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Landslides Detection System
Acoustic Emission Application

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ENGR 491 – Senior Design
Fall 2021

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ACKNOWLEDGEMENTS

In this section, our team would like to acknowledge and give our warmest thanks to the Endeavor Grant committee for funding this project along with the Pott College of Science, Engineering and Education. In addition, our team would like to acknowledge and show our gratitude to the following individuals for their guidance and advice through all stages of this project.

The University of Southern Indiana Department of Engineering:

Dr. Diersing

Dr. Tenant

Dr. Chlebowski

Dr. Kuban

Mr. Kicklighter

Jamie Curry

ABSTRACT

Communities exposed to landslide risk in low and middle-income countries seldomly have access to instruments to monitor slopes to provide a warning of instability because existing techniques are complex and expensive. Research and field trials have demonstrated that acoustic emission (AE) monitoring can be an effective approach to detect accelerating slope movements and to subsequently communicate warnings to users. The purpose of this project is to design, test, build, and implement a network-based landslide detection system along with an early warning system. The system will have the capability of monitoring and predicting a landslide and the ability to trigger an alarm to warn residents. This report describes the concepts consideration, the system overview, the sensor node, and the base station. Due to design specifications constraints, and global supply crisis, the students were not able to select an adequate sensor. The project resulted in the successful creation of a base station and network communication. While the inspiration for this project is a landslide detection system, similar systems that require low power long distance sensor networks could also utilize this project as a framework.

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1 INTRODUCTION

In what is considered one of the worst landslide disasters in decades, devastating floods and mudslides ripped through Freetown early in the morning on August 14, 2017, after three days of torrential rainfall. As many as 1,141 people have been confirmed dead or missing in addition to more than 3,000 people being left homeless. The collapse of the mountainside took place in two stages with the lower portion sliding into the valley with moments later the upper portion failing. Several houses and structures were damaged or completely submerged, killing residents – many still asleep – and some trapped inside. As many as 5,900 people were affected by the disaster that affected Freetown. [1]

Global change in climate, population, land use, and urbanization are expected to increase ground instability causing a rise in human and financial losses. Early warning systems for slope instability are needed to alert citizens of accelerating slope deformation behavior, enable evacuation of vulnerable people, and help minimize repairs and maintenance needed of critical infrastructure. [2]

1.1 OBJECTIVES

The goal of this project is to design, build, test, and implement a landslide detection sensor network with an early warning system using acoustic emission (AE). The AE sensors will have the capability of monitoring slope movements, predicting landslide events, and communicating with the alarm to alert the residents. To create a completed system, the students will need to create a sensor network that is affordable, robust, easy to install and use. Also, the sensor network shall operate in a range of different site conditions, monitor at appropriate spatial and temporal resolutions, quantify slope deformations (rates) that can pose a risk to the community, be self-sustaining, and require minimal human intervention.

1.2 Deliverables

The following requirements were decided on by the team to be met for the project to be considered complete.

1. Low cost
2. Long range
3. Support ADC

To meet the requirement of being low cost each of the sensors needs to cost no more than $100 per sensor node. Being capable of long-range transmissions is important as it allows for the system to be implemented in a wide range of rural and urban applications. The goal is to have a system capable of reaching ranges of at least 2 miles. To ensure a wide range of sensors will be compatible the capability of having an ADC will be needed.

2 BACKGROUND AND CONCEPTS

2.1 Statements of The Problem

A landslide is a physical phenomenon in which large amounts of rock debris break or slide down a slope leading to destruction along with the chance of seriously hurting or killing anyone in the way. Massive losses are caused by landslides yearly in different countries around the globe. Such losses could be avoided if a system could inform those nearby about the event in advance or at least give information about landslide trigger factors like water content in soil, tectonic activity, disturbance frequency of anthropogenic activities, lithology and various others. Below are some examples of existing landside detection methods.

2.2 Existing Detection Method

Remote Sensing or Satellite Technique: Satellite images in the optical region with high spatial resolution are used for producing landslide inventory maps and for mapping factors related to the occurrence of landslides such as surface morphology, structural and logical properties, land cover, and how these factors change with time i.e., temporal changes [3].

Photogrammetric Techniques for Landslide Monitoring: This technique is used for monitoring ground movements, often in mining applications. Aerial photographs that present an overall perspective of large areas and boundaries of existing slides can readily be delineated. Soil and rock formations can be seen and evaluated in their undisturbed state [3].

Ground-based Geodetic Techniques: Deployment of horizontal and vertical networks in investigation and control equipment in the at-risk area. Horizontal or vertical movements of the nodes are used to determine the amount of movement and estimating parameters. Production has stopped however due to this solution being cost prohibitive [3].

Acoustic Emission Sensor: Acoustic emissions (AE) are elastic stress waves generated by deformation of materials that propagate through the solid phase. These waves are known as super audible, meaning that they are frequencies too high to be detected by the human ear. AE are used in many industries to detect and quantify deformation mechanisms (e.g., crack formation and propagation in aeronautical components, pressure vessels and pipes). In soils, AE are generated by movement at particle-to-particle contacts and between soil particles and structural elements. AE monitoring is not as well developed in geotechnical monitoring applications as in other industries due to low energy levels of generated AE and the high attenuation of signals as they propagate through the ground. Both applications make it challenging to detect and quantify AE [4].

Although numerous types of the instrumentation and monitoring techniques are available, alarm systems providing a timely alert to people in the immediate vicinity of the landslide (e.g., flashing light and siren) when slope movements cause a predetermined threshold to be exceeded are not readily available for the public at this time.

2.3 EXISTING SYSTEM

Figure 1 shows the Geo-acoustic sensor (GAA2820) developed by RST instruments (a company based in Canada). This is a forecasting system that typically produces data that is interpreted by experts on a regular basis usually for a regional scale, with a typical output being danger levels that are made public with a bulletin.

Figure 1. This figure shows the GAA2820, which gives access to a Data Logger (RST GAA data logger and sensor) [11]

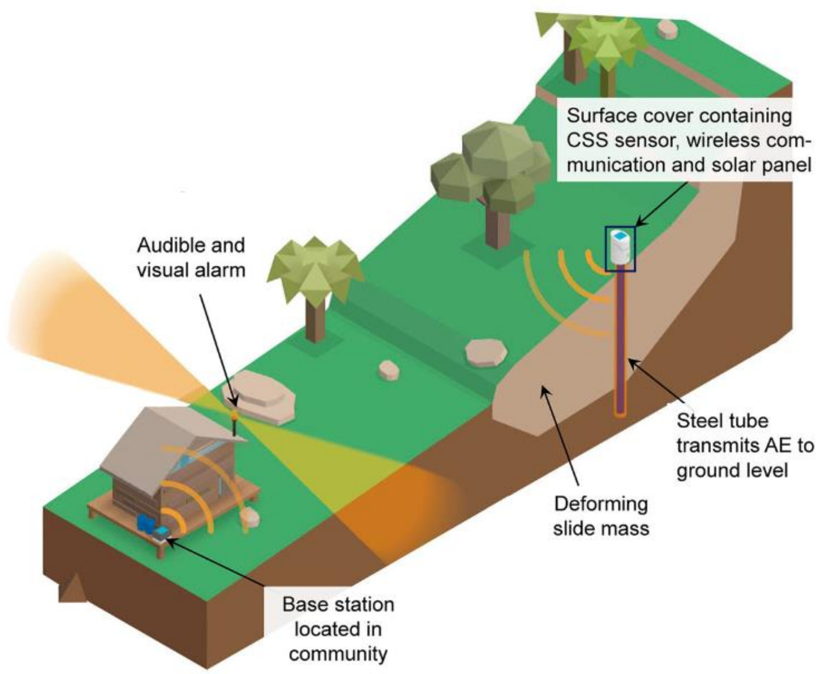

Figure 2. Full landslide detection system overview. The system will be broken down in subsystems with further analysis [4]

Figure 2 represents an onsite application landside detection system with one sensor node. The AE sensor is attached to the top of the steel tube and protected by an enclosure. As the slope moves, in addition to the material generating AE, the backfill material is deformed, generating high levels of AE. It should be noted that the system was initially developed to monitor slopes formed in fine-grained soils that generate very low levels of AE, hence the need to add noisy backfill material. The AE propagating up the steel tube to the sensor located at ground level where the waves are detected and converted to a voltage signal and quantified. AE attenuation in steel is very low, therefore, AE can propagate large distances along the waveguide (i.e., many 10sm) [5]. AE is quantified by counting the number of times the AE signal exceeds a pre-determined voltage threshold (called ring-down counts (RDC)). The threshold is selected to remove system and background noise. The AE are quantified as RDC over a pre-defined monitoring period, which is typically 15 to 30 min in length; hence, the system provides ‘near’ real-time information on the slope status (i.e., at the end of each monitoring period of 15 to 30 min, an alert can be triggered if the threshold is exceeded).

RST Geo-Acoustic sensor uses a piezoelectric transducer to create AE. Piezoelectric materials are characterized by their ability to output a proportional electrical signal to the stress applied to the material. This property makes piezoelectric materials useful as a primary sensor. Piezoelectric materials (piezo = pressure) possess the property that a voltage applied to them will produce a pressure field on the atoms in their lattice (a stress) with an accompanying overall contraction or expansion in one or more dimensions of the material (a strain). These materials can be cut along its axes in x, y and z directions.

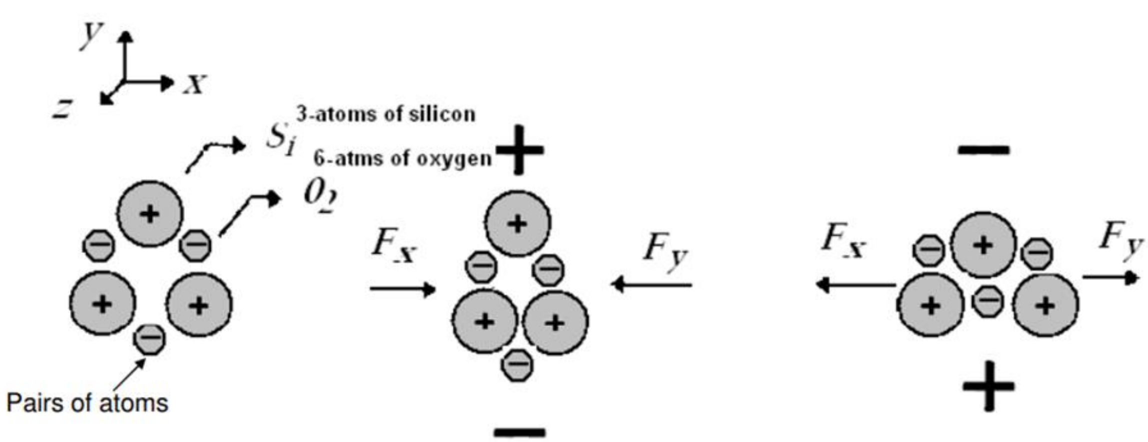

Figure 3- Piezoelectric material atomic view along the Z-axis

An asymmetric atomic structure will distort in an applied electric field. By the piezoelectric property of the material, electrical excitation is changed into motion and pressure, the necessary elements for acoustic waves.

The piezoelectric material acts as a capacitor, with the piezoelectric crystal acting as the dielectric medium. The charge is stored because of the inherent capacitance of the piezoelectric material.

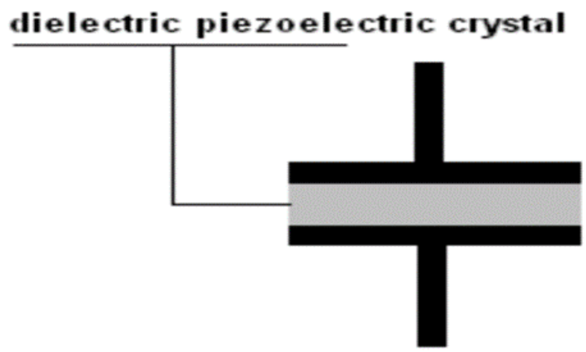

Figure 4- Two opposite faces of the transducer are plated with conductive metal films; a voltage generator V is attached to the electrodes to produce an electric field.

The piezoelectric is reversible. If a varying potential is applied to the proper axis of the crystal, it changes the dimension of the crystal, thereby deforming it. A piezoelectric element is used to convert motion to electrical signal.

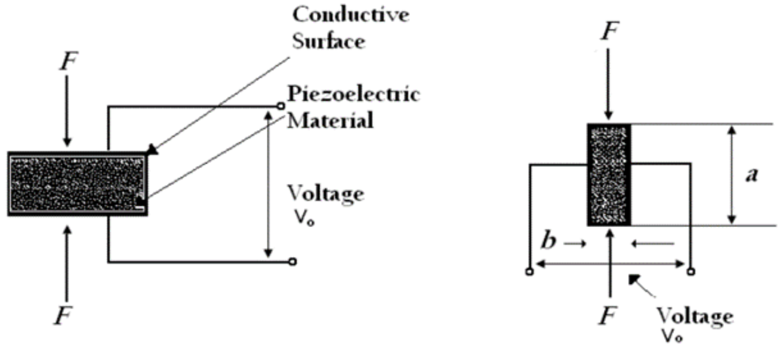

Figure 5- The charge appears as a voltage across the electrodes. The magnitude and polarity of the induced surface charges are proportional to the magnitude and direction of the applied force. [6]

The physical quantities like stress and force cannot be measured directly. The quantity that must be measured is applied along certain planes to the piezoelectric material. The voltage output obtained from these materials due to piezoelectric effect is directly proportional to the applied stress or force. The sensor is governed by Newton's law of motion F = ma. The force experienced by the piezoelectric crystal is proportional to the seismic mass times the input acceleration. The more mass or acceleration, the higher the applied force and the more electrical output from the crystal.

The voltage can be calibrated against the applied stress or the force so that the measured value of the output voltage directly gives the value of applied stress or force. The voltage output obtained is very small and it has high impedance so to measure the output some amplifiers auxiliary circuit are used. There are some properties on which piezoelectric materials should withstand like stability high output, insensitivity to extreme temperatures and humidity, and ability to be performed or machined into any shape. But none of the materials exhibiting piezoelectric effect possess all these properties. Quartz which is a natural crystal is highly stable, but the output obtained from it is very small.

A piezoelectric transducer offers very high frequency response that means the parameter changing at very high speed can be sent easily without any delay of time. Lastly, the rigidness of the piezoelectric transducers is small and have rugged construction, which is very helpful to determine the output. However, a piezoelectric transducers output is low which means the output obtained from the piezoelectric transducer is loaded so an external electronic circuit must be connected. Also, it has high impedance and the piezoelectric crystal have high potential that must be connected to an amplifier and an auxiliary circuit. This creates the potential to cause error in measurement. Piezoelectric transducers have a wide range of applications in different industry. For instance, it is used for dynamic measurements, studying high speed phenomena like explosion and glass waves and in aerodynamic shocks tube. For measurements of stress and force it is used with strain gauge for measurement of force stress and vibration. In automation companies the automation companies use piezoelectric transducer to detect detonations in engine blocks. [6]

2.4 SYSTEM SENSOR SELECTION

The sensor that needed to be selected for the project had several specifications: the power, the output, the frequency range, built in amplifier and cost. The crucial specifications were the frequency range and the cost. Table 1 shows a sample of the sensor that the students considered during this process. Most of the sensors that were considered did not meet the frequency specifications. The team even reached out to several different manufacturers to adjust the sensor frequencies to meet the specifications several times. However, the manufacturers either did not want to go through the process because it was not financially viable or because the amount of time and resources at their disposal. To overcome this challenge, the students decided to use a sensor bought from RST instruments. This will allow the students to do a proof of concept. Furthermore, even though the students are using the RST sensor, the students will still be selecting the microcontroller that can process data from the sensor and trigger an alarm. This is done in the hope that a future group could pick up the project where the current team left it and select a sensor that meets the specification requirements.

Table 1 - Sensor selection criteria and findings

Name	URL	Price	Sensor type	Freq	Output Type	Connector typer	Shiping lead time	Powered?	Notes
786-500	https://www.althense	unkown	Piezo	0.2 Hz - 14,000 Hz	Analog	MIL-C-5015 2 pin	china	no	
VS-JV10A-K04	https://www.mouser.c	$678.00	Piezo	**10 Hz - 15000 Hz**	Analog	3 pin connector	china	yes	Built-in IEPE pre-amplifier
603-Series	https://www.pcb.com	$99.00	Piezo	**0.5 Hz - 10000 Hz**	Analog	2-Pin MIL-C-5015	6 weeks	no	
622B01	https://www.pcb.com	$230.00	Piezo	**0.2 Hz - 15000 Hz**	Digital	2-Pin MIL-C-5015	5 weeks	no	
CA-YD-106	https://www.directind	need to request	Piezo	0.5 Hz - 12,000 Hz	Analog	co-axial	china	no	
CA-YD-181	https://www.directind	need to request	Piezo	1 Hz - 10,000 Hz	Analog	co-axial	china	yes	Built-in IEPE pre-amplifier
TV-22	https://www.directind	need to request	Piezo	1.5 Hz - 12,000 Hz	Digital	co-axial	ready to ship	no	
710xA Series	https://www.directind	need to request	Piezo	0.5 Hz - 15,000 Hz	Analog	co-axial	netherlands	no	
MTN/1100	https://uk.rs-online.c	$292.00	Piezo	2 Hz - 10000 Hz	Digital	co-axial	UK	yes	
VS-BV203-B	https://www.mouser.c	$180.00	Piezo	**10 Hz - 15000 Hz**	Analog	co-axial	UK	yes	Built-in IEPE pre-amplifier
LDT1-028K	https://www.mouser.c	$6.54	Piezo	N/A	Analog	twin wires	ready to ship	yes	

3 SYSTEM ARCHITECTURE

There are two main components of this project -- the sensor node, and the base station. The sensor node consists of the sensor itself (for this project's example a piezoelectric sensor for AE), a microcontroller, power supply, and LoRa transceiver. While the base station consists of: microcontroller, LoRa transceiver, power supply and relays controller audio and visual alarms.

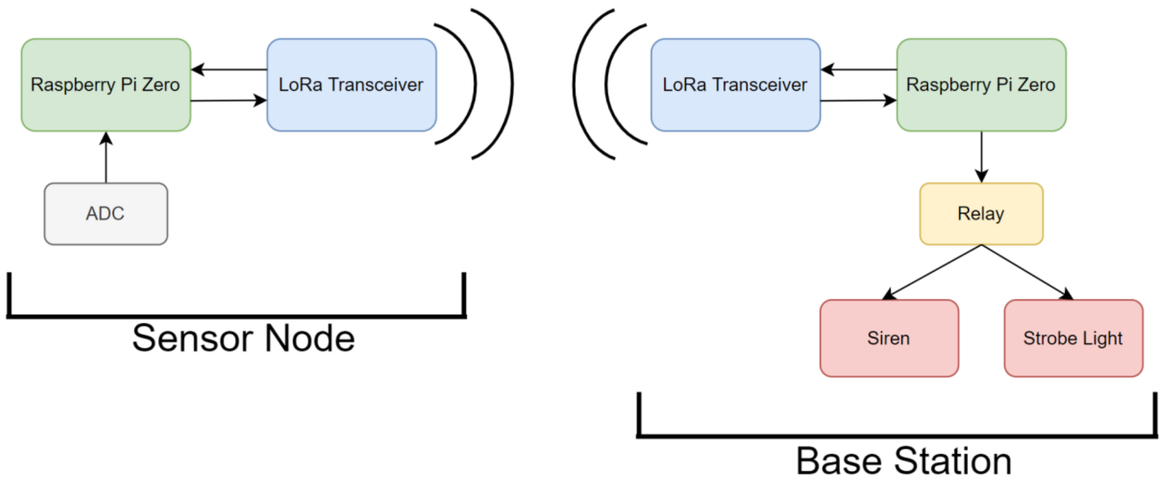

Figure 6. Block Diagram showing a two-sensor set up with wireless connection to base station.

3.1 COMPONENT SELECTION

When designing the sensor nodes, it was important to keep in mind the project's goal keeping each node under $100 and although the source of power does not fall into the scope of this project's considerations, efforts were made to keep power draw to a minimum. The heart of each sensor node is the microprocessor, in table 2 a decision-making matrix for the selection process is shown.

Mirco computer decesion making matrix				
	Criteria			
Scale 1-10	Computing power	Power consumption	Cost	Total
Raspberry Pi Zero	4	7	10	21
Raspberry Pi 4 B	6	5	7	18
Nordic nRF	3	6	7	16

Table 2 Micro Computer Decision Matrix

Another crucial part for both the sensor nodes and the base station is the transceiver that will be connected to the microcontroller. Once again, the design requirements were considered during the selection process. The criteria that each device was rated on included: range, power consumption and cost. Due to the design of the LoRa protocol specifically working to achieve both long range and low power usage it became a clear winner in both categories when compared to the alternatives. The next closest option came down to the Zigbee system while the lowest scoring system based of these metrics was Wi-Fi. Wi-Fi coming in with the lowest score makes sense when considering that this technology is mean for short to medium ranges when a large amount of data needs to be transmitted. The decision-making matrix for the wireless systems can be seen in Table 2.

Wireless technology decesion making matrix				
	Criteria			
Scale 1-10	Range	Power consumption	Cost	Total
Zigbee	5	7	7	19
Bluetooth	2	5	7	14
Wifi	3	3	5	11
Radio	5	4	6	15
LoRa	9	8	8	25

Table 3- Decision Matrix

3.2 INTERFACING WITH THE RASPBERRY PI ZERO

Due to its small form factor the raspberry pi zero does not offer many of the ports normally used to interface with computer. Instead, micro-USB and mini-HDMI ports will need to be used. In Figure 7 the three ports needed to connect with the Pi Zero can be seen in use. Starting from the top a mini-HDMI to HDMI adapter is connected to an HDMI cable going to the monitor. The next connection down is the Pi Zero’s data transfer micro-USB port, here a keyboard is connected. The last connector on the bottom is the power port and is connected to the power supply.

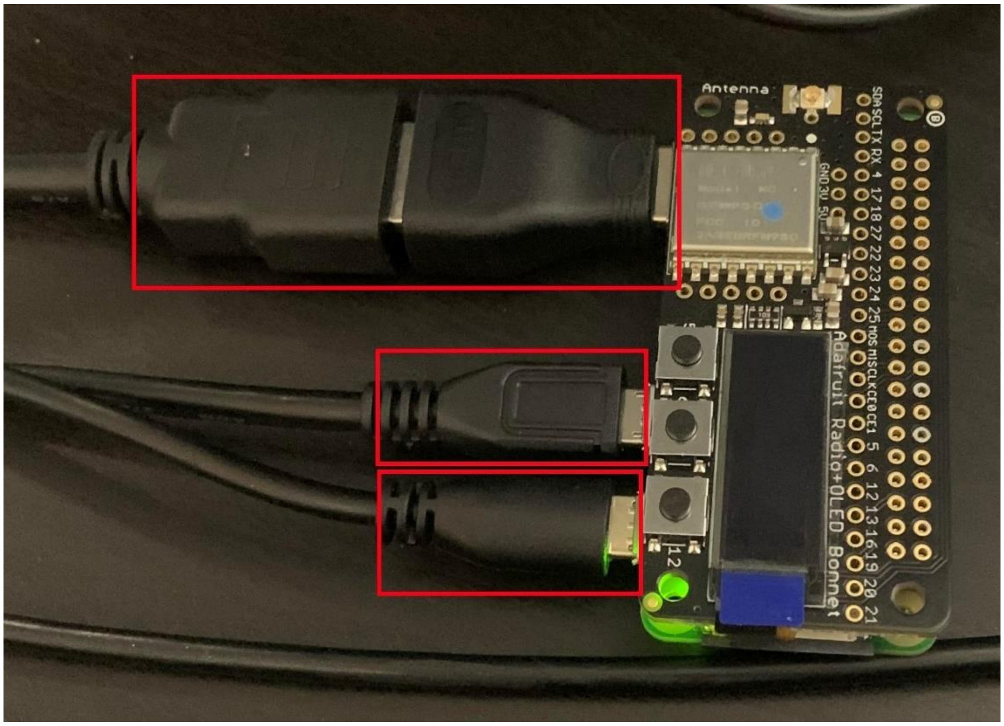

Figure 7- Raspberry Pi Zero Connections

3.3 PROBLEMS

When assembling the Raspberry Pi Zero and Ada Fruit rfm9x LoRa transceiver there seemed to be an issue with communication between the two boards. The protocol used to communicate between these two boards is the call I2C, which is a bus protocol allowing for multiple devices to transfer data using only two wires. The “i2cdetect” command was used in the Pi Zero’s terminal to display the available devices address. Initially when this was done no devices were shown as can be seen in Figure 8.

```
pi@raspberrypi:~ $ i2cdetect -y 1
     0  1  2  3  4  5  6  7  8  9  a  b  c  d  e  f
00:          -- -- -- -- -- -- -- -- -- -- -- -- --
10: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
20: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
30: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
40: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
50: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
60: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
70: -- -- -- -- -- -- -- --
pi@raspberrypi:~ $
```

Figure 8 - i2cdetect output

This led to troubleshooting possible issues starting with making sure the proper libraries had been downloaded. Ada-Fruit as the producer of the LoRa transceiver provides libraries available on their website for its devices. It was at first thought the installation of this library had been done incorrectly. It was found though that the libraries had been downloaded and installed correctly. It should also be noted that by default the I2C protocol is not activated, this can be changed in the Pi Zero's config menu. Upon checking these two items and then also verifying that the Pi Zero itself was running on the most recent update available from Raspberry the focus of the troubleshooting was changed from software to hardware. The LoRa transceiver plugs in directly into the header pins of the Pi Zero, below in Figure 9 (Raspberry Pi Zero on the left and LoRa transceiver on the right) a detailed view can be seen.

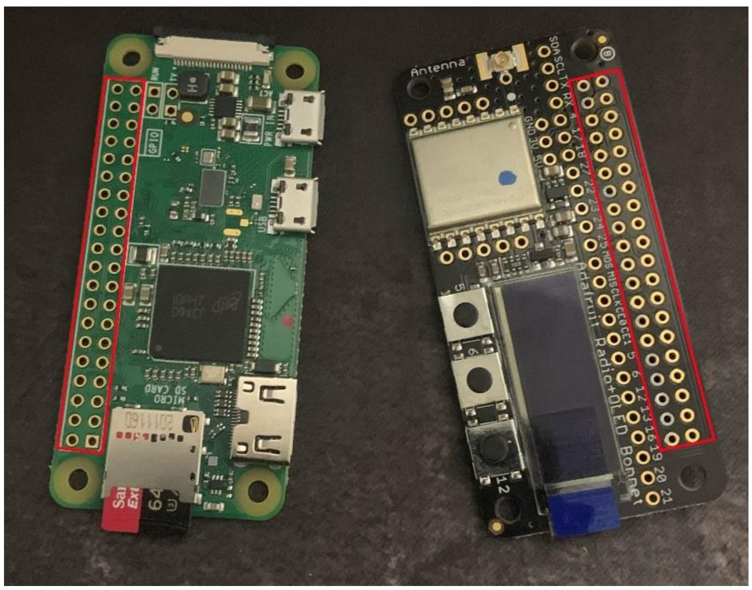

Figure 9 - Header pin locations on Pi Zero and LoRa boards

Specifically pins 5 and 7 (seen as SDA1 and SCL1 in Figure 12) are used for the I2C bus. Before testing these pins though the 5v and ground pins on the transceivers board were checked with a multimeter for voltage. During this test an issue was found as the meter showed no voltage. To fix this the pins on the raspberry pi side were soldered in place. A photo showing the result of this process can be seen in Figure 9.

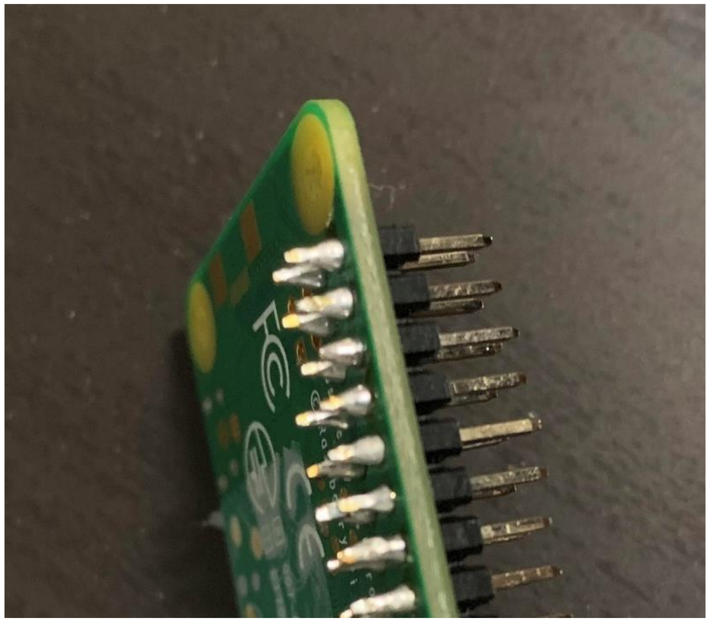

Figure 10 - Soldered Header Pins

Once this had been done the "i2cdetect" command was once again run and this time the device's address was shown as 3c, Figure 11. Soldering the pins completely fixed the issue allowing for testing of other aspects to continue.

```
pi@raspberrypi:~ $ i2cdetect -y 1
     0  1  2  3  4  5  6  7  8  9  a  b  c  d  e  f
00:          -- -- -- -- -- -- -- -- -- -- -- -- --
10: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
20: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
30: -- -- -- -- -- -- -- -- -- -- -- -- 3c -- -- --
40: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
50: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
60: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
70: -- -- -- -- -- -- -- --
pi@raspberrypi:~ $
```

Figure 11 - i2cdetect able to find device

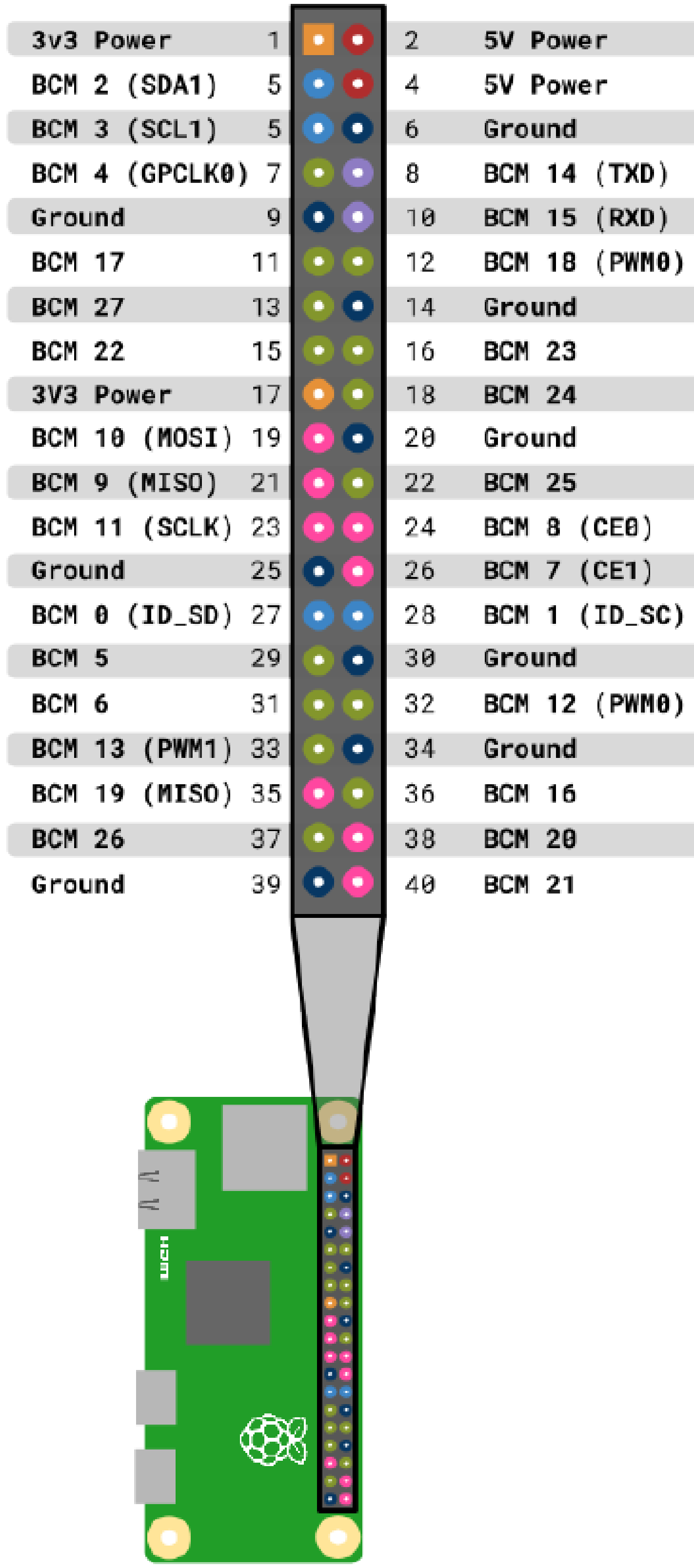

Figure 12 - Raspberry Pi Zero pin out (C. Carlson)

4 BASE STATION AND SENSOR NODE CODE

Each of the Pi Zero microcontrollers when not given any instructions would not know what to do and would not be able to complete any of the tasks needed for this project. This is where the code written specifically for both the sensor node and the base station comes into play. All the code written for this project was done in the latest version of python, python3. Both the sensor node and base station code can be seen in Appendix B and Appendix C respectively. In Figure 13 and Figure 14 a simplified flow chart of the code can be seen. While the base station and sensor node code is slightly different many parts stay the same. Both need to have libraries imported then the pins and buttons initialized along with the basic set up parameters of the radio. This is where the similarities stop as how inbound and outbound messages along with button presses are handled are different in each case.

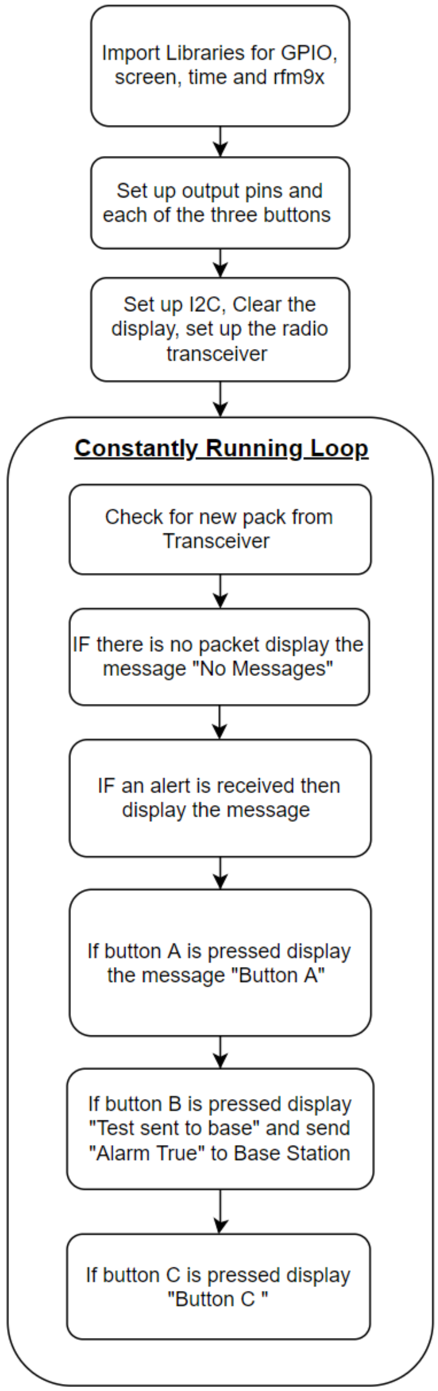

Figure 13- Sensor Node Code Flow Diagram

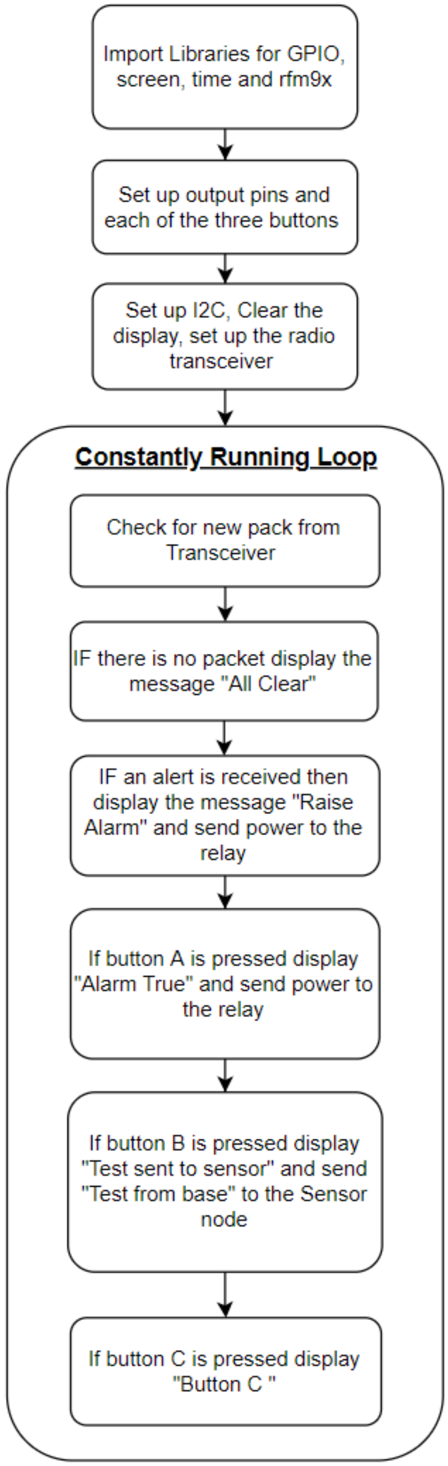

Figure 14 - Base Station Code Flow Diagram

4.1 THE SENSOR NODE

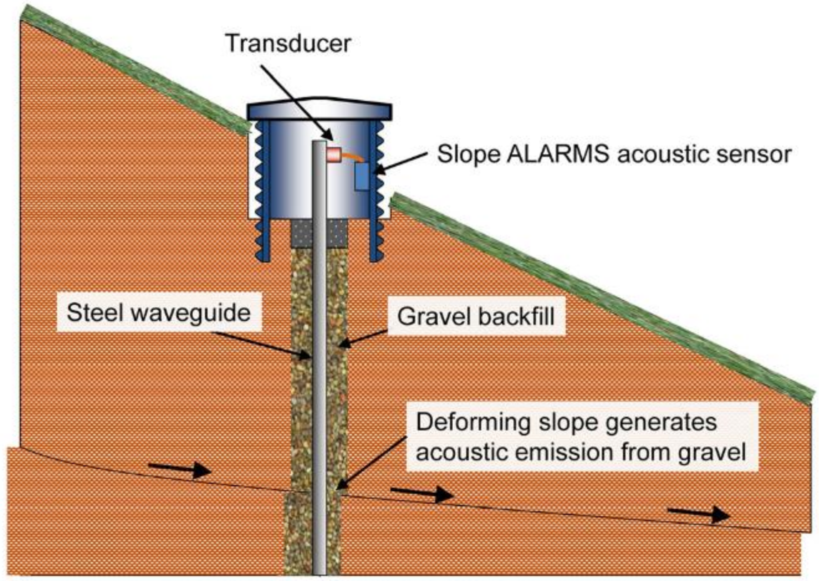

Figure 15- Installed sensor diagram of acoustic emissions sensor with enclosure [4]

The sensor will be a very important part of the project as this single part will be what will give all other parts their data and allow for detection of landslide events. The exact model of acoustic sensor has not been found, therefore is yet to be decided upon. The key factors that are being looked for are: cost, frequency range and documentation. Good documentation on the sensor that will be chosen will be key for keeping the project on task, as less work will be needed in the testing stage to learn about the sensor. An enclosure for the sensor will also need to be developed to protect it from the elements and from wildlife. An illustration of a similar sensor mounted to a wave guide with an enclosure to what is desired for the project can be seen in Figure *15*.

The current power source used by RST for each sensor node is a 3.6v battery. This solution does not allow for recharging for extended use something that would be very desirable for minimal maintenance operations. An important observation about that system is it would not easily support single board computers such as a Raspberry PI due to their voltage requirements. Alternatives include rechargeable batteries connected to a nearby solar panel. Power management will be a key part of this project as it will affect the entire system’s practicality when set up in remote locations.

For the time being, the students will focus on developing the tools to process the sensor signal and trigger a potential alarm. The sensor selection, enclosure design and implementation and the power are out of scope. To process the sensor signal, the students will be developing a Bandpass filter based on RST design specifications, and an amplifier if needed. Filters will allow some signals to pass through while blocking others. A bandpass filter allows signals of a certain frequency range ("a band of frequencies") to pass through the filter as-is. This range of accepted frequencies is called the passband. The size or range of the passband is called the bandwidth. With a bandpass filter, anything higher or lower than the selected frequency range will be blocked (attenuated). This is useful for removing unwanted noise by blocking everything that you know you will not be using anyway. One example is with the audio frequency range for use with music and processing speech; the audio frequency range for these applications runs from about 20Hz to 20kHz.

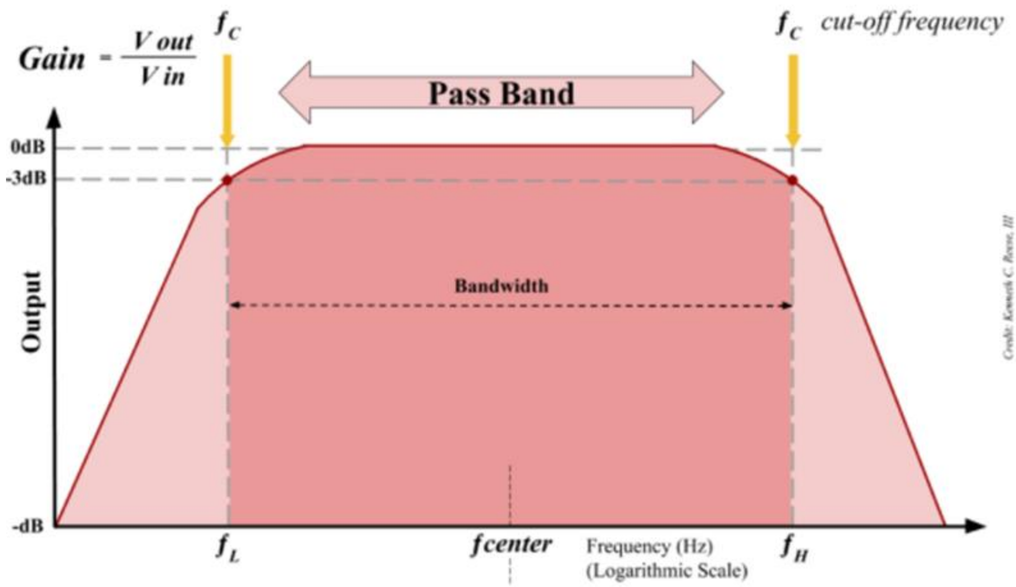

Figure 16 - A bandpass filter with low cutoff frequency (fL), center frequency (fC), and high cutoff frequency (fH) shown in relationship to bandwidth and pass band.

4.2 SENSOR SIGNAL PROCESSING

Bandpass filter

The student will design an n-th bandpass order digital filter with a low frequency fs=15KHz and a high frequency fp=40KHz. The filter order will depend on its ability to block unwanted signals. The student will use the MATLAB program to fulfill this task. To design the bandpass filter, the student transformed the bandpass specification to a normalized low pass filter specification. Since the filter being designed is a digital filter, the student pre-warp the specifications. The student decided to start the design with a third order filter but ended up using a fourth order filter.

Firstly, the student determined the normalized low pass filter zeros, poles and gain using the “buttap“ command in MATLAB. Once the poles, zeros and gain of the transfer function were found, the student created a transfer function for a Butterworth filter (NLP).

Furthermore, the student transformed the NLP transfer function to the Normalize Bandpass filter (NBP). This transformation was possible through algebraic manipulation (refer to the work cited for calculation). The algebraic manipulation allowed to find the zeros, poles and gain of the NBP. The calculations were made so that the student could obtain a generalized formula for the gains, poles, and zeros. This procedure was followed so that in case the filter was not meeting the requirements of the students, the only change that will be made to the code is the filter order. The NBP can be seen in Figure 17 below. Once the plot was populated, the student noticed that the NBP met the expectations.

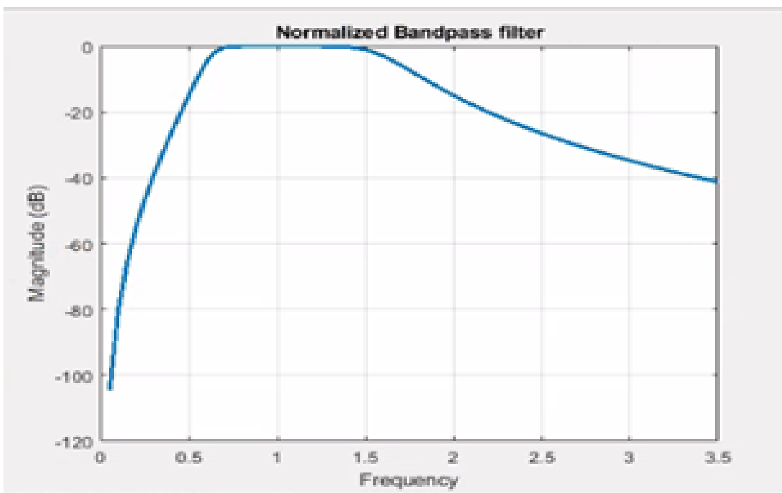

Figure 17- The graphical representation has a magnitude of 0 dB which meets the specifications.

Lastly, the student followed the same thinking process to come up with the gain, zeros, and poles of the bandpass filter. The algebraic approach can be seen in the reference section of the report. Figure 18 represents the overview of the bandpass filter; the overall layout matches the expected shape of the bandpass filter. Figure 19 reflects a zoomed in version of the bandpass filter. The student drew a horizontal line at y= -3dB. Figure 20 shows the lower and upper frequencies have -3dB as y intercept. The frequencies (lower and higher) do not exactly intercept at y=-3dB, but they are very close to -3dB. This confirms that the bandpass filter specifications were met.

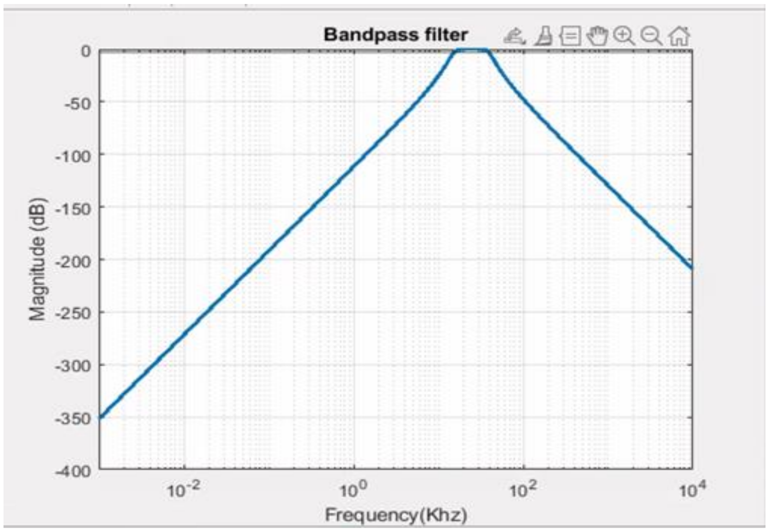

Figure 18 - - Bandpass filter graphical representation. The magnitude of the output does not go over 0dB

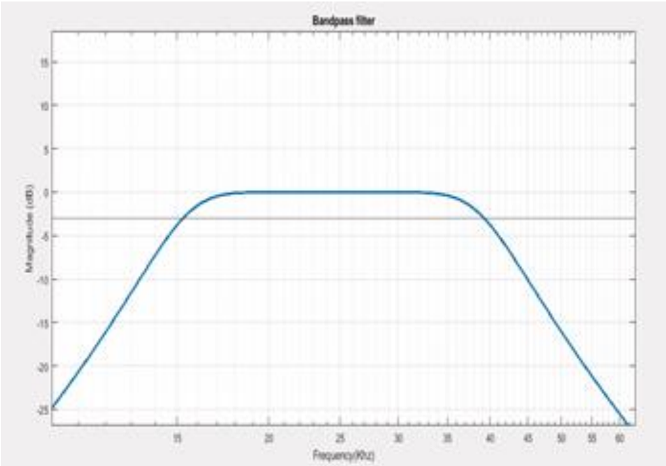

Figure 19 - This is a graphical representation of the bandpass filter with a focus on the lower frequency of 15kHz and the higher frequency of 40kHz

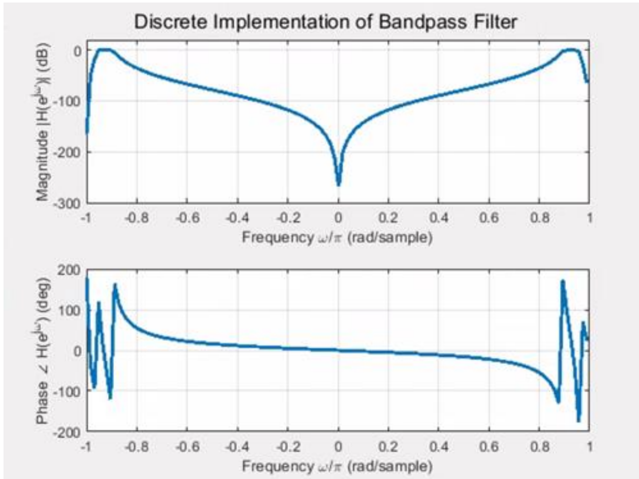

Figure 20 - This is a discrete implementation of the bandpass filter this was done through the bilinear transformation.

The bandpass filter is within 0.5% error of the expected bandpass. The transfer function obtained from the discrete implementation was used to implement the filter. The implementation program was written such that the voltages data from the sensor will be used as an input in a loop with a programed differential function. This loop also, has the ability to pass and store values that are in the bandwidth.

4.3 RING DOWN COUNT

Ring Down Count or RDC is a way of quantifying how many times a signal exceeds a set threshold given a certain time period. Based off the research of Dr. Dixon [4] RDC can be used to access if an alarm should be triggered for a landslide event.

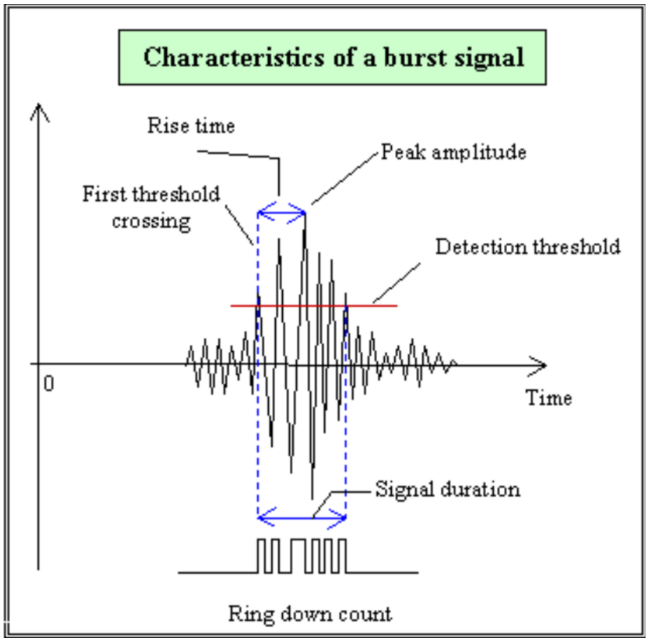

Figure 21- Characteristics of RDC [8]

In Figure 21 the red horizontal bar shows the detection threshold, this is a predetermined level that when exceeded by the incoming signal will add a value of 1 to the RDC. By looking at a specific time window, for example 60 seconds, a RDC value can be calculated and when the value goes over another predetermined amount an alarm can be triggered. To be able to use RDC in calculations for this project a MATLAB script was written that performs the RDC calculations. This MATLAB project can be referenced in Appendix E.

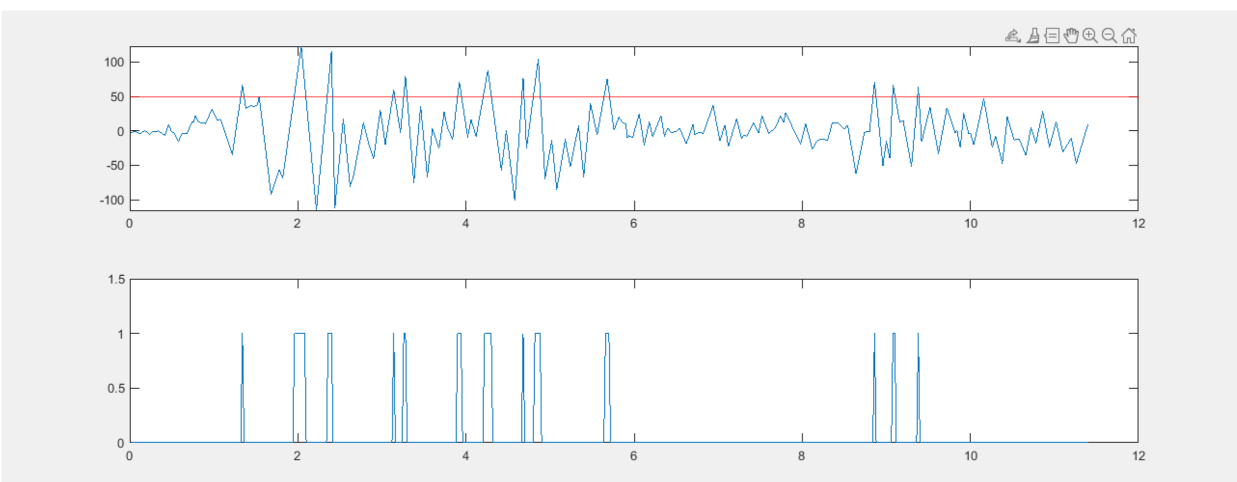

Figure 22 - MATLAB RDC Graph

4.4 HOW IT WORKS, BASE STATION

The base station shares many of the same components with the sensor node, both use the same raspberry pi zero and the same AdaFruit rfm9x transceiver. But the base station also is connected to a siren and strobe light creating the audio and visual alarm. Microcontrollers such as the Pi Zero were intended to only be used as the controller for such devices, not to be the power source. In order to control when power would be sent to these two devises a transistor and relay were used. The circuit that was used to connect the output of the microcontroller to the transistor to the relay can be seen in Figure 23. Here it can be seen that when power is sent to the pin assigned to the alarm of the Pi Zero it will allow the transistor to complete the circuit which will in turn energize the relay. When the relay is energized it completes the circuit sending power to the buzzer and siren until the power coming from output pin of the microcontroller turns off.

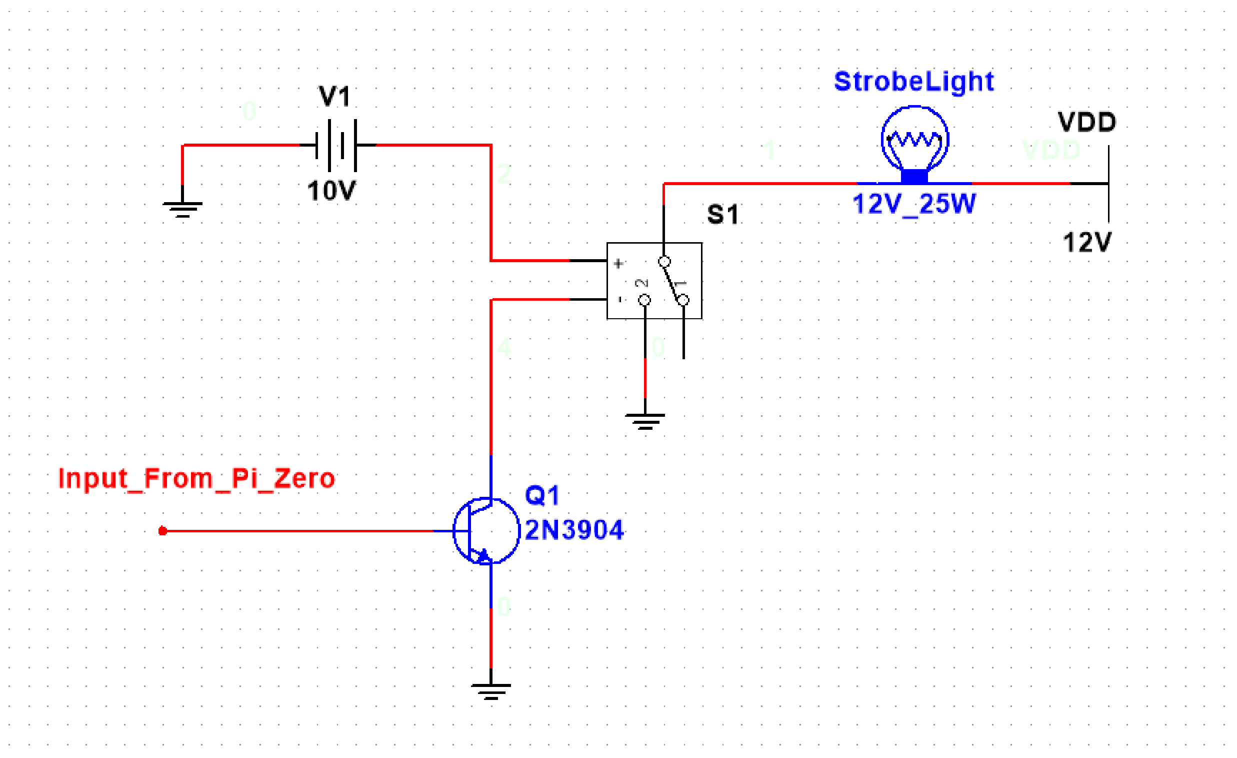

Figure 23 - Base Station Circuit

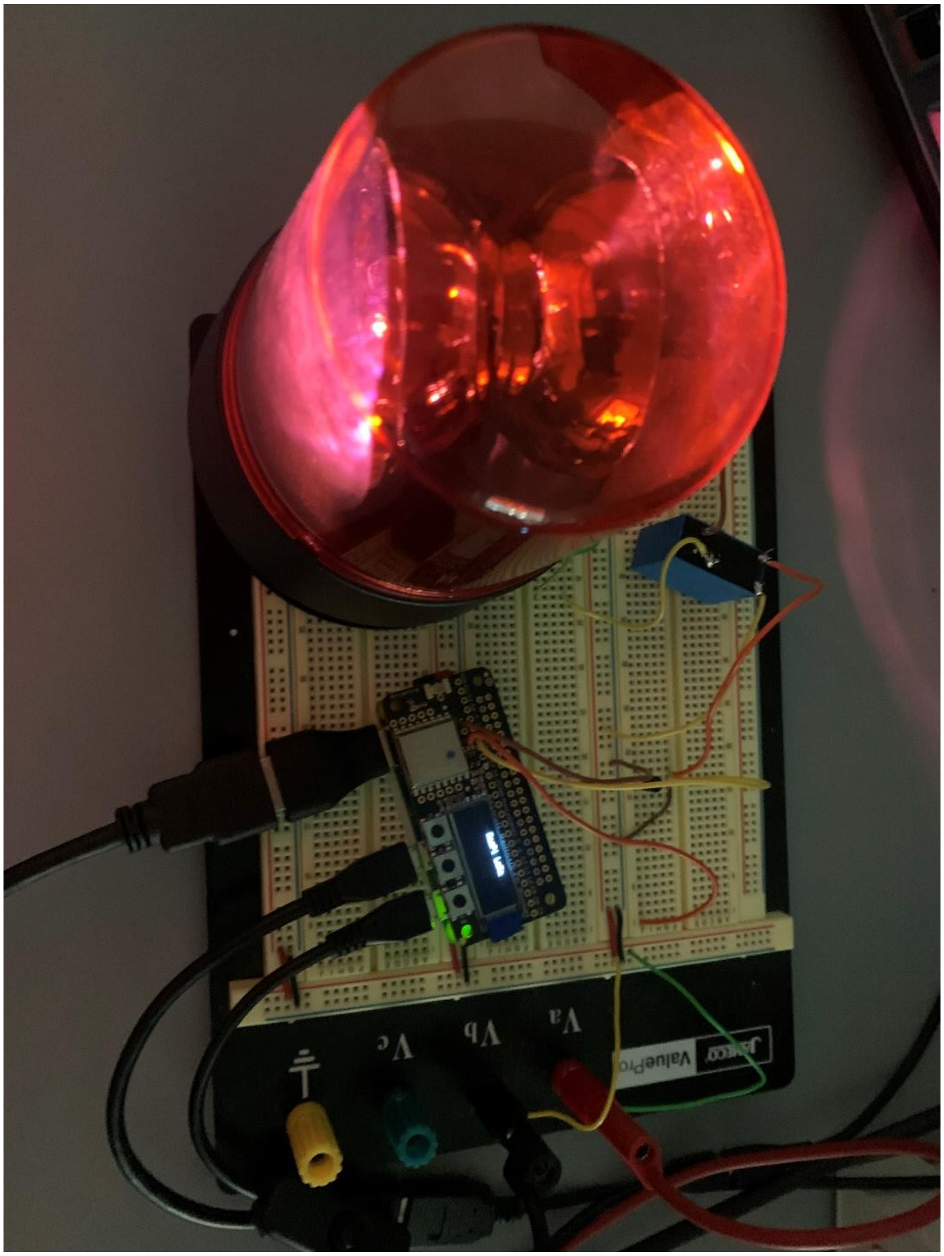

Figure 24 - Base Station Prototype

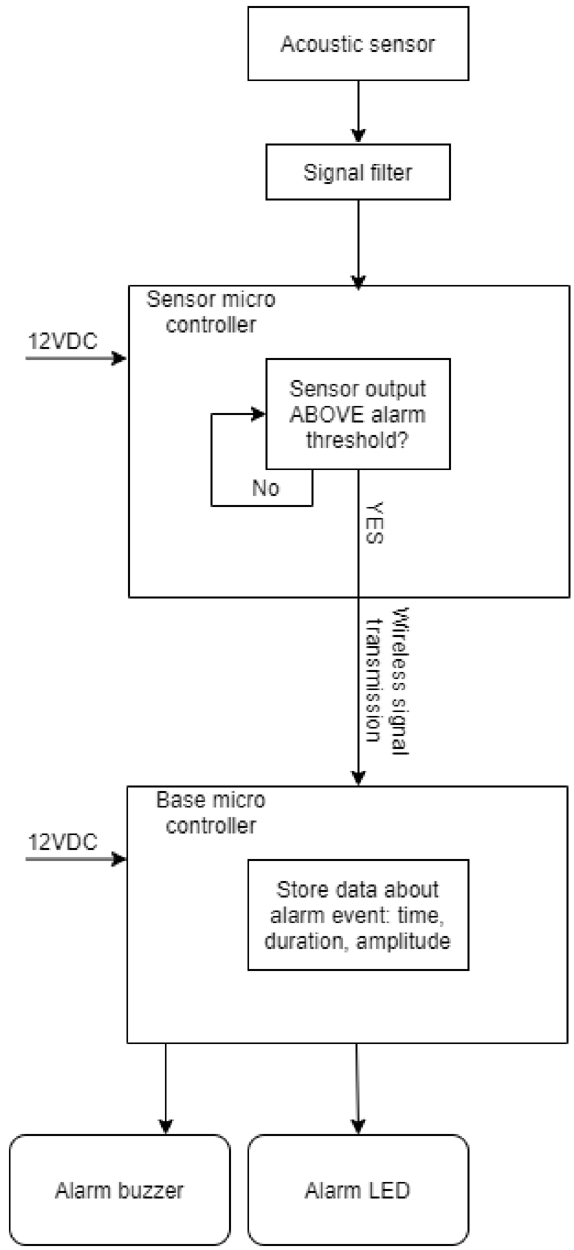

Figure 25 - System Flow Chart showing progress from sensor through alert system.

4.4.1 ADC

The ADC or Analog to Digital Converter is a very key step in taking the signal that is being produced by a sensor (analog) and translating it into a signal that can be used by the microcontroller (digital). As the raspberry Pi does not natively support an ADC an external device will be needed. The model chosen was the ADS1115 by AdaFruit. This unit can work off the same voltage as the raspberry pi (5.5v) and has a very low current draw of 150 µA (Texas

Instruments). This unit is a 16-bit model, allowing for sample rates up to 860 SPS (Samples Per Second). The higher the SPS the closer the digital representation of the analog signal will be. A graph showing how the analog wave is converted into a digital one is shown in Figure 26.

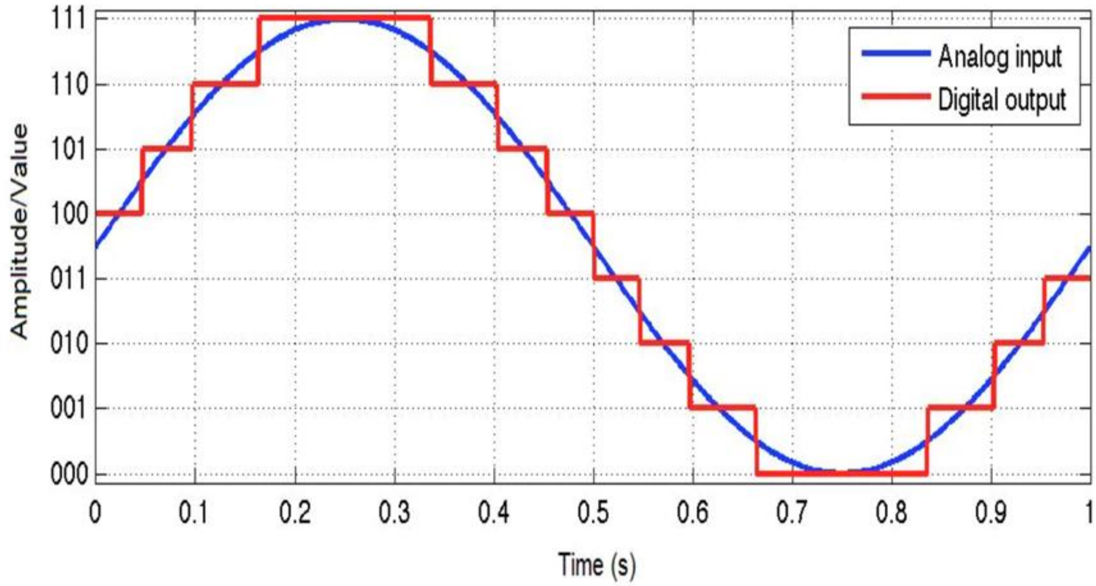

Figure 26 - Analog vs digital graph [6]

Here the analog signal that is to be converted is shown in blue, while the converted digital signal is shown as red. In this example there are 20 samples taken per second or 20 SPS, this is a relatively low amount as the ADS1115 is rated for 43 times more samples per second at 860 SPS. At each point that is being sampled a snapshot of the voltage is taken and then stored as a number. When using this ADC for this project it was important to find an ADC with a high SPS count as a higher sample rate will mitigate the chance of missing a spike in the analog signal. Because if the ADC has low resolution, it would be possible that in between samples of the analog signal there could be a sharp increase and the next sample may only capture the signal as its value is coming back down. An example of this is shown in the following two figures where the horizontal dashed lines represent a sampling of the signal. It can be seen in Figure 27 the peak is missed as it is between samples whereas in Figure 28 a higher sample rate is used, and the peak is captured.

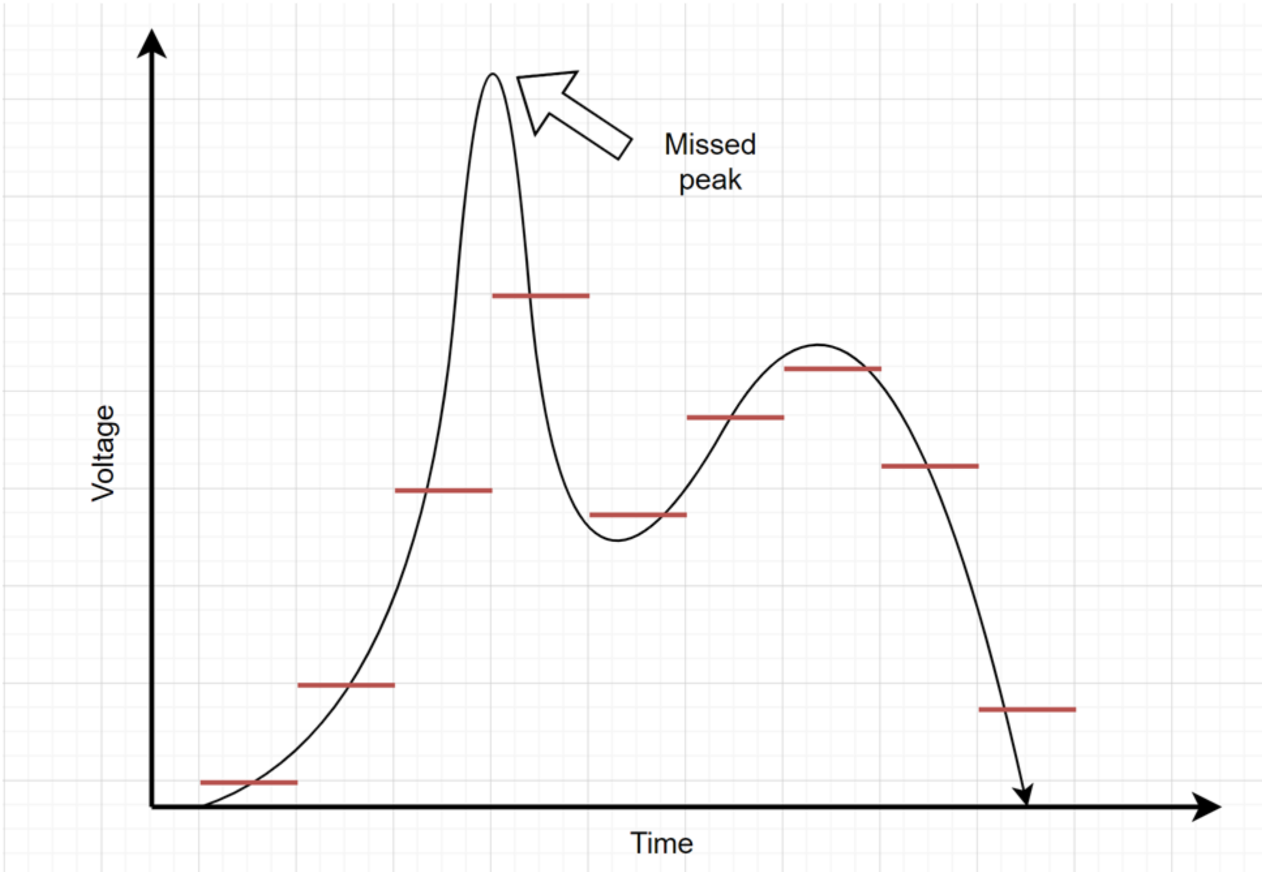

Figure 27 - ADC, low sample rate, peak is missed

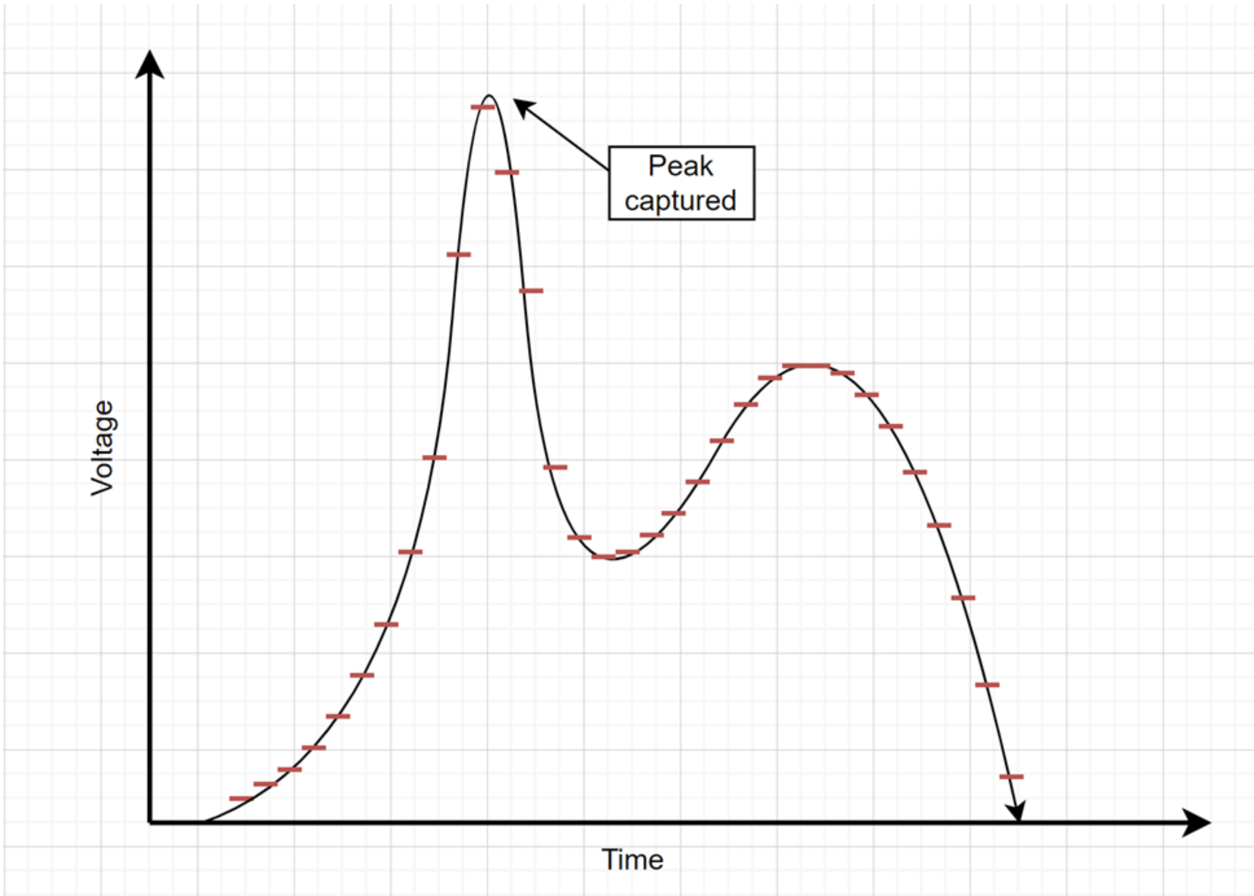

Figure 28 - ADC, high sample rate, peak is captured

4.4.2 LoRa Transmitter And Receiver

LoRa is a type of wireless protocol like that of Wi-Fi or Bluetooth but has distinct advantages over other wireless technologies. LoRa is a shortening of the words “Long” and “Range” and is a technology developed by Cycleo which was later bought by Semtech [7]. This technology was created with the goals being low power long-range communications, which fit perfectly for the use case of this project. The development used the already established Chirp Spread Spectrum (CSS) to create their proprietary system. A graph showing an example CSS signal can be seen below.

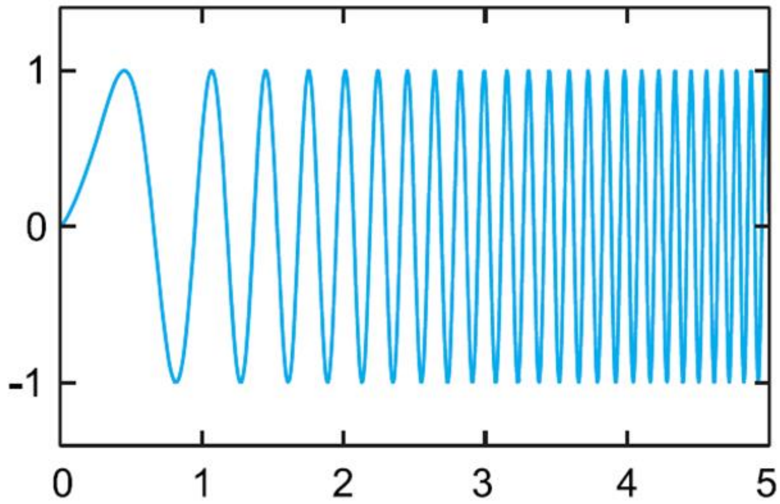

Figure 29 - CSS graph, the chirp signal is created by continuously varying the frequency being transmitted. [7]

Because bandwidth and power are proportional to each other for LoRa to achieve the impressive ranges that it is capable of, the bandwidth and therefore the amount of power used per transmission is limited. This translates to smaller packet sizes, meaning that systems wanting to use this protocol will need to consider this limitation. For the use case of this project a small data packet is acceptable as very little information needs to be transmitted.

Due to government restrictions the transmission of signals is only allowed at certain frequencies. One of the frequencies that can be used without a license is 915-MHz, and it is the frequency that the LoRa transceiver will be using [7]. This signal frequency can be freely used by the public, which will mean that no special licensing or monthly fees will be required when setting up the transceiver.

Link budget is a way to quantitate the capability of a transmitter to send a signal to a receiver. This not only considers the distance between the two but also obstructions such as foliage and buildings that will disrupt the signal [7]. Therefore, a higher link budget allows for longer range communication. When compared to other wireless transmission types LoRa has an incredible link budget.

To lower power draw, LoRa equipped devices use the Aloha protocol, which allows for multiple devices to send signals without needing them to have a constant connection with their gateway. This is the opposite of many other wireless communication protocols that do require a constant connection with their base station to time transmission from multiple devices. Since LoRa devices do not have a constant connection, they use a protocol called Aloha (B. Ray). By using this protocol, conflicting signals are randomly assigned a time to wait to avoid conflicting again with another signal.

4.4.3 LoRa Transceiver Range Testing

To test the real-world range of the Adafruit rfm9x LoRa transceiver one sensor node and one base station were set up and loaded with their respective scripts. Testing was done in an open field with clear line of sight between each unit. While the base station was connected to a power supply battery (seen in Figure 32) the sensory node was connected to power via a vehicle’s power. To find the maximum range that this system is capable of, an alarm signal was continuously sent using the button on the sensor node while continuously moving farther away from the base station.

Figure 30 - Field Range Test (Sensor Node)

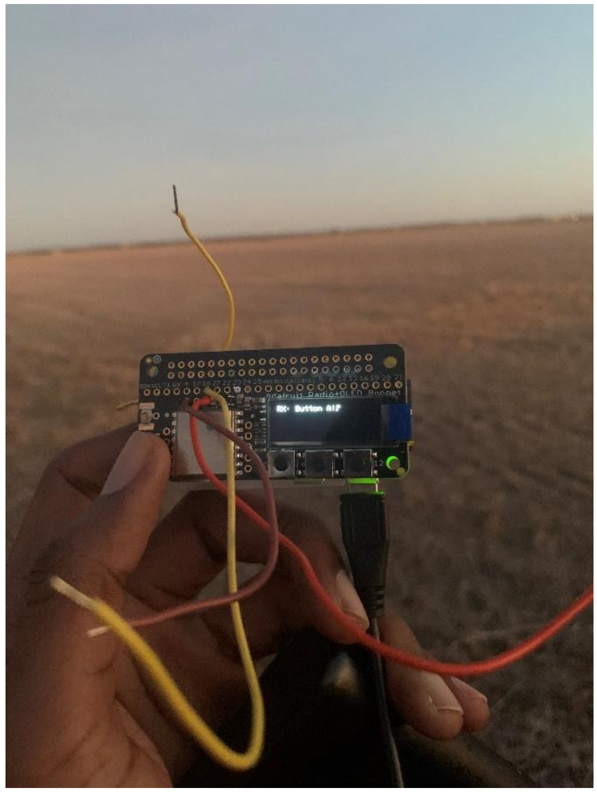

Figure 31- Field Range Test (Base Station)

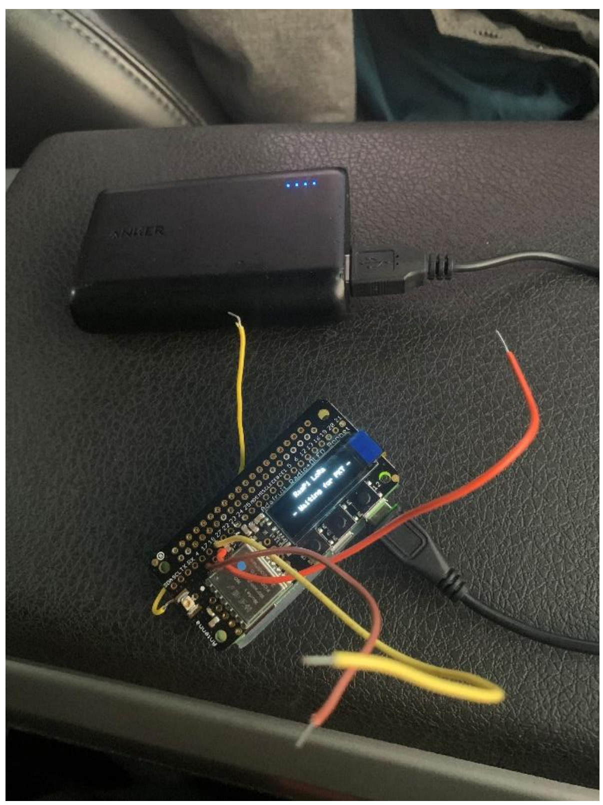

Figure 32 - Battery Supply Connected to LoRa Transceiver

By following a nearby road, the sensor node was moved to approximately 1.31 miles away from the base station before the signal was no longer able to be received. A map showing the location of the base station, signified as the blue mark and the sensor node shown as a white circle to the left side of the map can be seen in Figure 33. While the range goal set for this system was set at 2 miles, 1.31 miles of range is within the expected range for this device and could be improved by use of direction antennas or a simply a better antenna as currently the system uses only a solid core wire.

Figure 33- Range Test Location and Distance Map

5 FACTORS THAT IMPACT THE DESIGN

Economic Considerations

The economic potential of this project is promising because as global warming is affecting more regions in the world, the demand for natural disaster prevention will rise. Furthermore, the rise of innovative technology such as electric vehicles requires more minerals to supply these growing markets. Landslide detection systems can be used to save miners' lives. Finally, government contracts or partnerships with banks and non-profitable organizations can help fund the deployment of the landslide sensor across the world.

Environmental Considerations

Landslides affect low to middle-income communities in developing countries. The climate varies from tropical to polar. The most affected communities live in tropical climates where heavy rains contribute immensely to the landslide's events. The incidence of this phenomenon, usually triggered by natural hazards such as earthquakes, volcanic eruptions, heavy rainstorms, or cyclones, is increasing due to modern land-use practices, climate change, and deforestation.

Installing a landslide detection system in Sierra Leone, for example, will require a geological analysis. Understanding the type of soil and the geological layout of the region that will be receiving the sensor will be crucial to the success of the project.

Public Health, Safety, and Welfare

When it comes to a landslide, the victims do not usually have the time to realize the ongoing situation and evacuate in a timely manner. Some landslide events happen overnight when the victims are asleep. The use of technology in line with what this project aims to produce will allow for the detection of a potential landslide and alert the nearest inhabitants with enough time to evacuate the area, in theory even if the locals are asleep.

Global/Political Considerations

Between 1998-2017, landslides affected an estimated 4.8 million people (about twice the population of Mississippi) and caused more than 18,000 deaths. Climate change and rising temperatures are expected to trigger more landslides, especially in mountainous areas with snow and ice. As permafrost melts, rocky slopes can become more unstable resulting in a landslide. Landslides can cause high mortality and injuries from rapidly flowing water and debris. The most common cause of death in a landslide is trauma or suffocation by entrapment. Broken water, gas, or sewage pipes and broken powerlines can also result in injury or illness in the population affected, such as water-borne diseases, electrocution, or lacerations from falling debris. People affected by landslides can also have short- and long-term mental health effects due to loss of family, property, livestock, or crops. Landslides can also greatly impact the health system and essential services, such as water, electricity, or communication lines [9].

Social and Cultural Considerations

The benefits of this project to the public include increased safety, peace of mind, and protection of their homes and properties. While this project aims to create the most reliable system possible, it should be noted that no system is perfect, and there is always the possibility of the sensor not picking up the landslide event, therefore, not being able to warn the community. Because of this, it will be important to help users to understand the benefits and the limitations of the final product. The intended users will be from a wide range of cultures and backgrounds as it is our goal for this system to be available to anyone that would benefit from it.

6 LESSONS LEARNED

6.1 TEAMWORK

While the entire project has been a group effort, some parts have been delegated to certain team members to use time more efficiently. Matthew has been tasked with more of the hardware setup, research, and design for the base station. Jerome has been tasked with research, design, and setup for the sensor node and in addition to corresponding with suppliers. The team uses Microsoft Teams software to keep each team member connected and up to date. This software allows for team members to chat and make comments on specific sections of the project in addition to providing a central place to store all the files for the project for everyone to access. Working on a group project like this requires one to show respect and an open mind to someone else’s ideas. This team effectively showcased this during the entire semester. Everyone was able to show their personal ideas and designs to the group without worrying about negative criticism or being unheard. Everyone also contributed equally to all aspects of the project while emphasizing certain other points personally.

6.2 Good Design is the Result of an Iterative Process

Taking a project from an idea to reality is not a linear process. Throughout this project, the team learned that to successfully complete a project, the approach should not be linear. Having the ability to divide the project into sections that are independent is crucial. The team spent a major portion of the semester trying to work on the sensor node i.e., selecting an adequate sensor. This created a toll on the team since most of the efforts were going towards this task and were full of shortcomings. The team had to consider the overall project and realize that there are portions that could be accomplished. Completing several segments of the project independently allowed to quickly integrate the project when the parts were starting to come together. For example, since the team had the expected sensor specification, the bandpass filter was successfully designed without having the sensor.

Engineering design is a communicative and collaborative effort. Throughout this project, the team developed the ability to effectively work with one or more groups of people on a project. During group meetings, it was crucial to insure everyone was on the same page before any big decisions were made. This required in-depth discussions and respecting other points of view on a problem. Outside of the main group, weekly meetings were held with the project advisor. During these meetings, it was important to effectively communicate what the team had discussed and tested in the interim meetings. This allowed the project advisor to give the best feedback possible.

This project is, at its core, a civil engineering project. The team lacked knowledge and experience in this field starting out. This led to a collaboration with civil engineering professors, in depth research and collaboration with experts in the landslide detection field. By working alongside them the team was able to gain crucial information to use during the design process. Also, through collaboration and effective communication, the students were able to write two separate grants proposals for the project.

7 FUTURE WORK

The team encountered different areas for future improvement on the landslide detection network.

Below are recommendations for future work on this project.

7.1. *POWER*

As the current system does not include powering as a scope, the future work that could be done is the design of a power system that will make both the base station and the sensor node autonomous. Since the detection system will be used in remote areas, it is crucial to have a reliable power source with a backup plan in case of system failure. The use of solar panel on the sensor node and base station should be able to output enough power to support the base station and the sensor node. The power supply will mainly be used for the microcontrollers. The students may need to design or purchase a solar panel source that is convenient for the systems. This is a suggestion that will be judged by the future group based on available technology.

7.2. *MICROCONTROLLER AND SENSOR SELECTION*

The piezoelectric transducer seems like a promising route to pursue for realizing this project. Using the vibration laboratory at USI to test the RST sensor and evaluate the frequency range specification from Dr. Dixon's paper will help the students understand the impact of the frequency range. This will allow to redesign the filter with more accurate specifications and a more realistic bandwidth. The students will then be able to select a new microcontroller that could sample the bandwidth of the filter. The students will then create an algorithm to detect when the threshold is exceeded and send a signal to the base station.

7.3. *TEST IMPLEMENTATION, DESIGN ENCLOSURE, USER MANUAL*

Testing of the sensor will be a very important future step to tune in the trigger and filter to work best with the future set up. While full scale testing on a mountainside and causing a landslide to occur is not a practical route as multiple successive test need to be done right after another. In his research Dr. Dixon took the route of creating a lab size shear plane mechanism that was able to emulate the shearing plane caused by a landslide [4]. This is the route we would strongly suggest future groups investigate. Designing an enclosure that protects the sensor and microcontroller along with the transceiver will be another future consideration as this system will need to be weather resistant in a wide range of locations. The creation of a user manual that will assist in not only the onsite set up of this system but also help with issues that may arise during normal use will also be an excellent addition to this project.

8 CONCLUSION

The initial objective of this project was to design a landslide detection network with an early warning system. Due to challenges that were unsolvable for the time and resources allocated, the team shifted the focus of the project. The team decided to focus on the early warning system and wireless communication aspect of the project. The team was successfully able to achieve wireless communication between the sensor node and the base station. The team tested the communication system by triggering an alarm from the sensor node to activate the audio and visual alarms located at the base station. Even though all the requirements for the wireless communications were met, there is still an important amount of work to be done for bringing this project to life.

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APPENDIX A (COST SHEETS)

Base Station	
Part Description	**Price**
Raspberry Pi Zero	$40.00
8GB SD card	$8.00
LoRa Transciever	$40.00
Siren	$30.00
Strobe Light	$22.00
Relay	$12.00
Tansistor	$3.00
Wire	$5.00
Total:	$160.00

(1x) Sensor Node	
Part Description	**Price**
Raspberry Pi Zero	$40.00
8GB SD card	$8.00
LoRa Transciever	$40.00
ADC	$6.00
Total:	$94.00

APPENDIX B (SENSOR NODE CODE)

```
""""""
**** Sensor Node code ****

By Matthew Klein
USI student 2021
Senior Design project
""""

# Import Python System Libraries
import time
# Import Blinka Libraries
import busio
from digitalio import DigitalInOut, Direction, Pull
import board
# Import the SSD1306 module.
import adafruit_ssd1306
# Import RFM9x
import adafruit_rfm9x
# import RPi.GPIO module
import RPi.GPIO as GPIO
# immport sleep from time libary
from time import sleep
# can choose BCM or BOARD
GPIO.setmode(GPIO.BCM)
# set GPIO pin 23 as an output
GPIO.setup(18, GPIO.OUT)
# set GPIO pin 23 as an output
GPIO.setup(23, GPIO.OUT)
# set GPIO pin 24 as an output
GPIO.setup(24, GPIO.OUT)
```

```
# Set up Button A to Digital Pin 5
btnA = DigitalInOut(board.D5)
btnA.direction = Direction.INPUT
btnA.pull = Pull.UP

# Set up Button B to Digital Pin6
btnB = DigitalInOut(board.D6)
btnB.direction = Direction.INPUT
btnB.pull = Pull.UP

# Set up Button C to Digital Pin12
btnC = DigitalInOut(board.D12)
btnC.direction = Direction.INPUT
btnC.pull = Pull.UP

# Create the I2C interface using the standard SCL and SDA pins on the raspberry pi board
i2c = busio.I2C(board.SCL, board.SDA)

# Set up the 128x32 OLED Display using the adafruit SSD1306 libary
reset_pin = DigitalInOut(board.D4)
display = adafruit_ssd1306.SSD1306_I2C(128, 32, i2c, reset=reset_pin)

# Clear the display on startup
display.fill(0)
display.show()
width = display.width
height = display.height

# Configure LoRa Radio transciver
```

```
CS = DigitalInOut(board.CE1)
RESET = DigitalInOut(board.D25)
spi = busio.SPI(board.SCK, MOSI=board.MOSI, MISO=board.MISO)
rfm9x = adafruit_rfm9x.RFM9x(spi, CS, RESET, 915.0)
rfm9x.tx_power = 23
prev_packet = None



# Createa a while loop always set to true to constantly run a loop
while True:
    packet = None
    # draw a box to clear the image
    display.fill(0)
    display.text('RasPi LoRa', 35, 0, 1)

    # check for packet rx
    packet = rfm9x.receive()

    # If the packet is empty
    if packet is None:
        display.show()
        display.text('- No Messages -', 15, 20, 1)
    # when the packet is NOT empty
    else:
        # Display the packet text and rssi
        display.fill(0)
        prev_packet = packet
        packet_text = str(prev_packet, "utf-8")
        display.text('RX: ', 0, 0, 1)
        display.text(packet_text, 25, 0, 1)
```

```
    time.sleep(1)

if not btnA.value:
    # Send Button A
    display.fill(0)
    display.text('Button A', 25, 15, 1)


elif not btnB.value:
    # Send Button B
    display.fill(0)
    button_b_data = bytes("Alarm True\r\n","utf-8")
    rfm9x.send(button_b_data)
    display.text('Test sent to base', 25, 15, 1)

elif not btnC.value:
    # Send Button C
    display.fill(0)
    display.text('Button C', 25, 15, 1)


display.show()
time.sleep(0.1)
```

Appendix C (Base Station Code)

```
""""""
**** Base station code ****
By Matthew Klein
USI student 2021
Senior Design project
""""


# Import Python System Libraries
import time
# Import Blinka Libraries
import busio
from digitalio import DigitalInOut, Direction, Pull
import board
# Import the SSD1306 module.
import adafruit_ssd1306
# Import RFM9x
import adafruit_rfm9x
# import RPi.GPIO module
import RPi.GPIO as GPIO
# immport sleep from time libary
from time import sleep
# can choose BCM or BOARD
```

```
GPIO.setmode(GPIO.BCM)

# set GPIO pin 23 as an output

GPIO.setup(18, GPIO.OUT)

# set GPIO pin 23 as an output

GPIO.setup(23, GPIO.OUT)

# set GPIO pin 24 as an output

GPIO.setup(24, GPIO.OUT)


# Set up Button A to Digital Pin 5

btnA = DigitalInOut(board.D5)

btnA.direction = Direction.INPUT

btnA.pull = Pull.UP


# Set up Button B to Digital Pin6

btnB = DigitalInOut(board.D6)

btnB.direction = Direction.INPUT

btnB.pull = Pull.UP


# Set up Button C to Digital Pin12

btnC = DigitalInOut(board.D12)

btnC.direction = Direction.INPUT

btnC.pull = Pull.UP
```

```
# Create the I2C interface using the standard SCL and SDA pins on the raspberry pi board
i2c = busio.I2C(board.SCL, board.SDA)

# Set up the 128x32 OLED Display using the adafruit SSD1306 libary
reset_pin = DigitalInOut(board.D4)
display = adafruit_ssd1306.SSD1306_I2C(128, 32, i2c, reset=reset_pin)

# Clear the display on startup
display.fill(0)
display.show()
width = display.width
height = display.height

# Configure LoRa Radio transciver
CS = DigitalInOut(board.CE1)
RESET = DigitalInOut(board.D25)
spi = busio.SPI(board.SCK, MOSI=board.MOSI, MISO=board.MISO)
rfm9x = adafruit_rfm9x.RFM9x(spi, CS, RESET, 915.0)
rfm9x.tx_power = 23
prev_packet = None

# Createa a while loop always set to true to constantly run a loop
while True:
```

```
packet = None
# draw a box to clear the image
display.fill(0)
display.text('RasPi LoRa', 35, 0, 1)

# check for packet rx
packet = rfm9x.receive()

# If the packet is empty
if packet is None:
   display.show()
   display.text('- All Clear -', 15, 20, 1)
# when the packet is NOT empty
else:
   # Display the packet text and rssi
   display.fill(0)
   prev_packet = packet
   packet_text = str(prev_packet, "utf-8")
   display.text('RX: ', 0, 0, 1)
   display.text(packet_text, 25, 0, 1)
   if packet_text == 'Raise Alarm':
      GPIO.output(18, 1)       # set GPIO18 to 1/GPIO.HIGH/True
      sleep(10)                # wait 10 seconds
```

```
        GPIO.output(18, 0)        # set GPIO18 to 0/GPIO.LOW/False
        sleep(0.5)                # wait half a second

    time.sleep(1)
if not btnA.value:
    # Send Button A
    display.fill(0)
    display.text('Alarm True', 25, 15, 1)
    GPIO.output(18, 1)        # set GPIO24 to 1/GPIO.HIGH/True
    sleep(10)                 # wait 10 seconds
    GPIO.output(18, 0)        # set GPIO24 to 0/GPIO.LOW/False
    sleep(0.5)                # wait half a second

elif not btnB.value:
    # Send Button B
    display.fill(0)
    button_b_data = bytes("Test from base\r\n","utf-8")
    rfm9x.send(button_b_data)
    display.text('Test sent to sensor', 25, 15, 1)

elif not btnC.value:
    # Send Button C
    display.fill(0)
```

```
    display.text('Button C', 25, 15, 1)


display.show()
time.sleep(0.1)
```

APPENDIX D (MATLAB RDC CALCULATIONS)

```
% Matthew Klein, Senior project input testing


T = readtable('elcentro_data_small.csv');

T1 = T.Var1;

T2 = T.Var2;

i = 1;

RDC_threshold = 50;


x = [];

y = [];


for i=1:570


    if T2(i) > RDC_threshold

         x(end+1) = T1(i);

         y(end+1) = 1;

    elseif T2(i) <= RDC_threshold

         x(end+1) = T1(i);

         y(end+1) = 0;


    end

end
```

```
tiledlayout(2,1)

nexttile
plot(T1,T2)
yline(RDC_threshold,'red')

nexttile
plot(x,y)
ylim([0 1.5])
```

APPENDIX E (MATLAB BANDPASS DESIGN)

```
%Senior Design

%Bandpass filter

%Jerome Degbe

clc

clear all

%Specs

fs=40000; ws=2*pi*fs; As=40;

fp=15000; wp=2*pi*fp; Ap=2;

kff=sqrt(fs*fp);

kf=2*pi*kff;%Center Frequency

bww=(fs-fp);%bandwidth

bw=2*pi*bww

q=kf/bw;

nb=4;

%kf= 3;

fsample=8192; %sample frequency

Ts=1/fsample;


wpa=2/Ts*tan(wp*Ts/2); %Prewarp the specifications

wsa=2/Ts*tan(ws*Ts/2);


%Butterworth

%find the filter order
```

```
%[nb,wc]=buttord(wpa,wsa,Ap,As,'s'); %'s' is saying for cotinuous design

%[n,wc] n=filter order; wc=the 3dB cutoff frquency (half of the power

%before/half after)

[z_nlp,p_nlp,k_nlp]=buttap(nb); %zeros, poles, and gain

%n and number of poles should always be the same.

num_nlp=k_nlp*poly(z_nlp);

den_nlp= poly(p_nlp);

W=0:0.05:3.5; %define vector for normalized freq.

%Is it reasonable to have the normalized freq

Hb=freqs(num_nlp,den_nlp,W); %transfer function for butterworth

%Normalized Transfer BP

z_nbp=zeros(1,nb)

k_nbp=k_nlp*(q^(nb))

p_1=p_nlp(1:2);

den_1=poly(p_1)

a_11=den_1(2);

a_10=den_1(3);

roots(den_1)

p_2=p_nlp(3:4);

den_2=poly(p_2)

a_21=den_2(2);

a_20=den_2(3);

roots(den_2)

den1_nbp=[1 a_11*q 2+a_10*q^2 a_11*q 1]
```

```
den2_nbp=[1 a_21*q 2+a_20*q^2 a_21*q 1]


num_nbp=(k_nbp)*poly(z_nbp);
den_nbp=conv(den1_nbp,den2_nbp);
W_nbp=0:0.05:3.5;
Hb_nbp=freqs(num_nbp,den_nbp,W_nbp);
 figure(1)
plot(W_nbp,20*log10(abs(Hb_nbp)),'LineWidth',2.2)
 title('Normalized Bandpass filter')
 xlabel('Frequency')
 ylabel('Magnitude (dB)')
 grid
%Transfer function BP
z_bp=z_nbp
k_bp=k_nbp*(kf^nb)
p_nbp=roots(den_nbp)
p_bp=kf*p_nbp
num_bp=k_bp*poly(z_bp);
den_bp=poly(p_bp);
f=logspace(0,7,500);
W_bp=2*pi*f;
Hb_bp=freqs(num_bp,den_bp,W_bp);
figure(2)
semilogx(W_bp/(2000*pi),20*log10(abs(Hb_bp)),'LineWidth',2.2)
```

```
title('Bandpass filter')

xlabel('Frequency(Khz)')

ylabel('Magnitude (dB)')

axis([10 50 -8 2])

grid

yline(-3)


20*log10(abs(Hb_bp))

%Convert to DT using bilinear transformation

[num_bp,den_bp]=bilinear(num_bp,den_bp,fsample);

tf_dt_b=tf(num_bp,den_bp,Ts)


%DT frequency response

Wd=-pi:0.05:pi;

Hd_bp=freqz(num_bp,den_bp,Wd);

figure(3)

subplot(2,1,1)

plot(Wd/pi,20*log10(abs(Hd_bp)),'LineWidth',2.2) %Plot Wd/pi to see from -1 to 1 where 1=pi

xlabel('Frequency \omega/\pi (rad/sample)')

ylabel('Magnitude |H(e^{j\omega})| (dB)')

axis([-1 1 -300 20])

grid

subplot(2,1,2)

plot(Wd/pi,180*angle(Hd_bp)/pi,'LineWidth',2.2)
```

```
xlabel('Frequency \omega/\pi (rad/sample)')

ylabel('Phase \angle H(e^{j\omega}) (deg)')

grid

sgtitle('Discrete Implementation of Bandpass Filter')
```

APPENDIX F (MATLAB FILTER IMPLEMENTATION)

```
num=[8.645e-05 9.77e-15 -0.0003458 7.81e-14 0.0005187 6.395e-14 -0.0003458 2.665e-15
8.645e-05]

den=[0.5838 4.872 17.92 37.93 50.53 43.39 23.46 7.296 1]


%initiate delays
 x=randn(1,1000);
x01=0; x02=0; x03=0;x04=0; x05=0; x06=0; x07=0; x08=0;
y01=0; y02=0; y03=0;y04=0; y05=0; y06=0; y07=0; y08=0;
N=length(x);
num
den
 for n=1:N
  n=1;


y(n)=(num(1)*x(n) + num(2)*x01 + num(3)*x02 + num(4)*x03+ num(5)*x04 + num(6)*x05 +
num(7)*x06+ num(8)*x07+ num(9)*x08-den(2)*y01 -den(3)*y02-den(4)*y03-den(5)*y04-
den(6)*y05-den(7)*y06-den(8)*y07)/den(1);
  x01=x(n);
  x02=x01;
  x03=x02;
  x04=x03;
  x05=x04;
  x06=x05;
  x07=x06;
```

```
 x08=x07;
 y01=y(n);
 y02=y01;
 y03=y02;
 y04=y03;
 y05=y04;
 y06=y05;
 y07=y06;
 y08=y07;
end
```