Washington and Lee University

Final Report

Design of a Digital Stethoscope for the GI Tract

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ENGN 379- Capstone Design

Professor Woodruff

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Executive Summary

We spent the academic year designing a wearable, digital stethoscope for the noninvasive monitoring of the gastrointestinal tract using MEMS microphones to further Professor Jon Erickson's research. This report describes our methodology, final prototype as well as potential future work. Throughout this year, we identified the design objectives and constraints of our project, the stakeholders, similar research on this type of device, and the potential impact of the device on these stakeholders and the larger medical community. We conducted limited trials on fasted and fed subjects and compared our data to data collected from a Cardionics digital stethoscope purchased online. In doing so, we not only tested the accuracy of our stethoscope but also began to construct a database of bowel and stomach sounds. A summer research team will continue to work with this device and the catalog of bowel sounds starting in June of 2023.

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Introduction and Overview

Problem Statement

This report outlines the progress our team has made on our gastrointestinal digital stethoscope development throughout the course of the year, including our methodology, challenges, and final deliverables. Current methods for monitoring GI health, such as a colonoscopy or endoscopy, are inconvenient, physically uncomfortable, and costly. This year we worked to develop a noninvasive digital stethoscope that evaluates GI health through monitoring bowel sounds. Moving forward, Professor Jon Erickson's lab and research team at Washington and Lee University will begin to collect patient data, create a database of bowel frequencies associated with GI abnormalities, and continue improving upon our prototype.

Design Objective and Constraints

While considering the design of our device, we wanted to ensure that our device was cost-effective and could be worn comfortably and safely for long-term patient use. The final design consists of a small circuit board, four MEMS microphones, and custom stethoscope heads to attach the microphones to a patient using moleskin adhesive. Regarding electrical wiring, we ensured that the device is properly insulated to avoid patient contact with electrical currents through a small 3D-printed plastic case. The device accurately captures sounds within the bowel frequency range of 50Hz to 5KHz, where the majority lies around 200Hz. Lastly, we made our design as low-cost as possible, as the final prototype cost $88.87 to build. This is significantly more cost-effective than current digital stethoscopes on the market, such as the nearly $350 Cardionics digital stethoscope we tested alongside our device.

Ethical Considerations

At the beginning of the year, we outlined the following ethical considerations and kept them at the forefront of our minds as we developed our final prototype. We considered the important stakeholders in the scope of our project, the potential positive impact the device could have, the potential negative impact, and ways to mitigate the potential negative impact. Our ethical considerations served an important role in the steps we took in the development of our prototype, and thus they are included in this report in their full form.

Stakeholders

Through each iteration in our development of this device, we kept involved parties, such as Professor Erickson's team and the potential patients for the device, in mind so as to cater to their needs. As our primary client, Professor Erickson's team asked us to develop a small electrical device that can pick up, filter, amplify, and analyze sound signals from the bowel for cost-effective patient monitoring. His team can use this device in clinical studies for his research regarding health issues in the GI tract, and they can use it to collect data regarding bowel frequencies and sound patterns for different medical conditions. Future work will include developing a user interface for the team to collect and interpret data easily. Our team values accurate data acquisition and safe patient-device interaction, and we plan to develop a device that satisfies these requirements.

In addition to Professor Erickson and his team, we considered the potential patients involved in clinical trials as stakeholders in our design. When constructing the hardware, we ensured the electrical wiring was safe for human interaction, the device was small and comfortable to wear, and the adhesive to attach the device to the skin did not cause irritation. In a medical setting, upholding the values of respect and confidentiality are of utmost importance, so we maintained this standard and will continue to do so, not only when developing the device but also when interacting with the test subjects and future patients.

Potential Positive Effects of the Design

Our digital stethoscope offers numerous potential benefits to our clientele, the scientific and medical communities, and the public. Medical tests, especially on the GI tract, are traditionally invasive, uncomfortable, and time-consuming. Our digital stethoscope helps eliminate some of the issues with current screening methods. For instance, one of the significant benefits of our digital stethoscope is that it provides a less invasive, radiation-free screening method compared to existing options, such as upper gastrointestinal series, ultrasounds, MRIs, CT scans, and X-rays. Another benefit of our stethoscope is that it can be used for portable, long-term screening. Most current methods only offer screenings when the patient is in a procedure or doctor's office, which limits a doctor's ability to screen over a more extended period. Due to its potential ease of use, the stethoscope may be offered commercially for consumers to monitor their own GI tract if they are interested. Lastly, a benefit of our stethoscope is that it will offer a new device and research database to the medical community that can be used to further research and diagnosis in related areas.

Potential Negative Effects of Our Design

While our digital stethoscope has great beneficial potential in the medical community, it is also essential to understand the potential harms the stethoscope could have. Potential immediate harms include a possible skin irritation caused by the adhesive, the possibility of shocks to the patient if hardware or wires aren't appropriately assembled, and the case of inaccurate information misguiding the patient or medical practitioner using the device. It was essential to have these potential harms in mind while constructing the device to avoid their fruition. Similarly, in the long term, we may see potential harm to the community through cost increases and data breaches, which are frequently associated with new digital devices being introduced into the medical community. Patient costs may rise as the technology used in diagnosing and treating becomes more expensive, so one of our goals was to create a cost-effective and non-expensive solution. Secondly, as medical data shifts to a digital format, there is a potential harm in that personal data stored by our devices can be stolen. This data could be used to discriminate against patients who suffer from different disorders or sold to companies looking to advertise medication or treatments to potential patients. However, while our device is unlikely to cause either of these long-term impacts, it is crucial to understand the potential long-term harms. Understanding the potential long-term and immediate harms will allow us to pursue and construct the safest and most effective prototype possible.

Strategies for Mitigating Negative Effects

Along with understanding the potential harms, we effectively planned out methods to mitigate these harms to make our device as safe as possible. There are a few solutions we implemented to prevent immediate harm. First, we investigated different, safe, and minimally irritative adhesives for those who might have sensitive skin or are allergic to mainstream adhesives. Second, we were mindful when designing the device to ensure that no wiring was loose and the device was safe. Mitigating the harm of misdiagnosis was a more difficult task. We ran cursory tests to ensure our device was as accurate as possible, but it was challenging to produce a 100% accurate device. To reduce the chances of misdiagnosis, our team utilized the device in this early design phase to begin building a bowel sound database. Since little research draws definitive associations between particular sounds and known diseases, it is difficult to deliver a diagnosis at this stage in the project. Securing the data will also be essential to prevent personal data mining from the outside. It is possible that the data can be used maliciously and sold to third parties for advertising purposes. Currently, data is stored on an SD card and university computers; however, when implemented into a confidential hospital setting, future work will consist of taking further measures to prevent data breaches. Preventing this from happening will allow the patients and medical personnel to feel safer using our device.

Further, we hope to avoid the monetary exploitation of patients by preventing large companies' use of our devices. Despite its positives, capitalism has led to medical necessities becoming monopolized and a source of profit for large companies, an example being the price of insulin. This project aims to help people and make an affordable and accessible device that anyone can use to better their health, and our $90 device is a step in promoting healthcare equity.

Research and Literature Review

Throughout the first semester of the project, we researched existing digital stethoscopes used to monitor the heart and lungs, past studies that have looked at bowel sounds, and resources that detail the uses of different materials. The existing digital stethoscopes have shown us different ways to implement the hardware for our device and how similar devices have been used in past studies. Resources regarding research conducted on bowel sounds provide examples of different ways in which a noninvasive GI stethoscope could be used. Finally, resources specific to materials have helped us build a bill of materials and develop two prototypes.

Wang et al. (2019) present a solution similar to the design we aim to implement. The device discussed by their team uses micro-electromechanical (MEMs) microphones and a flexible, wearable model to monitor patients with mechanical intestinal obstructions or ileus. In addition to solutions that implement MEMs microphones, we have looked at studies that use piezoelectric microphones in a similar design. Du et al. (2018) present the most applicable model using piezo microphones to monitor the migrating motor complex or motility patterns. We have also viewed Professor Erickson's previous research and use of electrodes in monitoring colonic activity in response to meals.

Past solutions have helped make big-picture design decisions, and past studies have allowed our team to envision how our device could be implemented. Kaneshiro et al. (2016) and Namikawa et al. (2021) discuss the relationship between the sounds of the bowel and the development of ileus or bowel inactivity post-operation. These articles have provided valuable insight into the use of bowel sounds in detecting the effect of ileus, which can slow a patient's recovery and limit the ability to obtain essential nutrients. In addition to monitoring bowel sounds to see ileus, we looked at several resources that use digital stethoscopes to detect or study the sounds of bowel obstructions. These studies are less accurate with the current methods available.

In addition to investigating past solutions and studies, we have heavily researched signal processing to fully understand how to take the analog signal outputted by the microphone attached to the stomach first to a digital signal and then transfer the waveform from the time domain into the frequency domain. This process is well characterized by Allwood et al. (2019) in their examination of advanced signal-processing techniques for bowel sounds. It outlines the frequencies we should expect, the different signal processing paths we could take, and the theory of the transformations we will need to perform. The most used are fast Fourier transforms and wavelet transforms. Either of these methods could be applied to our design in the future.

Similarly, we researched different microphone options, microphone placement, and the number needed for a full scope of the sounds emitting from the bowel. Allwood et al. examine the number of microphones used and the type of microphone used in many previous studies ranging from two to six piezo electric transducers or electret condenser microphones. His research on these last examples' accuracy has helped point us to the Teensy microcontrollers, MEMS, and piezo electric transducer options explored further in the design alternatives section.

After selecting our materials and developing preliminary circuits for testing, we explored the best software applications for our prototypes. First, we tested the piezo microphones with a simple analog read and displayed the signal using the serial plotter shown in Appendix C. We explored different programming languages such as Python, Arduino, and LabVIEW and have concluded that a combination of Arduino and Matlab best suits our software needs (discussed further in the methods section). In weighing the pros and cons of different programming languages, we considered which programs would provide the best user interface, good packages for signal processing, and the ability to store the data. Our team relied on the LabVIEW, Arduino, and Matlab websites for tutorials and example projects to further our familiarity with the programs and their compatibility with the different microphones. We also used a Spark Fun demonstration video to implement our program that displays the voltage graph in Appendix C.

For the development of the MEMs software, we relied heavily on the Teensy discussion forum called PJRC. The forum provides examples of programs using I2S protocol, videos explaining built-in functions, and an audio design tool discussed further in the methods section. Because the MEMs microphones are a newer device, we originally struggled to find information to guide our implementation. The forum and the Teensy website served as a great guide in understanding I2S protocol and how it ties into the software.

Design Methodology

Design Alternatives Considered

Throughout this year, we have developed two prototypes simultaneously with different microphones: MEMS and Piezo, shown in Figure 1, but we ultimately decided to move forward with the MEMS prototype as our final device. MEMS microphones house a sound port on the bottom of the chip, allowing for direct contact with the skin, eliminating outside noise, and providing a more accurate signal. These microphones produce a purely digital output, further reducing noise and the need for extensive hardware filtration. Furthermore, MEMS microphones have a frequency range of 50Hz to 15KHz and transfer data through I2S protocols which are somewhat complex and compatible with fewer microcontrollers than other serial communication buses, like I2C.

On the other hand, Piezo microphones produce an analog output and require extensive hardware bandpass filtration and amplification to produce a legible signal. These microphones have a slightly broader frequency range of 31Hz to 65KHz and require less technical circuitry implementation and data communication methods. Overall, both microphones have the capacity to encapsulate relevant bowel sounds. MEMS microphones have a much more complicated electrical interface than the Piezo microphones but produce a more accurate signal with less noise than Piezo microphones.

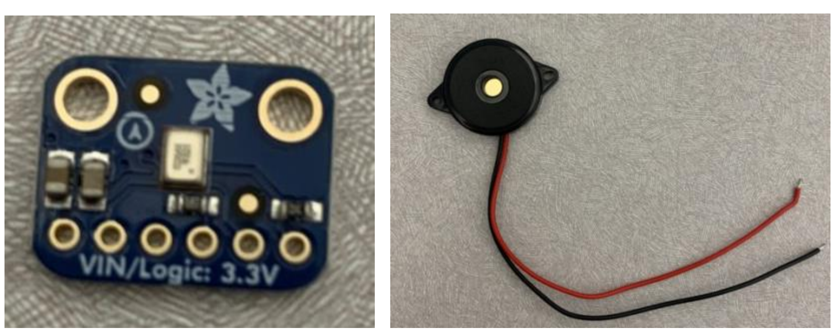


Figure 1: a) MEMS microphone; b) Piezo microphone.

MEMS Prototype: Hardware

We successfully wired four MEMS microphones to a Teensy 4.1- a process that was much more challenging than initially expected due to technicalities with I2S. The first two microphones are wired to the Teensy's first I2S port via stereo wiring, allowing for two microphones to transmit data along the same data line. The third and fourth microphones are wired to the Teensy's second I2S data output port, also through stereo wiring. Figure 2 demonstrates the MEMS prototype schematic and pinouts with four MEMS microphones.

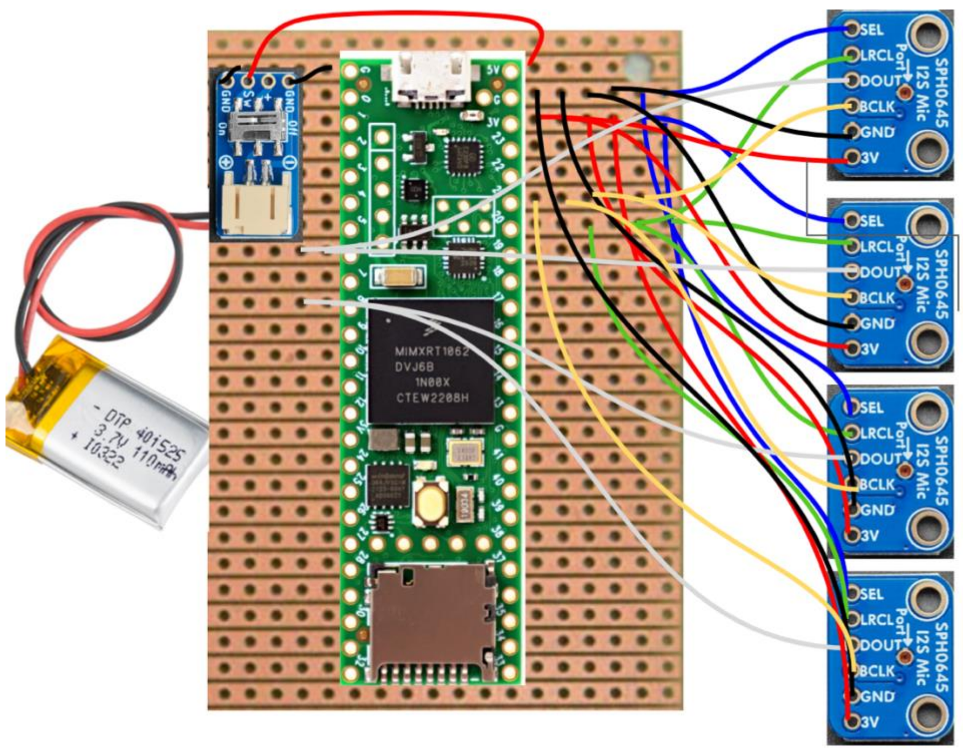


Figure 2: Diagram of final MEMS prototype wiring for four microphone connections.

For each microphone, the 3V and GND pins are connected to their respective pins on the Teensy. The left-right clock and base clock connect to Teensy pins 20 and 21, respectively, the digital output for the first two microphones connects to Teensy pin 8, and the digital output for the second two microphones connects to Teensy pin 6. The SEL pin on the MEMS microphones allows for the connection of two microphones to one digital port through stereo wiring. When the

SEL pin is connected to 3V, it occupies the right channel, and when it is connected to GND, it occupies the left channel. Figure 3 demonstrates the Teensy 4.1 pinout diagram, describing the roles of each pin. The final MEMS prototype incorporates a lipo battery, interfaced into the system via an Adafruit Breakout Board and a 64GB SD card mounted within the Teensy. These features allow for portable power sourcing and data collection.

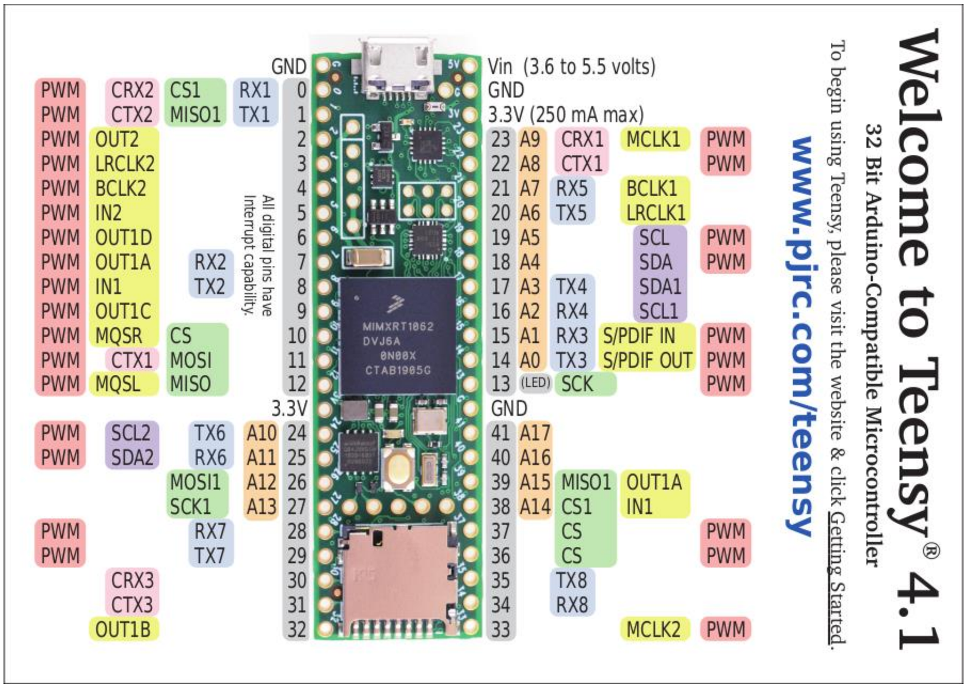


Figure 3: Teensy 4.1 microcontroller pinout diagram (Teensy 4.1 Pins).

MEMS Prototype: Arduino Code and Matlab Plotting

In addition to their more complicated hardware setup than the piezo microphones, the MEMs microphones required more code to display signals. Unlike the piezo, MEMS microphones have a digital output. Furthermore, the Teensy microcontrollers required the installation of Teensyduino (an Arduino extension).

We first tested a single microphone using an Arduino program developed by the Teensy founder Paul Stroughman that incorporates Fast Fourier Transforms to display different frequencies. We then used an online audio design tool (also developed by Paul) to help us build objects used in the code to display the “peaks” in the amplitude of the raw signal using a built-in function. The peak function essentially draws spikes in amplitude from the raw data to provide a visual change in the volume of the sound. At first, we multiplied the peaks by thirty to increase their visibility. After soldering additional microphones into the circuitry, we adjusted the program to display the peak for all four microphones. After testing the microphones with the multiplied peaks, we incorporated the built-in amplification function. The objects created in the audio design tool to display the peaks can be seen in Figure 4. We then tested the microphones and the software with the sound of the heartbeat played out of an iPhone. The waveforms matched our expectations, indicating that our microphones correctly collected and displayed loud sounds.

In order to record the data from our device, we added code to write the peaks and the time when they occurred in microseconds to an SD card. This allowed us to conduct trials in which we recorded sounds for longer durations of time and plotted the peaks vs. time in MATLAB. A plot displaying peaks in amplitude from the volume measured in volts can be seen in Figure 5. Originally, we did this by creating a long string containing all this information, then writing the string to a new line in a CSV file, but this proved incredibly slow. To improve the speed, we started pre-allocating space for each recording file before a recording began. This helped immensely. Along with pre-allocating, we stopped writing to the SD card every time a reading occurred and instead added each new line to the string and wrote the string to the SD card once it reached a certain length. This also helped speed up the device’s recording capabilities, which confirmed that communications between Teensy and the SD card areas slowed down the code’s execution.

While the peaks provide the best visualization for our data, we also wanted to include a program that could record the raw sound signal. We did this by writing the object i2s_quad to the SD card rather than the peaks. Because the program reports the raw data in bytes, it is not useful for visualization; however, Professor Erickson and his research team requested this data for its potential use in future signal processing. By writing the byte information rather than the peaks as a string, the device is capable of recording at higher frequencies. The Arduino and MATLAB code possess the potential for increased filtration and analysis. Future work with the software will likely involve filter functions specifically tailored to the expected frequencies of the bowel. Additionally, the raw signal can be used in Fast Fourier Analysis to explore how different frequencies of the bowel pertain to different conditions.

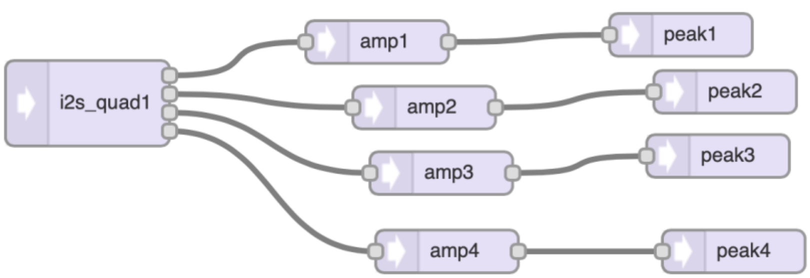


Figure 4: Teensy Audio design tool setup for four MEMs microphones and their signals.

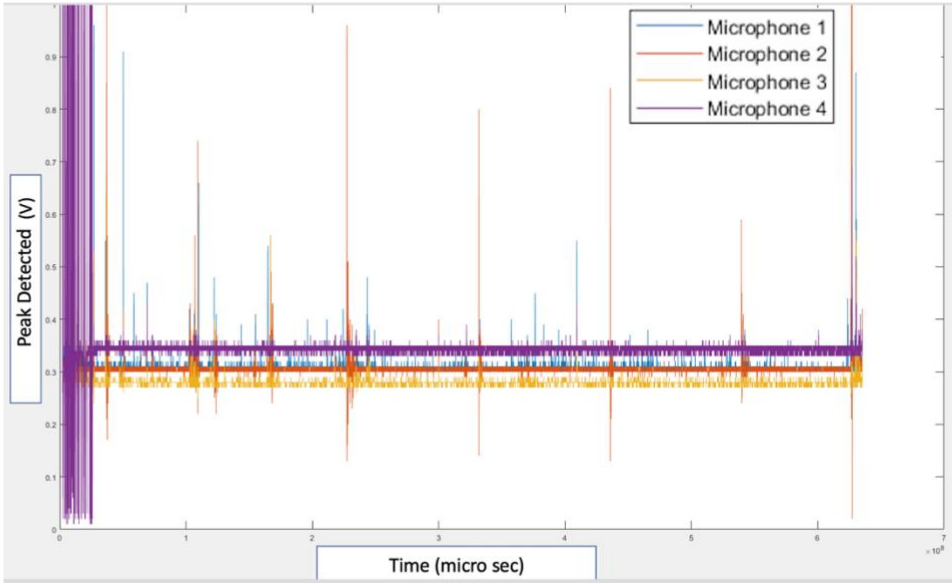


Figure 5: Display of peak outputs for four MEMs microphones during a 10-minute meal response test.

Piezo Prototype: Hardware

For the piezo transducers, we constructed an active bandpass filter, shown in Figure 6, that amplifies and filters the signal from the piezo microphone before delivering it to the computer. The bandpass filter operates between the cutoff frequencies of 47Hz and 650Hz, accepting frequencies within that range and rejecting those outside. We chose this filter design based on our research of bowel sounds, concluding that most bowel sounds occur at around 250Hz – the center of our bandwidth. While some bowel sounds occur at higher frequencies (possibly outside of our range) and some at lower frequencies (approaching the high pass cutoff frequency), we expect that this range will allow reading of the strongest bowel sounds but remain flexible to alterations of the bandwidth in the future.

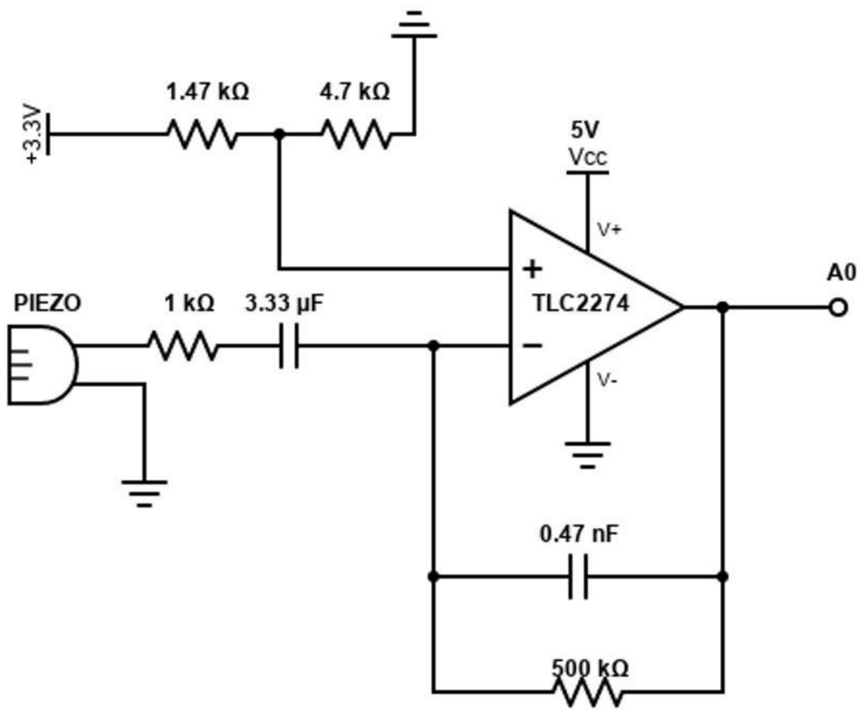


Figure 6: Circuit diagram of the piezo microphone device

To test the piezo microphone, we played sine tones inside and outside our bandwidth to ensure it was accepting those within and rejecting those outside. We also tested the microphone with human speech to ensure it is sensitive to sounds occurring away from the surface of the microphone, as well as heartbeats. Heartbeats are an appropriate test sound because they operate between 20Hz and – 500Hz depending on the person. They are internal bodily noises like the bowel sounds we plan to register in the coming term. From these tests, we have determined that more amplification is needed in the piezo circuit. Our microphone can register the sounds, but the variation in voltage readings from the signal is not significant enough, bringing into question the ability of the piezo microphone device to register bowel sounds.

Piezo Prototype: Arduino Code

First semester, we focused on developing code in LabView for the Piezo device, but we eventually transitioned to Arduino. We made the decision to proceed with Arduino in order to focus on data collection and recording. LabView is a visual programing language and might be useful in developing a user interface or visual display for the data further down the road. Arduino was more efficient in achieving our initial goals of recording and plotting signals. Furthermore, our team has experience working with Arduino but was new to working with LabView. Challenges with LabView and this decision are discussed further in the *Challenges and Limitations* section of this report.

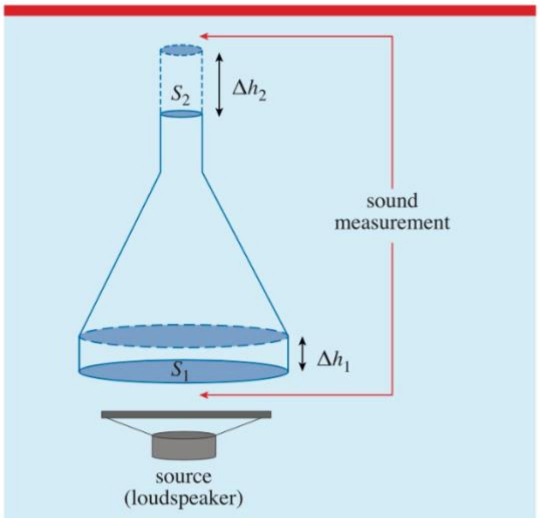
Since the MEMS device became the primary focus during the second semester, our team made fewer updates to the software. We took inspiration from code provided by Professor Erickson to implement our solution, but progress on the piezo software eventually halted as we decided to transition fully to the MEMs device. The main challenge in implementing the piezo code was the in-depth nature code of Professor Erickson's code. His collection of programs has been in development for two-and-a-half years, and trying to mimic his codebase was extremely difficult. In order to make the code functional, we removed a lot of the complexity. The software is functional, although barebones. It records the milliseconds since the program began running and the analog reading of the piezo microphone. It then writes the reading to a CSV file on the SD card. The processing can be performed after recording, but had we continued with the piezo device, our goal would have been to include signal processing within the Arduino code as well in order to create a device that does everything on its own.

Final Prototype Selection- MEMS

After creating early prototypes using MEMS and piezo microphones, we considered ease of circuitry implementation, the quality of the output signal, and size to eventually determine to move forward with the MEMS prototype. While we faced initial challenges implementing the MEMS microphones into the circuitry via I2S, we eventually were able to successfully implement and display peaks for four MEMS microphones on a relatively small footprint of a half-sized breadboard. Furthermore, the digital output of these microphones reduces the need for extensive hardware filtration and amplification, as required by the analog signal produced by Piezo microphones, thus further reducing the overall size of the prototype. Lastly, the MEMS microphone effectively captures all relevant bowel sound frequencies.

Coupling Piece

As the semester progressed, it became apparent that we needed to develop a piece to attach the microphone to the skin and focus bowel sounds into the microphone port. For the preliminary testing first semester, we utilized medical tape to attach the microphone. While this is a cheap alternative, it does not protect the microphone from movement or outside noise and is unsuitable for our final deliverable. Because of this, we have been developing a coupling piece in Autodesk Inventor to attach the microphone to the abdomen. The stethoscope head design will also provide additional amplification due to the pressure differentials at the two-sized openings, demonstrated in Figure 7.



$$\frac{p_2}{p_1} = \left(\frac{S_1}{S_2}\right)^2$$

$$\Rightarrow p_2 = \left(\frac{S_1}{S_2}\right)^2 p_1.$$

Figure 7: The relationship between the areas of a stethoscope head opening and the resulting pressure ratio (Esach, 2015).

The pressure at the smaller opening is multiplied by the ratio of the area of the larger opening divided by, the smaller opening squared. Thus, the first iteration of each device was intended to be as small as possible and maximize the ratio of the areas so that the microphone could sit as close to the skin as possible and provide a large amplification. These iterations for each prototype are shown in Figure 8.

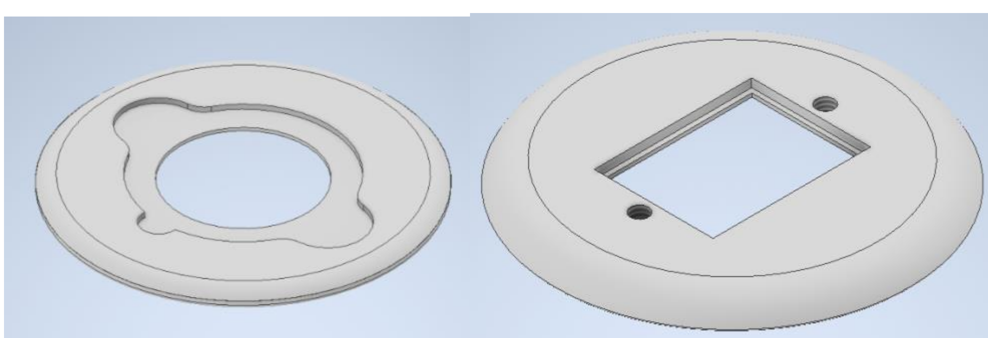


Figure 8: Inventor designs for the Piezo (left) and MEMS (right) microphone casings (not to scale).

The devices in Figure 8 did not work as intended, and through testing both designs, we found that these coupling pieces reduced the overall sensitivity of the microphones compared to when they were placed on the skin alone. We developed a second iteration of the coupling pieces to mimic existing stethoscope heads more closely. Instead of trying to place the microphone as close to the skin as possible, we decided to lengthen the space between the skin and the microphone, mirroring the shape of existing stethoscope heads. This shape showed improvement when comparing the microphone alone signal to the microphone signal when in the printed piece. Also, this second iteration allows for a small plastic membrane to attach to the stethoscope head. The attachment piece for the Piezo case will fit with industrial standard membranes, and the MEMS casing will fit with industry-standard pediatric stethoscope membranes. This allows for easy purchase and fitting to fix a membrane to each device. The second iteration of casings is shown in Figure 9.

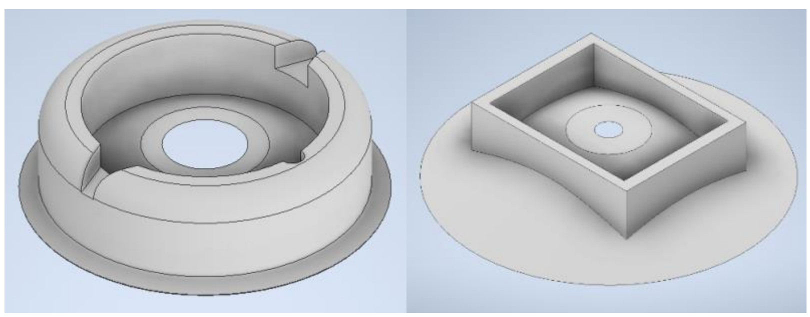


Figure 9: Inventor designs of the casings for the Piezo (left) and MEMS (right) microphones (not to scale)

After developing these two iterations, it was clear that there would need to be sizing adjustments made to house the microphones properly and align the microphone inputs to the stethoscope head openings. Similarly, a method for firmly securing the microphone to the stethoscope head would need to be introduced. However, we were able to test the shape of the microphone coupling pieces with this iteration to determine if any resonant frequencies were present due to the conic shape of the stethoscope head. In a sine sweep test (see testing and results, page 28), it was found that the conic shape resonance was present around the 1000Hz mark, which is outside of our listening range, so it should cause no problems.

Despite likely not encountering any resonant frequencies with the cone shape, we decided to alter still to funnel shape to reduce resonance even further. Esach et al. describe funnel shapes as a mode to reduce resonant frequencies. Because of this, all further iterations used a funnel shape. With evidence that the attachment piece amplified the signal with minimal resonances, the next step was to determine how to secure the microphone to the piece yet still have the ability to remove the microphone in case troubleshooting was needed. At this time, we also determined that the MEMS microphone prototype would be the sole prototype we would work on for the remainder of the term, so the piezo coupling piece advanced no further.

The third iteration of the coupling piece, shown in Figure 10, was designed with a roof and a second piece with a dove joint to hold the microphone in place.

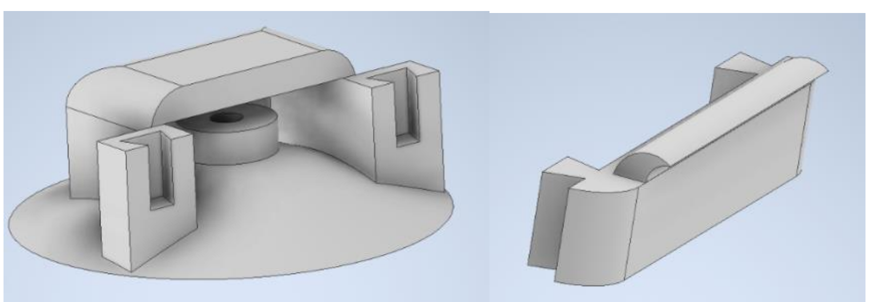


Figure 10: Iteration three of the MEMS coupling piece.

Although, with the resin printer we used, it was difficult to perfect the sizing precision necessary to form a solid joint between the two pieces correctly. Thus, the dove joint was replaced with a simple bar in iteration four, shown in Figure 11.

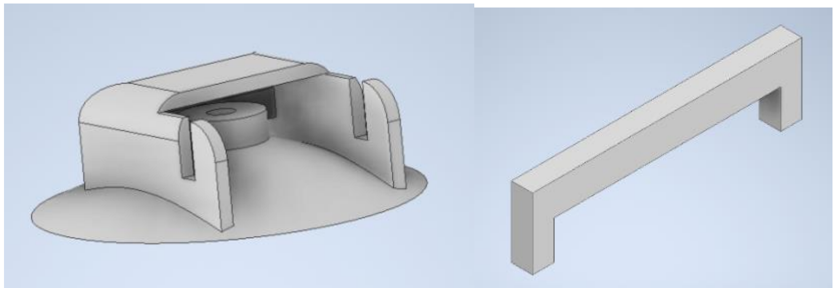


Figure 11: Iteration four of the MEMS coupling piece

The bar proved not strong enough to hold the microphone in place when the wires were disturbed by outside influence. This would not work to attach to a patient for a long period of time. The problems were in developing in the connection between the two pieces, so for the fifth iteration, we determined holding the microphone down must be done with a singular print. We attempted a few different iterations adjusting roofing sizes and filling in gaps between the microphone port and the curved shell of the coupling piece. However, none were able to attach the microphone to the piece adequately. Finally, through heavy brainstorming, we decided to attach the microphone using the built-in holes on the MEMS microphone, shown in Figure 12.

Figure 12: The holes used to attach the final iteration are visible at the top of the microphone.

Using these holes, we were able to secure the microphone to the coupling piece with fewer moving parts and less printed material. We designed the piece to have a solid base at the height of the port, and added extrusions at the place of the holes outlined above for a tight fit with the microphone. This piece proved effective and is present in our final design, shown in Figure 13.

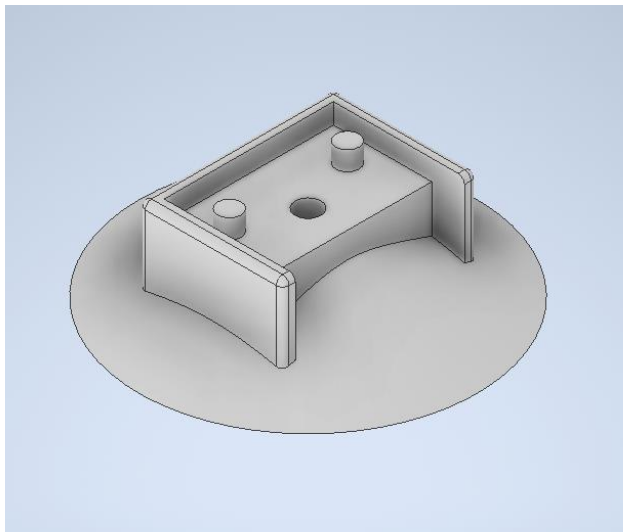


Figure 13: The final iteration of the coupling piece

Casing for Electrical Components

For the electrical components, we needed to design a case to protect the electronics from the patient and any outside disturbance and protect the patient from any exposed wires or sharp pins. We designed and printed a case in Autodesk Inventor that would tightly hold all of the electronic components together, shown in Figure 14. The bottom was planned to be cut out on a future date to allow the wires to exit freely and attach the microphones to the patient's abdomen.

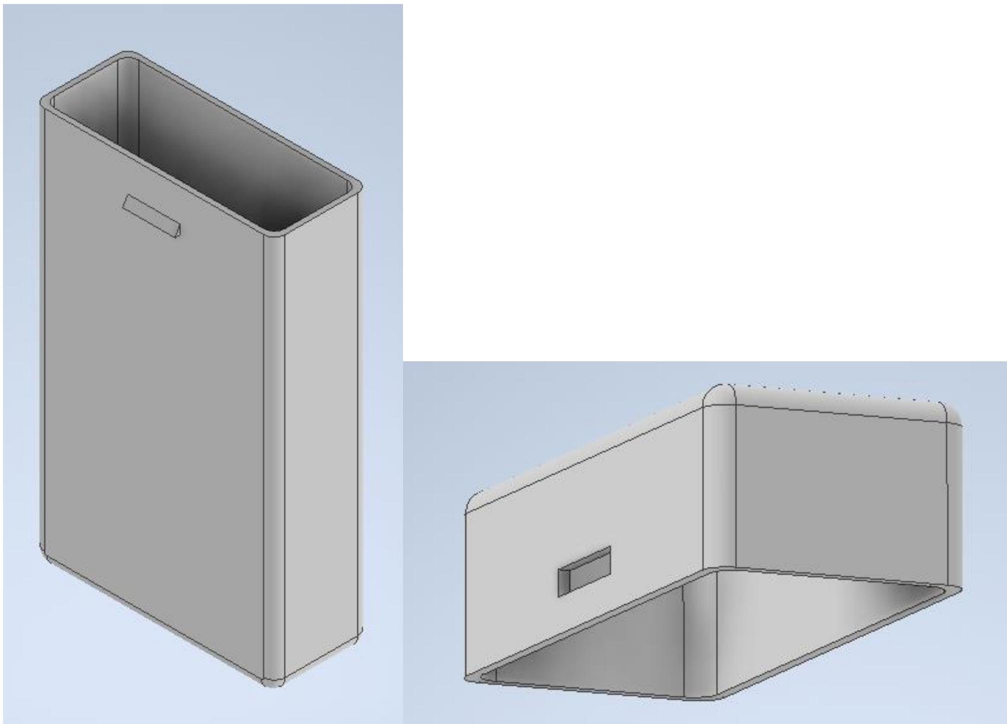


Figure 14: The box (left) and lid (right) casing design for the electronic components.

The box featured a small extruding lip, and the lid featured a small opening so that when the lid is slid on, it will catch at the opening and lock it closed. The bottom of the box was intended to be cut out to allow wires to exit, but this was not completed due to timing constraints.

Final Prototype

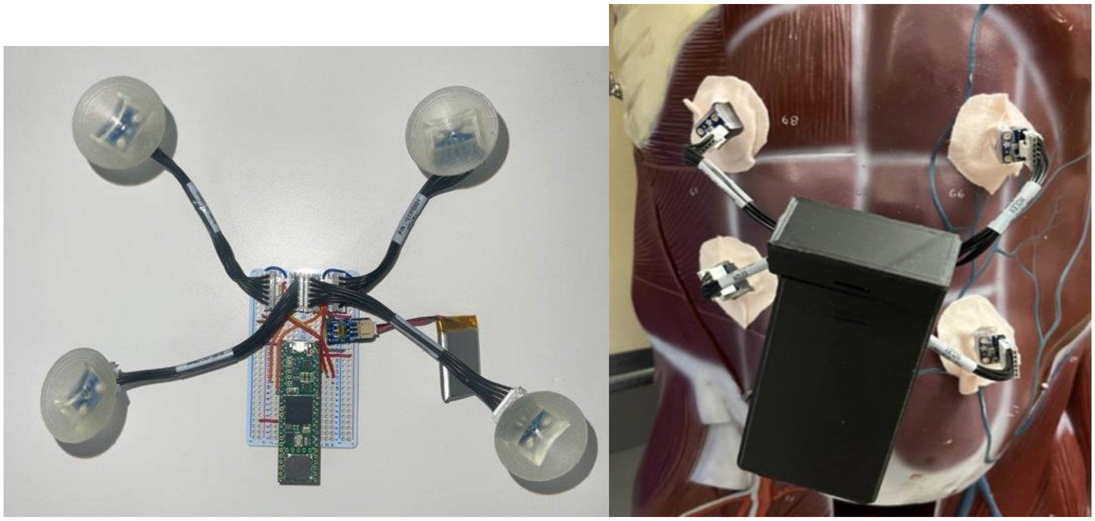


Figure 15: (left) Final prototype depicting circuitry and abdominal coupling pieces; (right) Device mounted on an anatomical human abdominal model

The final prototype, shown in Figure 15, depicts the final hardware design, including four MEMS microphones attached using snap connectors, four abdominal coupling pieces, a Teensy 4.1, and an Adafruit breakout board connected to a lipo battery. As shown on the right, the circuitry is placed in a sleek 3D-printed box for patient use to insulate the electrical components and prevent any harm to the patient. The device is mounted on the abdomen using ring-shaped pieces of moleskin. All subjects found this material to be flexible and comfortable yet also sturdy and somewhat water resistant. The MEMS microphones were mounted in male lock-in connector wires, which snapped into a female receptacle head, and soldered into the protoboard. These snap-in connectors allow for design flexibility and make it easy to switch between short and long connecting wires to accommodate for patients of different sizes. The Teensy and battery breakout board are mounted within receptacles soldered into the protoboard. This also allows for design flexibility- if the Teensy or another electrical component breaks, replacing it is simple and will not require any desoldering of major structures within the protoboard.

Testing and Results

Sine Sweep Test

To examine the analog amplification ability and the resonances present in the coupling piece, we performed a sine sweep test. The sine sweep test involved creating a speaker box that contained a speaker that would allow us to play sound directly into the microphone. A piece of ham was used to mimic the response of flesh to sound so the test resembled attaching to a human abdomen more closely. We used a small plastic box lined with foam to diminish sound exiting from the sides of the box, focusing all of the sounds toward the microphone. A thin cloth membrane was placed over the box to hold the ham, and the microphone was attached on top. Figure 16 demonstrates the experimental setup.

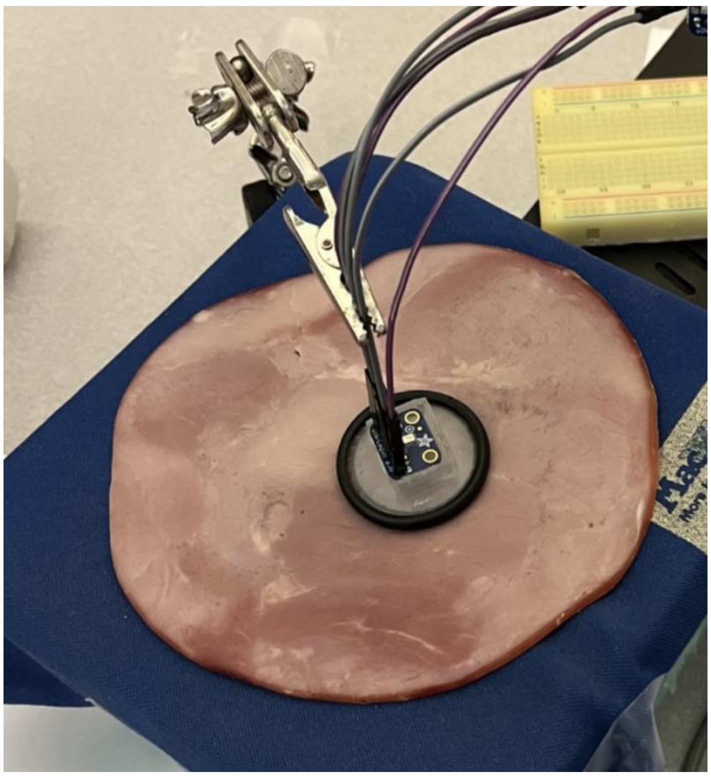


Figure 16: The box setup used for the sine sweep test.

The microphone was held in place by a small clamp, and a sine wave was played from the speaker sweeping through the audible human range of 20-20,000Hz. The wave was played at low, medium, and high volumes, and three different situations were tested: the control, the MEMS microphone alone with no attachments, the microphone with the coupling piece attached, and lastly, the microphone with the coupling piece and the purchased plastic membrane. We then used MATLAB to create a frequency equation relating to the time of the video and plotted the three situations against each other to examine differences in each.

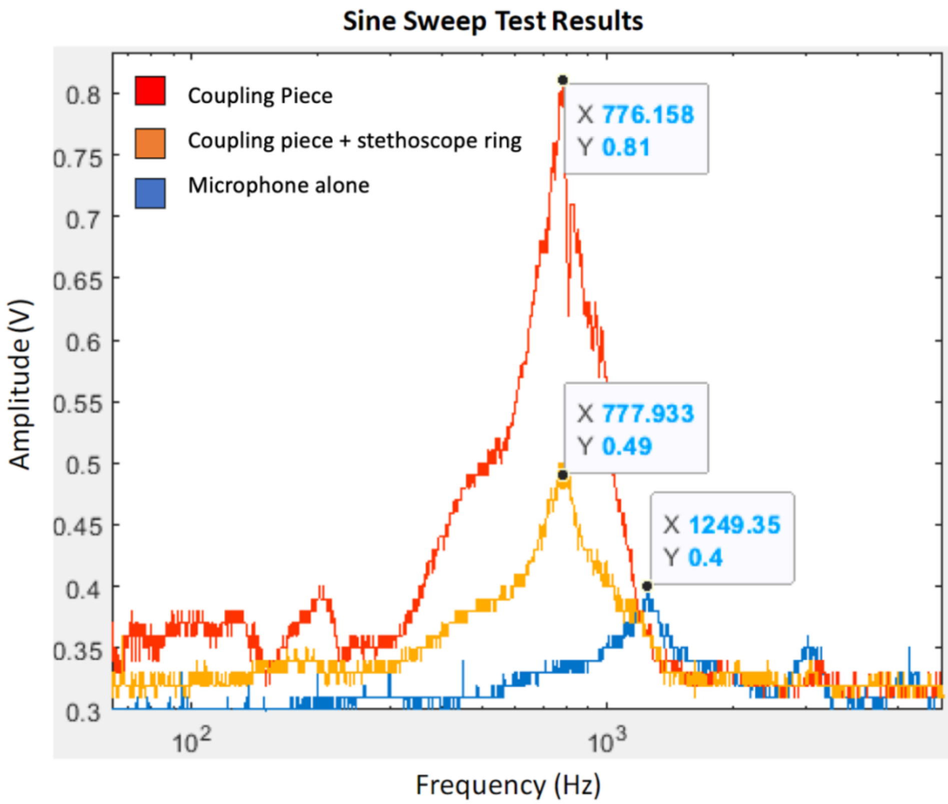


Figure 17: Sine Sweep Test Results

The results, shown in Figure 17, demonstrate that there is a resonance in all three situations between 750-1250Hz, depending on the situation. Both the coupling piece alone and the coupling piece with the plastic membrane see resonances at slightly lower frequencies than the control. It was difficult to determine where the resonances were present. Whether they were present in the speaker, the audio file, or the coupling piece was unknown. However, because the resonance exists at a high frequency, we showed no resonance in the sound from the bowel, which is most present at 200Hz.

Cross-Examining Results with Digital Heart Stethoscope

We decided to purchase an existing digital stethoscope to create a database of bowel sounds we can use for our project. The E-Scope is a digital stethoscope from Cardionics is intended to be used to listen to heart and breath sounds. Two existing settings on the device filter the incoming sounds to focus on either breath or heart sounds. The frequency range for heart sounds is 20-650Hz, and bowel sounds also fall in this range. We use the heart setting on the stethoscope to listen to our own sounds of the GI tract. This stethoscope allows us to identify and characterize bowel sounds, which was impossible with our incomplete device. Since there is currently no database of bowel sounds, we used this stethoscope to create our own mini-database. This purchase gives insight into what we are looking for when listening with our own stethoscope. We have successfully listened to both sounds originating in the stomach and intestine in different sections of the abdomen.

From the Cardionics recordings, we processed the signals and generated spectrograms to visualize the data. We applied a Butterworth filter to the data and graphed the results in Figure 18. The bottom graph shows a 3D plot of the spectrogram with the different colors corresponding to the intensity of the sound at that time. This plot allows us to visualize the data and clearly see areas of interest in the recording. The spectrograms generated from the Cardionics recordings helped us to catalog bowel sounds, but we weren't able to obtain as much data from our device due to the pace of the development. If time allowed, we would graph similar figures from our device as well.

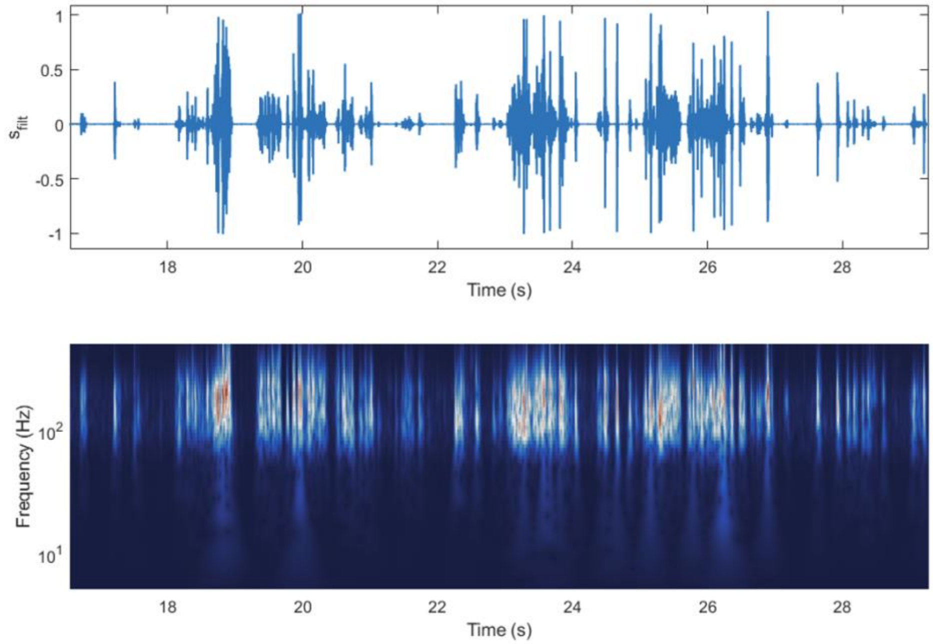


Figure 18: Spectrogram plots of the Cardionics recordings

Meal Response Testing

To determine the accuracy of our device and compare it to the existing Cardionics stethoscope, we conducted a meal response test. One of the locations on the abdomen was chosen as the main site for each test conducted because the Cardionics can only record in one location, compared to four with our device. For this test, the subject fasted for eight hours, then we mounted the device on their abdomen. We recorded their bowel sounds for ten minutes with our device and the Cardionics. The subject then ate a meal. Following the meal, we recorded their bowel sounds for another ten minutes.

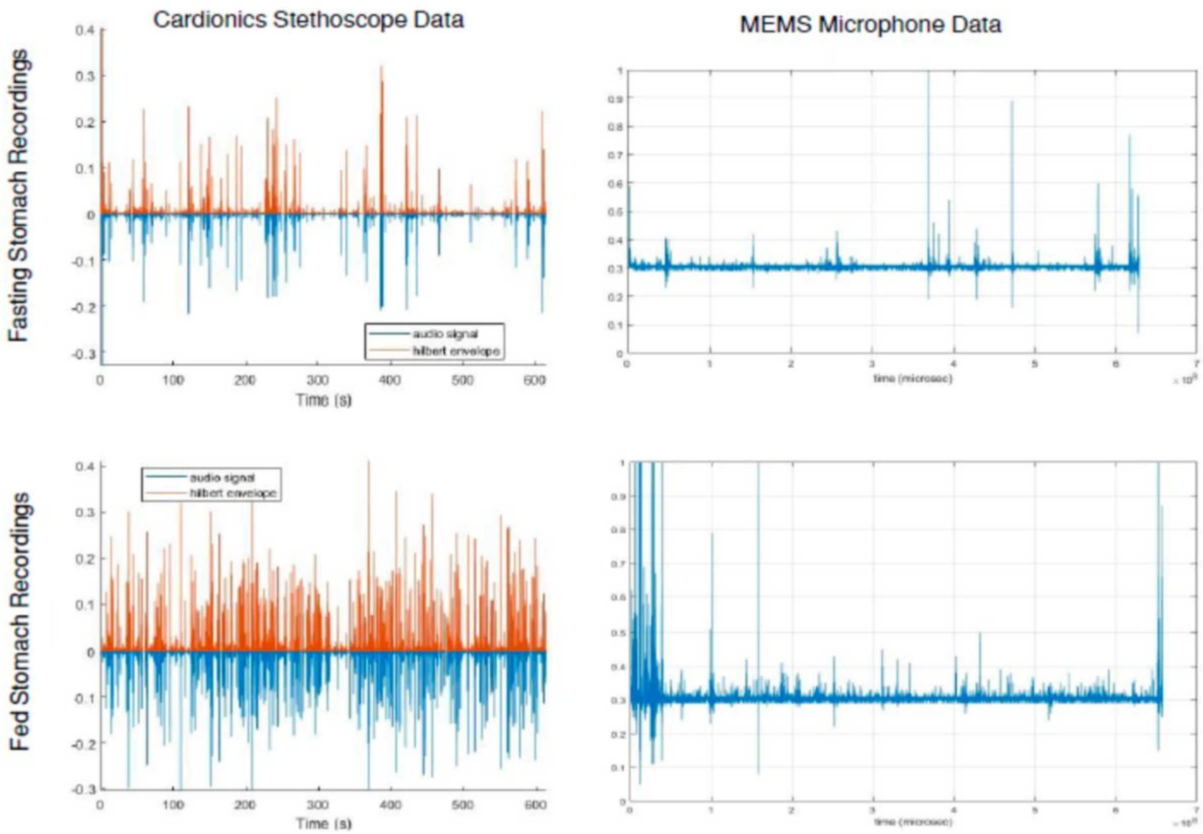


Figure 19: Resulting plots of the peaks from meal response testing of the stomach

Figure 19 shows the plots of the peaks from the Cardionics stethoscope (left) and our stethoscope (right) at the same location on the abdomen for both the fasting (top) and fed conditions (bottom). The y-axis is centered about 0 for the Cardionics data and 0.3 for our device, but we are specifically looking at the magnitude of the peaks for these plots. This plot of the Cardionics data was generated using a Hilbert transform to take the magnitude of the signal recorded so we can directly compare it to the data from our device.

We observed more bowel sounds when the subject was fed versus fasted, as shown in Figure 19. The two graphs on the bottom corresponding to the fed data show more peaks than the graphs at the top corresponding to the fasting data. The same pattern of sounds is also observed for the Cardionics stethoscope and our device when looking closely at the graphs and comparing specific time points. Our device recorded more external sounds than the Cardionics stethoscope, which we expected, but is something that can be improved with continued work on the stethoscope.

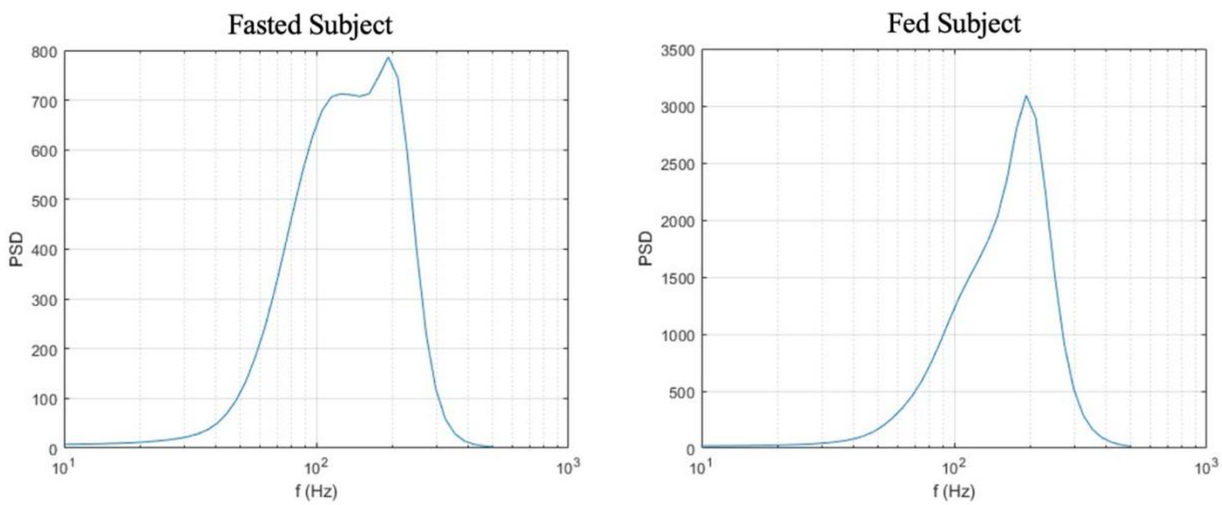


Figure 20: Observed frequency range of the bowels

Figure 20 plots the bowels' frequency range, with the most common frequencies creating the taller peak. As shown here, the fasted and fed subjects produced a similar frequency range in the stomach. Through our trials, we observed the most common frequency for bowel sounds to be around 150-200Hz, with the colon producing a lower average frequency than the stomach. This is reasonable because the colon tends to produce lower longer sounds while the stomach is higher and faster cracking sounds. With more time, we would conduct more meal response tests to continue to observe these patterns and solidify our findings from our limited meal response tests conducted.

Challenges and Limitations

Switching Software Language

We originally coded a software solution using the LINX package of LabView to show the output voltage from the Piezo device. However, after a discussion with Professor Erickson, this was proven to be an inefficient solution. The USB communication between LabView and the

Teensy device will be slower than the SPI communication between the Teensy and an onboard SD card. Additionally, LabView was not designed to be a standalone microprocessor controller language but as a data visualization system meant to work alongside other driving coding languages. Because of this, we scrapped the LabView code and began work on coding an Arduino-based solution. Simply monitoring the voltage of the microphone is quite simple, but writing the data to the onboard SD card in an efficient manner is more difficult and has been the focus of our work on the Piezo device. We decided to drastically simplify the code from Professor Erickson's code and implemented a solution that is both simple and effective.

Understanding I2S Communication Protocol

Understanding how to operate the I2S communication protocol was an ongoing challenge throughout this year, and it made adding more than one MEMS microphone to the system incredibly challenging. When trying to connect the two MEMS through stereo I2S wiring, we were able to generate an output signal in Arduino for only one of the microphones, despite closely following wiring techniques and pinouts outlined in the Teensy Audio Library. We used an oscilloscope to troubleshoot this and examine the exact source of this problem by looking at each of the individual data lines, shown in Figure 21, in real-time.

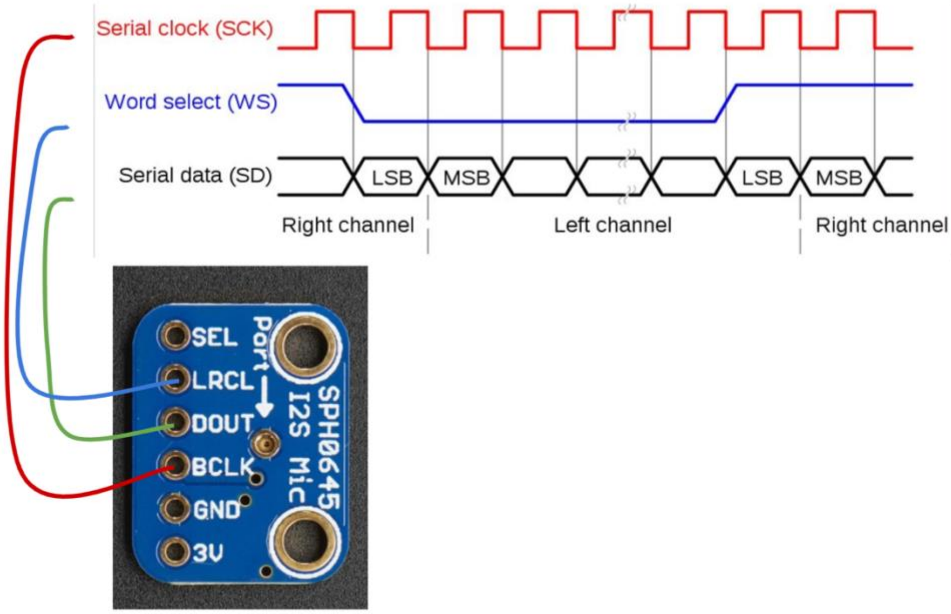


Figure 21: Interaction between clock timing for I2S Protocol and MEMS pins.

The serial clock of I2S corresponds to the bit-clock, or base-clock, of the MEMS, and it sets the continuous pulse and timing of the data transfer. The word select line corresponds to the left-right clock on the MEMS, and it toggles between the left and right channels when two microphones are connected through stereo wiring. Lastly, the serial data line connects to the data output pin on the MEMS and streams data signals collected by the microphone. When troubleshooting our two-microphone device with the oscilloscope, we noticed that when the word select line was low, indicating the left channel was being read, the digital output line was successfully displaying data. However, when the word select line was high, indicating it was toggled to the right channel, the digital output line was not outputting a signal. This led us to conclude that the problem with our setup lay within the digital output of the right channel. Upon making modifications to the Arduino code, we were able to display signal data for both microphones and continued to add two more microphones to the prototype.

Understanding how the audio developer tool corresponds to I2S ports was also difficult this year. Currently, our program uses an object called i2squad which receives a 16- bit four-channel audio from the i2s device. We tried a few different objects with similar names and functionality before successfully displaying a signal. The i2squad object allows us to include and display four peaks, which eventually allows us to transmit data for the four microphones easily. We may have to explore other objects to scale our device to more than four microphones.

Detecting Bowel Sounds with the Digital Stethoscope

Many challenges have arisen when listening to bowel sounds with the existing digital stethoscope. Bowel sounds are very subtle and irregular, so it is hard to predict when you may be able to hear them. It is also best to hear bowel sounds on an empty stomach or just after finishing a meal. We have found that we hear the most sounds when full instead of fasting and do not hear significant sounds between meals.

Another challenge is that the purchased Cardionics stethoscope detects subtle changes in movement, especially when a finger moves slightly when listening on the device. This makes it very difficult because when we hold the device on our abdomen, we need to hold it close, but then a lot of noise is detected. To combat this, we must listen very closely to distinguish between the bowel and other sounds and apply a filter to our data when processing the signals.

Conclusions and Future Work

Our team successfully developed a digital stethoscope to monitor the GI tract. The prototype is inexpensive and reasonably comfortable to attach to the abdomen. We successfully conducted trials that produced encouraging results. Although our capstone project has reached its conclusion, the stethoscope and the aggregation of bowel sounds into a database are ongoing projects. Professor Erickson and a summer research group will take the lead on the project starting in June.

Had we had more time, our team would have likely focused further on signal processing. Future work will likely involve increasing the filtration and amplification of the sounds and performing Fast Fourier Analysis on the raw data. Because there is no existing database of bowel sounds and no known correlation between the sounds and diseases, we do not know what characteristics of the sounds are most important. To ensure quality research on these correlations, we want our device to provide as much information as possible.

In addition to continued improvements in signal processing, the next steps with our device will include extensive testing. Our team would have liked to conduct more trials ourselves, but the hardware and software developments occupied the duration of the year. In the near future, our device could be worn for longer periods of time to track meal responses. The device could also be tested with the battery rather than the connection to the computer. This would demonstrate the device's performance on a patient while moving rather than sitting. Additionally, it will be beneficial to develop a user interface that allows the patient to easily access the collected data to promote transparency between researchers and the patient.

Finally, although our device can be worn relatively comfortably, later prototypes will likely incorporate a rectangular casing that can clip to a waistband or belt, removable attachments or adhesives, and different-sized wiring. We developed a casing to show that the hardware can be contained to protect the patient, but we did not focus on how the device would attach to the wearer. Different wiring and attachment pieces would allow the device to be adjusted according to each patient's body type.

The continuation of the development of our device shows a lot of promise in the area of gastrointestinal screening. With improved filtration and sound analysis, our device carries the potential to surpass current gastrointestinal screening methods. The portability, cost, and ease of use make our device attractive compared to the screening methods currently available. A digital stethoscope will hopefully someday be used to monitor the gastrointestinal tract.

Acknowledgments

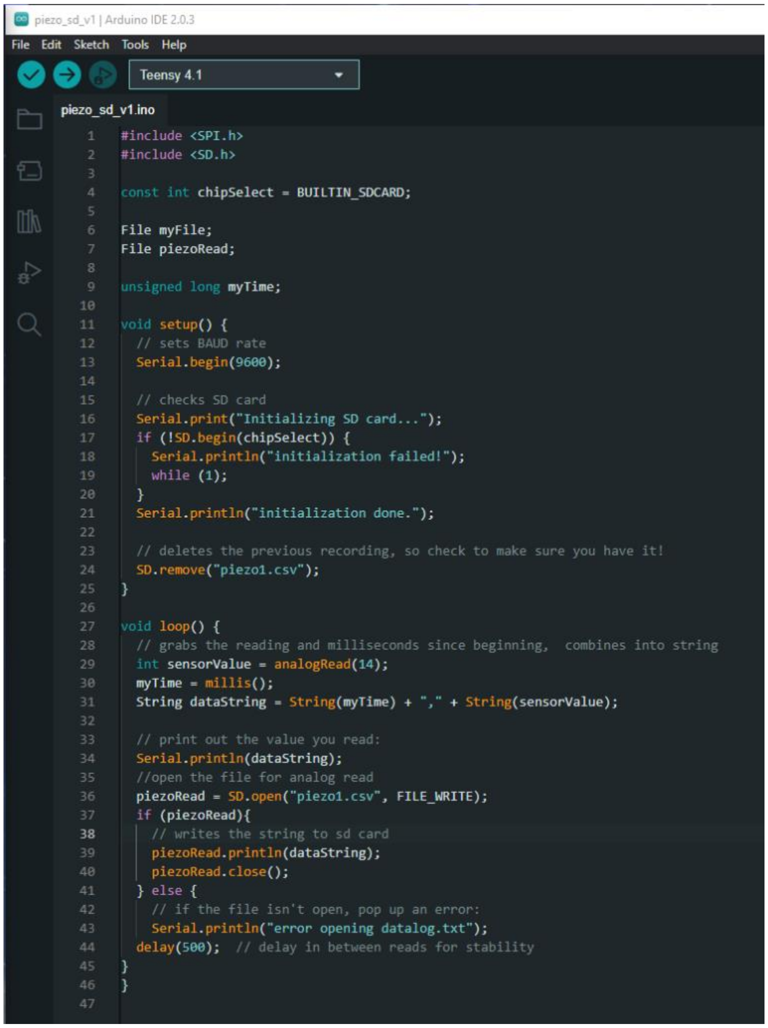
We would like to thank the Washington and Lee University's Department of Physics and Engineering for funding this project. We also want to thank Professor Erickson and Professor Woodruff for providing guidance on our project throughout this year and Chris Compton for helping us procure project materials.

Appendices

Appendix A: Code for writing the peaks from MEMs microphone to an SD card.

```cpp
#include <Audio.h>
#include <Wire.h>
#include <SPI.h>
#include <SD.h>
#include <SerialFlash.h>

// GUItool: begin automatically generated code
AudioInputI2SQuad        i2s_quad1;      //xy=111,94
AudioAmplifier           amp1;           //xy=259,74
AudioAmplifier           amp3;           //xy=270,170
AudioAmplifier           amp2;           //xy=275,123
AudioAmplifier           amp4;           //xy=281,221
AudioAnalyzePeak         peak2;          //xy=417,125
AudioAnalyzePeak         peak4;          //xy=419,248
AudioAnalyzePeak         peak1;          //xy=422,73
AudioAnalyzePeak         peak3;          //xy=429,189
AudioConnection          patchCord1(i2s_quad1, 0, amp1, 0);
AudioConnection          patchCord2(i2s_quad1, 1, amp2, 0);
AudioConnection          patchCord3(i2s_quad1, 2, amp3, 0);
AudioConnection          patchCord4(i2s_quad1, 3, amp4, 0);
AudioConnection          patchCord5(amp1, peak1);
AudioConnection          patchCord6(amp3, peak3);
AudioConnection          patchCord7(amp2, peak2);
AudioConnection          patchCord8(amp4, peak4);
// GUItool: end automatically generated code

// SD card chip select
const int SD_CS_PIN = BUILTIN_SDCARD;

File myFile;

unsigned long myTime;

String dataString;

void setup() {
  // put your setup code here, to run once:
  pinMode(LED_BUILTIN, OUTPUT);
  AudioMemory(50);
  amp1.gain(5);
  amp2.gain(5);
  amp3.gain(5);
  Serial.begin(115200);

  Serial.print("Initializing SD card...");

  if (!SD.begin(SD_CS_PIN)) {
    Serial.println("initialization failed!");
    return;
  }
  Serial.println("initialization done.");

}

void loop() {
  // put your main code here, to run repeatedly:
  myTime = millis();
  if (peak1.available() && peak2.available() && peak3.available() && peak4.available()) {

    float p1 = peak1.read();
    Serial.print(p1);
    Serial.print(", ");

    float p2 = peak2.read();
    Serial.print(p2);
    Serial.print(", ");

    float p3 = peak3.read();
    Serial.print(p3);
    Serial.print(", ");

    float p4 = peak4.read();
    Serial.print(p4);
    Serial.print("\n");

    dataString = String(myTime) + "," + String(p1) + "," + String(p2) + "," + String(p3) + "," + String(p4);
    Serial.println(dataString);

    myFile = SD.open("data.csv", FILE_WRITE);
    if (myFile) {
      myFile.println(dataString);
      myFile.close();
    } else {
      Serial.println("error opening data.csv");
    }
  }
}
```

Appendix B: Arduino code for the piezo device that records analog signal and writes to the SD card




```
#include <SPI.h>
#include <SD.h>

const int chipSelect = BUILTIN_SDCARD;

File myFile;
File piezoRead;

unsigned long myTime;

void setup() {
  // sets BAUD rate
  Serial.begin(9600);

  // checks SD card
  Serial.print("Initializing SD card...");
  if (!SD.begin(chipSelect)) {
    Serial.println("initialization failed!");
    while (1);
  }
  Serial.println("initialization done.");

  // deletes the previous recording, so check to make sure you have it!
  SD.remove("piezo1.csv");
}

void loop() {
  // grabs the reading and milliseconds since beginning,  combines into string
  int sensorValue = analogRead(14);
  myTime = millis();
  String dataString = String(myTime) + "," + String(sensorValue);

  // print out the value you read:
  Serial.println(dataString);
  //open the file for analog read
  piezoRead = SD.open("piezo1.csv", FILE_WRITE);
  if (piezoRead){
    // writes the string to sd card
    piezoRead.println(dataString);
    piezoRead.close();
  } else {
    // if the file isn't open, pop up an error:
    Serial.println("error opening datalog.txt");
  delay(500);  // delay in between reads for stability
}
}
```

Appendix C: Bill of Materials for Final Device

Part	**Quantity**	**Link**	**Total Cost**
Teensy 4.1	1	https://www.pjrc.com/store/teensy41.html	$31.50
MEMS Microphones	4	https://www.adafruit.com/product/3421	$27.80
16 position header connector to connect Teensy to Protoboard	2	https://www.digikey.com/en/products/detail/sullins-connector-solutions/PPPC161LFBN-RC/810188	$2.02

Switched JST-PH 2-Pin SMT Right Angle Breakout Board	1	https://www.adafruit.com/product/1863	$2.50
Lipo battery	1	https://www.adafruit.com/product/4236	$6.95
Half-sized protoboard	1	https://www.adafruit.com/product/1609	$4.50
Snap connector wire Part Number: 151370601: Mini-Lock-to-Mini-Lock Off-the-Shelf (OTS) Cable Assembly, 2.50mm Pitch, Female-Female, Single Row, 100.00mm OR 150.00mm (depending on subject BMI) Length, 6 Circuits, Natural	4	https://www.molex.com/molex/search/partSearchPage?isseriesPagination=yes&itemListRe=&itemList=&pQuery=q%253D*%253A*%2540fq%253Dcollection%253Aimpulse%2540fq%253Dcategory%253A%2522Cable%252BAssemblies%2522%2540fq%253Dproductname%253A%2522Mini-Lock%2522%2540fq%253Dassemblyconfiguration%253A%2522Dual%252BEnded%252BConnectors%2522%2540fq%253D&offset=20&currentQuery=	$8.00
Snap connector receptacle Part Number: 533750610 2.50mm Pitch, Mini-Lock PCB Header, Single Row, Vertical, Through Hole with Kinked Pins, Tin Plating, Positive Lock, 6 Circuits, Bag, 3.40mm PC Tail Length	4	https://www.molex.com/molex/search/deepSearch?pQuery=category%253A%2522PCB%2BHeaders%2522%2540productname%253A%2522Mini-Lock%2522%2540orientation%253A%2522Vertical%2522%2540terminationinterfacestyle%253A%2522Through%2BHole%2522%2BOR%2Bterminationinterfacestyle%253A%2522Through%2BHole%2B-%2BKinked%2BPin%2522	$2.60
3D Printed Abdominal Coupling Piece	4	3D printed using resin printer	$3.00
		Total Cost:	**$88.87**

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