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System of Networked Sensors for Detection and Characterization of Unauthorized Underground Activity

Executive Summary

For this project, we are tasked with designing a system of networked sensors for the detection and characterization of unauthorized underground activity. We received this research topic from the Capstone Marketplace through our Customer Mentor at the Stevens Institute for technology. Since this research topic comes from a government contract, the main purpose of this project is to provide security for government property. For example, this sensor array is based around the goal of providing security for military bases at home and abroad, government facilities, and national borders.

We have 5 members total in our team. Our customer mentor is William Shepherd from the Stevens Institute for Technology and our technical manager is Professor Tomas Materdey from the UMASS Boston Engineering Department. The team consists of 3 members; our two seniors are Augustus Standeven and Tyler McKean and our junior member is Yohannes Kidane.

Specific Aims

The main purpose of this project is to design a sensor system that can be easily set up and used by anybody. That means that one key element to this project is that it must be portable. It has to be lightweight and small enough for a single operator or user to set it up and use it. As well as this, the system has to be durable and unobtrusive, since it is meant to be left in a location for at least two weeks and detect people who are trying to remain covert.

Another goal of our project is for it to cover a 100 meter radius. We plan to accomplish this by creating several nodes and spreading them out in order to get a larger range of coverage. In addition, we plan on compiling a bill of materials and enough information for future teams to expand and learn from our project (in order to make it cover a larger area).

We also plan on making our sensor network wireless with a self contained powersource. This will allow the sensor array to be as covert as possible and as easy to use as possible.

The final goal for our project is to have the network be able to process data and categorize the types of signals received. We aim for the system to not only alert the user when it detects unauthorized movement, but to also tell the user (to some degree of confidence) what it thinks generated the signal (i.e. footsteps, a shovel, a truck, etc.). We plan to have the system display this information on a GUI on a laptop.

Background

In order to establish the background of our project, we must also address the project's significance. The project will mainly focus on the signal processing of unauthorized underground vibration data being collected by vibration sensors for the application towards Military and

Government perimeter security survelliance. There are a wide variety of surveillance systems and their preferred methods of detection, such as cameras, alarm systems, or human security guards. Our team is tasked with creating a system that would fit within this set of available systems, but rely more on ground vibrations as the main indicators of unauthorized movement on restricted grounds. A system which focuses on vibration data would be able to detect unauthorized movements above and below the ground and at greater distances than a camera surveillance system or human security guard outposts. The vibrations caused by vehicle movement, underground drilling or digging, and even footsteps could be detected long before an intruder or trespasser steps into the frame of a camera surveillance system. So, our system has an advantage of detecting unauthorized movements faster than a camera surveillance system, because it can use the vibration signals propagating in the ground to detect targets as they approach the restricted area either above or below the ground. To get an idea of these types of systems that already exist and especially, in order to design such a system, our team examined commercially available technology to establish a reference point for the design process.

Looking out into the commercial market, our group was not able to find a system that would be relatively low-cost, portable, durable, cover a large area, and be able to characterize the cause of the vibrations of which the sensors are detecting. Being able to design such a system that meets all these requirements became our team's initiative. So, it is important to address that our project is not necessarily developing some ground-breaking technology, but is rather going to use a culmination of different existing data collection techniques and technologies in order to provide an alternative that meets all the requirements we were asked for designing this system. The vibration data collection techniques and technologies will be elaborated on in the following paragraphs.

The type of sensors we are using to collect the vibration data from the ground are called geophones. A geophone is a ground-motion transducer that involves a coil of wire wrapped around a magnet and with the help of Faraday's law of electromagnetics, the time-varying magnetic field, due to the ground vibrations physically moving the magnet inside the geophone, conducts a current on the coil of wire thus converting vibrations into potential energy, or voltage. This voltage can then be discretized by means of sampling the signal with a microcontroller unit with capabilities of Analog-to-Digital conversion. We plan to use these geophones with a data collection technique used for collecting microtremor data called the Nakamura method [2]. This method involves using three geophones in a three-dimensional orientation, or cartesian directions, in order to minimize surface noise by normalizing the horizontal spectral amplitude with the vertical spectral amplitude [2]. The advantage of using this method is we can gather seismic activity data from the signals in the ground whether they are "P" waves or "S" waves. P waves propagate in the ground similar to how sound travels in the air and S waves propagate transversely in the ground. So by arranging three geophones as a single node in the network of sensors, we will be able to detect either or both of these types of seismic vibrations. Using this technique will optimize our signal detection as well, because having more sensors will lead us to gathering more accurate data and being able to cover a large area for surveillance.

Based on the type of signals we expect the sensors to detect vibrations from, some filtering of the sensor data will need to be considered. Ground activities such as digging with a shovel, driving a vehicle, and even footsteps all have similar frequency spectrum characteristics, in that these are all relatively low-frequency inducing motions [4]. The geophones themselves have a bandwidth between 10Hz to 240Hz, which is why they are mainly used for geophysical data collection like microtremors [2]. In order to fine tune the frequencies captured by the geophones, we will need to design a low-pass filter and amplification circuit to provide better resolution to our microcontroller sampling the signals. Using Nyquists' sampling theorem, we'd need to be sampling the signals at least twice the value of the highest signal of interest [5]. Now, we can expect a wide range of amplitudes and low-frequency characteristics based on what caused the excitation of the ground vibrations. Due to this fact, our group plans on designing an adjustable amplifier, who's gain can be varied based on amplitude. So if a very quiet noise or disturbance off in the distance is too weak while being detected, the gain of the amplifier stage can be adjusted to compensate for lack of volume. Once the signals are filtered and amplified from this stage of the system, the signals will need to be digitized in a processing unit and have the data displayed on a laptop.

The back-end of the design will involve a microcontroller tied to a laptop that will display the vibration data to a graphic user interface, or GUI. The purpose of this stage is to sample the filtered and amplified vibration signals and convert them from analog-to-digital so the signals can be processed and characterized. The current processing unit we are using for the project is an Analog Discovery 2, which features 14-bit ADC, real-time FFT spectral capabilities, and supports custom Python and C++ scripts that it can run [3]. These features will be utilized to display the real-time frequency spectra of the vibration signals, and in addition, will be able to run the characterization algorithm, which will compare the detected signals to a predefined library of signals the system would expect to observe. The learning algorithm will not be completely defined from scratch, because softwares like MATLAB offer similar algorithms in their tool boxes they have available. The learning algorithm we expect to use should be similar to how vocal and image recognition is achieved, where the algorithm will analyze the eigenvalues of the signals in the predefined library and uses these to compare to the incoming detected signals. When the system finds a match in the values, it will characterize the signal and display this characterization to the user in the GUI along with the real-time data analysis. As for the GUI, our team will need to customize our own interface using available tool kits in MATLAB and/or Python. The performance goals we are striving to achieve are that the system detects underground vibrations, processes these signals and displays the characterization of the signal to a 70-80% confidence to the user interpreting the data on a laptop GUI. This concludes the background for the project and the next thing to address is the Preliminary Work and Design Possibilities.

Preliminary Work / Design Possibilities

In the current state of the project, we did address several possible hardware approaches as we began to design the system and analyzed their trade-offs. At the beginning of the project, we needed to select which type of sensor would fit for the detection of underground vibrations. Types of sensors like accelerometers, gyroscopes, electromagnetic velocity sensors, and pressure sensors were all highly considered. Accelerometers are very popular sensors mainly used for general purpose shock or vibration, and tend to be very accurate with low noise. They measure the velocity or displacement over time, but these types of sensors are meant to be mounted directly onto the vibrating test surface, like a piece of machinery or motor vehicle part. Gyroscopes are an angular rate sensor that measures the rotation in three dimensions and should be used in addition to an accelerometer. Electromagnetic velocity sensors measure velocity directly and we found they were harder to come by. Pressure sensors, or acoustic sensors, are essentially microphones that measure vibration amplitude from the compression and rarefactions of the air pressure and also provide rich frequency content. The pressure sensors would not be able to make contact with the vibrating structure and would most likely need to be mounted off the ground. Alternatively, we discovered another type of sensor known as a geophone, after glancing over the previous laid out list of sensor types. Our team assessed that the best possible sensors for detecting underground vibrations would be the geophones, and perhaps an acoustic sensor in addition. Like we stated in the background section, the geophones have a relatively low frequency response, which would be perfect for detecting vibrations in the ground, however, the geophones do not have a high frequency response to them. This made the addition of an acoustic sensor the second best choice because of their high quality frequency responses. For now, our team is planning on using three geophones oriented in the cartesian directions (Nakamura method) to obtain vibration data tests. Judging on whether these results are sufficient enough for the project, we will also combine the acoustic sensors into the network of sensors as well. Lastly, upon deciding what type of sensors to use for the project, our group saw it best if we could make these sensors wireless to cover a wider area. However, after some research into the commercial markets, most of the options available were either too expensive or the wireless geophones were not compatible with our project. The wireless sensors we found could not be sold as a standalone sensor by itself, but were included into an embedded system. For these reasons we saw it best to carry out the project with wired geophones, and leave it up to another senior design group to improve on our project and make the geophones wireless.

One requirement for the project is to incorporate a printed circuit board (PCB) as part of the deliverables at the end of the Spring semester. Our team found it suitable that we meet this requirement by designing a filter and amplify circuit that would cut out the high frequencies and boost the low end frequencies, where we suspect the underground vibrations to exist. This means we must design an RC filter with an Op-Amp to achieve a cutoff frequency somewhere around 500 Hz. The geophones have a max voltage around 1.44mV and because the ADC has a max voltage of 5V, the gain of the Op-Amp should be about 3500 V/V [1]. From the research we've done so far, we found movements such as footsteps, dropping a weight, and a car all being detected from a geophone within the frequency range of 15-115Hz [4]. To get an idea of what seismic signals look like in the time and frequency domain, see [Figure 1] below.

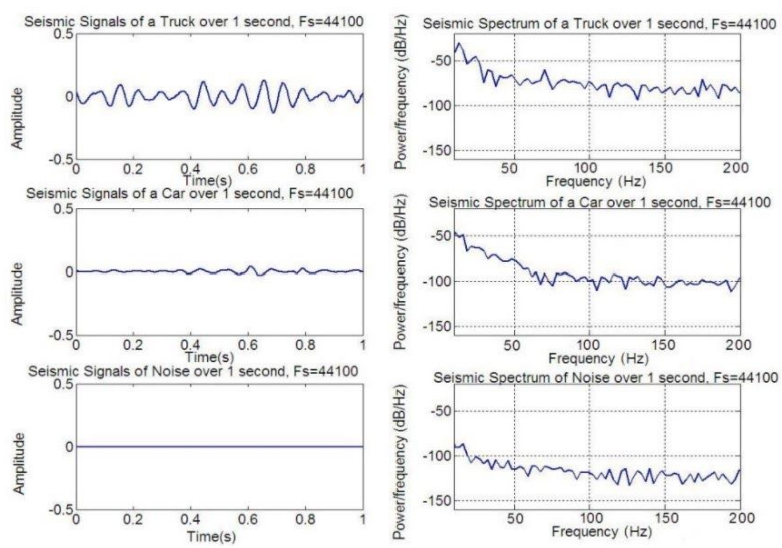

Figure 1 - Seismic Signals captured by a geophone of a Truck, Car, and Noise sampled at 44.1kHz

The most important component in the whole system is the microcontroller, and choosing the correct one to use based on its capabilities needed the most attention when selecting the hardware for the project. The microcontroller we choose must be able to sample the vibration signals, store the predefined signal library in its memory, execute the learning algorithm that will compare detected signals with the signal library, and be able to export the data out to the laptop GUI. Our team is only now just gaining experience using microcontrollers as both Tyler and Augustus are taking an EE elective on the topic of microcontrollers and their capabilities. So, when it came time to choose how the signals would be processed our Technical Manager, Prof Materdey, suggested we look into the Analog Discovery 2. After researching further into our TM's suggestion, we found that the AD2 meets a lot of the requirements needed for this project. It is mainly used as an all-in-one USB oscilloscope and instrumentation system, but is also capable of running custom Python and C++ scripts. It's compatible software interface called Waveforms, provides real-time data analysis in both the time and frequency domain. The AD2 also has dual programmable power supplies from 0V to 5VDC and 0V to -5VDC. These built-in power supplies could serve as power supplies to the filter and amplifier PCB, which would replace the option of 9V batteries to power it. The question of memory storage for the signal library and being able to timestamp disturbances into a log, however doesn't seem plausible for the AD2. In this case, we are thinking of incorporating an Arduino microcontroller that can provide the ADC operation and run the learning algorithm with the predefined signal library stored to an SD card on the microcontroller. Our team is still working through the final judgements on whether the AD2 can be completely replaced by another microcontroller or still be utilized for its real-time FFT and spectra analysis. Incorporating an Arduino wouldn't be too much of an addition as far as cost, but being able to replace the AD2 would save us hundreds of dollars in our budget.

The final stage of the project would involve exporting the data processed by the microcontroller into a custom laptop GUI for the user to interpret the signals the system is detecting. As far as custom GUIs, MATLAB offers a built in development environment or Python offers a development tool called Tkinter as an alternative. Our team is most familiar with MATLAB, so our first prerogative is to use MATLAB's environment, but Python's option may also serve as a promising fallback plan. There were no GUIs available that would display everything our project calls for, so having to design our own custom interface appeared to be our team's only option.

For the most part, our team is expecting to gain experience in numerous areas that this project envelopes. All team members have had experience making RC filters on breadboards for lab assignments, and Tyler and Augustus are gaining experience developing C programs for microcontrollers, and have previous signal processing analysis experience from previous coursework projects. Given that our team does not have a ton of experience with all the topics covered in this project, we can expect the development time to cover about 60% of the project. Once the components we need are compiled and ordered, our team's job is to do as much research needed and designing for the project up until the next project milestone in December. Following this next milestone, we will begin assembling and testing each stage: the geophones, the filter and amplifier, the microcontroller, and the GUI. Part of this phase would involve testing every possible stage as they are assembled until we can provide a fully functioning field test, where we can demonstrate the system's performance and report the results. Around the first spring milestone in March, we hope to optimize our system as much as we possibly can until the final milestone in May. We believe we have enough experience and resources available to us to achieve the project's goals with the design we've chosen.

Design Approach to be used

For our design we plan on using geophone sensors in order to detect underground vibrations. We plan on having 3 nodes in our sensor array, each with 3 geophones in order to receive the most accurate signal data. There will be a learning algorithm associated in the software of the project, which will be able to correlate the signal to different characterizations based on a signal library which the algorithm will reference. As well as this, we plan on having the output data be readable to the user from a laptop. The original project document we were given mentioned the output data being sent to a smartphone app, which due to limited time and resources, perhaps may be out of reach for us. So at the very least, the data will be readable from a laptop.

We plan on creating a database of different underground signals for our signal processing unit to compare its results to. This is also how we plan on testing our final deliverable: by creating signals that our algorithm can compare to a signal database we have assembled and tested beforehand. In order to test this deliverable and create these test signals, we are asking to have access to the UMASS Boston campus sometime in early 2021 to achieve prototype testing measurements. Since there is a lot of construction on the UMASS campus, this will serve as the perfect place to test the sensors ability to pick up a variety of signals, such as vibrations propagating underground from a large vehicle driving by, to smaller signals like those created from digging with a shovel. If we can not gain access to the UMASS campus, our backup plan is to test the prototype in a relatively open space, like a soccer field and provide the underground noise disturbances ourselves. A testing facility may also be provided from our CM - Bill Shepherd, but as of now, we are focusing on doing the testing ourselves or at the UMASS campus.

As a worst case scenario, we plan on being able to provide real-time signal processing of seismic/acoustic activity to be readable by a user on a laptop.

Milestones and Schedule

There are four major milestones for this project. The first milestone was the Formal Design Presentation, which took place 10/15/2020. In this presentation, we presented our initial design ideas, research, and schedule for the rest of the project. The second milestone of this project will be the Project Readiness Presentation, which is scheduled for 12/1/20. In this presentation, we will discuss the progress of our ideas from the Formal Design Presentation as well as the updated budget and project design. We also plan to present preliminary test results of our system at this point. The third major milestone is the Design Validation Presentation, scheduled for 3/15/21. In this presentation, we plan to be in the final stages of our project. We plan on having a working prototype with sensors, filters, amplifiers, signal processing, and classification. The only tasks that are left to do at this point should be to prepare for the final presentation, repeated testing, and validation of the system. The final major milestone will be the

Final Project Presentation, scheduled for 5/1/21. In this presentation we will present our final project to our colleagues and demonstrate how well the project fulfills our initial goals.

In order to complete this project we are using a Gantt chart to carefully plan each step of the project that needs to be completed. This Gantt chart is divided into 3 phases. The first phase of creating this project is titled “Research and Design.” In this phase, we are tasked with researching how each step of the project must be designed and what components we should specifically use. This phase will last from 9/7/20 to 12/4/20 and we will be tasked with obtaining and researching how to design and use the sensors, the filter and amplifier PCBs, the Analog Discovery 2, the learning algorithm, the signal library, and the GUI. The second phase, titled “Testing ”, will focus on testing the designs created in the research and design phase. In this phase, we need to make sure all of the sections of our project work together, as well as apart and are able to fulfill our project goals. This phase should last from 12/5/20 to 4/1/21. The final phase is the “Finishing Touch” phase and is scheduled to last from 4/1/21 to 4/30/21. In this phase, we will essentially wrap up the project and create our final presentation for the class.

Cost Estimate

Component	Price Per	Volume to Purchase	Supplier
SM-24 Geophones	$60.00	9	https://www.sparkfun.com/products/11744
PCB	$50.00	3	https://jlcpcb.com/
Resistors/Op-Amps/ Capacitors/Wires	~$20.00	?	Andrew Davis
Analog Discovery 2	$200.00	1	Andrew Davis

Pictured above is the cost estimate for all the components of our project. We are planning on designing our sensor array to have 3 nodes, each with 3 sensors. This will therefore require 9 sensors and 3 PCBs (since we need a filter and amplifier for each). We are expecting the costs of resistors, op-amps, wires, and capacitors (all to be used for the PCB) to not cost more than $20 total. The only part of our budget we are expecting to change is the $200 for the Analog Discovery 2. This is because we still have to research whether the Analog Discovery 2 can handle the data storage needs for this project, or if we need to use another microcontroller/ a Raspberry Pi. The estimated total cost for this project is about $910.00.

Expected Problems and how they will be resolved

For this project we expect to encounter 5 main problems. The first main problem we expect to encounter is that wireless sensors are much more expensive than wired sensors. Wireless sensors cost anywhere from $300 to $700, and if we were to get 9 of them that would leave no room in our budget for other costs. Our solution to this is to use wired sensors instead and to leave a detailed guide on how to make this project wireless for future senior design teams.

The second problem we expect to encounter is with our sensor data library. We expect that it will be difficult to gather enough geophone sensor data through our research, so as a solution we plan to make our own signal library. We plan on doing this at the UMASS Boston campus. This is because there is currently a lot of construction at the UMASS Boston Campus and this would be a good way to get a variety of signals (due to the heavy machinery).

The third problem our group expects to encounter when designing this project is that we aren't sure how to design our PCB. Since we don't have an adequate signal library yet, we are unsure how much we will need to exactly filter and amplify the received signals. In order to solve this problem, we simply need to conduct tests with our geophones and study the received signals.

The fourth problem our group expects to encounter while planning the design of this project involves the ground medium the signals will propagate through. We are unsure of how different ground mediums will affect the signals travelling through the ground and how much different mediums will skew our identification results. In order to solve this, our team has to do more research on how signals propagate through different mediums as well as conduct multiple tests in multiple different ground mediums.

The final problem our group anticipates encountering throughout the research and design phase of this project involves the Analog Discovery 2. We are unsure if this microcontroller will be able to accomplish everything we need it to. We know that the Analog Discovery 2 has adequate input ports as well as this ability to fourier transform the signals we receive, but as far as we know there is no SD card memory within the board. This may make it difficult to store a signal library. As a result, we are planning on either using another microcontroller, like an Arduino, or using the Analog Discovery 2 and a Raspberry Pi.

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