputs and send all the data for processing through the Raspberry Pi. Output peripherals include an M.2 SSD array for storing location and bird call identification information as well as an nbIoT cellular modem for remote management and monitoring. A USB hub has been placed onboard to allow for HID use and further expansion in the future. The success of this system is based on the proven reliability of the CM4 and its ability to handle the data processing of audio samples from the mic boards, machine learning capabilities of BirdNET for species identification, and integration of other input peripherals. In addition, power usage has been carefully designed and selected to operate based on the solar powered system specifications and optimizes energy usage in remote environments. The combination of the Raspberry Pi's computational power and power optimization strategies has ensured that the device is power efficient, and in addition the mainboard has served as the central hub for all data processing. The board has also been tested for functionality and power consumption to streamline further iterations.

3.1.2.2 Mic Boards

The mic boards contain four microphones for directional audio and a single high-resolution microphone for audio input. An STM32f4-based CPU allows for processing data to obtain the sound's angle of incidence for each timestamp it hears a bird call, which is then output over I2C to the mainboard[5]. The system requires a minimum of 2 microphone boards, with the possibility of adding more to improve localization accuracy. The success of the mic board is based on the reliability of the STM32f4's processor to ensure accurate processing of vectors for the mainboard to calculate the distance of the birds. In addition, the choice of microphones enhances the quality of audio samples for accurate filtering of background noise. Moreover, the selected components ensure the power specifications are met and the mic board can efficiently operate. As a result, by leveraging the STM32f4 processing, optimized microphone placement, and power optimization the mic board will serve as the localization tool for the mainboard. Measurements on an oscilloscope showed that we were able to achieve steady amplification and audio waveform recording. Analysis on the waveform and how it integrates with BirdNET have also been performed and are functional.

$$db = 20log(V/Pa)$$

$$Gain = R_{out}/R_{in}$$

The first equation describes what the decibel level is recorded from our audio source after the op-amp is recorded, while the second describes the gain of the device, such that the audio is able to be recorded.

3.1.3 Software System Design

This section provides insight into the design and purpose of the software system. Its main goal is to perform the process of audio localization and integrating BirdNET.

3.1.3.1 Software System

The software subsystem consists of a software package that is run on the mainboard and an accompanying firmware package that is run on the mic boards. The main focus of the software system is to be the mainboard package, as that has enabled the base requirements specified by project stakeholders. As the main software package has been developed, there has also been implementation of a localization solution involving the mic board firmware package.
In the fully developed version, the firmware and software work complementarily (see Figure 3.2): the firmware solution preprocesses audio, including denoising and breaking down localization vectors by frequency ranges to improve further analysis; the mainboard software package then uses this information to reconstruct the position of the bird, calling a BirdNET analyzer to identify the species and provide insight for preprocessing. The main software solution also records data from environmental sensors in a timeseries fashion, and has been containerized using Docker to improve development and maintainability.
This data is then written into files on the mainboard's SSD array. Each of the pieces of the stack have been individually tested before integration: testing BirdNET on static audio files through Dockerized containers has been performed, and test rigs for the firmware solution have been improved to be in line with updated development timelines.

4.0 DESIGN IMPLEMENTATION

The implementation of Project AVES involved a series of iterative design decisions, technical challenges, and refinements that ultimately shaped the final system—a robust, autonomous device for bird call localization, species identification, and environmental monitoring. This section outlines the critical factors that influenced our design solution, the major obstacles we encountered, the rationale behind key decisions, the evolution of our approach, and an economic analysis of our choices.

4.1 Design Decision Process and Iterative Development

The design decision process for Project AVES was highly iterative, shaped by ongoing testing, evaluation of alternatives, and the need to address technical challenges as they arose. Throughout development, the team continually refined both hardware and software components—making key adjustments in response to testing outcomes, such as switching amplifier designs for microphones and revising the mainboard approach after power delivery issues. This iterative approach ensured that each design choice was informed by real-world results and stakeholder requirements, ultimately leading to a more robust and effective solution for autonomous bird monitoring and environmental data collection.

4.1.1 Initial Concept and Requirements

The project was initiated with well-defined requirements: the device needed to identify bird species through audio analysis, localize their calls, gather environmental data, and function autonomously in remote locations with minimal maintenance. From the outset, the design prioritized robustness, low power consumption, modularity, and a form factor that would minimize disturbance to surrounding wildlife.

4.1.2 Main PCB Design Evolution

The mainboard was initially designed as a custom PCB built around the Raspberry Pi Compute Module 4 (CM4), intended to integrate sensor inputs, data storage, and communication modules. However, the first iteration of the PCB revealed a critical issue: the Raspberry Pi was not receiving power due to incorrect wiring, halting system operation and delaying further testing. After conducting trace-level debugging, the team decided to pivot to an off-the-shelf Pi I/O board for subsequent iterations. This change ensured reliable power delivery and accelerated hardware integration. Additional components, including USB, storage, and an ADC, were added to meet project requirements. This strategic pivot reduced development risk, saved time, and enabled continued progress on software and peripheral integration while the next hardware revision was in development.

4.1.3 Microphone Board and Localization Approach

Field testing using the STM32 BlueCoin development board demonstrated strong audio localization performance at short ranges of up to 20 feet[6]. However, performance rapidly declined beyond that range, particularly when detecting non-human sounds. These findings underscored the need for more sensitive microphones and enhanced signal processing capabilities to meet the demands of real-world deployments.

The microphone board was designed to enable accurate directional audio capture and preprocessing. Initial breadboard prototypes were used to evaluate various microphone and amplifier configurations. A custom op-amp circuit was developed but failed to produce usable output, leading the team to adopt a prebuilt Max4466 amplifier board. This solution offered reliable signal amplification and adjustable gain, though it was limited to a detection range of approximately 10 feet under lab conditions.

4.1.4 Software System and Integration

The software stack was developed with a focus on modularity and maintainability. BirdNET, the core model for species identification, was containerized using Docker to ensure cross-platform compatibility and simplify deployment. Custom software modules were created to parse logs and calculate localization vectors, enabling the pairing of detected bird calls with directional data. While the foundation for this integration was established, full implementation of timestamp matching was still in progress at the time of reporting. The system architecture supports independent testing of each subsystem, enabling parallel development and reducing overall project risk.

4.2 Obstacles and Adjustments

This section outlines the key technical challenges encountered during the project and the adjustments made in response. It covers issues related to power delivery and PCB design, including delays and a critical hardware flaw that prompted a shift to commercial components. It also discusses limitations in microphone sensitivity and localization range, leading to iterative testing and evaluation of alternative solutions. Finally, it addresses environmental durability concerns in the mechanical design and highlights the need for improved weatherproofing strategies. These experiences shaped the evolution of the system and informed future design choices.

4.2.1 Power Delivery and PCB Issues

The initial PCB's power issue posed a significant setback, preventing full system testing and stalling hardware progress. To overcome this obstacle and keep the project on track, the team made a critical decision to switch to a commercially available Pi I/O board for subsequent iterations, which ensured stable power delivery and allowed development to continue. Compounding the challenge, the shipping of PCB version 1.0 was delayed by nearly a month due to various logistical issues. As a result, the team was unable to test the custom hardware for an extended period and could only begin evaluation once the board finally arrived.

4.2.2 Microphone Sensitivity and Range

Laboratory and field testing revealed key limitations in microphone sensitivity and the effective range of sound localization. In response, the team explored alternative microphone types, experimented with different amplifier circuits, and evaluated potential commercial solutions such as AudioMoth. This iterative hardware testing approach enabled rapid prototyping and evaluation, providing valuable insights that informed future design improvements and guided the selection of more effective components for real-world deployment.

4.2.3 Environmental Durability

The mechanical design prioritized environmental resilience, featuring a central pole with branching arms to position microphones and protective enclosures to house the electronics. Structural integrity was validated through SolidWorks simulations, confirming the design's ability to withstand outdoor conditions. However, the team identified the need for further research into effective microphone weatherproofing solutions that preserve audio quality, highlighting an important area for continued development.

Table 9. Alternative Designs Considered

Alternative	Pros	Cons	Outcome
Custom op-amp circuit	Potential for tailored performance, cost	Difficult to debug, unreliable signal	Abandoned

	savings		
Prebuilt amp board	Reliable, adjustable gain, rapid prototyping	Limited range, less customizability	Adopted for prototype
BlueCoin dev board	Fast evaluation of MEMS mic arrays, proven design	Poor performance for bird calls, range limitations	Used for risk reduction
AudioMoth hardware	Proven in field, robust	Not fully open-source, integration challenges	Adopted Ideas from hardware for prototype

4.3 Economic Analysis (Cost/Benefit Analysis)

This section evaluates the financial decisions made throughout the project, balancing cost, risk, and long-term value. It compares the initial investment in a custom mainboard with the later shift to an off-the-shelf I/O board, highlighting the benefits of reduced risk and faster development. The selection of low-cost, readily available microphone components is discussed in the context of rapid prototyping. The modular system architecture is presented as a cost-effective strategy that supports future upgrades without requiring major redesign. Finally, the choice of solar and battery power is analyzed for its sustainability and long-term maintenance savings.

4.3.1 Custom Mainboard vs. Off-the-Shelf I/O Board:

Initial investment in a custom PCB was justified by the need for tailored I/O and compactness. However, the switch to a contingency off-the-shelf I/O board after the first failure minimized further financial risk and reduced development time at the end of the project, outweighing the sunk cost of the initial board.

4.3.2 Microphone Selection:
Prebuilt amplifier boards and off-the-shelf microphones were chosen for prototyping due to their low cost and immediate availability, allowing rapid iteration. Custom solutions were deprioritized until a reliable baseline system was achieved.

4.3.3 Modular Design:
The system's modularity allows future upgrades (e.g., more sensitive microphones, additional sensors) without major redesign, providing long-term cost savings and extensibility.

4.3.4 Power System:
Solar and battery power were selected for sustainability and reduced maintenance costs, with system power optimization prioritized to extend operational life in the field.

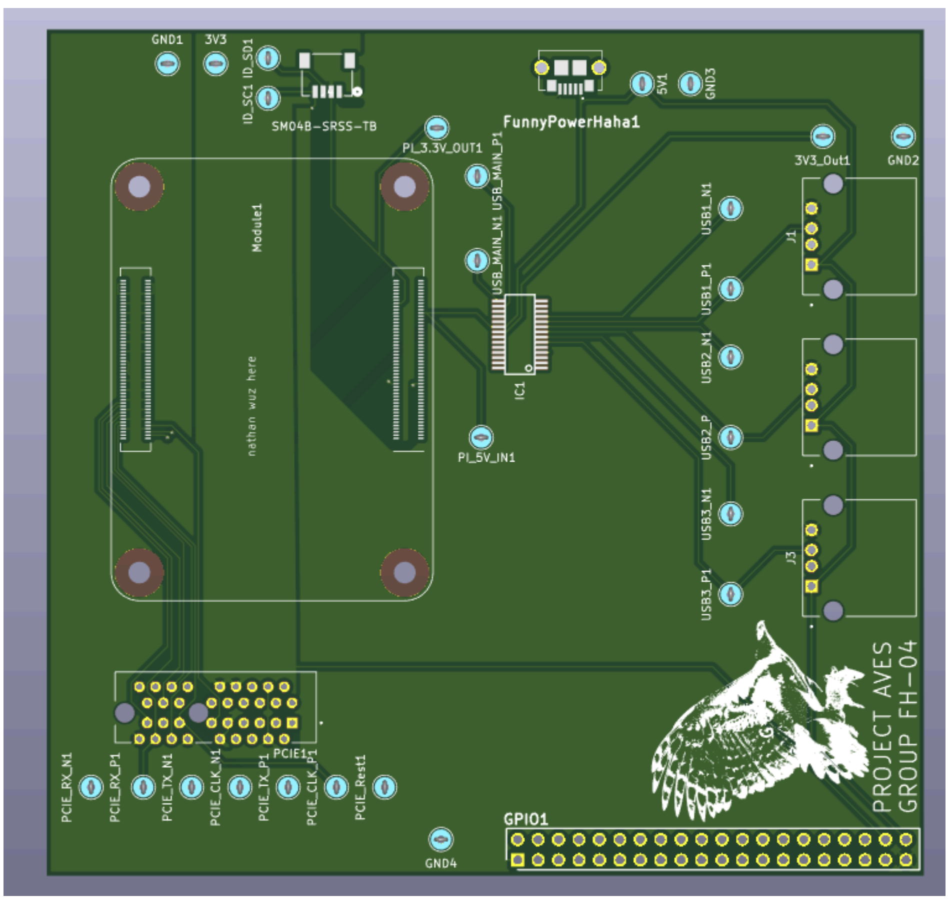
4.4 Innovations and Modifications
The Dockerized machine learning pipeline allowed for consistent deployment of BirdNET across various hardware platforms, significantly simplifying updates and maintenance. The vector-based localization system processed directional audio vectors and paired them with detected bird calls, laying the groundwork for future expansion into multi-device localization. Mechanically, the design featured a central pole with branching arms to optimize microphone coverage while ensuring structural stability and resilience against environmental conditions.

5.0 TEST AND EVALUATION
In order to fully verify functionality, integration, and reliability of both the hardware and software subsystems, testing and evaluation were essential phases of the project. This section outlines the testing methodologies implemented, discusses outcomes and highlights plans for future testing.

5.1 PCB Testing and Evaluation

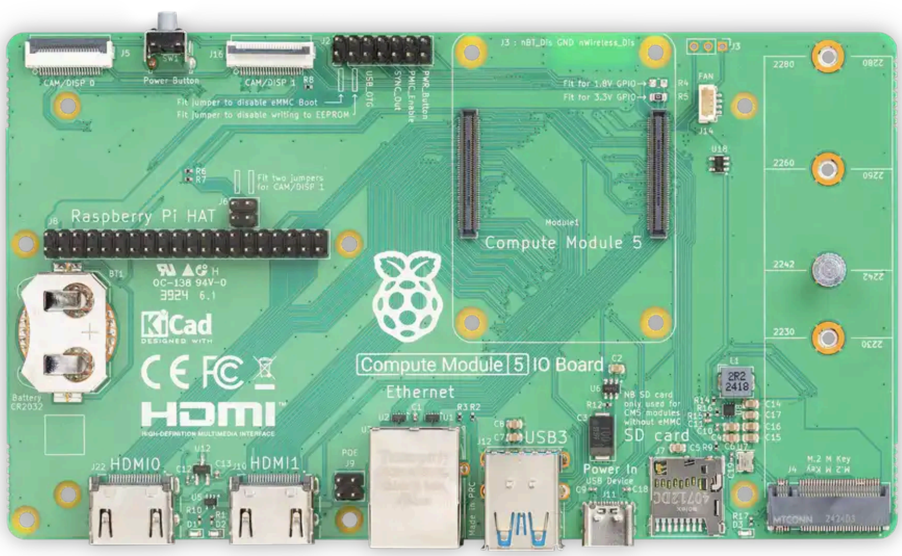
To systematically verify the PCB design and integration, an initial PCB test board was created with components spaced out to enhance accessibility and facilitate easier debugging with test points. The first test board integrated essential components including the Raspberry Pi Compute Module 4(CM4), Coral Accelerator chip[3], USB hub for microphone connection, I^{2}C Qwiic connectors for ADC sensor modules, USB micro port for power delivery, exposed GPIO pins, and a PCIe x1 connector added to support an M.2 SSD expansion adapter. Test points were strategically incorporated to speed up the debugging process.

Figure 5.1 Initial Test PCB Layout



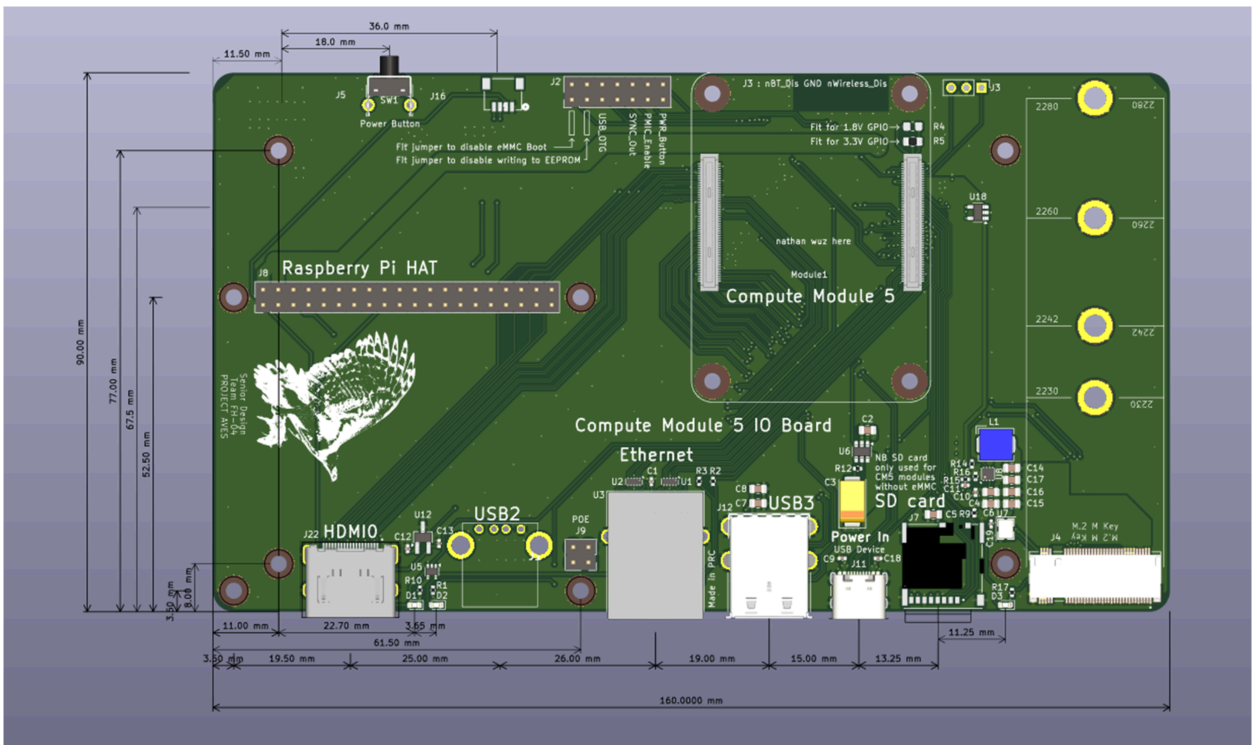
During preliminary evaluation, the team encountered significant issues, specifically with the CM4 failing to boot properly. To fix the issue, the team analyzed the official Raspberry Pi IO board schematics to identify essential design elements. After reviewing the board, the team decided to use it as a foundation for the next board to ensure that the necessary functionality would work as expected. Specifically, redundant or unnecessary IO was removed, such as reducing dual HDMI ports to a single interface, to simplify the circuit design. Additionally any connections that were necessary for project functionality but were not included in the general IO board, such as Qwiic connectors, were added.

Figure 5.2 Reference IO Board Layout



Following these revisions, a refined board was designed and fabricated incorporating key elements with a few changes for better debugging access as well. An upgraded Raspberry Pi Compute Module 5 Lite(CM5) was used instead of the CM4. Due to availability constraints for the original Coral Accelerator chip, a USB-based Coral Accelerator[4] was planned for the final version. A single HDMI port was added to make it easier to interact with the CM5 during development with an SD card slot dedicated to system booting. SSD storage was built in, bypassing the need for a PCIe to M.2 adapter resulting in a smaller form factor for the final PCB. Other components include an expanded USB-A port array, USB-C for versatile power and communication, dual Qwiic connectors to streamline sensor integration, Ethernet connectivity with options for Power over Ethernet(PoE), upgraded WiFi antenna, exposed GPIO pins for debugging, and a comprehensive array of diagnostic LEDs for boot, error, heartbeat/user indication and miscellaneous system status.

Figure 5.3 Revised PCB Design and Component Layout



Testing of this updated PCB is currently underway, with extensive testing and validation continuing through summer 2025.

5.2 Software System Testing and Evaluation

Software testing began by providing a controlled environment to verify core functionality. Initial software evaluations demonstrated promising results, notably with the localization and BirdNET pipelines.

5.2.1 Audio Localization Software Evaluation

To evaluate the localization pipeline, custom scripts were developed to generate simulated, controlled audio conditions. These scripts combined four independent audio sources into a singular four-channel input stream processed by the localization algorithm. During the initial software testing, continuous and accurate CSV logs were successfully produced, detailing localized sound sources. Subsequent testing expanded upon this, utilizing live audio recordings merged into a similar multi channel format, further validating the localization softwares accuracy under realistic scenarios.

Further evaluation will involve comprehensive field tests with dedicated four-channel microphone arrays, establishing real-time localization capability under actual environmental conditions.

5.2.2 Audio Localization Software Evaluation

Initial BirdNET test confirmed the software's capability for precise identification of bird species from audio samples, complete with accurate timestamp output. Following successful standalone validation, BirdNet was integrated into the previously tested localization pipeline. This combined pipeline was verified using test audio inputs, which were artificially generated by splicing together real audio samples, successfully demonstrating the automated identification of bird species and correlating them with corresponding location vectors derived from the localization software.

The full pipeline software evaluation, planned for summer 2025, will involve a live demonstration integrating both localization and BirdNET classification pipelines. This comprehensive test will verify the system's ability to deliver accurate, real-time outputs, including bird species, timestamps, and location coordinates, under authentic field conditions.

Through structured initial testing and detailed plans for future evaluation, Project AVES aims to ensure reliability and accuracy in delivering precise environmental and biological monitoring data.

6.0 TIME AND COST CONSIDERATIONS

The initial timeline decided upon during early stages of the project proved to be quite aggressive in light of constraints posed by political and production factors, leading to missed milestones. Issues arising from this were dealt with through renegotiating design considerations and realigning goals. The project met budgetary constraints posed by the class and stakeholders: most costs came from hardware fabrication and evaluation board purchases, and a large surplus remains for future work.

6.1 Timeline Challenges

Most of the delays pushing back project completion concerned mainboard PCB hardware iterations: receiving hardware later than expected led to reallocating large amounts of resources from other aspects of the project to troubleshooting and design of the main board and resulted in the implementation of a contingency plan.

Iteration 1, referred to as the "Test Board", was sent to JLCPCB at the beginning of December 2024 for fabrication, targeting early January completion for testing at the end of winter break. Production level issues led to delays of over a month, and the removal of the de minimis exemption delayed import, causing the PCB to be delivered on February 8th. significantly setting back mainboard design.

To compensate, deliverables surrounding peripherals and localization were deprioritized and group members working on tasks related to design of those systems were reallocated to mainboard PCB design. A contingency plan that used off-the-shelf hardware similar to the second mainboard PCB iteration was constructed in the event that specialized hardware couldn't

be tested. Finally, the team opted to have the manufacturer assemble much of the board for version two, attempting to decrease iteration time at a higher financial cost.
The contingency plan proved to be highly useful: having backup hardware allowed the software team to develop a large part of our solution despite setbacks on the other side, including proof of concept source localization software. As is standard practice for Raspberry Pi carrier boards, the mainboard is based on the reference design implemented by the contingency board, meaning that a properly manufactured mainboard will work similarly should the stakeholders continue to use our design.

6.2 Cost Considerations

Costs arising from development mainly included the purchasing of evaluation boards and PCB fabrication. Including miscellaneous items, the total cost did not exceed $1,000, and project stakeholders have informed us that more has been budgeted for development.

Table 10. Cost Breakdown by Project Factor

Project Factor	Cost (USD)
Mainboard V1- Manufacturing, Parts, Incidentals	235.96
Mainboard V2- Manufacturing, Parts, Incidentals	238.29
Raspberry Pi CM4 + 2 CM5 Lites, IO Boards	305.00
Mic Board Development- Parts, Evaluation Boards	125.85
Total	905.1

Table 6.2.1 shows total costs incurred by different aspects of the design. Though steps could have been taken to further decrease costs (e.g. opting for slower shipping times and spending more manual time on assembly), stakeholders have confirmed that less money than expected was spent on the project, though a hard budget cap was not defined by the organization.

7.0 SAFETY AND ETHICAL ASPECTS OF DESIGN

Project AVES integrates rigorous safety protocols and ethical frameworks to ensure responsible deployment in ecologically sensitive environments. The autonomous monitoring system prioritizes wildlife preservation, human safety, and environmental stewardship while adhering to professional engineering standards.

7.1 Electrical and Mechanical Safety

The design opts to use enclosures currently in use by stakeholders, which are IP65-Rated to withstand water ingress[9], with wiring adhering to industrial standards for outdoor deployment. Thermal management includes heat-resistant materials, and the use of Raspberry Pi based computing solutions enables relatively low thermal operation and automatic shutdown before damage can occur.

7.2 Wildlife Interaction

Passive monitoring causes no disruptive signals that interfere with animal behavior. Microphones are also positioned on elevated arms, which reduces physical contact with wildlife, and other design factors were discussed with stakeholders to ensure low interference with the surrounding environment.

7.3 Data Integrity

A Dockerized BirdNET pipeline reduces false positives in species identification. Logs include confidence scores. Additionally, future PCB plans include an additional data encryption module such as a TPM (Trusted Platform Module)[12] to ensure data isn't accessible by unauthorized users.

7.4 Ethical Framework

The project follows basic ethical principles adapted for autonomous environmental systems. It helps conservation efforts by collecting detailed data on bird activity and avoids environmental harm by using solar power. The software is open-source so others can check how it works and verify the data. The system also keeps clear logs with timestamps to track detections, directions, and sensor readings.

8.0 RECOMMENDATIONS

With further iterations of this project in the works, many areas of the project will benefit from enhancements for system performance and scalability. First, the vector based calculations used for audio localization should be improved for increased accuracy. In addition, instead of taking the average of the vectors when calculating the final vector, weighted averages can be utilized or other ways to combine vectors in this step. Next, microphone or microphone boards can be utilized and redesigned to better align with the localization algorithms, ensuring that hardware capabilities more efficiently support software development. This could include optimizing microphone placement, spacing, and orientation for more precise directional data. More efficient and compact PCB layouts can be designed for better system integration, thermal management and low power consumption. These improvements can be made through more testing and research and will significantly improve the system's performance, reliability, accuracy, and effectiveness. Finally, redefining project management constraints will help keep the project from running over time: future development should include more slack in deliverables to ensure tasks aren't tightly bound together.

9.0 CONCLUSION

This report provides an overview of the progress made by the team in developing an autonomous, solar-powered bird population and environmental monitoring system. The primary objective of this project is to create a self-sustaining device capable of accurately localizing bird calls, identifying species, and collecting environmental data over long periods of time. This system must be energy-efficient, durable, and capable of functioning in remote, off-grid locations with minimal human intervention. The following is a summary of the team's preparation, progress, and prospects for success in achieving these goals.

The team focused on designing a PCB that would support the device's low-power requirements while ensuring efficient thermal regulation. The PCB design underwent several iterations to optimize it for both power consumption and heat dissipation. Although the final design has not been physically fabricated or shipped as a Version 2 board, it is based on a validated reference design and is expected to perform as intended. Initial tests of the V1 PCB and simulations of the updated design confirm its viability, as it effectively manages power consumption and prevents overheating, thus increasing the likelihood of long-term, sustainable operation in the field. This successful implementation of the PCB design—despite not having a fully assembled V2 board for testing—represents a significant milestone in ensuring the system's reliability and durability in the harsh environments it is intended to monitor.

On the software front, the team has made significant strides in containerizing the BirdNET machine-learning model, which is used to identify bird species based on their calls. By using Docker, the model was successfully made portable across various hardware platforms, which simplifies the process of testing and ensures consistency in performance regardless of the underlying system. Additionally, a testing framework was established to facilitate the smooth operation of software updates and ensure that the model continues to perform reliably. This software deployment framework adds a layer of robustness to the project, allowing the team to quickly address any issues that arise and maintain a high level of software stability throughout the development process. In addition to BirdNET containerization, the vector based localization is fully developed and just has to be field tested in the following week for the presentation. The localization software takes audio from the microphones, creates vector files and sends a wav file to BirdNET. Then it pairs vectors with bird sounds heard in the wav file and averages the vectors to give us the final vector and species.

Through extensive testing and iterative development, the team has been able to address and mitigate several potential challenges. For example, localization accuracy has been improved, and the energy management system has been optimized, which significantly reduces the risk of system failure due to power shortages or overheating. Additionally, the successful deployment of the BirdNET model on the Docker platform has positioned the team to scale the system efficiently across different hardware platforms. Despite these successes, there are still areas that require further development. The primary challenge that remains is improving the localization system to reliably detect bird calls at greater distances. This will likely require enhancements to the signal processing algorithms and creation of a better microphone system. The team plans to focus on these improvements in the next phase of the project, aiming to expand the effective range of the microphones and refine the system's ability to localize bird calls in real-world conditions. With additional work in this area, the team is confident that the system will achieve a higher level of performance for successful long-term environmental monitoring. The project is solid, and the team's progress thus far provides confidence that the system will perform effectively in the field. As the team moves forward, the focus will be on further enhancing the localization system, ensuring the device's durability, and refining the software to optimize the system's overall performance.

REFERENCES

References

[1] A. Ouyang. (2022, July 29). Different Types of Soil Moisture Sensors [Online]. Available: https://www.seeedstudio.com/blog/2022/07/22/%EF%BF%BCdifferent-types-of-soil-mosture-sensors%EF%BF%BC/

[2] S. Kahl. (2013). BirdNET-Analyzer, GitHub repository [Online]. Available: https://github.com/kahst/BirdNET-Analyzer

[3] “Coral Accelerator Module,” Coral.ai [Online]. Available: https://coral.ai/products/accelerator-module

[4] “Coral USB Accelerator,” Coral.ai [Online]. Available: https://coral.ai/products/accelerator

[5] K. A. Griggs and S. P. Griggs. (2023, Jun. 6). Device for Acoustic Source Localization, U.S. Patent US11681007B2 [Online]. Available: https://patents.google.com/patent/US7415117B2/en

[6] J. P. Stachursky and L. P. Netsch. (2023, Nov. 21). Robust Estimation of Sound Source Localization, U.S. Patent US11825279B2 [Online]. Available: https://patents.google.com/patent/US11825279B2/en

[7] A. J. Fox and M. Caruana. (2020, Jul. 21). Drone-Enabled Wildlife Monitoring System, U.S. Patent US10716292B1 [Online]. Available: https://patents.google.com/patent/US10716292B1/en

[8] “Bird Songs,” USGS Patuxent Wildlife Research Center [Online]. Available: https://www.mbr-pwrc.usgs.gov/id/mexsong1.html

Appendix A: Relevant Standards

[9] IPX4 Waterproof Standard, IEC 60529, 1989.

- Specifies the level of protection against water intrusion for devices, ensuring durability in wet environments

[10] IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications, IEEE Standard 485-2020, 2020.

- Provides guidelines for estimating and sizing lead-acid batteries for stationary applications, ensuring energy storage efficiency

[11] ISO/IEC/IEEE Standard for Information Technology—Local Area Networks—MAC Bridges, IEEE/ISO/IEC 10038-1993, 1993.

- Outlines the protocols for local area network bridges to enable seamless communication between network segments

[12] Standard for Smart Identification in Internet of Things, P3411, 2023.

- Defines methods for identification and interoperability of IoT devices within smart environments

[13] IEEE 802® Networks for Vertical Applications, IEEE White Paper, 2024.

- Focuses on network standards and applications in specific industries like healthcare and manufacturing