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Preliminary Design: Acoustic and Environmental Monitoring System for Lab Animals

Revisions

Revision	Author(s)	Changes	Date
001	Jade Moore-Jackson, Hilton Truong, Ren Wen Lim, Emily Li	Initial creation of the 1st version	2023-02-01
002	Emily Li, Jade Moore-Jackson, Hilton Truong, Ren Wen Lim	Implement feedback from V01, Add sections 10 & 11	2023-03-16

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Acronyms

ESM	Environmental Sensor Module
FR	Functional Requirement
PR	Performance Requirement
SW	Software
OS	Operating system
V	Volts

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1 Purpose

This document describes the preliminary design for the Acoustic and Environmental Monitoring System for Lab Animals.

During the study of rodents in the lab for biomedical research, a common problem faced is that the researcher is not available to observe and record the animal's behaviors around the clock. To address this issue, an environmental sensor module (ESM), utilizing commercial off the shelf components, could be deployed into the laboratory or vivarium to capture the environmental information such as temperature, pressure, relative humidity, and visible light intensity to a higher degree of accuracy. The ESM would be capable of capturing the environmental data while monitoring the animal's activities. These animals are known to communicate through odors (pheromones), touch, visual cues, and vocalizations. The vocalizations produce auditory sounds that range from the low Hz to 10s of kHz, making it impossible for a researcher to hear all the vocalizations that are potentially being produced by the animals. Since these vocalizations can express an animal's state-of-being such as their playfulness, aggression, or pain, they are of high interest to the researcher.

Most pre-existing environmental monitors contain microphones that do not record in the ultrasonic range, and many are integrated solutions whereby the sensors are built into the vivarium to be sold as a complete enclosure. This is an expensive option that does not integrate well with the current deployed vivariums in the laboratory. Having a custom designed environmental sensor module equipped with an ultrasonic microphone will be both more cost-effective and suitable for being deployed to existing vivariums.

Creating the ESM with off the shelf parts and mostly plug-and-play components allows for ease of construction and scalability of the design. If there is a desire to monitor multiple enclosures, additional modules can be set up easily. As each separate module is designed to observe a single cage, the units need to be relatively small and easy to build.

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2 Concept of Operation

The high-level operation of the Acoustic and Environmental Monitoring System for Lab Animals is illustrated by the following user stories and use cases.

2.1 User Stories

2.1.1 User Story 1

I want to setup an ESM for the newly acquired enclosure. I place the ESM on the roof of the enclosure and position the ultrasonic microphone such that it is pointed downwards, towards the rodents. I then plug in a wire from the enclosure's feeder, one of the enclosures peripheral devices, into the ESM's open terminal for triggered recordings. I make sure that the ESM has an attached removable flash drive for saving recordings and that the microSD card that stores the ESM's firmware and software is inserted properly. I plug in the ESM to power and turn it on. This is illustrated in Figure 1 below in section 2.2.

2.1.2 User Story 2

I come into my lab and want to monitor a rat I have in its enclosure. I need the data to be collected continuously while the rat performs different tasks over the next 2 hours. I set the recording length to 2 hours in the configuration file and upload it to the ESM's Google Drive. I then press the embedded button on the ESM to start the 'Continuous Mode' recording. A few hours later, I come back to the ESM and remove the flash drive and plug it into my laptop to retrieve the recording. The recording filename contains the timestamp for when the recording took place. I also retrieve the file that contains the measurement data about the environment during the time of the recording. I check this data to see if the enclosure shook at all, and what the enclosures air composition was. To do this I look at the concentrations of the room's oxygen, carbon monoxide gas, and check if there was any ammonia gas as I know the lab next to mine works with it. This is illustrated in Figure 1 and Figure 2 below in section 2.2.

2.1.3 User Story 3

I come into my lab and want to monitor a rat I have in its enclosure. Today I want to observe if there are any vocalizations of the rat when the mechanical feeder on its enclosure activates. For these triggered recordings, I want to see if there are any vocalizations in the 5 seconds before the feeder activates, and during the 15 seconds after. I modify the relevant settings in the configuration file and upload it to the ESM's Google Drive as illustrated in Figure 2 in section 2.2.. After the mechanical feeder has been activated a couple times, I remove the flash drive and plug it into my laptop to retrieve the recordings. Each recording's filename contains the timestamp for when the trigger took place. I also retrieve the file that contains the measurement data about the environment at the time of the trigger. This data includes measurements for the ambient temperature, visible light intensity, and relative humidity.

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2.2 Use Cases

Table 1 is the summary of Use Cases found in Figure 1, likewise Table 2 is the summary of Use Cases found in Figure 2.

Table 1 - Use case descriptions for ESM

Use Cases in Figure 1	Description
Receive sensor module configuration	The ESM will have a config.txt file transferred to it that configures the sensor parameters of the ESM.
Configure enabled sensors	This config.txt will tell the ESM what sensors to turn on/off, controlling what data is attached to the recording.
Configure recording window	This config.txt will tell the ESM the lead and lag time to use when capturing a timed recording window centered on a trigger.
Set animals tag	This config.txt will tell the ESM what animal tag to include in the recordings meta data.
Set up ESM	This involves physically positioning the ESM on the vivarium and verifying the sub-components, so it is ready to capture recordings.
Ultrasonic mic attached and positioned properly	The ultrasonic mic must be plugged in to the ESM by USB, it should then be positioned so that it is pointed towards the vivarium from which the recordings will be captured.
Attached removable flash drive	The removable flash drive must be plugged in to the ESM by USB, this is to provide storage for the captured recordings and allow their retrieval.
Installed microSD card with firmware and ESM software	The microSD card that contains the software developed for the ESM as well as the firmware for the Pi must be installed into the Pi so that the ESM can function as designed.
Power on the ESM	A USB type C cable is plugged into the Pi, the other end is plugged into a 3.0A USB-C power supply. This will provide the power required for the ESM to operate.
Start recording	The ESM will begin parsing data and create a data file containing the ultrasonic sound recording and associated meta data from the other sensors enabled.
Record in triggered mode	The ESM will create a recording window when a rising edge voltage change is detected on the triggered input pin.
Record in continuous mode	The ESM will start a recording when the continuous mode recording button is pushed.
Retrieve data from flash drive	The flash drive is removed from the ESM, this flash drive contains the captured recordings.

Table 2 - Use case descriptions for interface system

Use Case in Figure 2	Description
Configure sensor module	The config.txt file will be edited with a text editor to provide the appropriate settings for the current lab experiment.

Configure enabled sensors	Inside the config.txt file the researcher will enable the sensors that they wish to have capturing data, disabling the rest.
Configure recording window	Inside the config.txt file the researcher will set the lead time, this controls how long before the trigger was received to capture in the recording, and the lag time, this controls how long after the trigger was received to capture in the recording.
Set animals tag	Inside the config.txt file the researcher will enter the animal's identifier (tag number) that is to be saved into the meta data of the recording.
Connect flash drive to computer to retrieve data collected	The removed flash drive (from ESM) is connected to the researcher's laptop, allowing them to see the saved recordings and retrieve all captured data.

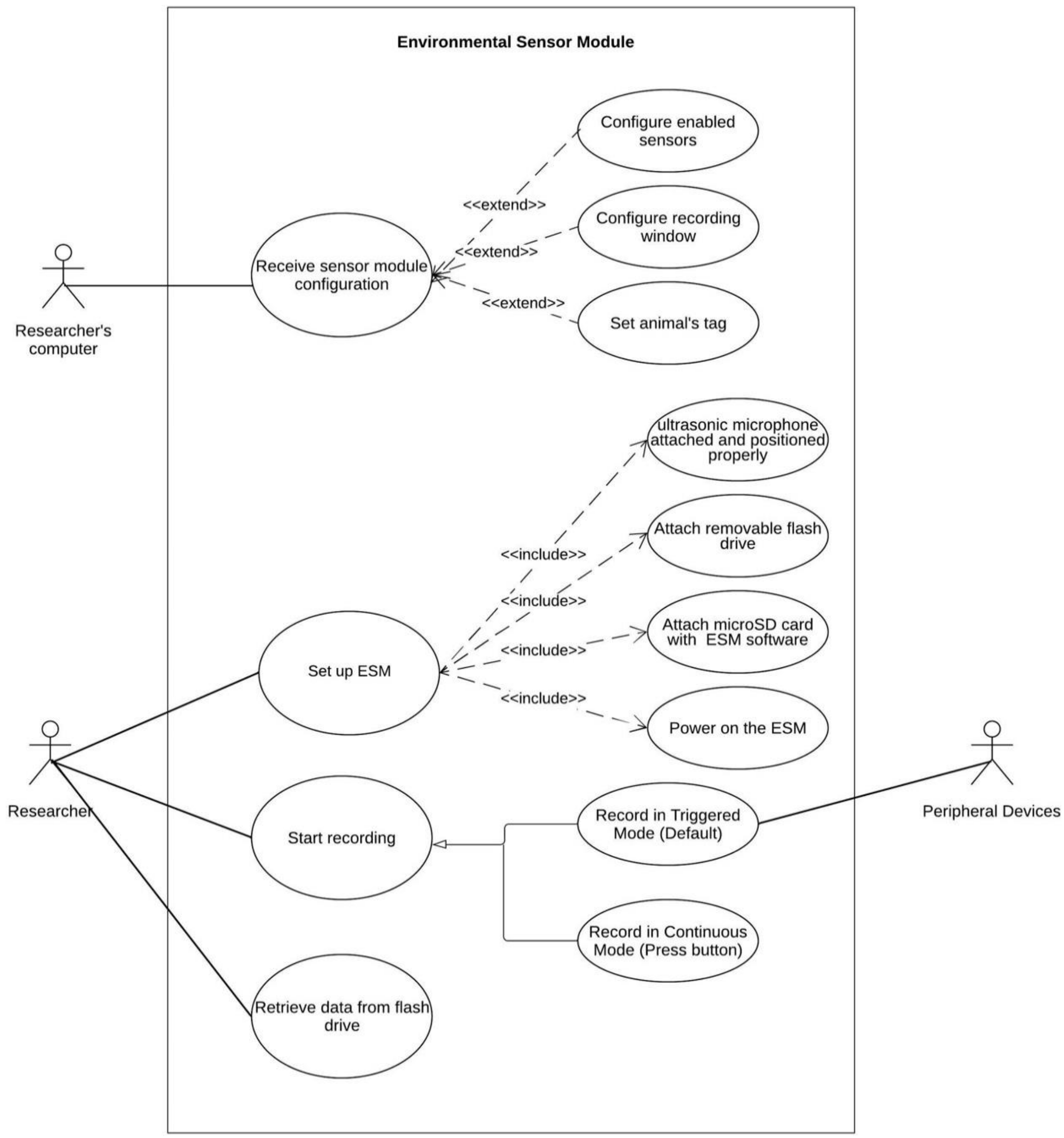

Figure 1 - UML diagram of use cases for the Environmental Sensor Module

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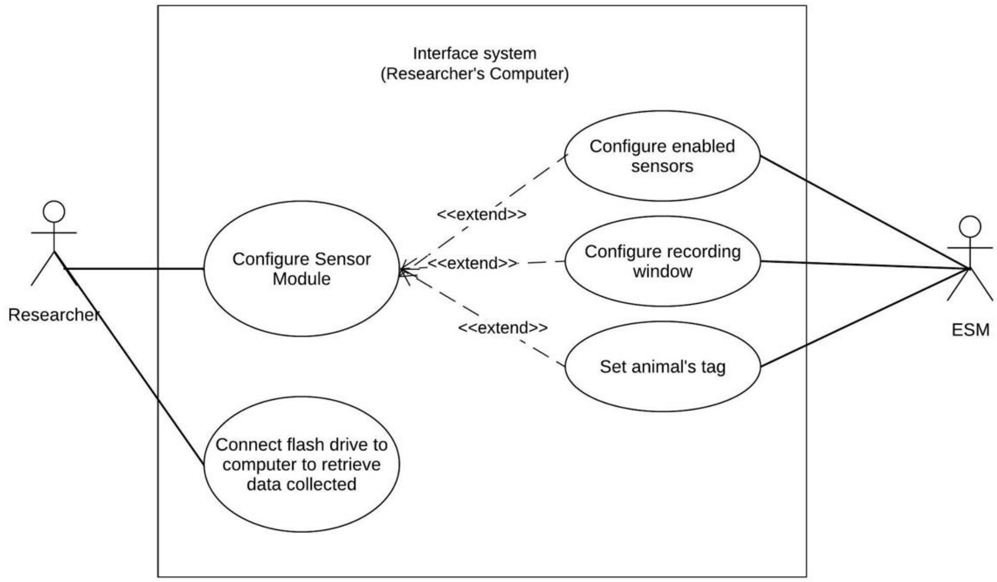

Figure 2 - UML diagram of an interface system that supports the configuration of the Environmental Sensor Module and data retrieval.

3 Functional and Performance Requirements

Table 3 lists the functional requirements of the ESM while the performance requirements are listed below in Table 4. The system requirements are listed in Table 8 found in section 5.

Table 3 Functional Requirements (FR)

FR #	Functional Requirement Description
FR-01	Needs to record lab animal vocalizations.
FR-02	Needs to measure vibrations.
FR-03	A light sensor to measure the intensity of light.
FR-04	A temperature sensor to measure the ambient temperature.
FR-05	A humidity sensor to measure the relative humidity.
FR-06	A gas sensor to measure oxygen concentrations.
FR-07	A gas sensor to measure carbon monoxide concentrations.
FR-08	A gas sensor to measure ammonia concentrations.
FR-09	Must continuously record audio from the moment a user pushes a button until the user pushes it again.
FR-10	Must record audio when triggered: a trigger from the user (or equipment) will initiate the saving of an audio recording window.
FR-11	There must be a way to retrieve the audio recordings and measurement data.
FR-12	There needs to a way to change which environmental quantities are currently being recorded.

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Table 4 Performance Requirements (PR)

PR #	Performance Requirement Description	Related FRs
PR-01	Acoustic recordings must be able to record from 20-100,000 Hz.	01
PR-02	Acceleration measurement with a range of at least ±1g	02
PR-03	A light sensor must be able to measure the intensity of light in the visible spectrum (0.4 to 0.7 µm)	03
PR-04	Temperatures in the range of -15C to 40C	04
PR-05	Relative humidity from 0 to 100%	05
PR-06	OX sensor based on NO2 detection from 0.05ppm to 10ppm	06
PR-07	Carbon monoxide concentrations from 10 to 800ppm	07
PR-08	Ammonia concentrations from 10 to 400ppm	08
PR-09	Must be able to change timing of triggered audio recording window (e.g., audio from 2 seconds before and 2 seconds after the trigger point must be saved).	10
PR-10	Sensors must be able to be digitally toggled on or off	12

4 System Design

This section deals with the design of the acoustic and environmental monitoring system for lab animals and provides information on the key functionality and factors taken into consideration when designing the system. The proposed system is designed to be integrated with existing lab animal enclosures to improve data collection during an experiment. The environmental monitor system is a raspberry pi combined with an ultrasonic microphone and the various environmental sensors detailed below. Taking into consideration the size of the enclosures and the long durations of the monitoring process, the ESM will need to be small and powered by a wall outlet. The ESM will run a custom Python program that will collect the data from the attached microphone and various sensors. The ESM can operate in two modes of recording as detailed below.

4.1 System Architecture

The combined deployment and component diagram, seen in Figure 3 below, illustrates the system architecture of the ESM. There is one main deployment target, that being the ESM module itself. Table 5, Table 6, and Table 7 (in sections 4.1.1, 4.1.2, 4.1.3 respectively) provide more in-depth details about the pictured component subsystems.

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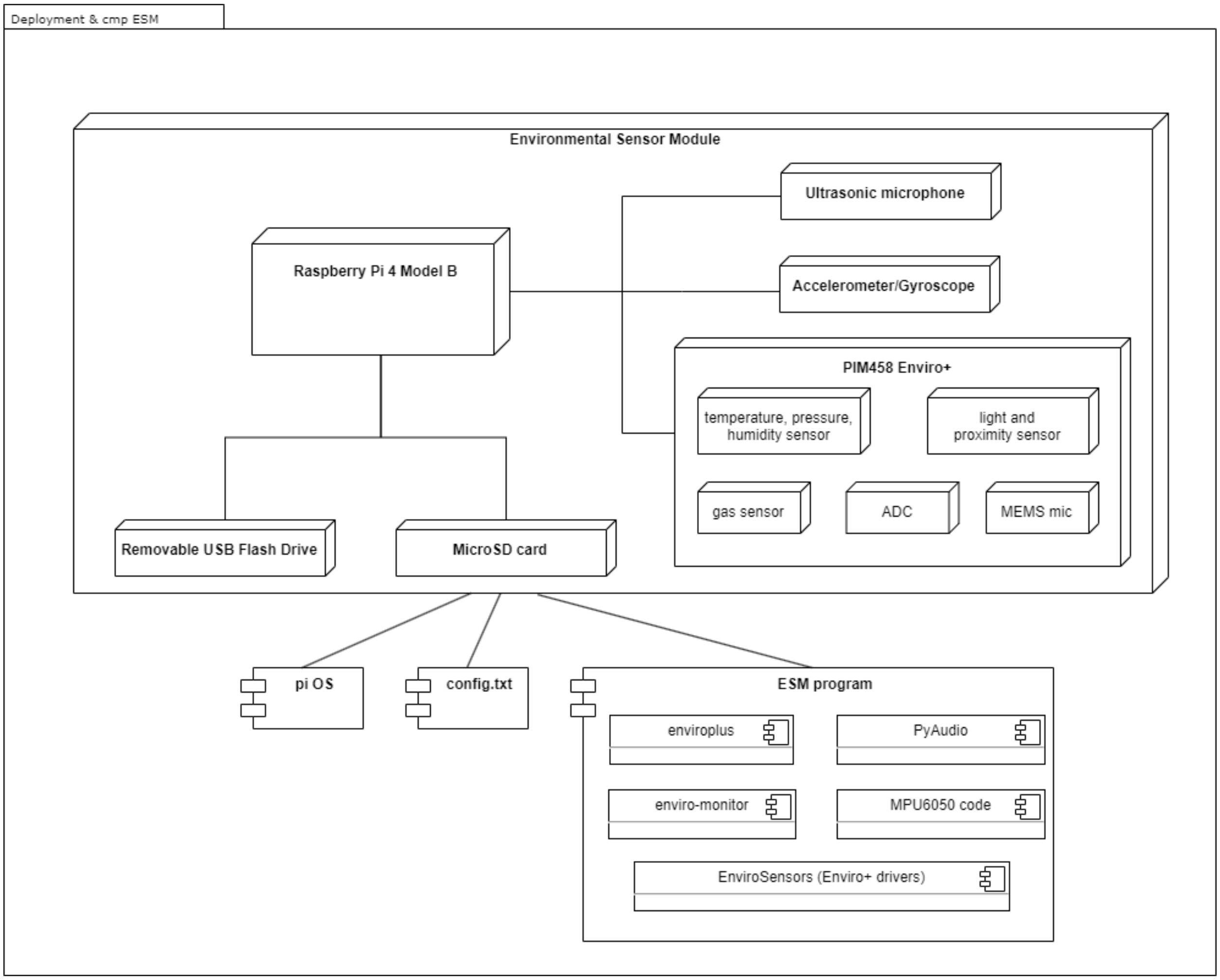

Figure 3 - ESM System architecture

4.1.1 Hardware Components

Table 5 - List of hardware components and functions.

Component	Function
Raspberry Pi 4 Model B [3]	A low-cost single board computer that will be used as the central processor of the ESM. It includes 4 USB ports and a 40 pin GPIO header that will be used for connecting the other modules. With 4 GBs of ram, and the ability to connect to Wi-Fi and Bluetooth, it provides flexibility of how collected data can be transferred over and from a host computer. With a quad core SoC, there will be enough computational power to handle the incoming data from the high-fidelity microphone and other sensors simultaneously.

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USB (Removable flash drive)	The removable flash drive will be used for data storage and enable file transfers from the ESM to a host computer. The removable flash drive can either be a thumb drive or an external hard disk/solid state drive connected to the Raspberry Pi through a SATA to USB cable.
microSD card [10]	The SD Card will be primarily used to store the Raspberry Pi Operating System (OS), the ESM program, and any other core functionality that is required for the ESM to be functional.
PIM458 Enviro+ [19]	The PIM458 is a Raspberry pi hat board which includes a multitude of sensors. It serves as an all-in-one board connecting to the Raspberry Pi with its 40 pin GPIO connection. It contains the following sensors: BME280 temperature, pressure, humidity sensor [4], LTR-559 light and proximity sensor [5], MICS6814 analog gas sensor [6], ADS1015 analog to digital converter (ADC) [7], MEMS microphone [8].
Accelerometer/Gyroscope [11]	The accelerometer/gyroscope is a 3-axis gyroscope and accelerometer that will be able to measure and detect motion that the module may experience. It will be able to detect the motion and record it through the libraries that are available online.
Ultramic 384k EVO [9]	The Ultramic 384k EVO is an ultrasonic microphone capable of recording up to 100000Hz and produces high fidelity recordings. This microphone allows for the capture of the lab animal vocalizations.

4.1.2 Firmware Components

Table 6 - List of firmware components and functions.

Component	Version	Function
Raspberry Pi OS (32-bit) [17]	Debian Bullseye with the Raspberry Pi Desktop (Released: 2022-09-22)	The Raspberry Pi requires an operating system to operate. Raspberry Pi OS is the official supported operating system. It’s a Unix-like operating system.

4.1.3 Software Components

Table 7 - List of software components and functions.

Component	Function
Environmental sensor program [20]	This is a custom program designed to operate the Environmental Sensor Module. The program will be launched when the Pi is powered on. It consists of two operation modes:

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	1. Continuous mode – audio recording will start when the user presses the start button and continue to record until the stop button is pressed. 2. Triggered mode – a trigger from the user (or equipment) initiates the saving of an audio recording window, as pre-defined by the user (e.g., audio from 2 seconds before and 2 seconds after the trigger point must be saved). The user can select which sensor data to be recorded by modifying the configuration file.
MPU6050 Code [12]	A Python code for interfacing Raspberry Pi with the MPU6050 sensor module. This will allow the Environmental sensor program to read the value of the Accelerometer and Gyroscope from the MPU6050 module.
enviroplus-python [13]	A public Python library for the Pimoroni Enviro+ sensor monitoring board. This will allow the Environmental sensor program to read the values for the light, temperature, humidity, and gas sensors on the board.
enviro-monitor [14]	A public Python library for the Pimoroni Enviro+ sensor monitoring board. This will allow the Environmental sensor program to read the values for the light, temperature, humidity, and gas sensors on the board.
Pimoroni Enviro+ Drivers [15]	Go library to read data from Pimoroni's Enviro+ sensors. This will allow the Environmental sensor program to read the values for the light, temperature, humidity, and gas sensors on the board.
PyAudio [16]	A cross-platform audio I/O library that can easily use Python to record audio. This will be used to read the values from the microphone.

5 System Requirements

Table 8 - System Requirements (SR)

SR #	SR Description	FR#	PR#	Notes
SR-01	3 Axis Gyroscope and 3 Axis Accelerometer MPU-6050 [11]	FR-02	PR-02	Can easily interface with the Raspberry Pi using Python code.
SR-02	Ultramic 384 EVO [9]	FR-01	PR-01	Has the ability to produces high fidelity recordings up to 100000Hz.
SR-03	Raspberry Pi Enviro+ Enviro Plus pHAT Board [19]	FR-03, FR-04, FR-05, FR-06, FR-07, FR-08	PR-03, PR-04, PR-05, PR-06, PR-07, PR-08	Compatible with the Raspberry Pi to provide environmental sensor readings.

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SR-04	Raspberry Pi OS [17]	FR-13	-	An operating system is required to run the monitoring unit with and the ESM program.
SR-05	ESM program [20]	FR-09, FR-10, FR-11, FR-12	PR-09, PR-10	A custom program designed to communicate with the microphone and sensors to collect environmental data.

6 Minimum Design

In this section a minimum design, the "walking skeleton" is described. The purpose is to define the functionality to be implemented in the first development iteration. The outcome is reported to the client providing an opportunity for early feedback.

Our minimum design will revolve around the ability to record audio from the ultrasonic microphone while in either of the two operating modes, and to retrieve those recordings. The client has expressed that the environmental data that has the highest priority for their work is the lab animal vocalizations. This is because the animals being studied produce vocalizations in the ultrasonic frequency range, and currently the client has no equipment capable of recording soundwaves with such high frequencies. In contrast the data provided by the other sensors can be acquired through other means. For this purpose, the walking skeleton was designed to focus on first implementing the ultrasonic microphone and its associated operational modes.

To achieve the walking skeleton, we identified 6 key elements of the design. Key element 1 is the basis of the design as it is the operational Raspberry Pi environment, serving as the microcontroller which interfaces the sensors to our developed software. The sensor for this minimum design is key element 2, the ultrasonic microphone, enabling the device to record ultrasonic vocalizations. Our developed software encompasses key elements 3, 4, and 5 enabling the microphone to function as the client proposed. Key element 6 is required so that the device could save data recordings which could then be retrieved by the client. These key elements are further detailed in Table 9 below.

Table 9 - Minimum Design

#	Key element	Function	Relation
1	Operational Raspberry Pi environment	The setup of the FW, python environment, and start-up routines necessary to support the rest of our intended functionality.	The ESM is turned on.
2	Functional ultrasonic microphone	The implementation of the necessary drivers, libraries, scripts and/or third-party software to be able to obtain recordings from the microphone with the desired audio	The mic of the ESM can capture ultrasonic vocalizations.

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		qualities, and to output them in a suitable file format onto the removable flash drive.	
3	Triggered Mode	The development of code to receive triggers via the Raspberry Pi's 5V input pins as well as implementation of a buffer-system that will allow us to obtain a window of recorded audio around each trigger.	The ESM is ready to make a recording if a trigger is received.
4	Continuous Mode	The implementation of a button and code to obtain a continuous audio recording.	The ESM is ready to make a recording if the push button is pressed.
5	Recording window configuration	The development of code to allow the user to change the how long before and for how long after a trigger that a recording is saved. These settings will initially be configurable via a .txt file.	The user can change the parameters of the triggered recordings.
6	Removable flash drive	Storage for the ESM's recordings.	The user can retrieve the recordings.

7 High-level Hardware Design

At the center of everything, the Raspberry Pi 4 model B will be controlling everything. It will host the software and all the modules will connect to it. It contains a quad core SoC and a multitude of ports, including a 40 pin GPIO and 4 USB. The board also contains a microSD card port, allowing for expandable storage.

In the microSD slot we will have a 128GB microSD card from SanDisk, with a read speed of 160MB/s and a write of 90MB/s it should be quick enough for the data to be written continuously. With 128GB of storage there should be ample space for the high-fidelity data to be stored for an extended period if desired.

In a USB port, if desired, a USB thumb drive or external storage can be plugged in allowing for the collected data to be stored there. The transfer rate of USB 3.0 should be enough for the high-fidelity data to be stored there without issue.

In one of the USB 3.0 ports the Ultramic 384k EVO will be directly connected to the Raspberry Pi for audio recordings. It is a microphone capable of recording up to 100000Hz and produces high fidelity recordings, therefore it is best for it to use a USB 3.0 port due to data transfer speeds.

In the 40 pin GPIO we will connect the Pimoroni Enviro+ monitor. As it is Pi hat, it can be slotted on top of the 40 pin GPIO of the Raspberry Pi. As the Enviro+ module contains most of the required sensors, there

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will not need to be any connections that will have to be wired or soldered. The temperature, humidity, light and gas sensor readings will just be taken through software.

The 6DOF 3 axis accelerometer/gyroscope will ideally be connected to the GPIO headers on top of the Pimoroni Enviro+ board which is connected to the Raspberry Pi 4. The accelerometer will allow for the detection of any motion or vibrations that the module may go through.

The Raspberry Pi's 5V pin will also be connected to a trigger to receive an electrical pulse from another device when an event has occurred with the other device.

8 High-level Software/Firmware Design

The Raspberry Pi will use Pi OS Raspbian 11 (bullseye) and no custom firmware will need to be developed.

The ESM program will be written and designed in python. There will be a main function that will run and initialize all the sensors and microphones. It will take instructions from a config file determining which sensors should be on and recording. The config file should also contain directives on setting the lead time and lag time of a recording after the trigger. Each sensor will have a separate module for itself. Based on whether the mode is continuous or triggered, the main function will determine when and what modules are to be called.

The microphone module will take an input if recording length with a lead time and lag time. There will be two different functions that the main can call, one for continuous recording, one for triggered.

The accelerometer module will have a function that takes no input. The module will record any motion and log the timestamps to a log file. It will also contain a function to check whether there were any logs produced between two given timestamps.

The light sensor module will have a function that will be called and will record a recording at a set interval into a log file. There will then be a getter function that retrieves the values from a given timeframe.

The temperature sensor module will have a function that will be called and will record a recording at a set interval into a log file. There will then be a getter function that retrieves the values from a given timeframe.

The humidity sensor module will have a function that will be called and will record a recording at a set interval into a log file. There will then be a getter function that retrieves the values from a given timeframe.

The gas sensors module will have a function that will be called and will record a recording at a set interval into a log file. There will then be a getter function that retrieves the values from a given timeframe.

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9 Prototype Budget

Table 10 is a cost summary of the components required to realize the outlined prototype.

Table 10 - System Budget for the prototype (ROM)

Component	Mfr P/N	Mfr	Qty	Unit Price	Extended Price
Raspberry Pi 4 Model B	RAS-4-4G	Raspberry Pi	1	76.95	76.95
Raspberry Pi Enviro+ Enviro Plus pHAT Board	PIM458	Pimoroni	1	69.95	69.95
SanDisk Extreme microSDXC UHS-I Memory Card	SDSQXAV-256G-GN6MA	SanDisk	1	31.60	31.60
3 Axis Gyroscope and 3 Axis Accelerometer 6DOF	GY-521	WayinTop	1	12.99	12.99
Ultramic 384 EVO	UM384EVO	Dodotronics	1	€220.00 $316.92 CAD	316.92
				Total Cost	508.41

10 Alpha System Design

This section deals with the alpha system design of environmental sensor module. The environmental sensor module is a custom-built module designed to be integrated into existing laboratory vivariums to collect accurate data for research purposes. The alpha design will have some changes to the hardware and software aspects. One hardware issue that has risen is that the limited RAM size on the Raspberry Pi limits the duration of an uninterrupted (continuous) audio recording that can be made. In the prototype design a Raspberry Pi with 4GB RAM was used. In the alpha design, a Raspberry Pi with a higher RAM capacity (8GB or higher) will be used. A hardware upgrade of a Raspberry Pi model with higher RAM can increase the duration of the recordings. It will allow the researcher to leave the ESM in continuous recording mode for longer periods of time unattended. The researcher would then be able to record in new scenarios such as leaving the ESM to record overnight while they are away from the lab.

Another issue that has arisen is the overall size of the module. Initially, the Enviro+ board with the temperature sensor was deigned to be placed on top of the GPIO connection pins on the Raspberry Pi. Due the amount of heat the Raspberry Pi generates when the environmental sensor program is running, the temperature sensor reads a much higher temperate value than the actual room temperature. To collect an accurate reading of the room temperate, the sensor would need to be placed further from the board of the Raspberry Pi. This results in having a bigger module than the initial design. A possible future

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upgrade would be to design a casing for the module that will allow the Raspberry Pi and the temperature sensor to be placed together without affecting the accuracy of the temperature reading of the room.

From the software aspect, the environmental sensor module can also be made more accessible by having a more user-friendly interface for controlling the configuration of the module such as controlling it via a simple mobile app. This mobile app would serve as a complete interface solution to the ESM, allowing users to login and view the ESM system. They would be able to change the ESM settings, hiding the config.txt and making the configuration process simpler and easier. Furthermore, the user would now be able to listen to recordings by using the app and download the ones they choose to. By offering access to the audio recordings by using an app, in contrast to retrieving the raw audio files, we would gain the freedom to offer the user a more data-rich experience. This means we would be able to do things like data processing, adding flags to the audio track at points of interest to the user as configured by the user. In summary, the presentation of the ESM recordings and the associated meta data would become a lot more user friendly by viewing a front-end system rather than working with the raw data. By making the ESM system more accessible, it would allow the researchers that are less technically savvy to also use the ESM. By making the environmental sensor module easier to use, the researchers will spend less time on training and fiddling with the module, allowing them to spend more time on their research and focus on the data produced by the ESM.

From the hardware aspect, the environmental sensor module can also be made more functional by adding a camera system. By having access to an optical instrument, we could begin to implement visual data collection in conjunction to the audio data collection and environmental data. This would allow the researchers to better correlate events that are happening in and around the vivarium to the recorded vocalizations.

Once the prototype demonstrates accurate audio recording along with various environmental sensory data collected, the above-mentioned improvements can be incorporated into the module for a more seamless solution.

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10.1 System Architecture

The system architecture of the alpha product, illustrated in Figure 4 below, evolves upon Figure 3 - ESM System architecture seen in section 4.1. The biggest change is the addition of the smartphone deployment target. This introduces the additional Bluetooth hardware and software components on both the ESM and smartphone. With the new smartphone target, a new software component is introduced to serve as the ESM mobile app. The configuration is moved from a .txt within the ESM to the smartphone app. The last additional component is the new camera hardware subsystem added to the environmental sensor module. The Raspberry Pi 4 model B is offered with larger RAM sizes so it can remain the same while still being upgraded for this new architecture.

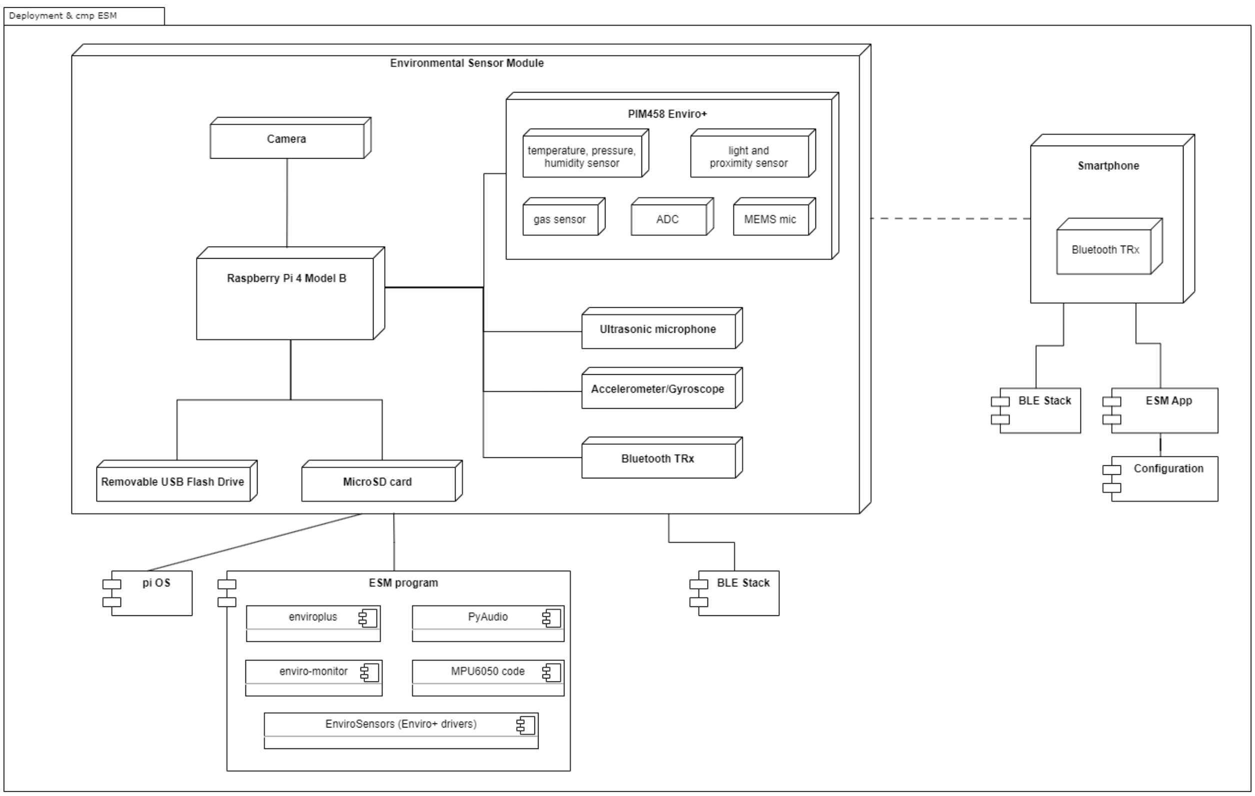

Figure 4 - System architecture for ESM alpha

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10.2 Block Diagram

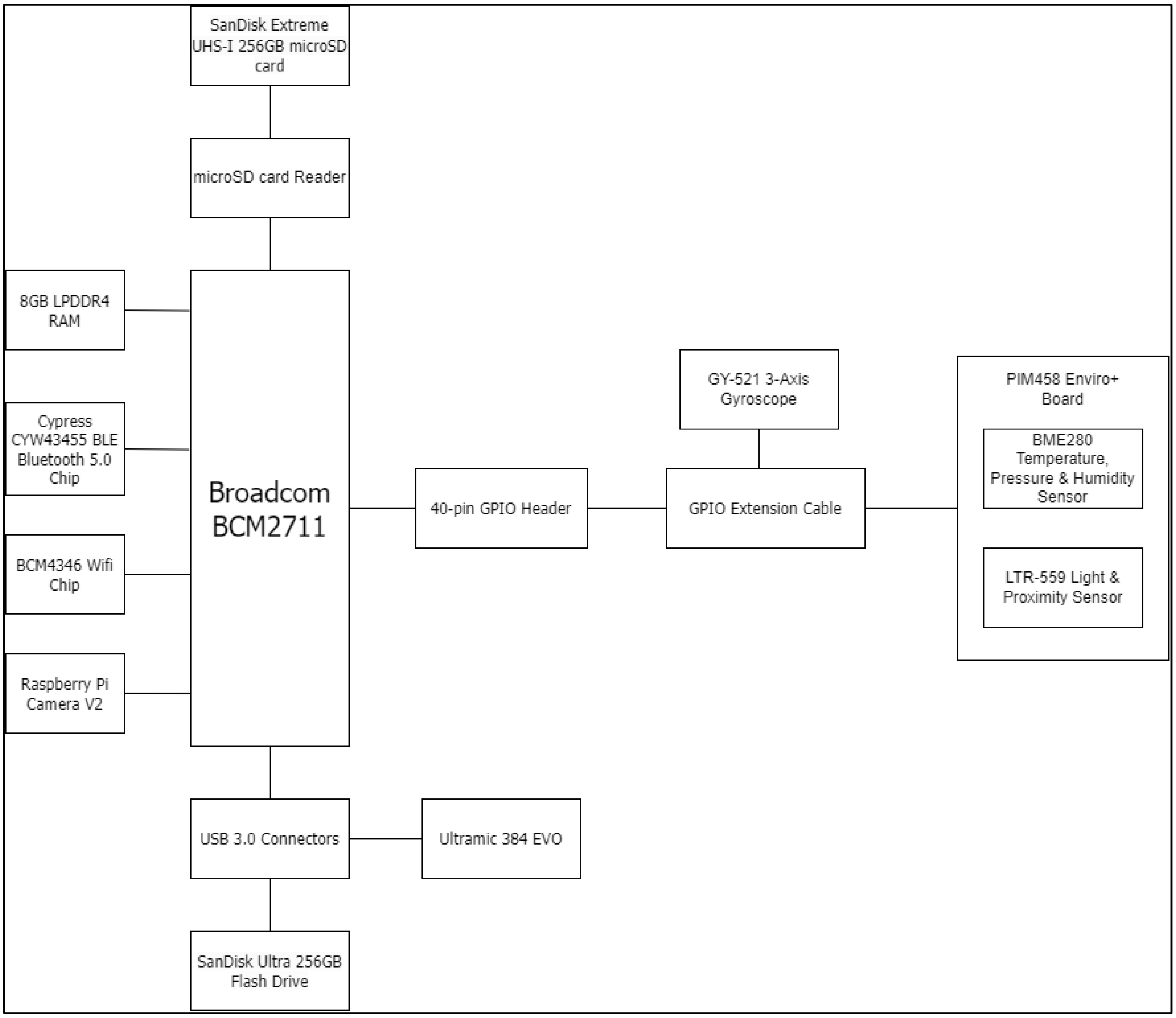

Figure 5 - Block diagram for ESM Alpha

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11 System Budget

The system budget for the Alpha product is presented in Table 11 below, the items identified in Figure 5 that are purchased are listed as a component.

Table 11 - System budget of the alpha product.

Component	Mfr P/N	Vendor	Vendor P/N	Qty	Unit Price	Extended Price (1000)
Raspberry Pi 4 Model B/8GB (includes power supply)	RPI4-MODBP-8GB	Newark	64AH2041	1	104.25	104.25
Enviro+	PIM458	Amazon	PIM458	1	69.95	69.95
SanDisk Extreme microSDXC UHS-I Memory Card	SDSQXAV-256G-GN6MA	Amazon	SDSQXAV-256G-GN6MA	1	31.60	31.60
3 Axis Gyroscope and Axis Accelerometer 6DOF	MPU6050	Amazon	MPU6050	1	12.99	12.99
Ultramic 384 EVO	UM384EVO	Dodotronic	UM384EVO	1	316.92*	316.92*
Raspberry Pi HQ Camera M12	SC0870	Digi-Key	2648-SC0870-ND	1	78.24	78.24
2.7mm Wide Angle M12 Lens	SC0947	Digi-Key	2648-SC0947-ND	1	39.12	39.12
GPIO Extension	83-17044	Newark	31AC4873	1	6.02	6.02
Custom 3D print casing**	N/A	N/A	N/A	1	1.05	1.05
Yield					100%	95%
Subtotal					$660.14	$693.14
Packaging and shipping ***					19.99	19.99
Return					0%	5%
Landed Costs					$680.13	$713.13

** After conversion from Euro to CAD.*

*** The cost for a custom 3D printed casing was estimated by downloading the .stl files of a popular raspberry pi 4 case [21]. These files were then loaded into Ultimaker Cura 5, a 3d model slicing software, then using typical 3D print settings (& 100% infill), the models were sliced, and the amount of filament needed to create the case was found. This was estimated to be 16g for the bottom and 19g for the top. Using PETG filament at an average $30/1000g, or $0.03/g, and a total of 35g of filament per case, a cost estimation was calculated to be $1.05.*

*** The cost of packaging and shipping is based on the flat rate box and ship service offered by Canada Post. This includes a small shipping box and postage for anywhere in Canada [22].

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When sourcing components we compared prices between a few different vendors, mainly Digi-key, Mouser Electronics, Newark, and Amazon. The Raspberry Pi 4 Model B/ 8GB can be purchased from either PiShop or Digi-Key. Price per unit for all of items are as listed in Table 11 above.

The ESM is a highly custom-designed module for a specific research and development use within a laboratory environment for recording audio and various environmental sensory data during experiments. It is not being approached from the perspective of having a product to bring to a market, therefore it differs from the typical product's system budget used in evaluating the scaling costs of a manufactured product. The main cost driver for this module is the components used in its construction, namely the Raspberry Pi 4 with 8GB RAM, the ultrasonic microphone, and the Enviro+ board that features a range of sensors all in one. All the components used in building the ESM are commercial off the shelf parts, these COTS components do not offer a reduction in unit cost for ordering in bulk, at least not to the public customer on the previously mentioned vendor sites. The ESM can be easily package into a small shipping box with honeycomb kraft paper to protect the module. A detailed breakdown of the costs is shown in Table 11. Due to the specific design of the ESM of measuring ultrasonic lab animal vocalization recording and environmental sensory data, the market for this product is limited to a niche audience with very specific research requirements. This may not translate into a large enough market for over thousands of units. However, if the market for environmental sensor modules increase to over 1000 units, the landed production cost could likely be changed by potentially negotiating a reduced cost for a COTS component.

Unlike most products which see a reduction in cost with an extended price by scaling to more units and using that purchasing power to buy in bulk at a reduced cost, our product gets more expensive from the fact that at the scale of assembling 1000 units, we would expect some of our ordered components to be wrong or damaged, increasing our costs from reduced yield and increased returns which drives the landed costs up. This increase in cost for our device is not offset by a reduction in component cost as previously mentioned.