Final Report
Foot-mounted Step Width Measurement
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1.2 step

Executive Summary

Our team identified the lack of a reliable apparatus that can measure step width outside of a laboratory environment. Measuring step width could prove critical in identifying and researching the development of certain neurological disorders affecting step gait. The problem statement developed reflects that closely: *Our goal is to design a device to* ***measure the step width*** *of patients for extended periods of time, outside the laboratory environment.* A list of requirements and specifications has been developed; some that are applicable to the prototype we developed, while others are intended for the end-product, but could still be influenced by engineering decisions we make. Some requirements and specifications pertain to engineering-specific features, such as shock resistance, battery life, storage capacity, and most of them enhance the accessibility and ease of use of our solution, especially for the target audience of our product. Building on these requirements and specifications, the team entered the concept exploration phase with divergence in mind. A vast number of potential solutions, approximately 40, were generated. Using sketches and technical information about developed solutions, as well as techniques such as Morphological Analysis and Pugh Charts, the team slowly started to narrow down solutions to a select three: Time of Flight, Ultra Wide Band, Ultrasonic. Due to unfortunate shipping dilemmas, the ultra wide band concept was removed from consideration. Time of flight and ultrasonic sensors were purchased and an Arduino and breadboard were acquired for prototyping. Testing was performed with a sequential progression of increasing complexity. **Static tests were performed to verify distance measurement capabilities and calibration** before progressing to dynamic tests and lastly on foot tests of both sensors. From preliminary testing, the ultrasonic sensor provided erratic and inconsistent data that did not meet the specifications for accuracy and precision. Thus it was **determined that time of flight was to be used for the final design** solution. After conducting these preliminary tests, the team sought to verify the solution by constraining step width to a known, constant value, and comparing the output data to this ground truth. This can be seen in Figure 30 on Page 34. Along the way, an **algorithm was developed to aid in data processing** and identifying steps using median and low pass filters. Throughout the project, various mounting solutions were examined and developed. This culminated in the development of a CAD design for a mounting solution, although there was not enough time to build it out. The results from verification testing indicate that the design solution **correctly identifies 85% of steps**, and **has an error of ±1.16 cm**. With the conclusion of this project, the team is confident that the prototype can be refined further and optimized to produce even more meaningful results, and perform longer timespan testing and research with patients that have gait disorders.

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Problem Definition

In biomedicine, there is a collection of nervous, musculoskeletal and cardiorespiratory conditions which, amongst other bodily systems, also affect gait [Pirker, 1]. By gait, we refer to locomotion achieved through the movement of human limbs, or more informally, walking [Stanford Medicine, 2]. These conditions, referred to as gait disorders in academic terms, can be monitored over time by logging various gait parameters using appropriate technology.

1 shows three of the most important parameters which are monitored for medical applications: step width, length, stride. Logging these three indices allows us to calculate different statistical components such as minimum, maximum, mean, and variance, which are often mentioned and analyzed in a variety of studies on gait disorders [Pirker, 1].

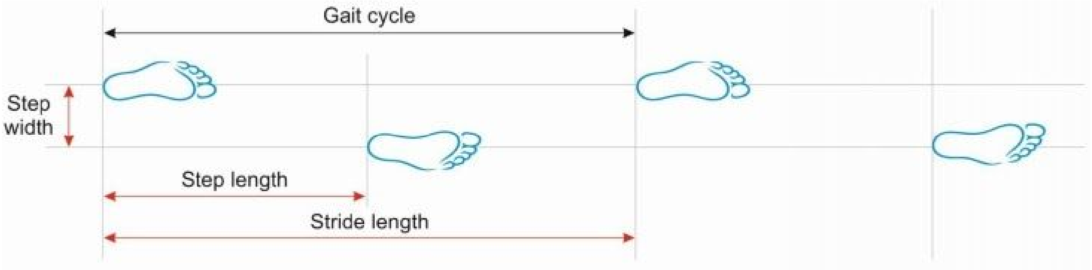


Figure 1: Graphical representation of relevant gait parameters [Pirker, 1]

There is a vast number of gait disorders, some of which kinesiologists, podiatrists, and neurologists know very little about due to their novelty and rare occurrence. Figure 2 on Page 6 shows a representation of what step location looks like for some of the more well understood gait disorders. Please note that the first row, a), shows the walking pattern of a healthy control. It is is easy to see that for example, thet people suffering from spastic paraparetic gait struggle with making long steps: thus, we would expect their stride and step lengths to be very short. Likewise, somebody that struggles with cerebellar ataxic gait will have difficulty controlling the lateral movement of their feet due to lack of limb coordination [John Hopkins,3]. Thus, we would expect to see a large variance/deviation in their step width. Also, please note that conditions shown in Figure 2 are not exhaustive; many more neurological conditions that exhibit gait disorders can be mentioned. (ex: Multiple Sclerosis, Normal Pressure Hydrocephalus etc.)

However, Figure 2 is very limiting in that it shows a continuous progression of unusual walking behaviour. In reality, this is not consistent with some of these neurological conditions. For a lot of these, gait disorders can be intermittent, cutting in and out based on external or internal triggers [APDA, 18]. For Parkinson’s disease for example, this phenomenon is called freezing and is not fully understood yet; that is to say that it is unclear what causes patients to start and stop exhibiting gait anomalies [APDA, 18]. Gait anomalies can take hours to appear and thus there is evident interest in monitoring gait for long periods of time (days-weeks) in order to encounter such phenomenon and log it.

Certain studies have been able to use laboratory equipment to also measure step width [Stolze, 4]. For example, Stolze looked at the step width and foot angle of patients suffering from Parkinson's Disease and Normal Pressure Hydrocephalus. His results are shown in Figure 3 on Page 6. Please note that the hollow circles, ○, show the walking patterns of 11 healthy control patients. Please note that foot angle degree is another parameter used in gait analysis, however measuring or analyzing it is out of the scope of our project.

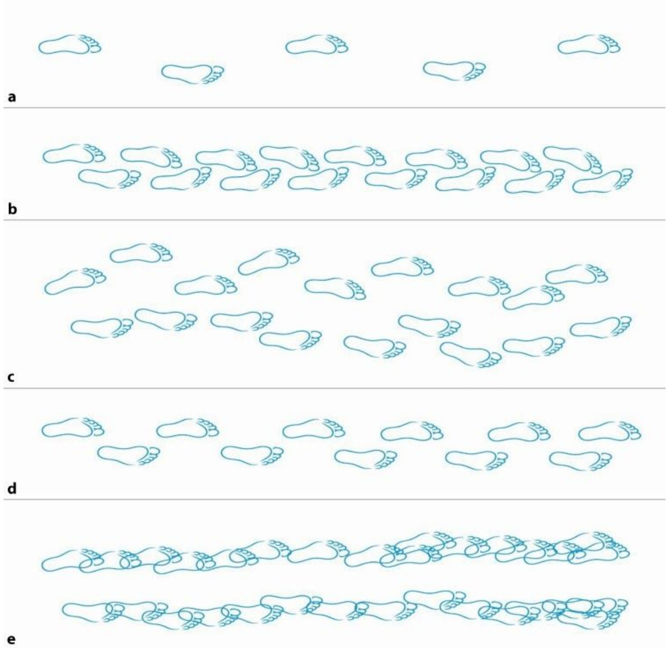


Figure 2: Graphical representation of walking patterns for various gait disorders [Pirker, 1]

a) Healthy Control b) Spastic Paraparetic Gait c) Cerebellar Ataxic Gait

d) Parkinsonian Gait e) Frontal Gait

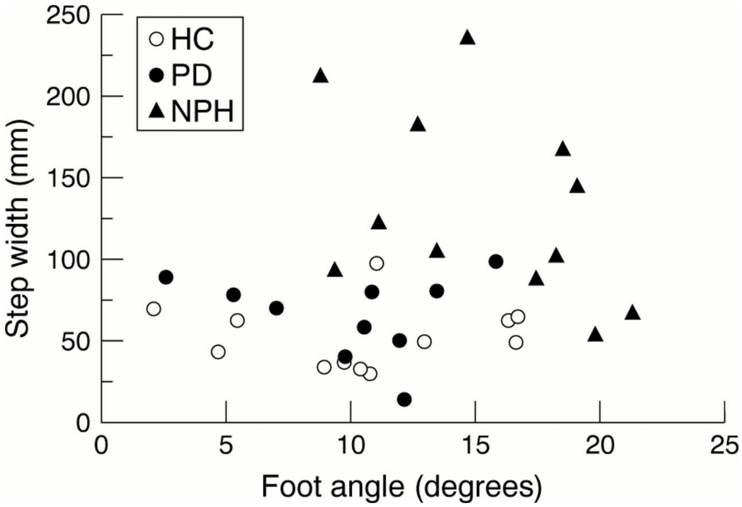


Figure 3: Step width measurements for various brain diseases [Stolze, 4]

○ - Healthy Control ● - Parkinson's Disease ▲ - Normal Pressure Hydrocephalus

Figure 3 proves unequivocally that step width varies between healthy people and those suffering from some neurological conditions. For instance, Stolze's data suggests that people suffering from Normal Pressure Hydrocephalus not only have a much wider step width, but also a greater variance in step width. Similarly, it appears that people suffering from Parkinson's disease have similar mean step width with healthy people, but slightly larger variance. Such data is a very useful tool for doctors to track the severity of peoples' conditions. However, it is important to underline the fact that these experiments were conducted in laboratory settings using highly specialized technology which is not readily available. These technologies are presented below.

Laboratory Gait Analysis Solutions

Two of the main gait analysis tools used for in-lab applications are roll-up walkways and motion capture. However, these are only available in research facilities and specialized clinics.

Roll-up walkways, such as the GAITrite, are likely the most convenient in-lab gait analysis platform [Access Health, 5]. They are easily transportable in portable trunks, roll out in just seconds and connect to specialized computer software with a USB cord. They offer great position localization precision, 1%-5.9% for the brand mentioned above, and require very little setup [Webster, 6]. Patients simply walk on the mat and data is being processed in real time by a computer. Such a system is shown in Figure 4. However, their prices are quite high, ~$25,000 . Furthermore, walkways are limited in the number of steps that can be tracked since the first and last steps are lost due to transient walking effects when transitioning onto and off the walkway.

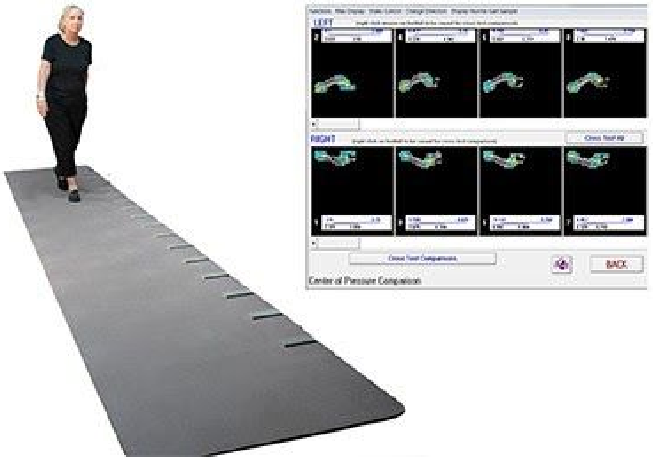


Figure 4: Roll-up walkways offer a convenient in-lab testing setup [Access Health, 5]

Another extremely accurate in-lab gait analysis system is through motion capture systems. These are networks of cameras which track reflective markers taped to certain locations on a person's limbs. The footage is then interpreted by a specialized software to create a stick-figure like animation of the person's locomotion [Leijendekkers, 7]. These systems offer market-leading position localization accuracy and precision, around 0.0017mm [VICON, 8]. Unfortunately, these systems are not without faults; they are difficult to set up and require frequent calibration, they necessitate sticking reflective markers to patients, and most importantly, such setups are extremely expensive, costing upwards of $100,000. Figure 5 shows an image of such a system being used.

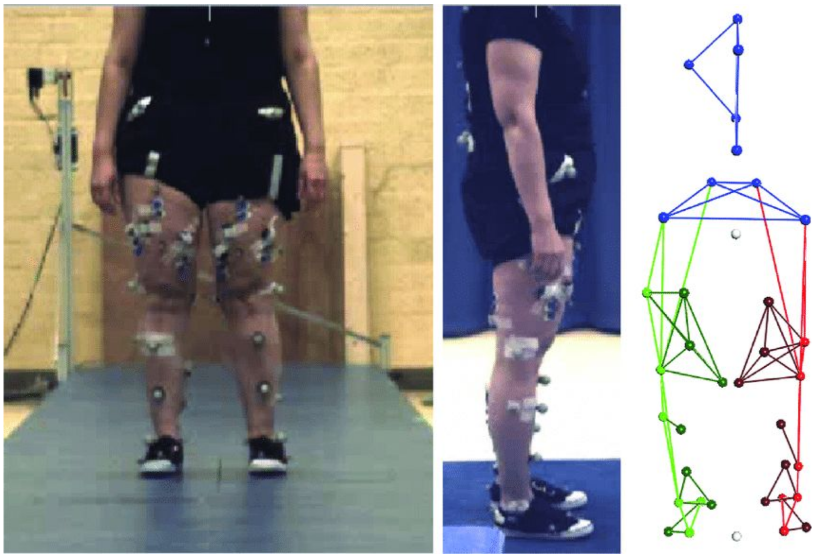


Figure 5: Physical setup and computer generated human model for a motion capture system [Leijendekkers, 7]

Out of Laboratory Gait Analysis Solutions

Unfortunately, laboratory gait analysis solutions offer only a small glimpse into the locomotion of patients. These techniques only log data for at most a few hours, and are limited to the gait patterns people exhibit inside the lab, which may be different from gait while going out everyday life. Subconsciously, people often change the way they walk in a lab when they are aware of constant monitoring. For this reason, out of lab gait analysis technology has been developed. A vast majority of out of lab gait analysis relies on Inertial Measurement Units or IMUs. An IMU data logger is shown in Figure 6.

Figure 6: Two IMU data loggers attached to the laces of somebodys' shoes [Stammel, 10]

These are small, lightweight and inexpensive circuits which contain accelerometers, angular rate gyros, and often magnetometers [Gaitup, 9]. They track motion with respect to individual reference frames and integrate acceleration to obtain velocity and then displacement. Costs for such devices vary between $1000 and $2500 and they offer good position localization accuracy under a very compact housing [Gaitup, 9]. Unfortunately, due to the nature of operation of IMUs, they are unable to track motion with respect to a fixed reference system. Thus, they are only able to track individual legs' steps and strides, not the distance between them, the step width. Furthermore, this technology is also prone to drift (error which grows with time due to integration of acceleration to get velocity). This technology limitation has led us to identify a gap in the market for gait analysis technology. At this moment there are no readily available, compact, out of lab, non-intrusive, and cost effective ways to measure step width.

Problem Statement

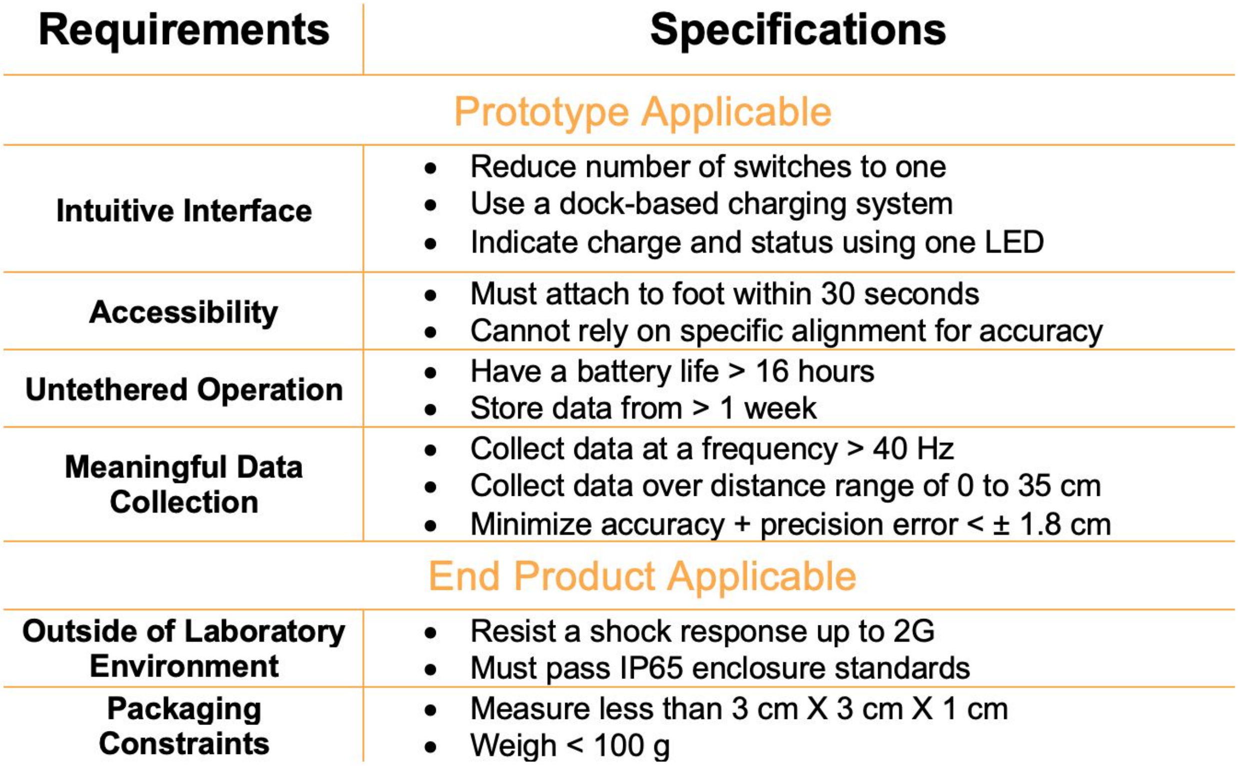
Having identified the need for an improved method to track step width the team established the following problem statement:

> *To better monitor gait disorders, advance understanding of what triggers intermittent gait episodes, and track the severity of certain neurological diseases, it is vital to develop a way to measure and log step width.*
>
> *Our goal is to design a device to* ***measure the step width*** *of patients for extended periods of time, outside the laboratory environment.*

Stakeholder Requirements and Engineering Specifications

Working off this problem statement and research into current solutions, the team developed requirements and specifications by which to evaluate proposed solutions. Table 1 displays the requirements and specifications for the step width measurement solution. The table is divided into two sections: Prototype Applicable and End-Product Applicable. Due to the timeline of the project, the stakeholder has identified certain requirements that are critical for development in the deliverable prototype within the timescale of the project, and end-product requirements that should be considered in the design process, but are not necessarily critical to the deliverable's immediate success. The prototype requirements are concerned with device interface, untethered operation, and data collection. The specifications regarding these requirements are the most critical in the scope of this project. The end product applicable requirements deal with operation outside of the environment and packaging constraints. The following section details all the requirements found in Table 1, and the justifications for each corresponding specification.

Table 1: Summary of stakeholder requirements and engineering specifications four step width measurement solution



Requirements	Specifications
Prototype Applicable	
Intuitive Interface	• Reduce number of switches to one • Use a dock-based charging system • Indicate charge and status using one LED
Accessibility	• Must attach to foot within 30 seconds • Cannot rely on specific alignment for accuracy
Untethered Operation	• Have a battery life > 16 hours • Store data from > 1 week
Meaningful Data Collection	• Collect data at a frequency > 40 Hz • Collect data over distance range of 0 to 35 cm • Minimize accuracy + precision error < ± 1.8 cm
End Product Applicable	
Outside of Laboratory Environment	• Resist a shock response up to 2G • Must pass IP65 enclosure standards
Packaging Constraints	• Measure less than 3 cm X 3 cm X 1 cm • Weigh < 100 g

Intuitive Interface: According to Motti [12], elderly patients introduced to devices with novel technologies often take longer times to operate the device. To decrease the learning curve associated with operating the device, inputs and additional technology required for operation of the device should be minimized. To accomplish this requirement the device will only have a single switch to turn on data collection. This will allow the user to turn on the device, place it on themselves, and continue on with their daily activities not having to provide additional inputs to guarantee data collection.

To allow for ease of use when charging, the device will use a dock-based charging system. This is prefered since it will eliminate the need to understand any proprietary technology regarding charging, and it will incentivise recharging the device since the docking station is an intuitive solution and an often already familiar system. Charging is expected to be performed overnight on a daily basis.

Accessibility: The device will be used by patients with neurological conditions such as Multiple Sclerosis that often have trouble with fine motor skills [Bethoux, 13]. Therefore, it can not be expected that users of the device will have precise control of the orientation of the device when placed, or be able to place the device in the exact location specified. To facilitate the device to be accessible for these users, it is imperative that the device be able to operate successfully in a wide array of orientations, or not rely on a specific alignment by the user to collect accurate data.

The intended users of the device may not necessarily have fine control of their motor skills. In order for the device to not cause the user undue burden, it must be easily put on. The complete process of attaching the device to the user’s foot must be able to be accomplished within 30 seconds and performed by the user. The time to put on the device was selected to not take away from the users other daily living activities and should be as simple for the user as washing their hands.

Untethered Operation: To properly identify gait patterns, data must be recorded for weeks or months [Carling, 14]. Unfortunately, current technology for step width analysis is suited only for a collection time of one day in laboratory conditions. In order to improve upon this technology and properly measure step width, this device must be capable of untethered operation. Specifically, the device’s battery life must be greater than 16 hours. This will allow the user to use the device all day without having to take time to recharge it and potentially miss out on data recording opportunities. The device’s minimum data collection time must be at least one week as well. As a result, it is necessary that the device can store at least a week's worth of data in its own memory so that the user will not have to return to the lab frequently.

Meaningful Data Collection: To ensure that the collected data is sufficient to identify gait disorders, it must be able to accurately model step width over a long period of time. The device therefore must collect data at an appropriate frequency, range, and accuracy for walking.
Based on previous studies, the average human step frequency was found to be 2 Hz [Pachi, 15]. In order to accurately model this, the device must sample data above the Nyquist frequency, 2.1 times greater than the walking frequency. However, based on feedback from the first design presentation, a higher sampling rate of up to 40 Hz would be necessary for better resolution.

Next, the device must have an appropriate range for collecting walking data. It has been shown that patients with neurological diseases frequently demonstrate steps widths over 20 cm [Webster, 6][Stolze, 4]. Therefore, in order to capture the full range of step widths, the device must have a range from 0 cm to 35 cm.

Finally, the device must collect data at an appropriate accuracy. The variability of step widths for neurological patients has been shown to be greater than 1.5 cm [Paterson, 20]. This device then must have an accuracy better than ±1.5 cm to fully capture the variations in step width.

Use Outside the Laboratory Environment: Since identifying gait disorders can take weeks or even months, this device must be designed for use outside the lab environment. Also, since the primary goal of this project is to develop the technology necessary for step width measurements, and not the final product, the following list of requirements do not directly apply to the deliverable prototype. However, the device should not provide an obstacle for miniaturization and integration in the future.

Since this device will eventually be worn out in the world, during day-to-day activities, the final iteration must be robust enough to survive for weeks at a time. Common accelerations caused by footstrikes can be up to 2G in magnitude, and the device must be able to withstand these conditions [Werkhoven, 21]. The final product must be able to resist footstrike downward accelerations of up to 2G.

Another factor that goes along with use outside of a lab is weather. When this device is being worn out into the world, it may encounter rain, dust, spills, and other elements that are destructive to electronics. Therefore, the eventual enclosure for the final product must pass IP65 water and dust resistance specifications [IEC Standard, 22].

Packaging Constraints for Use on Shoe: Due to the device's placement on the shoe of the user, certain requirements are necessary to guarantee that the device does not impede the day to day lifestyles of the users. According to Sagaldo [Sagaldo, 11], elderly and neurologically disabled patients often have decreased muscular strength. This, coupled with a study conducted by B.M Nigg showing that during intense physical exercise, an extra 100g on one foot increases energy consumption by 0.7-1/0%, emphasize the importance of minimizing the weight of the device [Nigg, 19] . A mass of less than 100g for the end device is required to allow for the user to walk without hindrance from the device.

Additionally, it is critical that the form factor of the device not impede the step motion of the user. Therefore, the device must be compact in volume. Device dimensions of less than 3cm x 3cm x 1cm will accomplish the requirement for a compact form factor.

Concept Generation

Motivation

After defining our problem, and synthesizing the engineering requirements and specifications, we then moved forward into generating design concepts. Due to the wide range of our design space, we decided on a “quantity over quality” ethos for our initial brainstorming. This means that we brought up any idea that we could think of, and did not rule any concepts out until a later stage.

Procedure

After completing the problem definition phase, we decided to develop concepts for distance-measuring technology and attachment methods in parallel. Our team took a wide-ranging approach to developing design concepts, starting with brainstorming and a mind map. For this first phase of generating design ideas, we came together as a group and used divergent thinking to generate as many solutions as possible. At this stage, we reserved judgment on the feasibility of any design, and worked to build synergistically off of each other. To facilitate this brainstorming, we chose to make a mind map of our thought process, which can be seen in Appendix A.1. On this mind map, we started with some general categories of measuring distance, such as using properties of waves, detecting fields, and revisiting current solutions like IMUs. From these categories, we were then able to put together a wide range of possible solutions from research on various industries. Likewise, for attachment concept generation, we made a separate section of the mind map where we pooled every method to attach our device to a shoe.

After the initial concept generation, we then began to categorize and research promising ideas. Categorization gave us an excellent visual breakdown of the possible merits and drawbacks of each design concept. For example, one of the categories we used was continuous measurement versus discontinuous measurement. By sorting our concepts into these categories, we were able to identify which technologies would constantly record data, and which ones would only record at set intervals. We also used previous solutions to inform our concept generation. By researching previous attempts at solving our problem, we could get a sense of what ideas could be ruled out early, and which ones show promising results.

Concept Development

Motivation

Once individual ideas were generated and sorted it was deemed necessary to further evaluate the possible designs generated. This is critical to the generation of the ideal solution because it allows each concept to have time to be investigated for the merits of its application, and potential downsides. When in the generation phase, it is easy to suggest concepts that may not be of real world practicality. This phase of development allows for these concepts to be pushed aside, and for more applicable concepts to receive the attention and research necessary to evaluate their potential as a solution.

Procedure

Each concept that was previously generated was first subject to an initial practicality check. Here, solutions that would have no real world promise were thrown out and not subject to further development. An example of this would be radiation as a method of deducing distance. The remaining concepts were then evaluated based on the principle of operation first, and then investigated further to identify pros and cons of the concept. These included accuracy, cost, range, and foreseeable issues implementing the concept. To understand and contextualize the technologies generated during concept generation, a large amount of time and research was invested into learning more about the concepts generated and how they would work in the real world in an attempt to resolve distance.

Based on what information was found regarding the concept and the associated technology, an initial sketch showing the concept attached to a shoe and its means of operation was created. Seven such sketches dealing with novel concepts were generated. Bundled with this sketch were facts pertaining to the principle of operation, range, accuracy, cost, and potential issues seen with the technology. Figure 7 on Page 15 shows an example sketch used when generating a concept that uses Time of Flight technology. For brevity of this paper, the three most promising concepts are detailed here, while the remainder of the concepts are detailed in Appendix A.2.

Concept 1: Laser Sensor - Time of Flight (TOF)

Time of flight sensors have been used in many industries to measure distance. The sensor works by measuring the total time it takes to bounce a laser off of the first target in its field of view. This round trip time is then used to calculate the distance to the object. Because a single TOF sensor has a field of view of about 27 degrees [SparkFun, 24], multiple sensors may need to be used to ensure that the sensors would catch the foot as it passes. A proposed sensor has a range of 4 cm - 4 m, accuracy of ± 2mm, and costs $25 [SparkFun, 24]. The concept is illustrated in Figure 7 on Page 15.

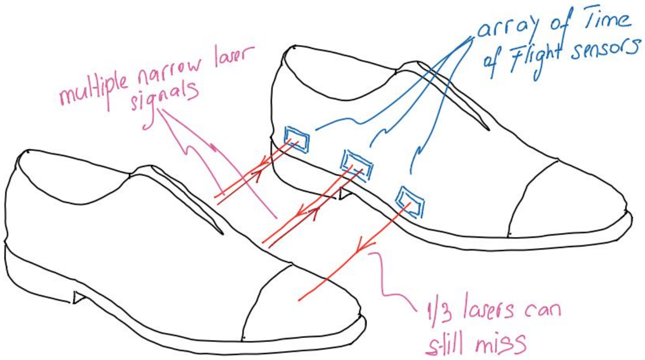


Figure 7: Time of Flight sensors are very accurate solutions to the distance measurement problem. An array of sensors would be required to ensure the distance is properly measured

Concept 2: Ultra Wide Band (UWB)

Ultra Wide Band is a short to medium range localization protocol that uses radio transceivers operating at 3--7 GHz [Wikipedia, 30]. UWB uses a transceiver chip connected to an antenna to estimate the distance between the instruments. It has a range of 1 cm - 70 m and an accuracy of ± 2 cm [Decawave, 28]. At $40 per sensor ($80 total) it is slightly expensive, however the technology has been proven to be reliable and accurate [Future Electronics, 29]. This is a relatively new technology so it may be difficult to interface with traditional hardware such as an arduino as well. A schematic that shows the operation of this technology is shown below in Figure 8.

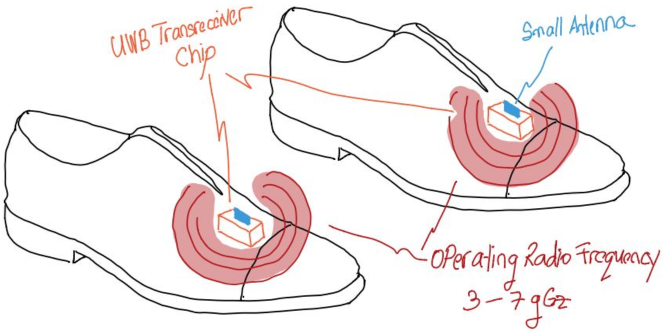


Figure 8: An ultra wide band system requires a transceiver chip and small antenna on both feet to measure distance.

Concept 3: Ultrasonic Sensors

Ultrasonic sensors bounce high energy sound waves off of a target, and record the time it takes for the wave to return to the sensor in order to deduce distance. These sensors are commercially available, and have a well understood operating principle. This makes implementing them an appealing solution, and allows for rapid prototyping. Research into these sensors found that ultrasonics have a range of 2cm to 4 m, and a resolution of +/- 3mm [SparkFun, 31]. Due to the technology being well developed, a sensor for a price of 4$ can be obtained [SparkFun, 31]. With all of the promising aspects of this technology, there is still concern regarding the wide field of view of the sensor. This wide field of view may pick up obstacles or objects behind what is intended to be detected, resulting in erroneous recordings. Figure 9 depicts the implementation of the concept on a set of shoes.

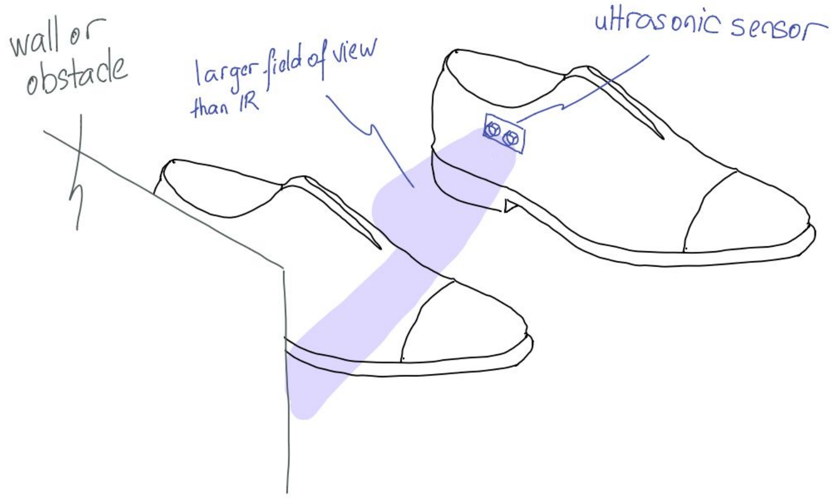


Figure 9: A concept using an ultrasonic sensor is shown. As can be seen by the highlighted area, the field of view of the sensor may impede accurate measurement of distances between the feet.

Device Attachment Concepts

While it was critical to further develop concepts regarding technologies and how they will be implemented to resolve distance, another significant area of concept development dealt with how the concept will be attached to the user. A similar brainstorming session first took place regarding attachment methods, with further development taking place in the same manner as previously shown for the differing technology development. Shown in Appendix A.2 are these attachment concepts, and an accompanying sketch displaying how they would look when implemented.

Hardware Interfacing

Lastly a quick brainstorming session was done in regards to the hardware that will be used to interface with the distance measurement technology. For the scope of this project, key interfacing considerations include ease of use, timeline, our past experiences and strengths, and sizing. Low fidelity prototyping will be performed later in the project for technology verification and validation. For the end product, it is likely that a custom made circuit board will be used to downsize and package everything together as efficiently as possible. Ideas for hardware interfacing include Arduino, Raspberry Pi, Teensy boards communicating with the sensor(s) using I2C or SPI protocols. Data processing and storage could be performed either in real time onboard, via wireless transfer, or after testing for our prototype. The methods for hardware interfacing will depend strongly on the chosen technology and will be discussed later in this report.

Concept Evaluation

Motivation

After generating, researching, and developing a wide variety of solutions, we created a strategy that would support the convergence of solutions. Since we hold commitments to both our stakeholder, and the capstone project within ME450, it was vital that after we came up with a wide variety of options, we narrowed it down to the most promising ones. This was repeated for both the technology development, and implementation aspects of concept generation.

Procedure

In beginning the concept evaluation process, a gut check was first used to rule out unfeasible ideas. Based on engineering experience and knowledge accumulated over the years by our team, ideas that seemed entirely unfeasible were the first ones to be eliminated. For instance, solutions which pose a high safety risk such as radioactivity, or solutions which visibly restrict motion such as a string potentiometer, were removed without further evidence. Next, a set of assumptions was created to aid in further narrowing down the possible solutions. These are presented below:

1) Since none of these solutions have directly been used for step width measurements before, it is imperative that we *validate the technology using both theoretical and experimental means*.
2) Although this may not be the case for certain individuals, Dr. Ojeda suggested that we *assume patients' feet may wander across each other intermittently as they are walking*.
3) None of the technologies we decide to move forward with *should constrain who the possible end users could be, in terms of engineering inclusivity* and equitability.

The final concept evaluation stage we deployed was creating two Pugh Charts, one for the main distance measuring technology, and another for physical implementation. These are an established way of comparing how a variety of solutions stand against a standardized set of requirements which best represent the requirements and specifications developed in the earlier sections of this report. More details about the process of creating the Pugh charts and the process used to index information within are presented in Appendix A.3.

Findings

From the concept generation and evaluation process we identified the three most promising solutions for step-width measurement outside the laboratory environment. These are: Ultra wide band, Time of Flight, and Ultrasonic. The process of narrowing down these selected concepts will be discussed next.

Solution Development

At the end of concept evaluation it was decided that three concepts would be examined and analyzed *Ultra Wide Band*, *Time of Flight*, and *Ultrasonic*. However, due to unforeseen shipping issues and time constraints the analysis and development of ultra wide band could not take place, eliminating it from further examination. These circumstances have thus resulted in two concepts being examined in parallel - Time of Flight and Ultrasonic.

The first step in solution development required obtaining and configuring the hardware required for each concept. In the case of the Time of Flight solution, the VL53L1X was selected, and ordered from SparkFun. This breakout board has an IR laser ToF sensor, along with included Arduino libraries to resolve distance measurements. These qualities made this sensor attractive, along with its 4 cm to 4 m range, and millimeter resolution. Two such breakouts were ordered to allow for contingency in the event that one sensor was broken or did not perform to specification.

For the ultrasonic solution, the HC-SR04 was selected, and ordered from SparkFun. This sensor provides 3 mm resolution, along with 2 cm to 400 cm range. These boards are ubiquitous in many different applications, and have extensive supporting documentation online, making it a great choice for this application. The units are also very cost-effective, and so three were ordered for redundancy.

An Arduino and additional hardware was obtained from the stakeholder to allow for testing to take place. In conjunction with the breadboards, wires, and miscellaneous Arduino compatible components obtained from the stakeholder, a soldering kit was borrowed from the X50 assembly room. With these items in the possession of the team, solution development began at the hardware level with integration of the sensor packages to an Arduino, with the requisite code being written to facilitate testing.

Testing Overview

For setting out to evaluate the time of flight and ultrasonic sensors, a chronological progression of experiments was planned out. By decomposing the problem into smaller manageable experiments of increasing complexity, we are able to verify and validate the sensors and the data they output together. Starting off with no objects moving, then progressing to one dynamic object before moving the sensors onto the foot allowed for verification of data collection without any complexities causing difficulties. A separate test was performed to determine the horizontal field of view of each sensor. Initially, testing both sensors at a time enabled rapid parallel workflow and provided one ground truth zero distance between the two sensors. However, in later dynamic testing only one sensor was used at a time to reduce load on the Arduino and thus maximize sampling frequency. Once moving the sensor onto the foot, initial tests involved simple walking to verify on-foot collection and prototype mounting before progressing to larger timespan testing, and testing with constrained step width. This sequential progression was critical to the success in verifying and validating the technologies.

Sensor Testing Setup

To begin testing it was deemed necessary to have a hardware setup that facilitated both easy data collection and flexibility in testing situations. As mentioned previously, the purchased sensors for TOF and ultrasonic sensors were designed to integrate directly with Arduino. As such, the sensors were wired in accordance with their setup guides on a singular breadboard connecting to the Arduino. This breadboard was mounted to a cardboard box that the components shipped in. Additionally, a button was added to a separate breadboard to allow for data collection to be controlled by a physical input. Figure 10 depicts the initial sensor package setup.

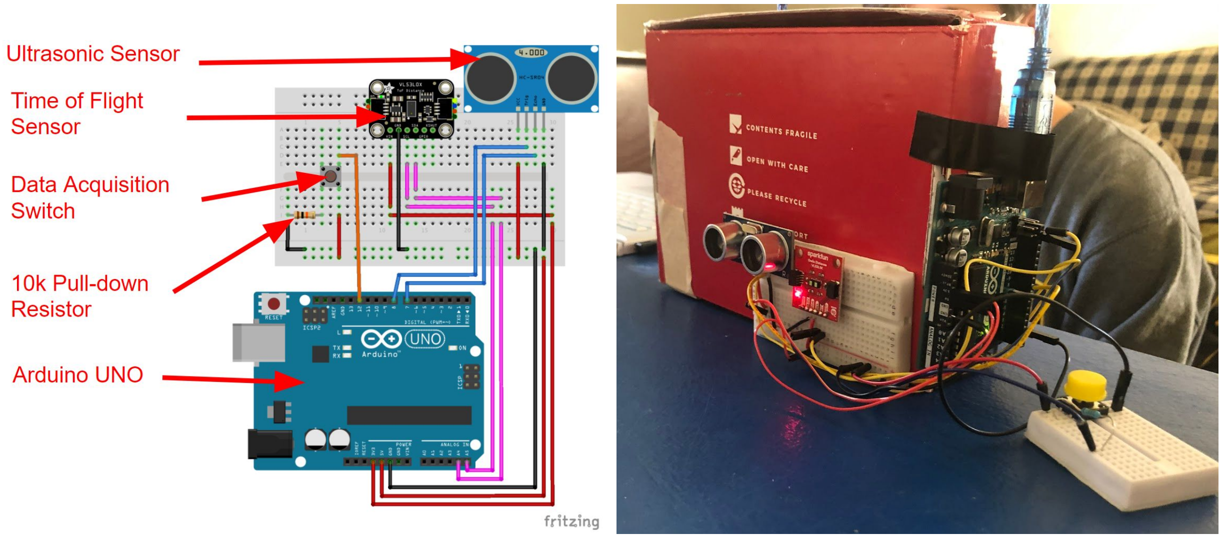


Figure 10: Circuit diagram showing components of sensor testing setup and signals: I2C Protocol Data, Ultrasonic Digital Data, Switch Digital Data, Power & GND. Of note is the additional breadboard in the real life setup. This was added to allow for the button initializing data collection to be more easily pressed.

The benefit of this setup was its well defined geometry. The surface of the breadboard with the sensors connected provided a mutual reference point for measurements from the sensors. This was critical in order to allow for calibration curves to be generated later on in solution development. The setup also allowed for data to be collected from both sensors simultaneously as long as the target was large enough to be in each sensor's field of view- this proved to be helpful also when generating the calibration curves for the sensors. Due to the fact that the hardware was mounted to a light weight but stable box, the hardware could be moved and positioned easily allowing the testing setup to change but not requiring any new wiring. This ultimately resulted in low turn around times for a new test setup, and facilitated rapid testing across the solution development. Additional information on the testing workflow and computer interface can be found in Appendix A.4.

Static Sensor Calibration Testing

Using the box-mounted testing setup described above, the next step was to take static data to generate a calibration curve for the sensors. An experiment was designed to take distance measurements from each sensor at varying distances measured by a ruler between the prototype and a cardboard box target. Data was recorded for a period of 30 seconds before moving the cardboard box incrementally back from 5-40 cm. Figure 11 shows the setup for static testing.

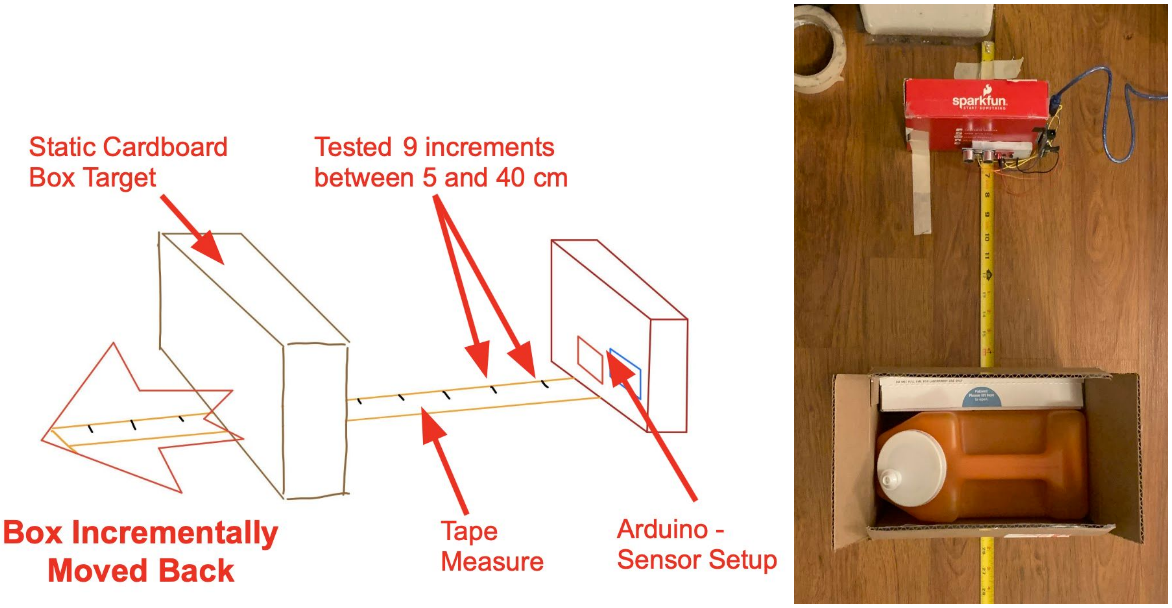


Figure 11: Static sensor calibration testing setup

The main goal of calibration testing was to verify that the sensor reading is proportional to a controlled physical distance. Additionally, the intercept of our linear regression determined the offset between the sensor's zero point and the beginning of our tape measure where we understood true distance = 0 to be. Sufficient data collection of 30 seconds allowed for precision precision error to be determined for each sensor. The error in the actual distance was considered to be the resolution error of the tape measure increments. Linear fitting was performed in MATLAB_R2019b. The testing setup calibration for both time of flight and ultrasonic are shown in Figure 12 on Page 21.

As seen in Figure 12, the static calibration confirmed the linear dependency and precision errors for the both technologies to be sufficient for further investigation. In later testing, the calibration equations for each were used to convert between sensor output and true distance. For future calibration, the team aims to use a gait lab to verify the calibration and improve the accuracy of fit and converted measurements. However due to both in person COVID shutdowns and time constraints this was not possible.

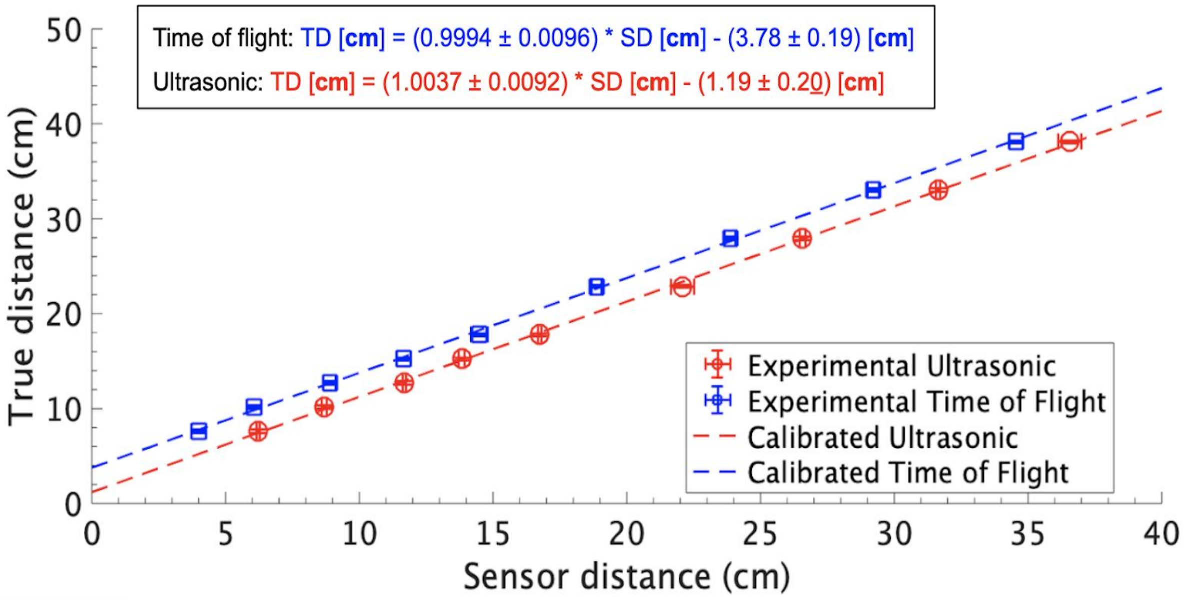


Figure 12: Calibration curves confirm linear dependency between sensor distance and linear distance for both sensors (max. true error is ± 0.16 cm & max. measured error is ± 0.43 cm)

Field of View Test

In order to determine the field of view with our sensors a simple test was performed. The field of view is important with the chosen technologies because it plays a big part in determining the time an object, in our case a foot, will spend in front of the sensor. A greater field of view makes for a longer time window to measure the foot but could cause issues with detection of objects other than the foot. A box was dragged at a fixed perpendicular distance from the testing box setup until detected by the sensor as shown in Figure 13.

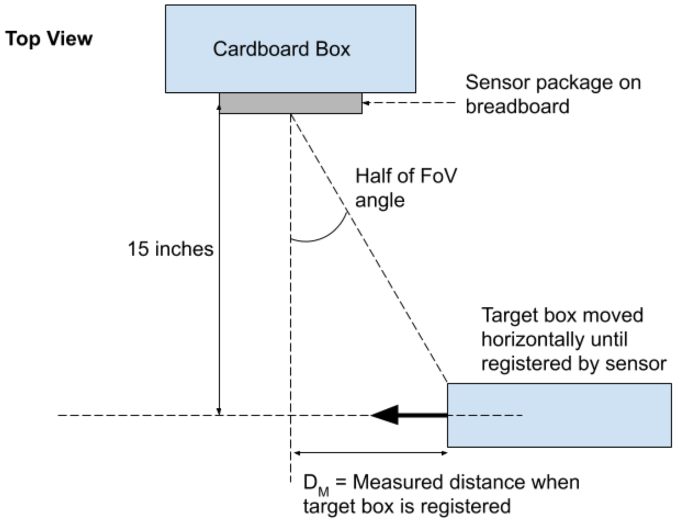


Figure 13: Procedure for finding sensor field of view

From this point, a trigonometric calculation was performed to determine the field of view. Our results are time of flight: 29.863 ± 0.008°, for ultrasonic: 26.268 ± 0.008 °. For our purposes of foot detection we believe these fields of view to be adequate. Further testing in an on-foot environment will be able to determine if external object detection is an issue.

Dynamic Velocity Test

After completing the static sensor calibration testing, the next logical step was to move into dynamic tests. The experiment diagram can be seen in Figure 14, and an image of the setup can be seen in Figure 15.

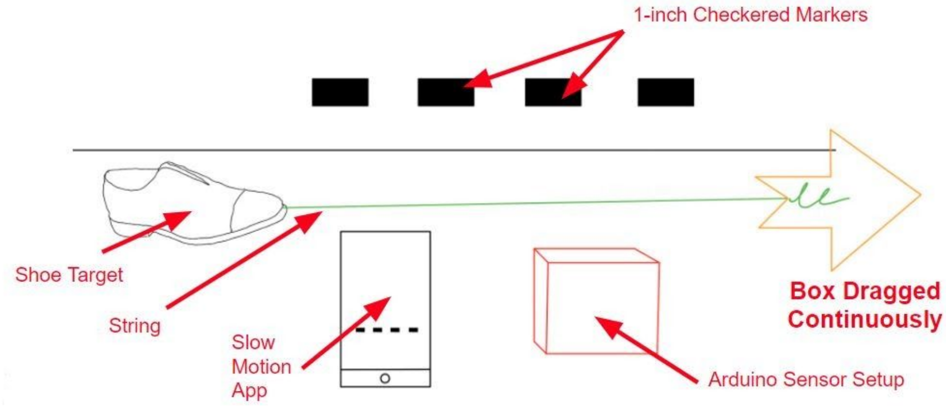


Figure 14: Dynamic Velocity Testing Diagram. The shoe target was pulled at constant velocity parallel to the sensor package. The velocity was estimated using evenly spaced checkered markers and a slow motion camera app, and was found to be ~0.5 m/s

Figure 15: Dynamic Velocity Testing Experimental Setup

This test was done to determine the performance of each sensor on a moving target, and to find how many data points can be gathered as the shoe moves past the sensor. The perpendicular distance from shoe to sensor was varied three times, at 13.5", 9.5", and 6.25". For each distance, three trials were performed for each sensor. The resulting data from the 6.25" series for each sensor can be seen below in Figure 16.

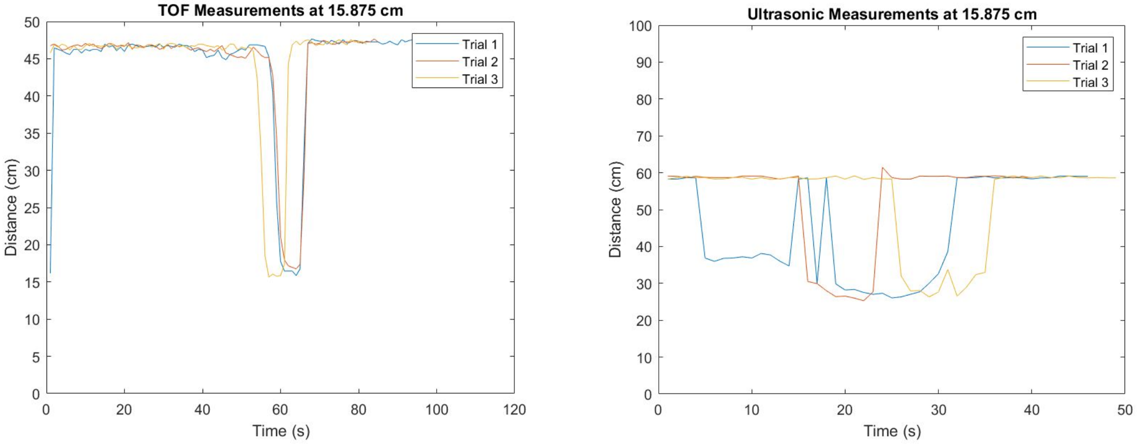


Figure 16: ToF and Ultrasonic Dynamic Tests at 6.25" (15.875 cm)

As can be seen in the left half of Figure 16, the ToF sensor resolved distance quite well, with clear intervals where the shoe is in the field of view. The accuracy was also excellent, right in the 15 cm to 16 cm range. The ultrasonic sensor was quite a bit worse, as seen in the right half of Figure 16. The sensor recorded the distance as roughly 30 cm, which is a significant deviation from the true value. Additionally, there were a few spikes in the data, as can be seen above. These spikes are most likely due to false readings from the sensor, but the large distance offset does not have a simple explanation.

Preliminary Walking Test

After the completion of the dynamic velocity test, the team developed an untethered testing setup that allows the time of flight and ultrasonic sensors to measure distance data without connection to a computer. As seen in Figure 17 on Page 24, a micro SD breakout board (Adafruit Product ID:254) was added to the system to download the distance measurement data from the sensors. Complicating the hardware setup was the fact that with the addition of the micro SD breakout, the Arduino was using both SPI and I2C communication protocols to interface with hardware. While this was initially seen as a potential issue, the provided libraries allowed for easy troubleshooting and easy updating of the previously developed code. Additionally, the Arduino was connected to a USB power bank to supply power to the whole system without direct connection to a wall or computer.

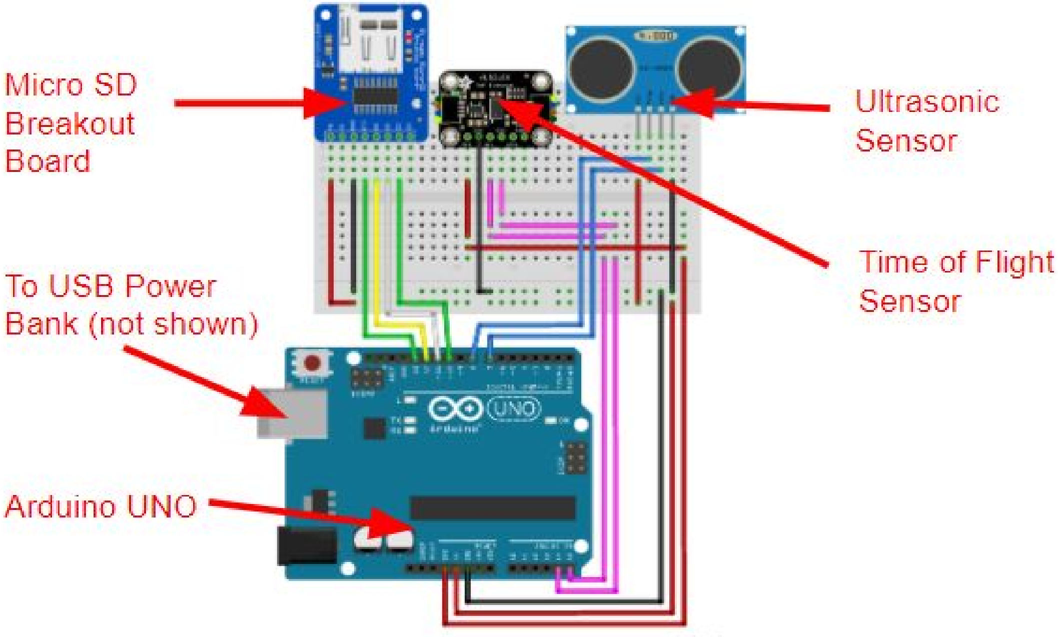


Figure 17: Circuit diagram showing components of untethered testing setup and signals: I2C Protocol Data, Ultrasonic Digital Data, Power & GND

This testing system was attached to a foot using a velcro strap to connect the breadboard and sensors directly to the inner-midpoint of the foot. The arduino was tucked into the bottom of the jeans and the battery pack was tucked into the sock as seen in Figure 18.

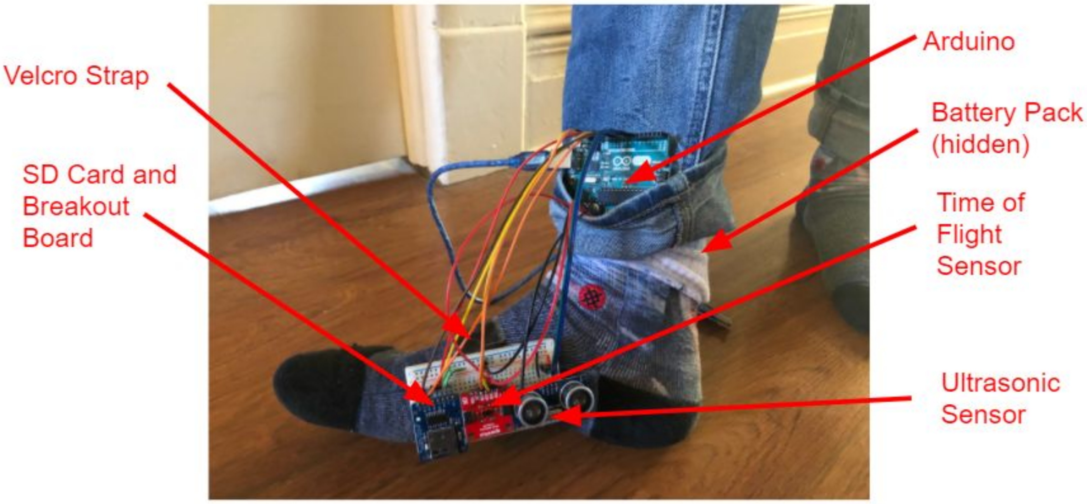


Figure 18: Preliminary foot-mounted testing setup used to analyze data output

To conduct this test, the test subject turned the Arduino on by plugging in the power bank, took a few strides, and then turned the arduino off. Initial results from this test were very promising. Minima in the data likely indicate the foot being picked up as it swings in front of the sensors. For each dip, there are 3-4 data points that confirm that data is non-spurious. This data is showcased in Figure 19 on Page 25.

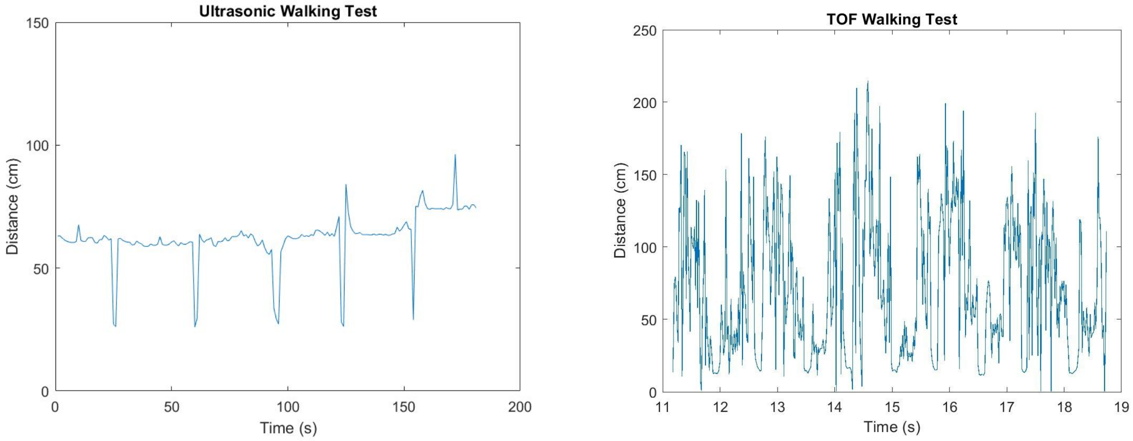


Figure 19: Distance reported by the Ultrasonic and ToF sensor as a function of time for preliminary on-foot testing.

Risk Assessment

Due to the fact that the design is a prototype, there are a few risks involved with it that will be resolved by the development of a clean, more compact, factory made design. The primary risk involved with this device is the tripping hazard. Because the device is strapped onto the inside of the foot, the user can easily trip on the sensors, wires or battery while taking a step with their opposite foot. In the current state of the system, it would be fairly likely for the user to trip over it once over an entire day. If the user struck the sensor hard, it could very easily damage the sensor or take out wires.

The user may injure themselves by tripping as well. Since the users of this device are primarily elderly and may have conditions that already hinder their movement, it is likely that if they were to trip, they could easily get hurt. With this information, it is vital for future iterations of the design to be more compact and reduce the risk of tripping. The team created a CAD model in the Detailed Design Solution section that reduces the risk of the user tripping and protects the system from getting damaged. After applying this change, the risk is minimal enough to the system and the user to ensure complete safety.

Additional risks come from using lithium Ion batteries and electricity in general. Batteries always have a potential for malfunctioning after being damaged. This is a very small risk that can be accepted just by using well known and used battery systems. In the current prototype state, there is also a very low risk of electric shock. After putting protective shielding around all electronics, there will be almost zero risk of shock.

Detailed Design Solution

Based on the results of the preliminary testing as discussed above, the time of flight sensor was chosen for the final design solution. This was determined primarily through the dynamic velocity testing and preliminary walking tests. Using the same processing algorithm, the time of flight sensor outperformed the ultrasonic sensor in terms of accuracy, noise, and step detection. In Figure 16, the time of flight sensor showed much better results from dynamic velocity tests, with clearly defined valleys when the shoe passed. The ultrasonic sensor had worse results, with noisy peaks that obscured some of the data. Additionally for this test, the time of flight sensor recorded a distance of 16 cm, which is only 0.125 cm off from the true value. The ultrasonic sensor recorded a distance of 30 cm, very much off from the true value.

Although the final prototype remained rather crude, the team also created a future solution, which could be implemented given more time. The two main components of this solution were shrinking down the current Arduino/breadboard/sensor setup into a single, integrated PCB, and a more robust and permanent mounting solution. First, there were some issues with the current electrical system, as it consisted of multiple breakout boards and other components wired together, as opposed to a more centralized solution. This gave rise to the possibility of hookup wires being unplugged, and led to a more cumbersome mounting procedure. Additionally, the Arduino is too large for this application, and so a downsized control solution would be beneficial. Based on these limitations, the team proposed the following design for an end product solution. All of the components would be mounted on a custom PCB to minimize space. As can be seen in Figure 20, the SparkFun VL53L1X ToF sensor will still be used, although this design incorporates just the sensor itself without the breakout board. The ATMega328p microcontroller used on the Arduino worked well for this application, and supports I2C interface. Instead of using an SD card like the prototype, this design would incorporate 8 GB of onboard flash memory for data storage. For data acquisition, this new design would move to a Bluetooth module for wireless communication capabilities, and would have a back-up microUSB port. Finally, a 1 Ah battery would provide a 12 hours of continuous usage, based on a 50 mAh maximum draw from the components, plus a 1.5x safety factor.

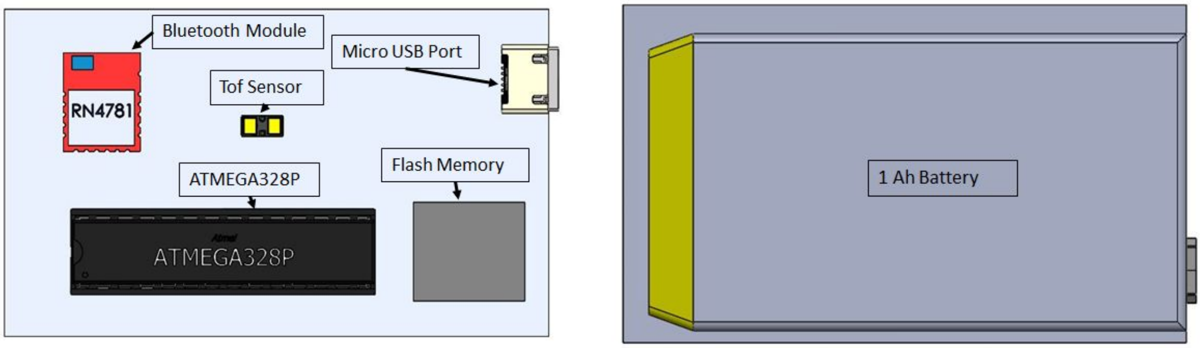


Figure 20: Mockup of Custom PCB Design.

The prototype mounting method was also a concern, and the team proposed a new design for a final product. The current velcro strap works well for testing purposes, but would not be appropriate for a device meant to be worn for days on end. Additionally, the strap design does not meet the requirement for not relying on specific alignment, as it can easily be moved inadvertently. Therefore, a new rigid mount was designed, and its details can be seen below in Figure 21. Furthermore, non-symmetric magnetic pegs would be used to automatically orient the device in the right direction, and snap the housing to the charging station. This is shown in Figure 22.

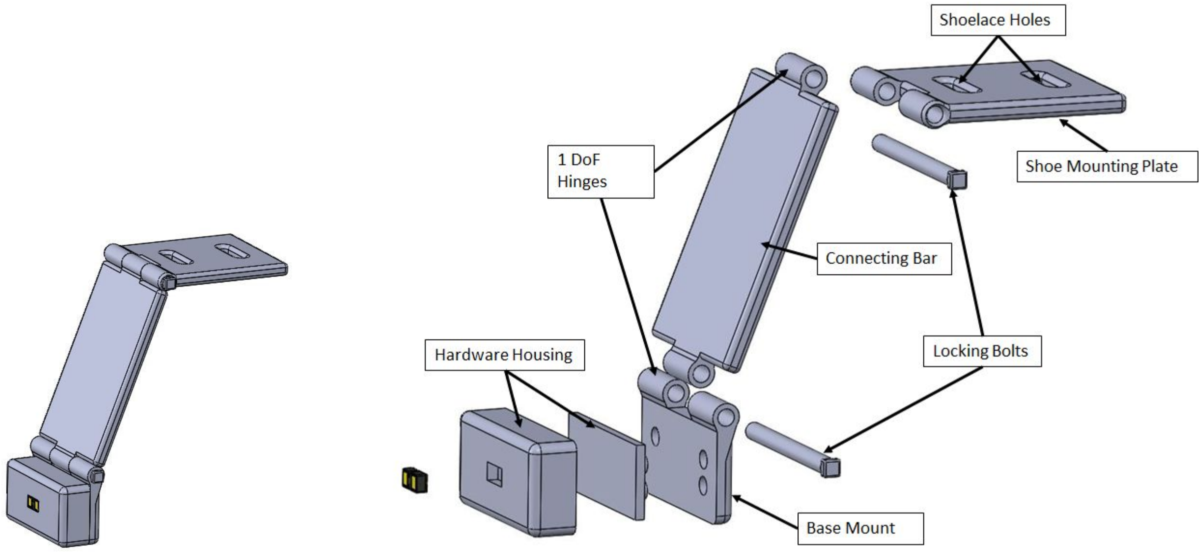


Figure 21: Proposed End Product Mounting Solution. The PCB would be located in the hardware housing, which can easily be detached from the mount. The mount itself would be attached to the shoe by threading the top plate in with the shoelaces. Alignment of the sensor would then be achieved by the two 1-DoF hinges, which can be locked in place by tightening the two screws.

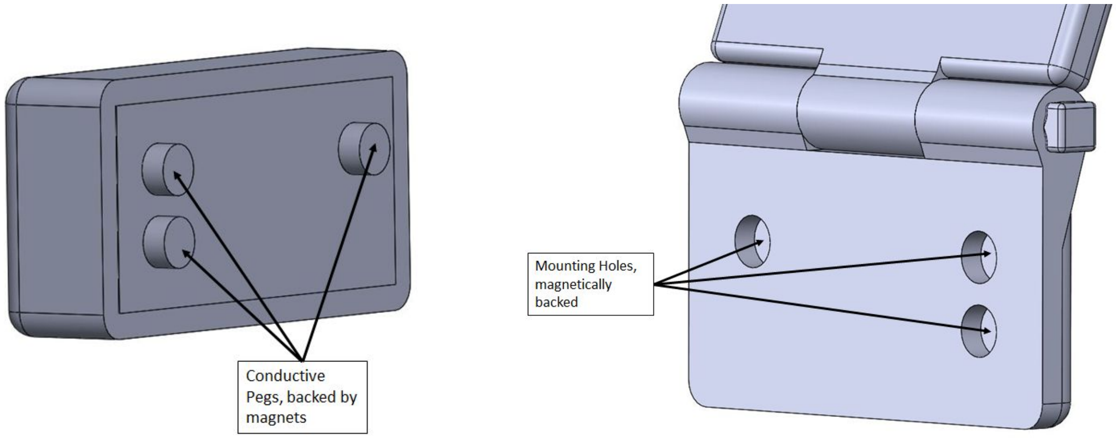


Figure 22: Proposed End Product Mounting Solution, Alignment Magnets Detail. The hardware housing would be attached to the base mount by magnets. The magnets are located behind the conductive pins of the hardware housing and in the recesses of the base mount. The asymmetrical pattern of these

magnets would then allow for repeatable and precise alignment of the hardware housing. Finally, in order to further simplify the interface of the end product, the team also began work on designing a dock-based charging solution. Using the same magnetic attachment method as above, the hardware housing can quickly attach and detach from the charger, and incorporates conductive pins for power transfer.

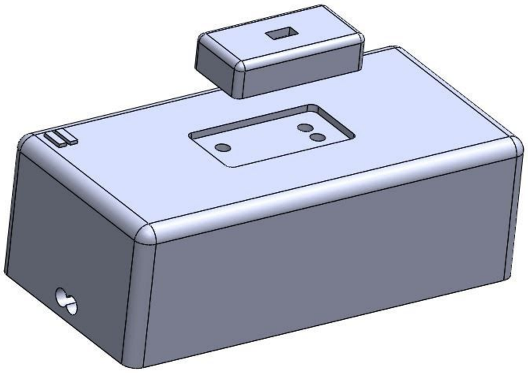


Figure 23: Dock-Based Charging Solution. The conductive pegs on the bottom of the hardware housing magnetically attach to the charger, and transfer power to the battery.

Verification

Engineering Analysis - Guided Walking Test

To further develop the time of flight sensor, the team conducted a second walking test to find how accurately the sensor can measure the distance between two feet. While the team did not have access to a gait lab to get a precise step-width measurement, that would not stop the resourceful engineers. The next best option was to create a walking lane using 2”x3” planks on either side of the lane to align the feet to maintain a specified distance. Using the makeshift rails, step width was held constant. The lane width was made to be 16 inches based on the normal step width of the test subject. Before conducting the test, the team measured the distance between the sensor and the inside of the subject’s feet to be 6.5 inches.

Figures 24: The second walking test was conducted using rails made from 2” x 3” pieces of wood and supported by bricks. Thes rails aligned the subject’s step width to a distance of about 6.5 inches

Once testing was concluded, data processing could begin. The time of flight data was the first to be plotted and analyzed. The sensor output in cm was calibrated using the calibration curves previously defined, and was plotted against the time of the measurement. Additionally, a straight line was added to the plot at 6.5 in (16.5 cm), the distance measured between the feet of the test subject. This was added to allow for the sensor output to be compared to the ground truth distance. Figure 25 shows the data from the fourth walking trial.

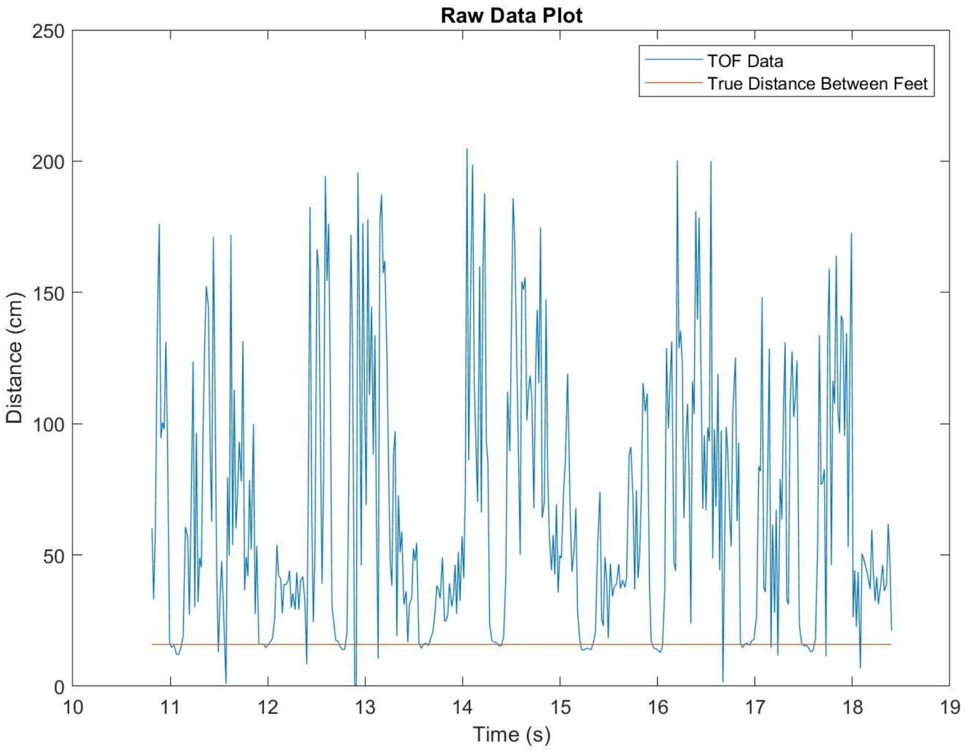


Figure 25: Fourth walking trial of the TOF sensor. Note the several dips below the true distance line, and the overall noisy signal.

As seen in Figure 25, the data was promising, but does have some points of concern. One issue was that there were multiple points where the sensor peaks far below the true distance. These peaks can be seen at 11.5 and just before 13 seconds. The sensor output also appeared to be quite noisy, which did not aid in determining how accurate or consistent the measurements are. However, when considering the valleys that dip below the true distance line, there did appear to be promising data collected. These valleys consisted of multiple data points, and all seemed to occur at the same distance value. This pattern was consistent with what was expected when observing a step, but was occurring at lower value than expected.

In an effort to reduce the noise and provide a clearer image of what is taking place, the team performed filtering and transformations on the data. First a Fourier transform was conducted on the data to attempt to use a low pass filter on the data. The process for this can be found in Appendix A.5. It was determined that this low pass filter would need further development as it reduced the accuracy of the detected minimums due to the filtering of necessary high frequency parts of the signal. Therefore, a median filter was attempted instead. Figure 26 on Page 31 shows the same data ran through a 4th order median filter.

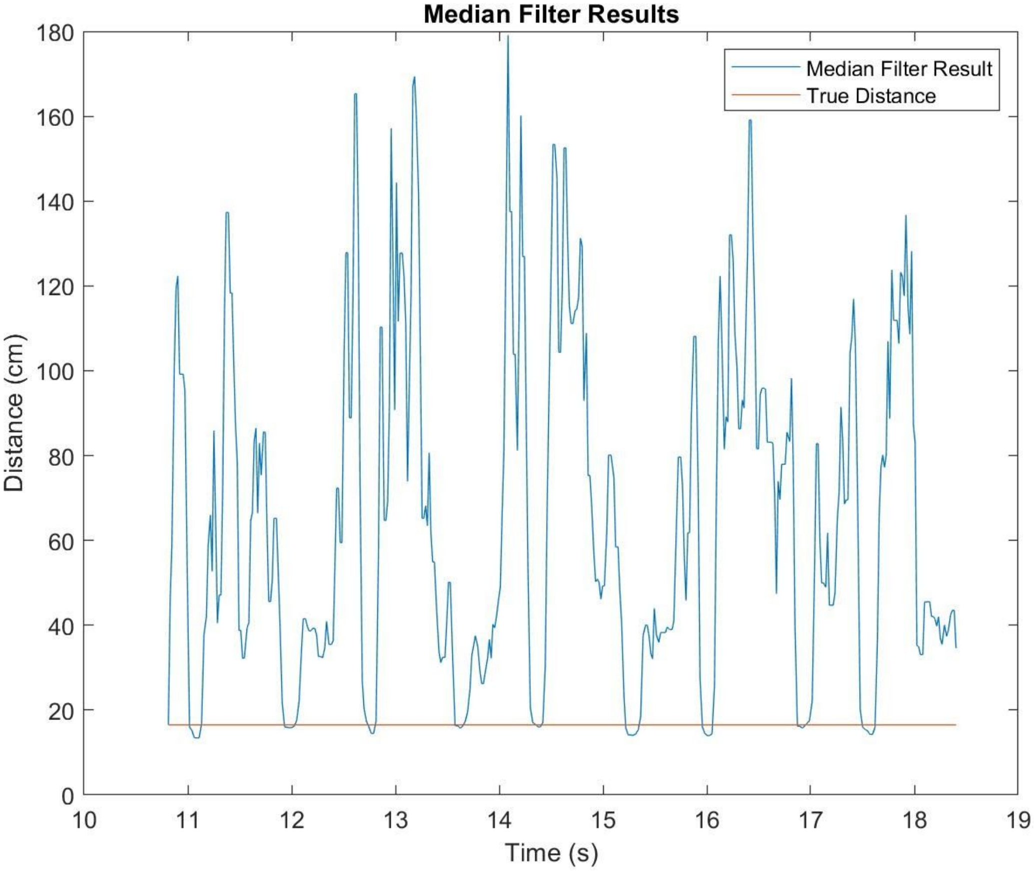


Figure 26: Trial data ran through a fourth order median filter. The sensor output retrained its shape, but removed high frequency noise.

As seen in Figure 26, the median filter provided results that did not have a time shift, something seen in the low pass filter, and retained the general shape of the signal pre-processing. This was encouraging to observe because it indicated that a simple filtering method would allow for the minimums to be more prominent, and for higher frequency noises to be eliminated as well. Additionally, median filters are known to retain signal edges, while reducing noise, something not accomplished by the previous filter. Therefore, due to its simplicity and comparable results to previous filtering techniques, a median filter was used for verification algorithms.

The next step in verification was to extract the recorded local minima in an attempt to evaluate their accuracy. This was accomplished via the use of MATLAB's find peaks function. First, the data was inverted to allow for the local minima to now become local maxima. Additionally, a constant offset was added to the values to allow all peaks to occur in the positive domain. Both the inversion of the data and the constant offset were necessary to facilitate the operation of the find peaks function. The same data found in Figure 26 was run through this algorithm resulting in Figure 27, on Page 33.

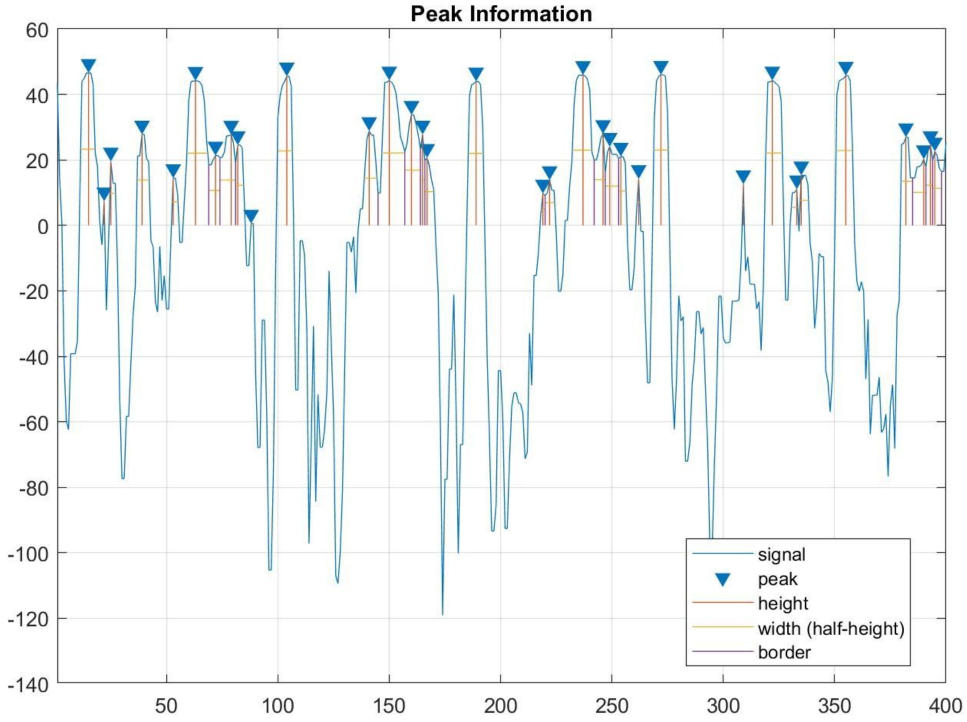


Figure 27: The find peaks algorithm produced these results, dictating the signal, detected peaks,and the height and width corresponding to each peak. Of note is the lack of axis labels. This is due to the nonsensical meaning of the y-axis, as it represents the inverted signal offset by a constant value to make values positive - meaning there is no physical meaning behind the value.

The findpeaks function allowed for evaluation of peak characteristics. We found the widths of the peaks to be of great importance as noisy data and actual feet detection recorded different widths. Thus, a peak width of 8, meaning 8 samples, was found through trial and error to isolate steps predominantly, but did result in an occasion erroneous step detection. Figure 28 on Page 34 displays the 'peaks', or in this case, minimums, determined to be steps. As can be seen in Figure 28, the algorithm was not perfect and did identify some signals as a step when not intended.

The algorithm was able to correctly identify steps in the signal but also occasionally mis-identified the signal as a step. This was due to the fact that the peak identified by the find peak function had a width within a similar range of those peaks found during a step occurring. This was not to discredit the algorithm, however, as it was more critical to ensure that all possible steps were detected rather than dismiss real steps by having a finer width specification.

Verification was now possible that an algorithm could be applied consistently across all trials. Figure 29 on Page 34 displays the detected steps plotted against the true signal output, showing that they do coincide with the median filter's data analysis.

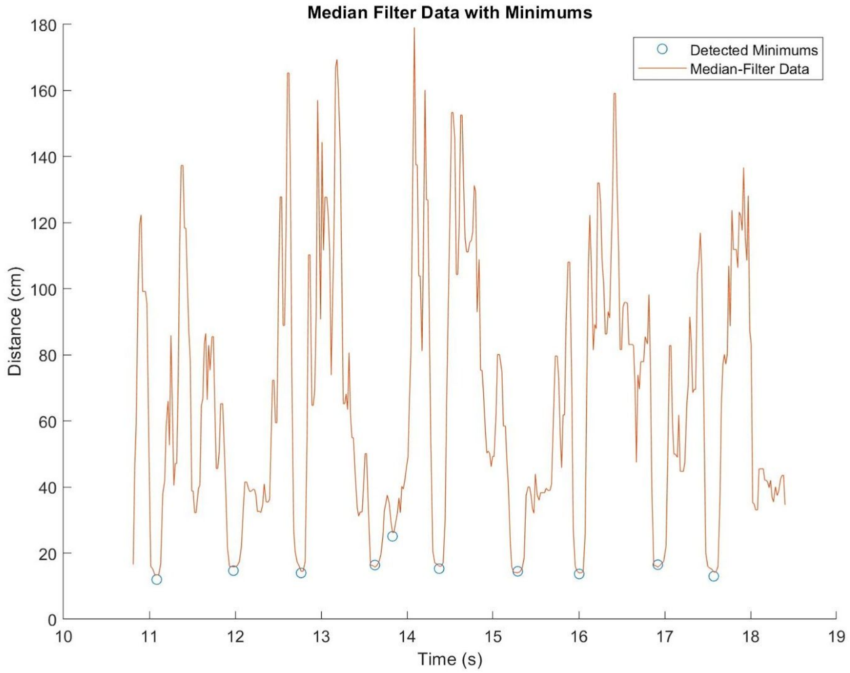


Figure 28: The results from the findpeaks algorithm. The algorithm developed correctly identified the local minimums indicating a step, but also misidentified a point just before 14 seconds.

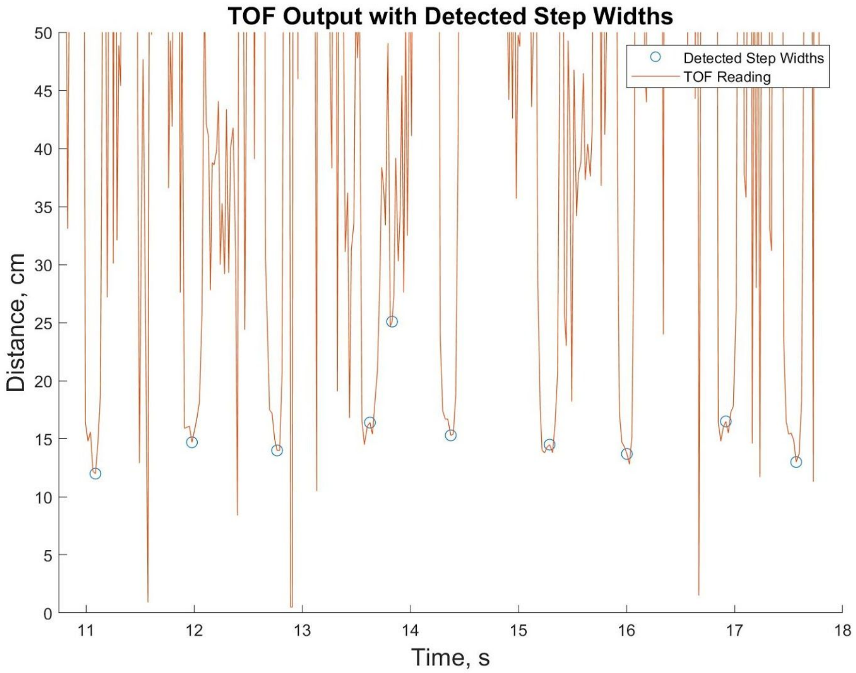


Figure 29: The detected step widths plotted against the raw TOF data. The alignment of these detected widths with the raw data confirms that the median filter does a good job of reducing the noise to allow for the peaks to be easily detected, while not losing accuracy in the actual values of the signal.

Finally, it was possible to verify the performance of the design by plotting the detected minimums as a function of time. The success of this plot indicated that the solution presented solved the stakeholder's needs and allowed for the variation in step width over time to be observed and recorded. Figure 30 shows the results from the data previously shown.

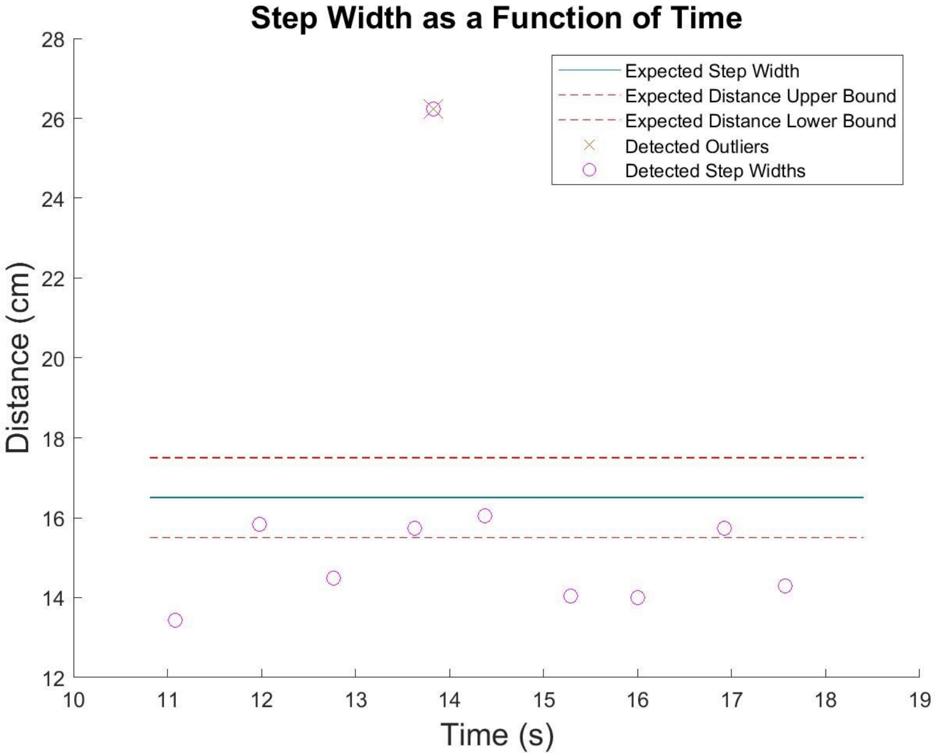


Figure 30: Comparison between computed step width and expected data

As seen in Figure 30, the step widths plotted fall within the typical range of someone walking. The blue line displays the true distance from the side one of one shoe to the other found during the verification testing. This value was 16.5 cm. The red lines show an interval of 1cm above and below this value to indicate what error was to be expected. The point seen at around 26 cm is a result of the algorithm misidentifying a step, and is not of concern as it is easily identifiable as an outlier. While those distances plotted below the lower bound do fall out of the interval plotted, it does not indicate that those values are inherently erroneous. Instead, it is possible that the step width of the subject did fall to those values during testing. Without access to a motion capture lab it is impossible to decipher whether these results are incorrect, or if the step width was variable across the testing. Therefore, the conclusion from this plot is that the design used to detect step width has acceptable performance as it can track step width as a function of time, but further testing is required to validate the precision of the solution.

The aforementioned data analysis was conducted for all trials of the design that took place. Table 2 lists the results obtained.

Table 2: Results from 4 trials restricting step width. Each trail saw the prototype and algorithm detect all steps, and some signal spikes that appeared as steps. However, they can be ruled as outliers. The mean deviation from the expected value of width is shown for each trial. Appendix A.6 displays the coresponding plots for each trial.

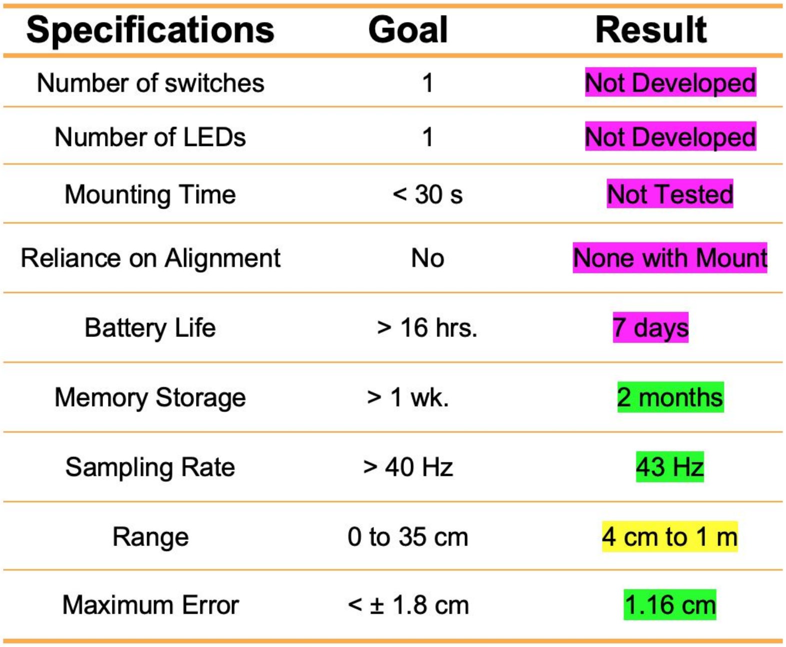
Trial	Steps Taken	Steps Detected	Outlier Steps	Mean Deviation from truth
1	9	11	2	1.368 cm
2	9	10	1	.9989 cm
3	7	8	1	1.21 cm
4	8	9	1	1.108 cm

The trial results revealed that the prototype was quite capable of detecting when a step occurred. Even more encouraging was the fact that when an additional step was found due to the signal processing, according to the median average deviation of the point, it was considered an outlier in all trials. Therefore, with additional statistical analysis, the package was able to detect all steps taken and had a maximum mean deviation from the expected width of 1.368 cm. This verifies the protype's step detection performance.

Requirement Verification

Once the prototypes performance was determined and analyzed, conclusions could be made regarding how the solution fit the requirements and specifications set out at the start of problem definition. Table 3 lists the prototypes performance against the initial requirements.

Table 3: Requirements and specifications set out for the project, and the results obtained. Green items indicate a goal was met, yellow indicates a goal that is close to being met, and magenta indicates items that were out of the project scope during the time allotted.



Specifications	Goal	Result
Number of switches	1	Not Developed
Number of LEDs	1	Not Developed
Mounting Time	< 30 s	Not Tested
Reliance on Alignment	No	None with Mount
Battery Life	> 16 hrs.	7 days
Memory Storage	> 1 wk.	2 months
Sampling Rate	> 40 Hz	43 Hz
Range	0 to 35 cm	4 cm to 1 m
Maximum Error	< ± 1.8 cm	1.16 cm

Completed Goals

Maximum error

The intended maximum error goal, which includes both accuracy and precision error, was met. This goal was set at +/- 1.8 cm as the stakeholder identified this amount of error would still allow for measurements that provide new insight into how step width varies over time. The error presented, 1.16cm, is the result of averaging the mean deviation from the estimated step widths in Table 2. This mean does not take into account steps detected that are classified statistically as outliers.

Sampling Rate

The sampling rate desired was to be above 40Hz. This sampling rate was determined based on the frequency of human gait, 2Hz, and the desire to resolve multiple points per step instance. In the end, the sensor was calibrated and operated successfully at a rate of 43 Hz, meeting this specification.

Memory Storage

The memory storage requirement called for data to be stored for greater than one week. This timespan was chosen to allow for data acquisition to take place on a week by week basis, facilitating maximum data collection. The estimated prototype storage would allow for data to be stored for 2 months on a 4 gigabyte micro-SD card. This well exceeds the requirement set out, and depending on storage method, could be expanded to even further the amount of time data could be stored for.

Goals Needing Improvement

Range

The desired range was specified as 0 to 35 cm. This range was determined by the value for average step width of 8cm, and the tendency of those with gate disorders to have a wider gate, somewhere in the range of 8-20 cm. However, the prototype was found to resolve distances from 4cm to 1m. In reality, this range likely satisfies the stakeholder requirements and would provide meaningful insight into step width, meaning that this range is likely acceptable. However, since the original specification was given as 0 - 35cm, range has been labeled as needing improvement as it does not exactly meet what was desired from the project outset.

Goals Needing Future Development

Battery Life

The desired battery life called for a battery that would allow for operation times greater than 16 hours without requiring a recharge. Due to the limited ability of the team to create a physical prototype, and lack of resources including final PCB designs, this goal was not able to be fully realized. Instead a portable battery bank was used to power the prototype. The battery used had 5000 mA hours and in theory, assuming a power draw around 25mA, could provide power for 200 hours continuously. While this greatly exceeds the required timeframe, the formfactor of the battery is not consistent with what the final design would call for - a much smaller physical footprint is necessary. Therefore, this goal was specified as needing future development as there are battery solutions available commercially that provide the form factor and performance required, but the implementation of such a battery was deemed out of scope for this project as technology verification was more imperative.

Reliance on Alignment

The design was intended to have no reliance on alignment, meaning the utilized sensors and hardware would operate regardless of the placement on the foot. This was decided due to the target population for the device often having trouble precisely aligning a sensor onto their shoe. The solution presented included a mount and a sensor package that could only attach to the mount in a single direction due to asymmetric magnets. Upon construction of the proposed final design, the system would not have a heavy reliance on alignment after the initial setup. This is ideal and accomplishes the stakeholder's requests. However without access to the resources required to construct such final design, it is not proper to label this goal as fully developed.

Mounting Time

The final design was intended to have a mounting time off less than 30 seconds. This requirement was put in place to facilitate conscious design choices that would allow for ease of application for the end user. However, due to the same reasons listed in reliance on alignment, further development into the mounting hardware was not possible. The prototype used for verification had a very precarious mounting process and took longer than 30 seconds to mount. However, the final design proposed includes a one time applied mount to the shoe, and a removable sensor package that with its alignment magnets, would allow for mounting in under 30 seconds. Therefore, this goal has been designated as needing future development.

Number of Switches

The number of switches in the final design was specified to be one. This was due to the stakeholder identifying that the population using the device would benefit from an easy to use device that required very little user input. Due to the lack of development in the final design's housing, it was not possible to restrict the user input to a single switch. The proposed final design and hardware has been selected so that it will allow for a single switch to operate the entire design. The current software implemented for the prototype also can operate under the use of a single input switch. This means that with further development, it is entirely possible to meet this goal, but further development is required.

Number of LEDs

The number of LEDs in the final design was specified to be one. This was due to the stakeholder indicating that a simple user interface like an LED that indicates charging and activity status would be beneficial to the target population. Due to the same restraints listed regarding the switch requirement, this goal was not met. However, due to the low power draw of an LED and the easy addition of code to manipulate an LED's color, it is possible for this requirement to be met.

Discussion and Recommendations

After concluding the verification of the prototype solution, the team reflected on the project and began looking for possible improvements to the design. In this section, the performance of the prototype solution is examined, and various suggestions for future progress on this concept are introduced.

Project Reflection

Overall, the team believes this project is still a work in progress but thus far very successful. Despite the hiccups experienced from the COVID-19 pandemic such as not receiving the UWB device, a fully functional sensor prototype was created and tested thoroughly. The key strengths of the sensor are its ability to detect step widths within the accuracy specification 85% of the time, detect steps nearly down to the range specification, sample at 43 Hz, and store enough data for untethered operation. The key weakness of the device is that the mounting apparatus hasn't been developed nearly as much as the sensor itself.

Looking back on the project, it would have been beneficial to order parts sooner in order to ensure the team got adequate testing time. Having a working UWB device would have been extremely helpful in the concept evaluation and development phase. After testing the ultrasonic and TOF sensors, the team decided that on paper they were essentially equally, if not more, effective than the UWB. However, had the team been able to test with the UWB sensor, a different conclusion could have been made. Additionally, a consistent and functional mounting apparatus would have been very helpful for consistent testing. By actually manufacturing the mount, weaknesses in the design may have been exposed, allowing the team to develop the mount further. Overall, the project is in a very good place with the prototype manufactured and significant data taken and analyzed. The team is also content with current data processing and step width identification algorithms although there is always room for improvement.

Stakeholder Recommendations

As previously mentioned, time constraints and COVID-19 restrictions prevented the team from implementing the detailed design solution described earlier. As one of the major recommendations, the team suggests that this more integrated solution be further developed. Collaborating with someone skilled in PCB design is recommended to further the development of this component. Additionally, the new hardware housing and shoe mount should be manufactured, and tested to see if they constrain the sensor package adequately.

Software remains an area of potential improvements as well. The current software implemented is capable of running the sensor package as intended and allows for data to be stored locally. However, it is believed that further investigation into the hardware specific libraries utilized could provide improvements to the system’s operation. Since the library code is one level lower than the code the team has written, it is believed that further understanding of how these libraries operate could allow for modification of them to meet the design’s specific needs.

Investigation into the TOF hardware is also recommended. The particular package used in the final design has the ability to change its field of view. It is believed that tuning of this field of view would allow for less noise and less frequency detections of the ground. Investigation into other available TOF packages would be worthwhile to see if competing solutions offer different sample rates and features. One immediate advantage another sensor may have is an increased sampling rate as this would allow for more data points to be resolved during each step. Additionally, if some TOF sensors provided additional feature sets, they may be better suited for this application.

Data processing has allowed for verification of the designs performance, but also can be improved greatly. The current algorithm relies on median filtering, which in this application provides acceptable results, but has less physical intuition compared to other filtering methods. For example, a low pass filter with frequency cut offs related to the frequency of the human gate is likely more robust, and has an easily understood justification. It is also important to note that the final implementation of the design will likely have additional sensors added via the stakeholder, such as an IMU. The data processing technique should then be reliable enough to be expanded on with additional sensor input.

Conclusion

Our team has identified a gap in the step-width measurement segment of out-of lab gait analysis, especially with the purpose of identifying various neurological diseases that impact gait.. Based on that, we set out to develop a low cost solution that would accurately measure step width reliably and for extended periods of time, while being cognizant of the reduced motor skill & physical and technological abilities of our target customers. The team found a variety of sensors and technologies that might meet our requirements, conducted testing and validation using two sensors (ultrasonic and Time of Flight), and found ToF to be more accurate, less noisy, and generally more robust. We conducted distance and field of view calibrations for the ToF sensor and calculated the associated errors. This enabled us to design and conduct experiments where we strap an Arduino powered prototype to the foot, control the foot-to-foot distance using guide rails, and measure the output from the sensors. Using MATLAB, we designed an algorithm that uses different types of filters to clean up the data, computes step width, and compares it to the ground distance truth. Using this process, we found that we are able to identify 85% of the steps, for which we get a true distance prediction error of 1.16 cm. Unfortunately, due to the limited time frame,it has not been possible to make a more permanent prototype. However, first steps were taken towards designing the appropriate mounting mechanism in CAD, and relevant hardware components were selected. To fully validate the use of Time of Flight technology for step width detection however, more testing is required, especially with more accurate true distance measurements, as well as with more robust filtering algorithms.

Author Biographies

Benjamin Bloom: Ben is from Highland Park, Illinois and decided to major in mechanical engineering at the University of Michigan because he loves learning through designing and building. He is passionate about the aerospace industry and is part of the design team, M-Fly. Outside of classes and projects, he loves to bike, watches Michigan Hockey and is a member of Theta Tau professional engineering fraternity. After finishing his degree, he will be working full time at Northrop Grumman as a mechanical systems engineer.

Ryan Heaney: Ryan is originally from Minneapolis, MN, and chose Michigan Engineering from a life-long passion for cars. His focus on hands-on work and design led him to mechanical engineering for a major. Outside of school, Ryan loves cycling, music, and skiing. After graduation, Ryan will be working as a Product Development engineer for the Ford Motor Company.

Jeremy Punch: Jeremy was born and raised in Ann Arbor and grew up with the university of Michigan as a backdrop. He knew he wanted to be an engineer after taking a high school introduction to engineering design course. Jeremy chose mechanical engineering due to his passion for learning how things are made and work. Jeremy is a member of the Supermileage student design team and is currently the chief engineer. For the future Jeremy hopes to complete a Master's in Mechanical Engineering through the SUGS program at UofM.

Brendan Scherer: Brendan is from Rockwood Michigan and attended the University of Michigan to further his education in engineering. Brendan has always been interested in aerospace applications and wants to apply his mechanical engineering background to the industry. Outside of class Brendan enjoys building high powered rockets and participating in Theta Tau, a professional engineering fraternity. Post graduation Brendan will be joining Northrop Grumman as a systems engineer working in their commercial space division.

Radu Tolantan: Radu was born and raised in Bucharest, Romania, and came to the United States to build as many flying machines as the days allow. He is passionate about control system analysis and design, and dreams of becoming a Product Support Engineer with Airbus. In his free time, Radu enjoys getting involved with educational programs: designing curriculum, teaching, and getting to know his students through lighthearted and introspective teaching.

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Special thanks goes out to all of those who made this project possible. Without their continued support the project would not have been anywhere near as successful as it has been. Lauro Ojeda, our project sponsor, who was always willing and able to help and provided materials for us to prototype. Noel Perkins our instructor who provided support and guidance along every step of the way. Heather Cooper who facilitated our in-person lab work and provided us with electrical components and tools to borrow. Bogdan Popa who consulted with us about the use of acoustics technologies as possible localization methods. Kathleen Sienko who provided feedback on our progress in a discussion meeting. Lastly our fellow classmates that critiqued our work and pushed us to get the most out of our design.

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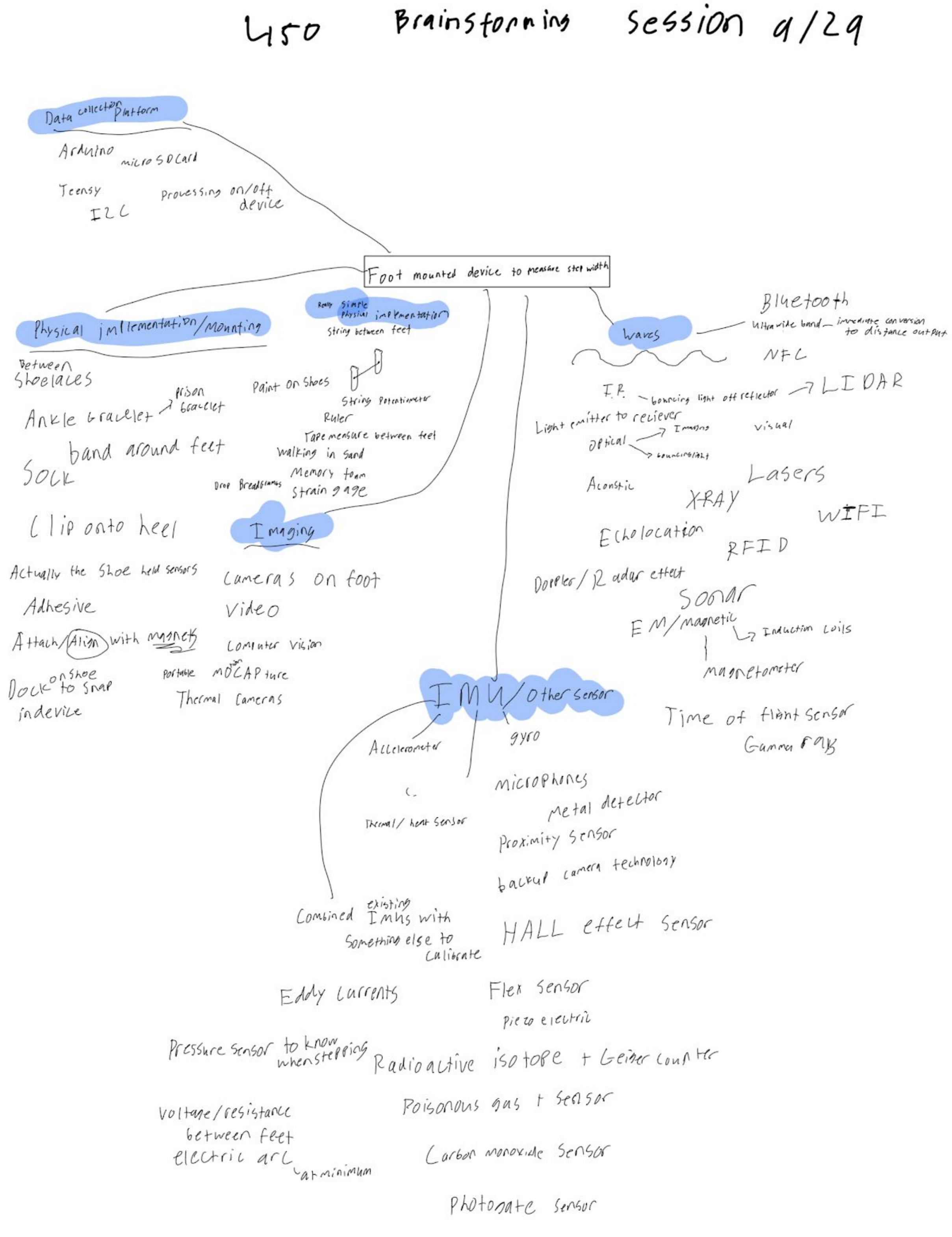
Appendix A.1- Concept Generation Mind Map



Appendix A.2: Additional Concept Generation

Concept 4: Magnetic & Electromagnetic Fields

Electromagnetic fields can be generated by something as simple as a refrigerator magnet, or something more involved such as a solenoid. Magnetic fields have well understood behavior, and several sensors have been developed to detect the fields generated. Some of these sensors include Hall effect sensors or magnetometers.

A design that utilizes the principles of magnetics is illustrated below. The sketch displays a strong magnet placed on one shoe, and a sensor on the other. Magnetic field strength varies with a 1/r^3 dependency, and therefore detection of field strength can allow for distance to be resolved. A range of up to 10 cm was found utilizing a reasonable magnet size. This was computed using a specialized magnet analysis application [K&J Magnetics, 25][K&J Magnetics, 26]. Accuracy was determined to be limited by the magnetometer and Hall sensor noise [SparkFun, 27]. An early estimate of cost for a system depicted below would range around 40$ [K&J Magnetics, 26]. Some issues discovered with this concept include the fact that the required magnet for detection would attract a metal plate at 10cm with 1.2 lbf [K&J Magnetics, 25]. This concept is shown below in Figure A2.1.

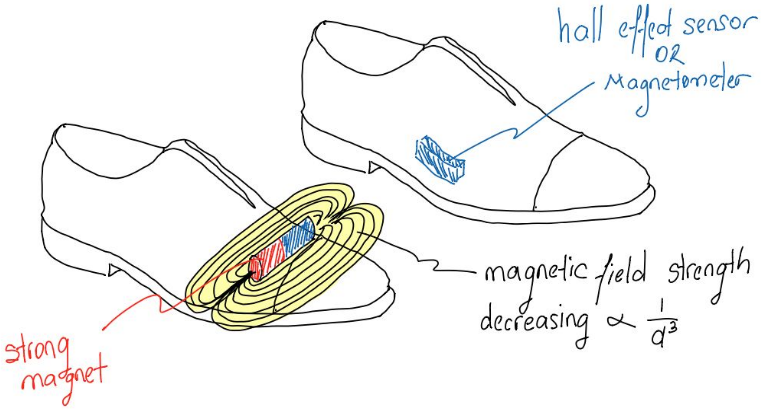


Figure A.2.1: The magnetic field concept. A magnetic sensor is placed on one shoe, with a magnet placed on the other. Distance is determined by the detected field strength.

Concept 5: RFID

RFID allows for short range proximity sensing and data transfer through the use of passive tags and an antenna. Due to how the technology operates, a tag will only activate when the signal it is intended to receive is within a certain range. Therefore, the technology does not resolve distance as much as it is only activated at a certain distance. The range of activation was found to be between 10 - 30 cm [SkyRFID, 32]. A starter kit utilizing RFID was found to be around 50$ [SparkFun, 33]. While the protocol is a well established part of smartphone technology and other near field communication applications, it does have some downsides. As Figure 11 on Page 14 depicts, a large array of sensors would be required to accurately determine distance; these would have to be placed in the 2D plane that walking takes place in and thus would be very cumbersome to implement properly.

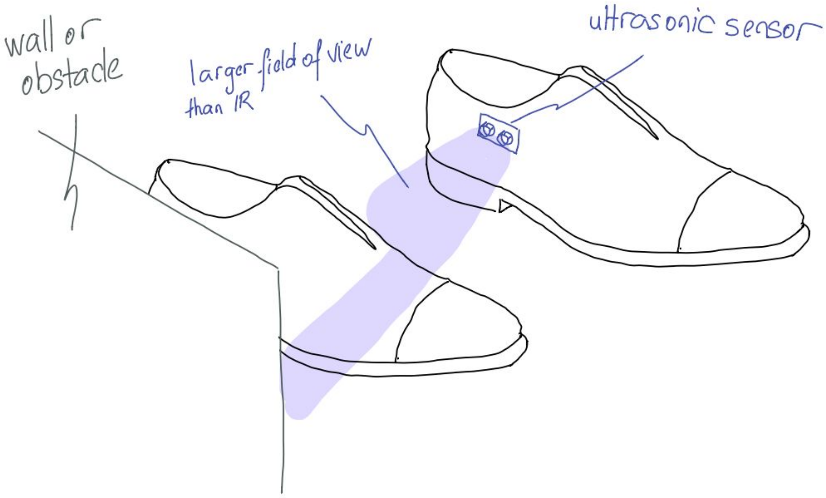


Figure A.2.2: A concept using an ultrasonic sensor is shown. As can be seen by the highlighted area, the field of view of the sensor may impede accurate measurement of distances between the feet.

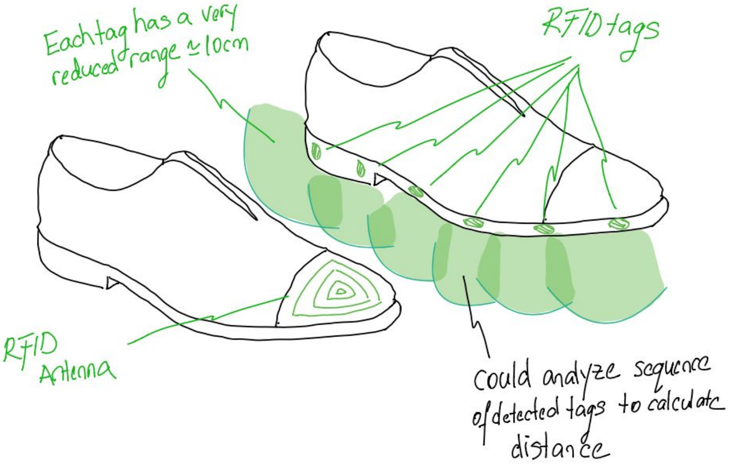


Figure A.2.3: A concept utilizing RFID for distance detection. An array of sensors would be required to deduce distance based on the order of activation.

Concept 6: Light Sensor - Infra Red (IR)
Using infrared light as a means of detecting distance by bouncing a light wave off of an object and recording the travel time is a well established distance measuring technology. A range of 4 -30 cm [SparkFun, 35] was found to be acceptable for light sensors using the infrared range, and an accuracy of +/- 1% can be expected [SparkFun, 35]. Due to the fact that this technology is well understood, an introductory unit can be purchased for around 14$ [SparkFun, 36]. However, some issues are well known with this technology. The main being that interference from natural light is common in outdoor environments [Lucas, 37]. Figure A2.4 shows an example of this concept.

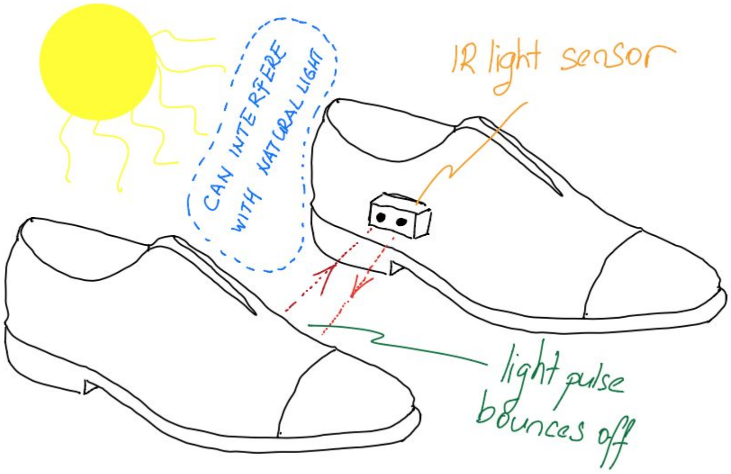


Figure A.2.4: A concept using an IR light sensor. As can be seen in the image, natural light can cause issues with light detection due to the similarities in wavelengths.

Concept 7: Motion Capture

An all encompassing, albeit highly involved, concept would be motion capture. This concept would require a camera placed on one foot that would take images of the other foot as it passes through its field of view. The range of measurement for this concept would depend on the field of view of the camera and lens used [Rosenbrock, 38], as would the accuracy. Motion capture systems can cost as high as 2000$, but a simple camera can cost around 65$ [SparkFun, 39]. Research found that this concept would require special attention to power draw, post image data processing, data storage, and data formatting. An additional issue is to optimize the storage and minimize the power draw, a solution that only takes images when one foot is close to another would be ideal, requiring non continuous data capture [Rosenbrock, 38]. Figure depicts this concept.

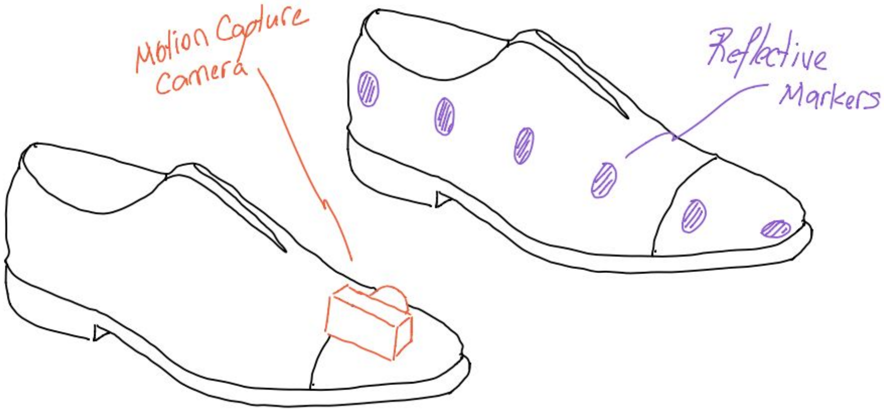


Figure A.2.5: A motion capture concept. A camera is mounted on one foot, with reflective markers placed on the other. Post processing would allow the size of the markers in the image to result in a distance measurement.

Morphological Analysis

After completing the concept generation phase, we found that nearly all of our solutions had faults in certain categories. By creating a morphological chart and comparing the functional categories each solution is in, we were easily able to see what solutions could possibly be used in conjunction with each other. This action then allowed us to develop more concepts, minimize downfalls and maximize effectiveness of our concepts. Thus, using morphological analysis, we were able to extend our thinking and come up with a variety of new solutions, Concepts 8-10.

Table A.2.1: Morphological analysis was conducted using the chart presented below to combine different positive aspects of the technologies considered above

	Solutions				
Fields and Waves	Magnetic	Electric	Acoustic		
Sensors	Ultrasonic	Force	IR Light	Magnetometer	Accelerometer
Calibration	RFID	Ruler	Bluetooth		

Concept 8: Magnets and Pull Force

The first concept developed using morphological analysis was a combination of magnetic fields and a force sensor. As seen in Figure 14, a magnet would be attached to each foot, with its field attracting the other magnet. On one side, a force sensor is attached, which measures the magnetic force exerted. Since magnetic force follows an inverse square relationship with distance, the force observed by the sensor can be translated into a distance measurement. Using a magnetic simulation application, the range was found to 35 cm, at which point the pull force would be 0.03 lbf [K&J Magnetics, 25][K&J Magnetics, 26]. The accuracy was found to be ±0.003 lbf [SparkFun, 34], with a total system cost of $40 [K&J Magnetics, 26][SparkFun, 34]. Some potential issues were found as well, for example, for the magnetic pull to be sensed at the maximum range of 35 cm, the force exerted at a closer range of 8 cm would be 12.6 lbf [K&J Magnetics, 25][K&J Magnetics, 26]. This is a vig safety concern, especially for our target customers, older people with reduced motor control.

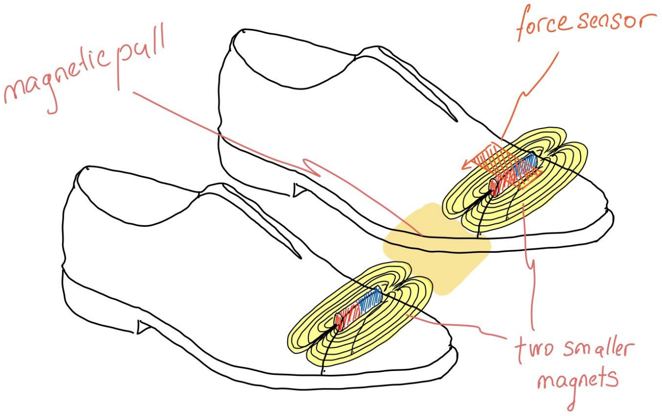


Figure A.2.6: Magnetic pull sensor concept setup. The attraction between the magnets is inversely proportional to the cube of distance.

Concept 9: Acoustic Intensity Sensing

The acoustic intensity sensing solution works very similar to the magnet and magnetometer solution, but instead it uses a deconstructed ultrasonic sensor as an emitter and a receptor. The system would be able to deduce distance by measuring the intensity of the sound and calculating the distance based on how much the intensity decreased. The range of this solution would be 4cm - 8m, resolution is ± 3mm and the cost is about $4 [SparkFun, 24]. This design has promising features, however it may be difficult to verify the sound intensity with some amounts of background noise. This solution is sketched very roughly in Figure 15.

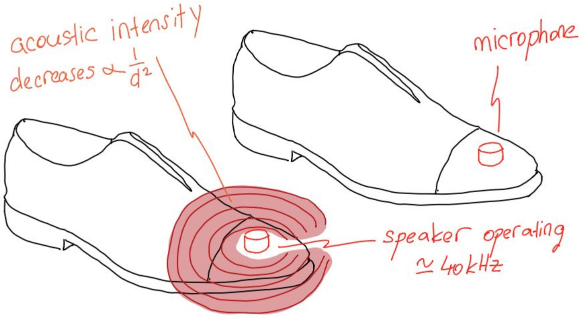


Figure A.2.7: An ultrasonic sensor is decomposed into a speaker and a microphone to measure acoustic intensity and deduce the distance between the feet.

Concept 10: Integrated IMU - RFID Solution

This concept combines RFID technology with IMUs placed on each foot to log movement. This fusion was done to eliminate the main issue with IMUs, which is the independence of the reference coordinate systems. The concept consists of an IMU and RFID tag on each shoe, and a calibration mat with RFID antennas spaced apart at a known distance. By stepping on these designated areas, the IMUs can be calibrated with a known reference dimension, giving an initial condition for their movement. As drift begins to accumulate, the mat can be used again to recalibrate the axes of the IMUs. The accuracy and range are heavily dependent on the IMU drift specs, and the full cost of the setup would be $65 for the IMUs and RFID components [SparkFun, 33][SparkFun, 40]. This solution is attractive as the stakeholders for this project are very experienced using IMU data, and so this concept may integrate well into their existing framework. However, there are some potential issues that arise, most notably, the hardware implementation and the dependence on the calibration mat. If the IMUs drift quickly enough that the mat has to be used frequently throughout a day, this would be inconvenient for the end user, and would not really satisfy our requirements for out of the lab use. A possible implementation for this solution is shown in Figure 16 on Page 18.

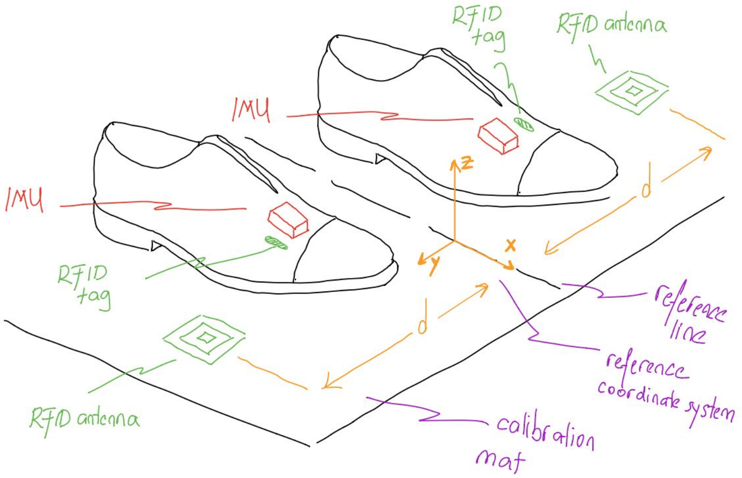


Figure A.2.8: IMU and RFID combined solution. The RFID calibration mat sets an initial distance apart for the IMUs, and calibrates the coordinate axes to remove drift.

Concept 11: Ankle strap

An ankle strap would facilitate a simple procedure to put on and remove the device. An adjustable strap would make it possible to fit users of all sizes. Shortcomings of an ankle strap might be the inability to wear comfortably with pants and the band rotating around the leg over time, causing poor alignment of the measurement technology. This physical implementation is shown in Figure 17.

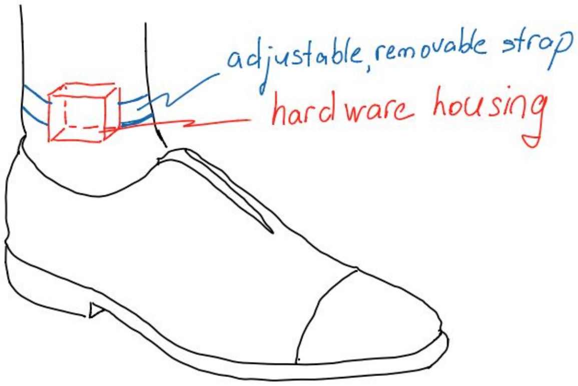


Figure A.2.9: Ankle Strap mounting attachment. The device is fixed to the patient’s ankle with an adjustable strap, which is removable for data collection and charging.

Concept 12: Shoelace Pouch

Rather than attach the device to the user’s foot or shoe, it may be possible to place it in a pouch into or above the shoelaces. The user comfort and unobtrusiveness of this concept are appealing as the device could simply be forgotten about once it is positioned. It would be a simple procedure to put on, however some users may not be able to easily place the device into and out of the pouch for overnight charging outside the shoe. The pouch would need to be carefully sized to hold the device still and prevent any jostling about while walking. This attachment method is shown in Figure 18.

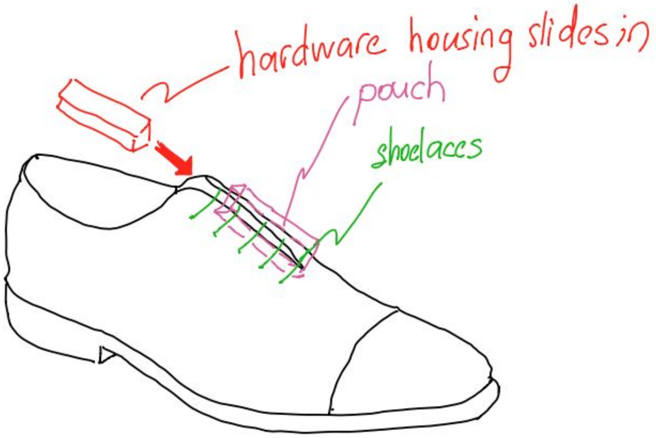


Figure A.2.10: Shoelace Pouch mount concept. The shoelaces run through holes in the pouch, which the hardware device can be slid into.

Concept 13: Magnetic Attachment and Alignment

Magnets may provide a unique way to attach the device to the user's shoe. Sufficiently strong magnets would maintain a consistent device alignment while placement similar to the shoelace pouch idea would be unobtrusive. It is unclear how the magnets would be installed on the user's shoe and there could potentially be interference if an electromagnetic distance measurement technology were chosen. This unique attachment method is depicted in Figure 19.

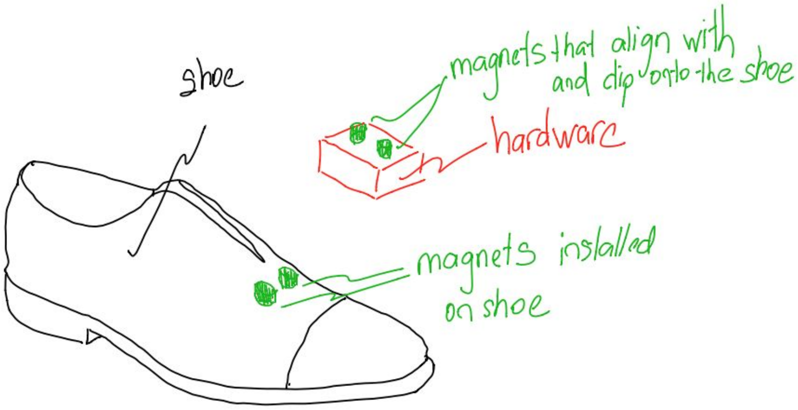


Figure A.2.11: Magnetic Attachment concept. Small magnets are embedded in the shoe, which align with magnets on the device.

Concept 14: Clip Attachment

A clip could be a simple way to attach the device to the user. With a single metal loop attached to the hardware housing the device could fit onto either socks or pants of the user, enabling some flexibility. Swaying with the motion of the pants could potentially cause problems, as well as the possibility of the clip falling off the user, something we can not tolerate happening. This attachment method is depicted in Figure 20, alongside two of the items of clothing it can attach to, trousers, and socks.

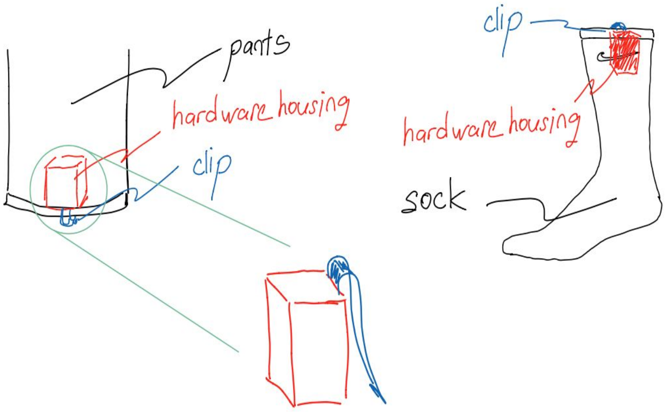


Figure A.2.12: Clip Attachment. A spring clip is integrated to the back of the device, which allows it to be attached to pants or socks.

Concept 15: Built-in shoe implementation

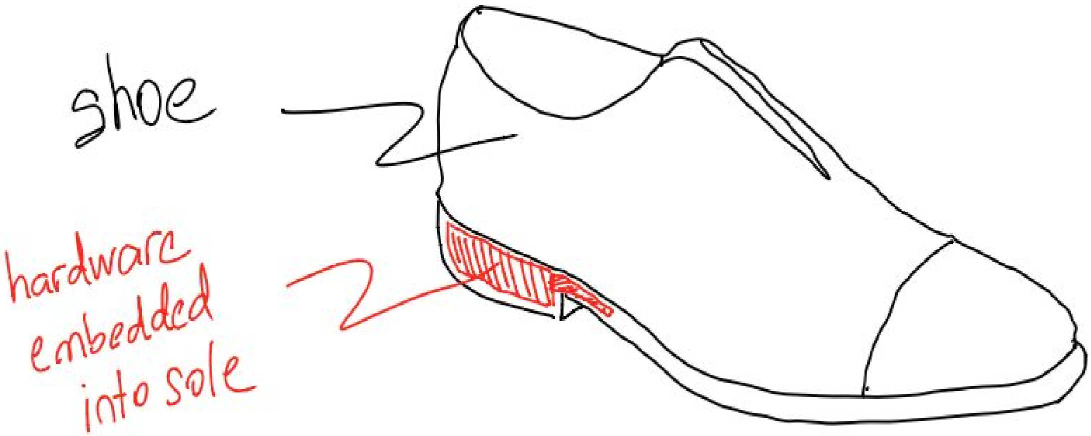


Figure A.2.13: Built-in shoe concept in which the hardware would be housed in the sole of the user's shoe.

Concept 16: Velcro/Adhesive Attachment

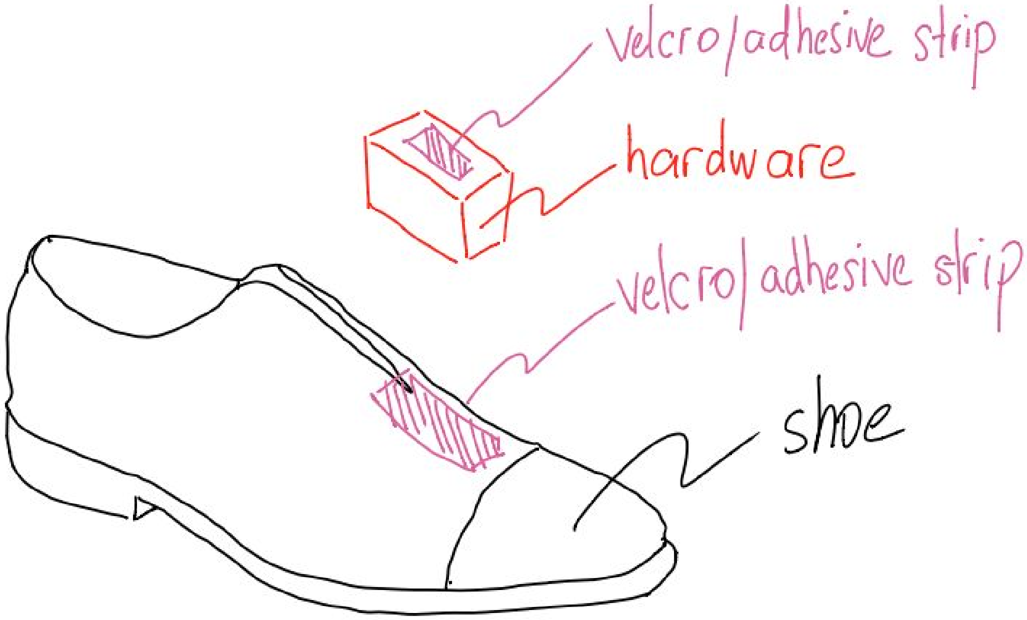


Figure A.2.14: Velcro or Adhesive concept where strip of adhesive material would be used to fix the device to top of user's shoe

Concept 17: Foot Strap Attachment

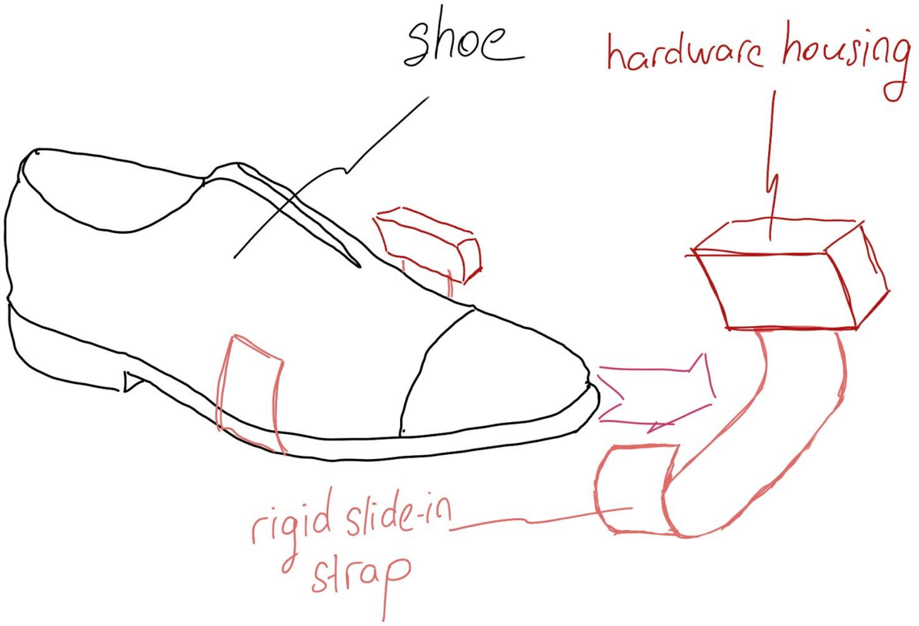


Figure A.2.15: Slide-in foot strap concept in which a rigid adjustable strap holding the hardware would wrap around the users foot.

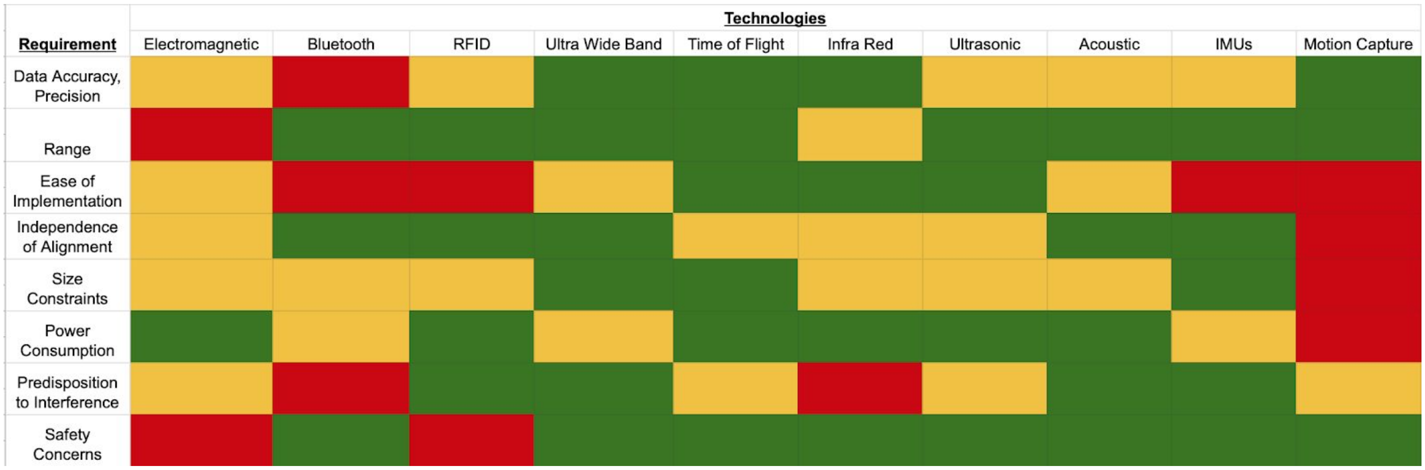
Appendix A.3: Pugh Chart Concept Evaluation

Pugh Chart for Distance Measurement Technology

The list of requirements against which ideas would be compared was developed based on the Reqs. & Specs. chart in Table 1, on Page 7. In the interest of conciseness and robustness, some requirements were clustered into overarching categories, such as Data Accuracy and Precision, or Ease of Implementation. With regard to the latter, this has constantly been one of our main concerns - whether or not these technologies which have not been used for gait analysis in the past can translate to the task of measuring the distance between feet, and how easy is it for a team of engineers with a mechanical background to enact this transformation. Another criteria we considered was size - this was done not by looking at the actual size of the PCBs which carry these technologies, but rather by understanding the size of the active component which enables the technology to work, such as emitters, receptors, lasers, ICs etc.

Another important characteristic of our Pugh chart is the lack of assigned weights for the requirements imposed. Although we considered that possibility, we found weights to be fairly artificial. Furthermore, they do a poor job expressing the imperative nature of all requirements to be met. Lastly, we decided that a failure of any of our requirements would lead to a failure of the entire solution, and thus decided to implement a color scheme-based Pugh chart; red refers to a requirement not being met, yellow to a requirement possibly being met, and green to a requirement met with relative ease. The Pugh chart for Distance Measurement Technology is provided in Table A3.1.

Table A.3.1: Pugh Chart used to compare Distance Measurement Technologies



	Technologies									
Requirement	Electromagnetic	Bluetooth	RFID	Ultra Wide Band	Time of Flight	Infra Red	Ultrasonic	Acoustic	IMUs	Motion Capture
Data Accuracy, Precision	🟨	🟥	🟨	🟩	🟩	🟩	🟨	🟨	🟨	🟩
Range	🟥	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩
Ease of Implementation	🟨	🟥	🟥	🟨	🟩	🟩	🟩	🟨	🟥	🟥
Independence of Alignment	🟨	🟩	🟩	🟩	🟨	🟨	🟨	🟩	🟩	🟥
Size Constraints	🟨	🟨	🟨	🟩	🟩	🟨	🟨	🟨	🟩	🟥
Power Consumption	🟩	🟨	🟩	🟨	🟩	🟩	🟩	🟩	🟨	🟥
Predisposition to Interference	🟨	🟥	🟩	🟩	🟨	🟥	🟨	🟩	🟩	🟨
Safety Concerns	🟥	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Technologies with at least one red mark were removed from consideration due to their failure or relative difficulty in achieving any of our requirements. Thus, it was possible to identify clusters of adequate ideas by looking for concepts which have green and yellow scores only. Based on our chart, these are *Ultra Wide Band, Time of Flight, Ultrasonic*, and *Acoustic*. Please note that the last two, would likely end up being merged into one solution, in an attempt to cancel out the relative minuses they each have, and harness their respective individual advantages.

Pugh Chart for Physical Attachment

Working off of our initial requirements, we derived further categories to consider in the physical attachment of the design and evaluate concepts against. Criteria such as reliability, reusability, alignment and ease of attachment were based off of the need for an accessible design. Impact on walking and safety concerns stem from the requirement for an untethered device for use outside the lab environment. Price comes not only from the constraints of our project, but also the constraints for an end product device. It is important to note that in this chart we are considering just the physical attachment of our device, or how the design will be attached to the user's foot. The choice of technology will have an impact on the final implementation that we go with. As with the technologies Pugh chart, we opted for a qualitative weighting system. This helps to remove our biases in scoring devices numerically. Again, red signifies a critical failure to satisfy the category. Yellow is sufficient, and green means a requirement is fulfilled with ease. The Pugh chart for physical attachment is shown in Table A3.2

Table A.3.2: Pugh Chart for physical implementation of device

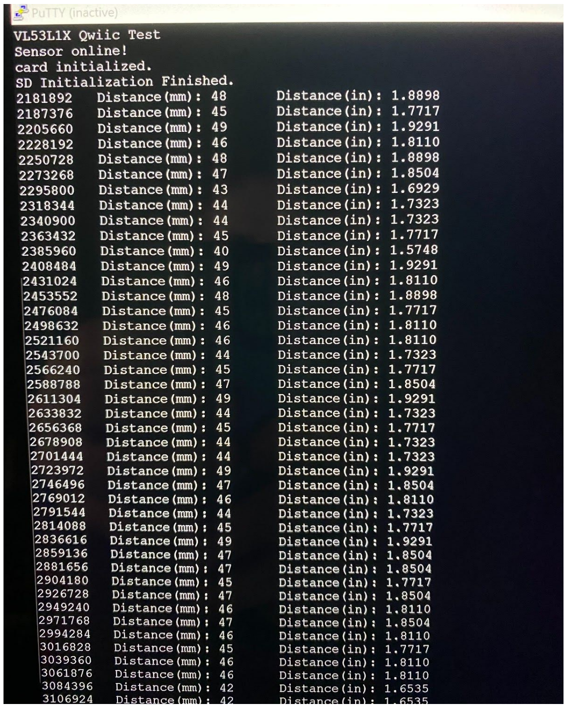
	Attachments							
Requirement	Magnetic Attachment	Velcro	Adhesive	Ankle Bracelet	Shoelace pouch	Clip	Foot Strap	Built-in shoe
Alignment	🟩	🟥	🟨	🟨	🟩	🟩	🟩	🟩
Ease of Attachment	🟩	🟩	🟨	🟨	🟨	🟨	🟩	🟩
Reliability	🟩	🟨	🟥	🟩	🟩	🟨	🟩	🟩
Reusability	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟥
Safety Concerns	🟨	🟩	🟩	🟩	🟩	🟩	🟨	🟨
Price	🟨	🟩	🟩	🟨	🟩	🟩	🟩	🟩
Impact on walking	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟩

Attachment methods that scored red in requirements were removed from further consideration in the design. The red scores represent a critical failure to meet requirements. For example, a technology built into the shoe design would be great for most considerations, however would not be reusable between patients, and improper sizing may pose safety risks for the user. The promising ideas of the *Shoelace Pouch, Ankle Bracelet, Foot Strap,* and *Magnetic Attachment* scored well in most categories. Further evaluation of these attachment methods will be performed once the finalized technology has been developed, since there is a dependency between the technology and how it will be able to be mounted to the user.

Appendix A.4: Data Processing Workflow

Data was collected from the initial setup via serial connection to a Windows PC. PUTTY, a terminal emulator program, was used to record and observe the output from the sensors during testing. PUTTY was deemed necessary to use because the COM port display in the native Arduino IDE does not allow for terminal output to be saved or for copying from the data stream. This meant that even though the team could observe the datastream in the Arduino IDE, the data could not be recorded or saved. PUTTY remedied this issue.

Two default test setups were saved within PUTTY, one for TOF testing and one for ultrasonic testing. The only difference between these two setups was the baud rate. Figure 22 depicts the standard PUTTY output for the TOF sensor.



```
VL53L1X Qwiic Test
Sensor online!
card initialized.
SD Initialization Finished.
2181892   Distance(mm): 48      Distance(in): 1.8898
2187376   Distance(mm): 45      Distance(in): 1.7717
2205660   Distance(mm): 49      Distance(in): 1.9291
2228192   Distance(mm): 46      Distance(in): 1.8110
2250728   Distance(mm): 48      Distance(in): 1.8898
2273268   Distance(mm): 47      Distance(in): 1.8504
2295800   Distance(mm): 43      Distance(in): 1.6929
2318344   Distance(mm): 44      Distance(in): 1.7323
2340900   Distance(mm): 44      Distance(in): 1.7323
2363432   Distance(mm): 45      Distance(in): 1.7717
2385960   Distance(mm): 40      Distance(in): 1.5748
2408484   Distance(mm): 49      Distance(in): 1.9291
2431024   Distance(mm): 46      Distance(in): 1.8110
2453552   Distance(mm): 48      Distance(in): 1.8898
2476084   Distance(mm): 45      Distance(in): 1.7717
2498632   Distance(mm): 46      Distance(in): 1.8110
2521160   Distance(mm): 46      Distance(in): 1.8110
2543700   Distance(mm): 44      Distance(in): 1.7323
2566240   Distance(mm): 45      Distance(in): 1.7717
2588788   Distance(mm): 47      Distance(in): 1.8504
2611304   Distance(mm): 49      Distance(in): 1.9291
2633832   Distance(mm): 44      Distance(in): 1.7323
2656368   Distance(mm): 45      Distance(in): 1.7717
2678908   Distance(mm): 44      Distance(in): 1.7323
2701444   Distance(mm): 44      Distance(in): 1.7323
2723972   Distance(mm): 49      Distance(in): 1.9291
2746496   Distance(mm): 47      Distance(in): 1.8504
2769012   Distance(mm): 46      Distance(in): 1.8110
2791544   Distance(mm): 44      Distance(in): 1.7323
2814088   Distance(mm): 45      Distance(in): 1.7717
2836616   Distance(mm): 49      Distance(in): 1.9291
2859136   Distance(mm): 47      Distance(in): 1.8504
2881656   Distance(mm): 47      Distance(in): 1.8504
2904180   Distance(mm): 45      Distance(in): 1.7717
2926728   Distance(mm): 47      Distance(in): 1.8504
2949240   Distance(mm): 46      Distance(in): 1.8110
2971768   Distance(mm): 47      Distance(in): 1.8504
2994284   Distance(mm): 46      Distance(in): 1.8110
3016828   Distance(mm): 45      Distance(in): 1.7717
3039360   Distance(mm): 46      Distance(in): 1.8110
3061876   Distance(mm): 46      Distance(in): 1.8110
3084396   Distance(mm): 42      Distance(in): 1.6535
3106924   Distance(mm): 42      Distance(in): 1.6535
```

Figure A.4.1: The datastream seen from a TOF test in PUTTY. Of note is the distance being displayed in both mm and inches. Each of these measurements is time stamped with a time in microseconds since the Arduino was turned on.

Once the hardware setup and communication with the Arduino was established, modification to each sensor's code took place. These modifications allowed for the sampling rate of each sensor to be increased and also allowed for time-stamped data to be recorded. Table 5 shows the characteristics of the data that was obtained from each sensor during testing. Note that the baud rate refers to the number of bits per second being transferred from the sensor to the microcontroller. This is different from the sensor's sampling rate, which refers to how many times each second distance can be computed.

Table A.4.1: Sensor output and communication characteristics are displayed below.

Sensor	**Time of Flight**	**Ultrasonic**
Baud Rate	112500	9600
Sampling Rate	31 Hz	46 Hz
Distance Output Unit(s)	mm, inches	feet, inches
Time output	micro-seconds	micro-seconds

Appendix A.5: Low Pass Filtering

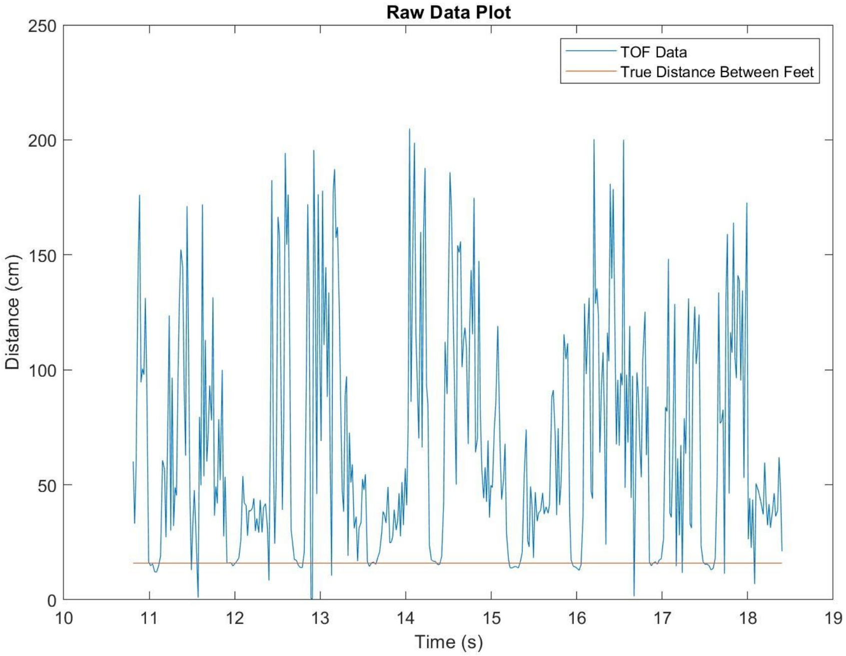


Figure A.5.1: Fourth walking trial of the TOF sensor. Note the several dips below the true distance line, and the overall noisy signal.

Fourier analysis was conducted on the data seen in A5.1 in an attempt to filter the signal. The design of the filter was to be low pass. This was done with the intention of observing the frequencies that are most prevalent to the signal, and what frequencies may be contributing to the noise observed. Figure 34 on Page 35 shows the transform for trial 4.

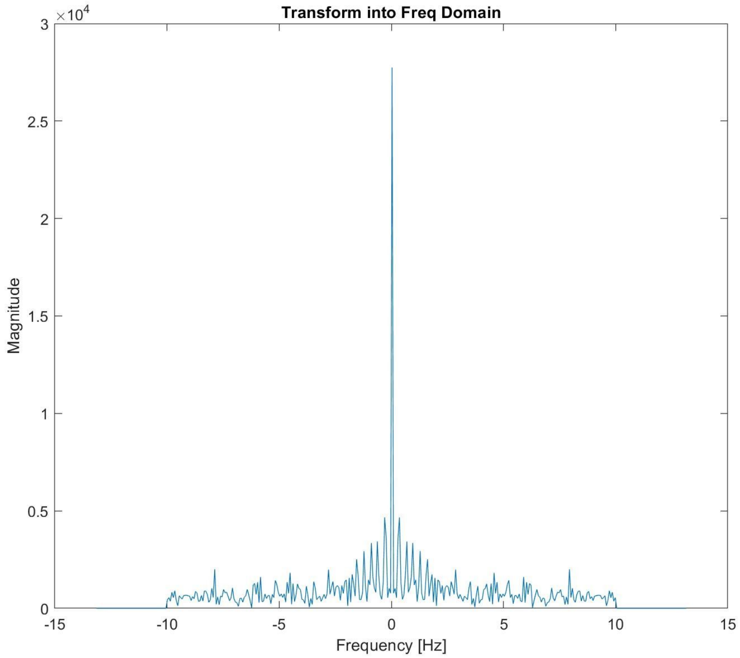


Figure A.5.2: Fourier transform of the walking test data. The plot ideally would mimic a sinc function in this application.

Once a fourier transform was conducted, Figure B5.1 allowed for a frequency cut off to be determined. Due to the nature of what the team intended to observe in testing, a sinc function was expected. This was because the signal from the sensor ideally would be picking up a series of step functions in the time domain. What can be seen in this figure is sinc-consistent behavior until frequencies around 5 and -5 Hz. Any frequency outside of this range was deemed to be noise, and zeroed in the frequency domain. An inverse transform was then conducted. Figure 35 on Page 36 shows this transform.

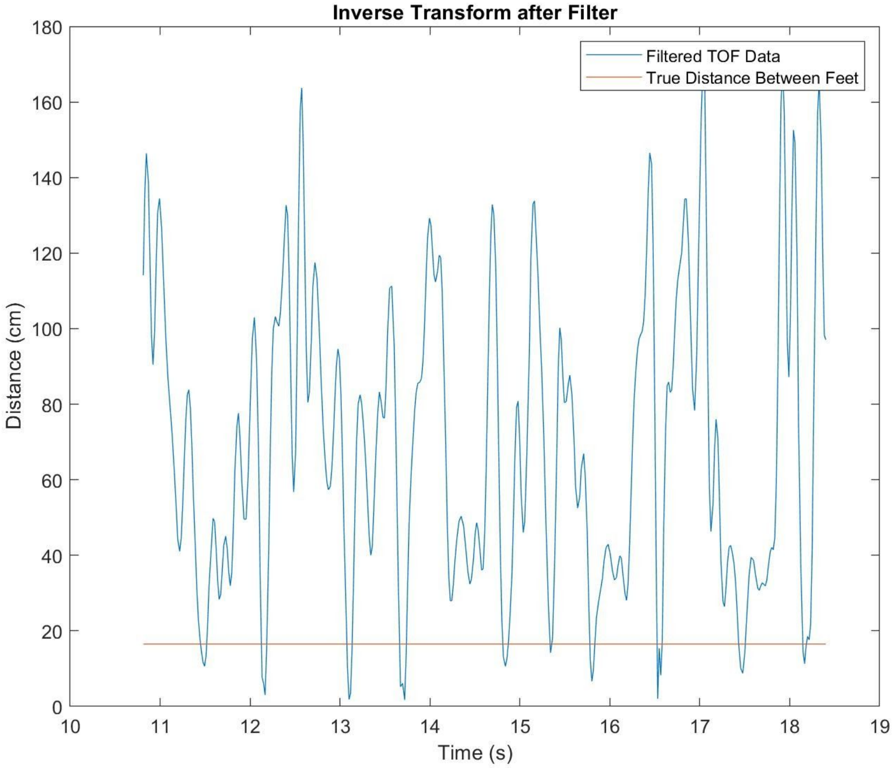
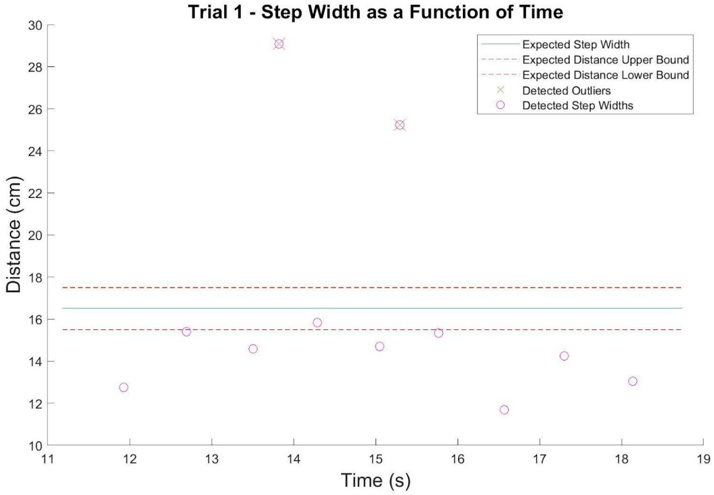


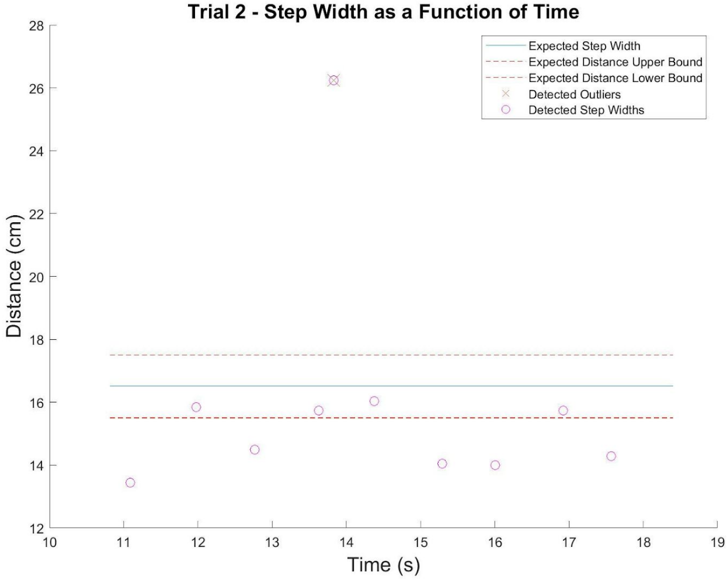
Figure A.5.3: Inverse transform of the data with the removement of finer frequencies.

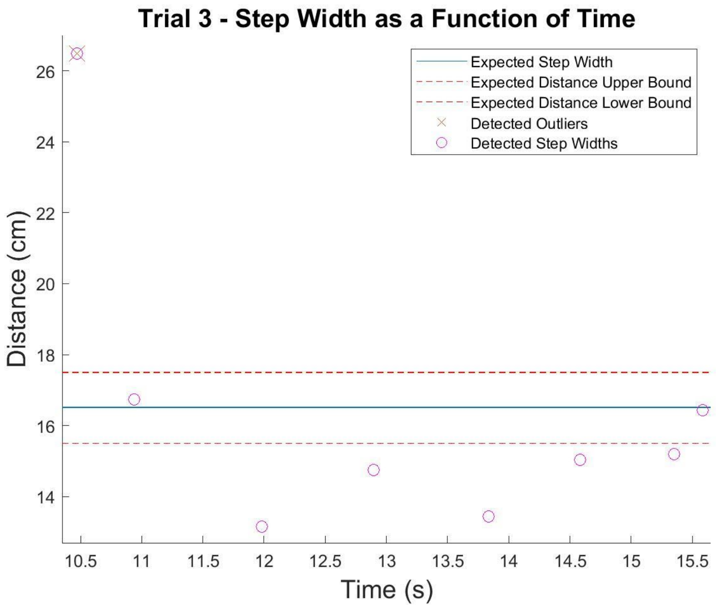
As can be seen in figure C5.1, the signal is now much less noisy and contains less of the severe dips observed previously. There were reasons to believe that this was the right direction for data processing. Mainly, the number of dips below the true distance line was now consistent with the number of steps observed during testing, 8 steps. However, the accuracy of these minimums was adversely affected due to the finer frequencies being filtered from the signal. Additionally, a time offset was introduced that shifted the data. The results from this filtering analysis were encouraging, however, further investigation found that a median filter may be easier to implement for this project, and accomplish similar results.

Appendix A.6: Additional Verification Plots

Additional plots used for verification can be seen here. These plots show the detected step width for each trial as a function of time.







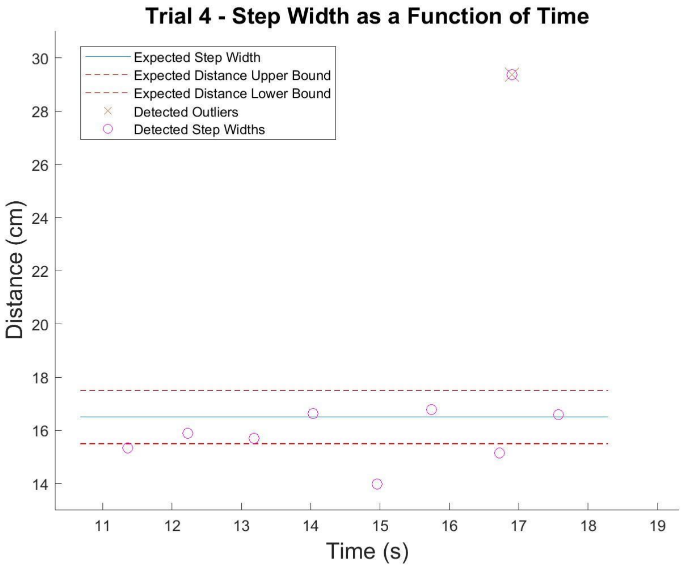


Figure A.6.1: Step width trials results.

Appendix B.1: Engineering Standards

Most engineering projects have unique and highly specific requirements and specifications. This allows designers to cater to their unique audiences and create a highly customized experience for their end user. This train of thought is, in many ways, also applicable to what we considered and deployed when we created 1,2 step.

However, under certain circumstances, devices that operate in certain similar conditions are expected to meet similar specifications, or engineering standards as they are referred to formally. These sets of specifications allow projects of different shapes, sizes, and scope to abide by the same legislation and ensure uniform expectations.

In the case of 1,2 step, we realized that since our device is to also be used outside, it requires weatherproofing. We could have come up with a comprehensive list of waterproofing specifications; however, since a lot of projects need to be protected from the elements, the *International Electrotechnical Commission* (*IEC*), created a standard, IEC Standard no. 60529:1989 - "*Degrees of protection provided by enclosures* (IP Code)". This standard specifies protection criteria a product must meet in order to receive appropriate IP ratings.

In the case of 1,2 step, we are designing for IP65 ratings, which mean a totally dust tight enclosure, coupled with protection against low pressure jets from any angle. We believe this is the worst case scenario use for a gait analysis sensor, that could be used outdoors in dusty , rainy, or snowy conditions. In the future, we might also consider using a standard for drop and shock resistance, if we find this to be appropriate.

Appendix B.2: Engineering Inclusivity

Taking a step back and looking at one of the key goals of 1,2 step, we set out to make step width and gait analysis more accessible to all populations. To build on that, at all steps in the design cycle, we were very cognizant of the reduced skills and abilities of a potential customer, and designed in order to cater to these differences.

For example, our solution is mainly destined towards older populations, who often lose fine motor skills, and have difficulty interacting with technology. For this reason, we developed a solution which self-aligns using magnets, and requires minimal user interaction to function; in other words, we greatly increased the accessibility of 1,2 step by simplifying its features for customers with reduced physical and cognitive abilities.

Another step we took toward inclusive design was simplifying the design and operation of 1,2 step. Whether we are talking about the magnetic-docking chagrin system, or the very simple parallelepipedic housing, we actively tried to reduce the complexity of our systems, in order to minimize the points of failure.

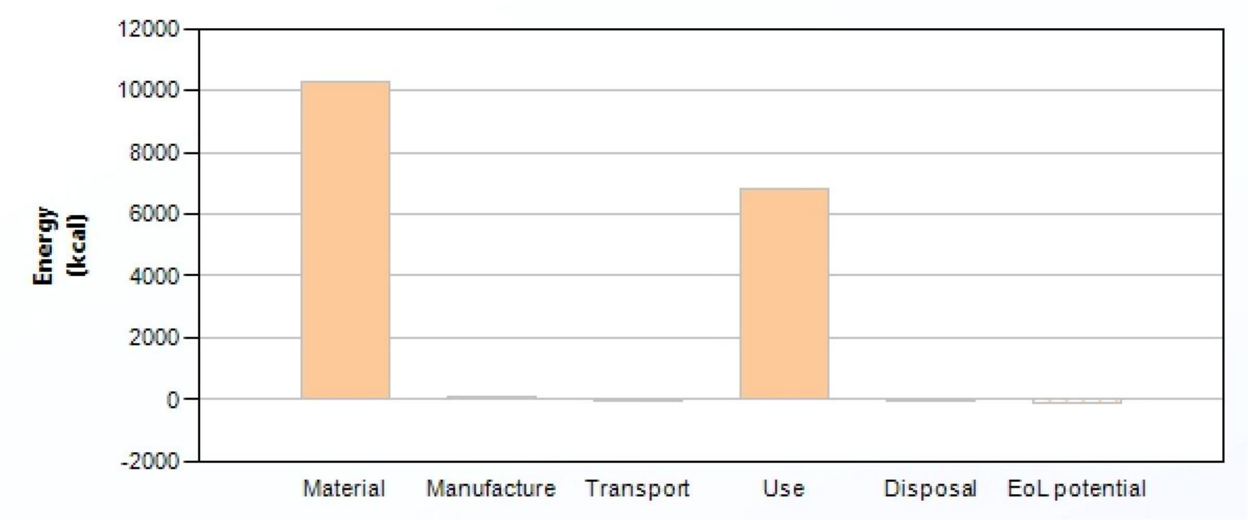
Realizing that certain conditions may disable people from using our solution as it is currently designed, we are considering making the plans open source. This would further allow people that need accurate gait analysis, but cannot adapt to the operation of 1,2 step, a chance to implement modifications of our design in order to attend to their own needs.

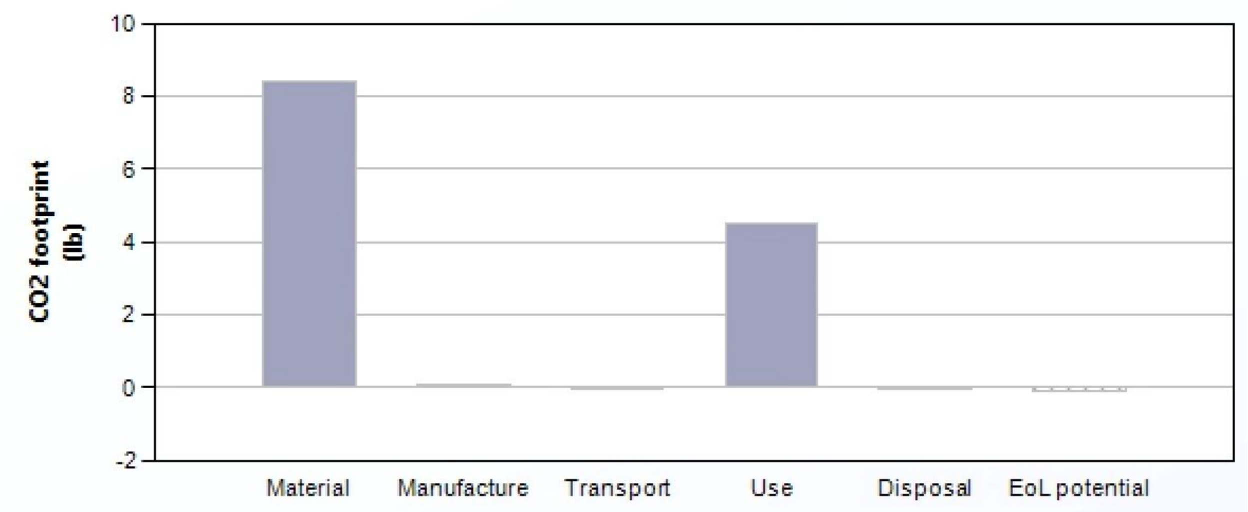
Appendix B.3: Environmental Context Assessment

To present quantitative proof of the ways our solution considers the broad environmental context, we used an Eco Audit created in *Granta EDUPACK 2020*. This type of audit considers the environmental footprint of the materials required to build our product, as well as other sources: manufacturing, shipping, and exploitation.

Components inputted in the audit include the plastic housing, metal hinge pins, attachment magnets, Li-Ion battery, electronics, and PCB solder. The country of manufacture was set to China, with shipping and trucking to the US considered, alongside energy needs for charging the Li-Ion battery. We assume that the device can be used for four years

Given below are the raw CO2 footprint and Energy outputs from *EDUPACK.*





As you can see, the “Material” represents the largest source of both CO2 emissions and Energy consumption. This is followed by “Use” as the second most polluting component of the lifecycle.

As a point of reference, an average car would create the same amount of CO2 (~ 13 lbs.) by driving for 36 km [1]. Furthermore, for the 4 year expected lifetime of our product, the total energy consumption (~ 17000 kcal) results in approximately a 0.57 Wah, which is less than, which is almost 20 times less than an iPad charger [2]. Thus, compared to the positive impact on neurological disease diagnosis and medical research, the toll on the environment imposed by our solution is insignificant.
This makes us confident that the benefits brought to society by 1,2 step will not be outweighed by its environmental impact.

[1] European Environment Agency "*Average CO2 emissions from new cars and new vans increased in 2018*" - retrieved from : https://www.eea.europa.eu/highlights/average-co2-emissions-from-new on Dec. 5th 2020
[2] WIRED *"Choose the Right Charger and Power Your Gadgets Properly"* - retrieved from: https://www.wired.com/2013/12/charging-devices-faq/ on Dec 5th

Appendix B.4: Social Context Assessment

To understand the social impact of our solution, we used a cost analysis created in *Granta EDUPACK 2020*. Together with battery and electronics pricing from SparkFun (electronics are not supported by *EDUPACK* cost analysis), we created the following table that shows the life cycle cost analysis of our solution. We are assuming a 4-year product life, with a discount rate of 4% for net present value (NPV) costs. The replacement cost comes from installing a new battery after two years of use.

			1,2 Step	
Cost	**Type of Cost**	**Source**	**Value (USD)**	**Conversion to $P**
Material	Present	CES	6	6
Electronics	Present	SparkFun	50	50
Manufacturing	Present	CES	1	1
Transport	Present	CES	0.1	0.1
Electricity Use	Annual (4 years)	CES	0.1275	0.01275
Environmental	Annual (4 years)	CES	1.85	0.185
Maintenance	Annual (4 years)	CES	2	0.2

Replacement Parts	Future (2 yrs)	SparkFun	10 [1]	2.066115702
Disposal	Future (5 yrs)	CES	0.0004	1.36603E-06
Total				**59.6**

We have not found an appropriate initial purchase price for our solution; this would likely be the task of marketing and sales teams. However, the relatively low total price, (~ 60$) should allow for significant profits to be obtained, even as the purchase price is kept to a minimum. For comparison, an integrated IMU logger used for gait analysis can cost 2000$ [2]. Even a greedy corporation that monetizes our solution for 200$ would still obtain a 230% profit (140 $). Thus the incorporation of relatively cheap technology would allow 1,2 step to reach a wider customer base, thus increasing its impact on society. Such devices, IMU loggers, have been on the market for extensive periods of time now. The untoward societal consequences created by their commercialization have been minimal. Due to the similarity in scope and use of our solution to IMU loggers, we can posit that it's unlikely to cause more harm to society than gain. In other words, planetary and social systems will likely be better off, and thus the technology would be self sustaining and ultimately sustainable.

[1] SparkFun "*Lithium Ion Battery - 1Ah*" - retrieved from : https://www.sparkfun.com/products/13813 on Dec. 5th 2020

[2] GaitUP *"Detailed gait & running analysis"*

Appendix B.5: Ethical Decision Making

One of the main considerations when designing medical devices is HIPAA, *Health Insurance Portability and Accountability Act*. In terms of keeping patient data secure, federal acts are extremely stringent. Thus, as engineers that incorporate different technologies into a device that could ultimately diagnose neurological conditions, we need to ensure that data is kept secure and private.

For example, with the implementation of a Bluetooth module to facilitate rapid data transmission, a new weak point in the system appears. Although Bluetooth protocol is relatively secure, a scenario where data is accidentally transmitted to a device that is not authorized to view gait parameters is not completely out of the question.

Hence, all decisions we would have to make as developers, would need to hold privacy and safety on the uppermost level. Thus, if we ever are presented with a difficult choice between corporate agendas, and patient's interest and privacy, we will always act with dignity and make decisions based on the different *Codes of Ethics* from the National Society of Professional Engineers (NSPE) and the American Society of Mechanical Engineers (ASME).