Aid for Visually Impaired: Indoor Navigation

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Abstract

There are a plethora of devices targeting outdoor navigation using GPS like Google Maps. However, the solution for indoor localization and guidance is rather limited. Aimed for millions of individuals across the world suffering from visual impairment, our solution facilitates indoor navigation. Using a combination of IMU sensors and pre-existing Wi-Fi access points, the device tracks the person’s location and trajectory and provides a guided path with audio feedback. This report will tackle specific components of our project.

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1. Motivation

1.1 Problem Statement

'Globally, at least 2.2 billion people have a vision impairment or blindness, of whom at least 1 billion have a vision impairment that could have been prevented or has yet to be addressed' [1]. More so, there are a number of diseases like diabetes and hypertension [2] which can lead to blindness so the potential number of users is quite extensive. Individuals with visual imparities find it difficult to find their way around. In the outdoors, one can use applications like Google Maps which uses GPS and also provide audio feedback for people who have difficulty with sight. Indoors, GPS cannot penetrate buildings and so the problem of localization and navigation becomes difficult. We aim to provide a solution which can help the visually impaired to be able to properly navigate indoors.

The primary motivation of this particular project was to provide more autonomy and freedom to individuals with visual impairment. Our idea is about a device, in the shape of a rectangular box, and it utilizes a combination of Wi-Fi beacons and an Inertial Measurement Unit. The sensors track the location of the user and direct him/her towards the desired destination. Using the device, the user can navigate through their homes and known locations without any issues thereby tackling a primary barrier of movement without sight. Given the pre-loaded maps of certain important locations, a visually impaired individual can navigate himself/herself through grocery stores, apartments, etc. The potential impact is quite considerable and we are extremely excited for the project.

There are a number of research studies which investigate the problem and have suggested/created solutions. One such instance is 'PERCEPT Indoor Navigation System for the Blind and Visually Impaired' [3]. The device consists of a pair of gloves with an android based software containing bluetooth, WiFi, text to speech modules. The user needs an android smartphone which the device connects with and the Arduino processes the information using the PERCEPT subsystem (incorporating Google indoor technologies and phone GPS) to feed into the speakers as instruction. *'It provides the user approximate location (using WiFi and cellular and GPS technologies) and has no navigation function. Since the system is designed for sighted users, the map and user location do not have to be accurate'* [3]. Our product approaches the problem quite differently. Firstly, the box device is independent without the need of an android based smartphone (individuals with visual disability often don't have a smartphone or won't be able to operate effectively) and secondly, we are utilizing an IMU to locate the user and keep track of the path by the user while also navigating through the directions and constant sound feedback ensuring he/she is on track to the destination. On top of this, our device would be much cheaper than the PERCEPT product.

Another similar product for indoor navigation for the blind is 'LowViz' [4]. The device is targeted towards enormous venues like a cruise ship, a hospital, an Ikea store, conferences and help individuals with visual disability navigate. The idea is to mount small iBeacons, about the size of a D-cell battery, throughout the building and the iOS device recognizes these iBeacons via bluetooth and helps the user in navigation [4]. Our product does not require the installation of over a hundred beacons in a building and also does not require the assistance of a smartphone/iOS device. The cost to set up such a platform and environment would limit the number of buildings due to initial capital investment and the extent of individuals with visual disabilities the device can have an impact on. Our device is independent, cheaper and is able to navigate the user with constant feedback.

An instance of a similar approach is 'Unsupervised Indoor Localization' proposing a product 'UnLoc' [6]. The paper uses a combination of IMU and WiFi access points and gets a location accuracy within 2m. It uses similar sensors and shows promising results which speaks to the feasibility of our project. On the other hand, we do not utilize the framework of 'unsupervised' localization on the sensor features.

1.2 Solution

The underlying motivation behind the project by Team 73 in Spring 2019 is similar to ours which is to facilitate navigation for individuals with visual impairment. Using a system of bluetooth sensors across particular locations inside each of the rooms and appropriate corridors, the intent is to create a 'walkability map' of all rooms in an apartment/area and then localize the individuals [9]. Using the location, the device can pinpoint the exact positioning of the person and guide with directions [9]. The primary hardware components include bluetooth beacons and receivers, memory card and batteries. *'The blind person will also be carrying a bluetooth compatible wearable-device, which will connect to the bluetooth beacons'* [9]. Similar to our implementation, their project uses a memory module to store all the information (map, beacon positions and information etc.) while the main application is handling the localization and navigation [9]. The device sends through voice feedback to the user based on the feedback from the software module, which is similar to our project. The difference is that our device, on top of directions (right, left, forward, backwards), tracks the path of the user and gives a constant audio ticking feedback by comparing their location to the computed path.

For the indoor localization aspect of the project, we have decided to use an IMU. Most mobile phones today come in-built with an IMU. An IMU consists of three sensors - an accelerometer, a gyroscope and a magnetometer. The data from the IMU sensors can be used to perform dead-reckoning, which essentially means to track a person's trajectory given their previous location and counting the number of steps (can be done using an accelerometer). Since IMU sensors are all relative sensors, the error over time can build up and result in incorrect trajectories. To lessen this error, we will take the help of pre-existing Wi-Fi access points and sensor data together and perform course-correction to improve localization accuracy.

The device is the shape of a box containing the IMU, power system and microcontroller on the inside and the outer surface consists of the start and option buttons as well as the speakers. We plan to have an audio-controlled device which will be used as an interface for the user. Once the start button is pressed, the box device will have a speaker which will give options of locations (like bathroom 1 at home or aisle 5 in a grocery store) within intervals of 2s. The user will press the control button on the desired option. The system will derive an optimal path using algorithms with the help of a pre-existing map. We will then track the user's path and compare it with our pre-built path. Feedback to the user will be given in the form of a sound that will increase in pitch linearly according to how much the user's path is away from the actual path. This audio sound will decrease its pitch as the user corrects his position and is now closer to the desired path. Once the user has reached the destination, the speakers will output a success message.

Our solution is better than the existing solution by Team 73 in Spring 2019 in the following ways:

- The reach goal of the current solution hopes to aim for a better and more accurate localization. Our algorithm and process for indoor localization will be more accurate than the existing one, where only Bluetooth beacons have been used as compared to using IMU sensors along with WiFi access points. Bluetooth beacons rely on installing these beacons in the room/space and need constant maintenance and periodic replacement, all of which is eliminated by the proposed solution.

- Our usage of audio signals for input versus touch is easier and more intuitive for the user. Specifically for visually impaired users, who usually either carry a walking stick or a guide-dog, their hands might be occupied and the touch sensor would be difficult to access. Audio inputs will resolve this issue.

- The existing solution incorporates a vibrational feedback which increases in intensity as the user strays away from the desired path. It might be easier for users to distinguish subtle changes in sound pitch as compared to vibrational intensities, and thus, a sound output that changes in pitch might be a better solution for the user.

- The previously implemented solution needs a decent number of bluetooth beacons to help them achieve their desired accuracy for localization. For our implementation, we utilize the already existing WiFi APs in most existing indoor environments, which reduces the overall cost of our implementation compared to theirs.

The problem of creating an indoor navigation aid for the visually impaired relies heavily on the ability to accurately localize the user in the given indoor environment. This problem is more complicated than it might seem especially considering that we've had such great success with GPS for outdoor localization. Indoors, this becomes an issue as GPS cannot penetrate through the several barriers including floor divisions, walls, other materials. We have attempted to solve the indoor localization with a design consisting of an IMU along with multiple WiFi Access Points. As is a common metric to evaluate a lot of projects, the accuracy of the algorithm plays an important factor in evaluating the success of the project. Through our suggested method, we can theoretically suggest a path that deviates less than 3 metres for more than 95% of the time which is a significant improvement over the existing implementation, which could only guarantee a maximum of 5 metre error about 80% of the time. It is a bump up in both the accuracy of the path as well as the reliability of the algorithm.

The existing solution proposes the use of 5 bluetooth beacons for an apartment having the dimensions of 27 metres $\times$ 14 metres. The purpose of indoor localization is to help the visually impaired to be able to navigate in unknown indoor environments like shopping malls, academic buildings and so forth. These environments tend to have way larger square footage than that of an apartment.

Let's consider the Electrical and Computer Engineering Building for example. The dimensions of a single floor of the ECEB is roughly around 7000 m^2 .

Therefore,

$$27 \times 14 \rightarrow 5\ beacons$$
$$7000 \rightarrow x$$

$$\therefore x = \frac{7000 \times 5}{27 \times 14}$$

$$\therefore x \simeq 120\ beacons$$

The cost of each beacon used by the previous solution is $\$22$.
Therefore the total cost of the bluetooth beacons will be $22 \times 120 = \$2640$.

Our solution uses existing WiFi APs in the indoors infrastructure to aid us with the localization process. The only sensor we will need to achieve similar and better accuracies is an inexpensive IMU and a WiFi module, the total cost of which can be assumed to be at a maximum of $\$40$. This shows a cost reduction of approximately 66x as compared to the previous solution, thus making our implementation more practical, cost effective and scalable with better accuracy.

The third improvement we made was by incorporating audio cues rather than haptic feedback. Based on the results of a research paper (cited below), it makes it clear that having audio feedback trumps the haptic feedback in terms of the users completing the tasks faster (mean = 351s), have fewer misplacements (mean = 3.23), double check their task and the result less frequently. This goes on to prove that users perform their tasks better when given audio feedback over haptic feedback.

Table 2. Experimental results regarding total time to complete tasks for the 13 groups and regarding misplacements, result checking and double checks.

	Audio/Haptic/ Visual feedback	Audio/Visual feedback	Haptic/Visual feedback
Performance (sek.) (n=13, F=34.87*)	M=250 SD=47.7	M=351 SD=91.8	M=594 SD=205
Misplacements (n=13, F=32.67*)	M=1.23 SD=0.73	M=3.23 SD=1.17	M=4.31 SD=1.38
Double checking (n=13, F=38.58*)	M=1.38 SD=0.96	M=5.77 SD=1.42	M=9.08 SD=1.93
Checking of result (n=13, F=105.1*)	M=2.08 SD=0.95	M=4.23 SD=1.09	M=5.92 SD=1.61

*= significant at 99,9% level

Figure 1

The initial proposal of the previous project was to change the vibrational frequency of the tactile feedback to help the user differentiate between different directions. However they soon realised that the frequency changes could only be noticed at very low frequencies of about a 100Hz. To fix this, they had to incorporate two separate wearable devices, one on each hand. The left-hand sensor vibration would indicate that the user should move left, and the right-hand vibration would indicate that the user should move right. If both of them vibrate, then the user was to move in the forward direction.

Assuming that the sensor in the two hands needed to be powered, there is no mention of how these two separate devices would communicate with each other. There is also no accommodation in the case that the user would need to move backwards or turn around to reach his desired location. Our implementation uses simple audio feedback to accomplish the same task, without the hassle of needing separate devices in each hand. Our system also requires that the audio output be in the 2000 Hz - 5000 Hz frequency range. The average human ear is known to be most sensitive to sounds within this frequency range, hence making it easy for users to interpret these audio commands to allow for smooth indoor navigation.

1.3 High-Level Requirements

1. The system should be able to determine the user's location within an accuracy of at most 3 metres.

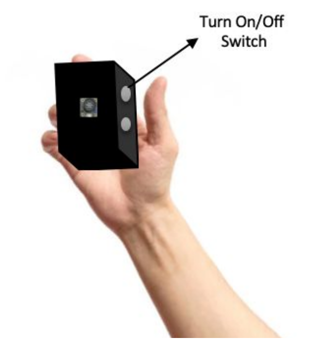
2. The system must be able to calculate a feasible path from the user's determined location to their desired destination within 2 seconds.

3. The processing algorithm should be able to estimate the number of steps taken by the user for three different positions of the IMU (placed still in the hand while walking, placed in the pocket, swinging in hand while walking) with an error of less than 3 steps.

4. To ensure audible and interpretable feedback, the system must output audio in the frequency range of 2000-5000Hz to make it easily decipherable to the human ear.

1.4 Visual Aid

Step 1: The user turns on the device by using the on/off switch, as shown in the figure 1 [7]. Once it is on, the speaker will output an audio recording indicating that the device is activated.



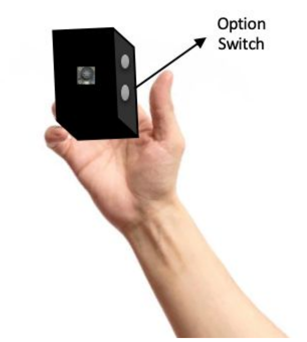


Figure 1: Turn On/Off   Figure 2: Option Selection   Figure 3: Device Navigation

Step 2: The device, as shown in figure 2, through the speaker, outputs an audio of the names of the locations and the user selects the destination he/she wishes to go to by pressing the option button when the desired location is outputted by the device.

Step 3: The device guides the user by giving direction (left, right, straight, backwards) and there is a constant beeping sound feedback which becomes louder if the individual does not follow the path in the system, as shown in the figure 3 [8].

1.5 Block Diagram

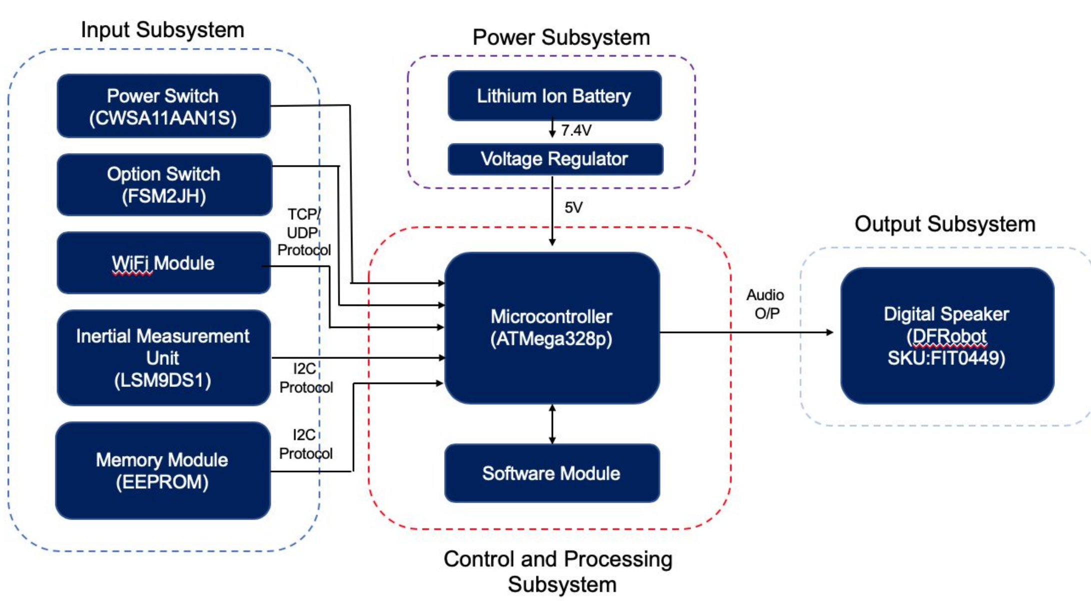


Figure 4: Block Diagram

2. Implementation

2.1 Implementation Details and Analysis

The basis of our project lies in the implementation of IMU-based localization of the user which can be achieved by Pedestrian Dead Reckoning (PDR). PDR essentially involves collecting data from the user while they are walking and then processing this data to output their trajectory. To solve the problem of PDR, we need three data points:

1. Number of steps: n
2. Walking direction for each step: θ_i
3. Step length for each step: l_i

Once we have these three parameters, the position of the user can be given by:

$$P(x, y) = \sum_{i=1}^{n} (l_i cos(\theta_i) , l_i sin(\theta_i))$$

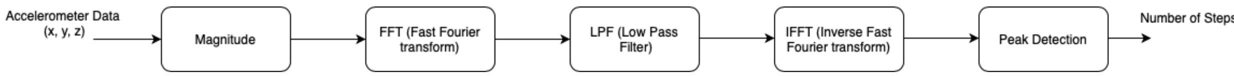
For the purpose of data collection, we will use an IMU which contains an accelerometer, a gyroscope and a magnetometer.

2.1.1 Step Counting

One of the basic concepts of localization and path detection involves the usage of the accelerometer. An accelerometer measures the relative acceleration of the body along the three axes. We can use the data from the accelerometer to compute the number of steps taken by the user. If we have the initial location of the user, and the direction he is facing, then by using the number of steps and average step length, we can determine the user’s location at any given time.

To test our hypothesis, we used the IMU to collect accelerometer data and further performed signal processing on the raw data to compute the number of steps taken. The raw data is in the form of acceleration vectors in the x, y and z directions for multiple time steps. Our accelerometer sampled the data at a frequency of 100Hz. We performed this calculation for three different orientations of the IMU - placed stationary in the hand while walking, placed in the pocket while walking or swinging while walking.

The processing algorithm followed was as follows. First, the magnitude is calculated for the accelerometer vector data for each sample. Then, this waveform is centered about the X-Axis. We then perform a Fast Fourier Transform of the accelerometer data. This signal is passed through a Low Pass Filter to smoothen the data and eliminate noise. The inverse fourier transform is taken. After this, we perform peak detection on the signal and the number of peaks is then estimated to be the number of steps taken by the user.



Case 1: The IMU is held static in the hand while walking

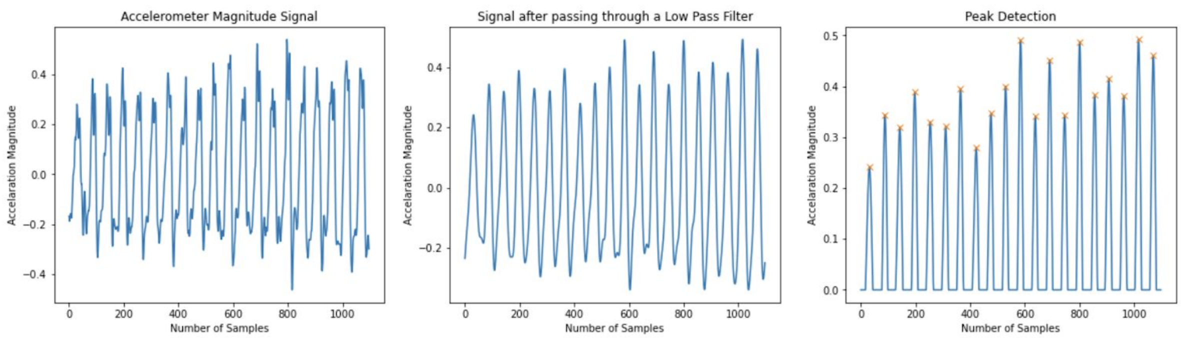


Figure 5

Ground Truth number of steps - 20
Number of peaks detected - 20

Case 2: The IMU is inside the pocket

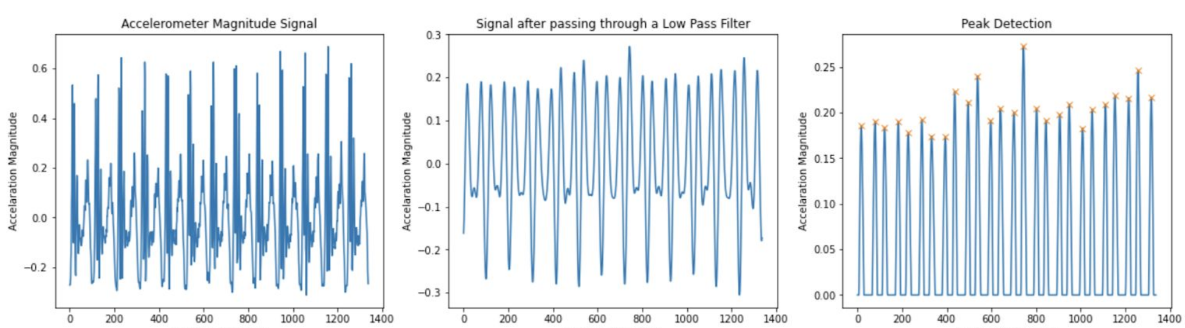


Figure 6

Ground Truth number of steps - 25
Number of peaks detected - 26

Case 3: The IMU is in the hand which is swinging while walking

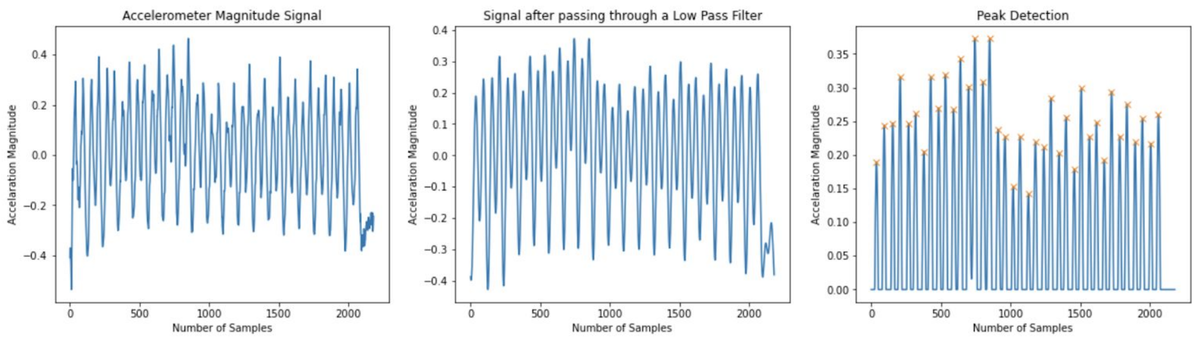


Figure 7

Ground truth number of steps - 38
Number of Peaks detected - 38

We performed this process 5 different times for each of the three orientations of the IMU and always observed the estimated number of peaks to be accurate within 2 steps of the ground truth.

Now, the average step length is estimated to be about 0.73 metres. Thus, the maximum error in location estimations is calculated to be $0.73 \times 2 = 1.46$ metres. This is within the tolerance of the system which states that the localization accuracy must be within 3 metres.

2.1.2 Orientation Tracking

To estimate walking direction, we need to be able to track the orientation of the IMU. Assuming that initially the IMU is static, the accelerometer data and magnetometer data can be used to determine the initial orientation of the IMU. We can achieve this by using Rotation matrices.

Let us consider that the initial local normalized accelerometer reading is given by $a_l = [a_{lx}\ a_{ly}\ a_{lz}]$ and the initial local normalized magnetometer reading is given by

$m_l = [m_{lx}\ m_{ly}\ m_{lz}]$. Assume that the initial rotation matrix is R. Using the concept of rotation matrices, we have:

$$R \cdot (local\ vector) = (global\ vector)$$

Therefore,

$$\mathrm{R} \cdot \begin{bmatrix} a_{lx} & m_{lx} \\ a_{ly} & m_{ly} \\ a_{lz} & m_{lz} \end{bmatrix} = \begin{bmatrix} a_{gx} & m_{gx} \\ a_{gy} & m_{gy} \\ a_{gz} & m_{gz} \end{bmatrix}$$

where, a_g is the normalized acceleration in the global frame and m_g is the normalized magnetometer reading in the global frame.

The initial orientation of the IMU is then given by the transpose of the Rotation matrix, R.

To track the orientation of the IMU, we need to perform gyroscope integration for each time-step. Given the gyroscope data, we can infer the rotation axis and rotation angle in the IMU's frame. Once this is converted into the global frame using the previous rotation of the IMU, we can compute the instantaneous rotation matrix ΔR. The rotation matrix for the next instant can then be given as follows:

$$R_{i+1} = \Delta R_i \cdot R_i$$

Thus, we can track the orientation of the IMU continuously, using the data from the gyroscope.

We collected some data by moving the IMU, and plotted the orientation of the IMU using the gyroscope data as follows:

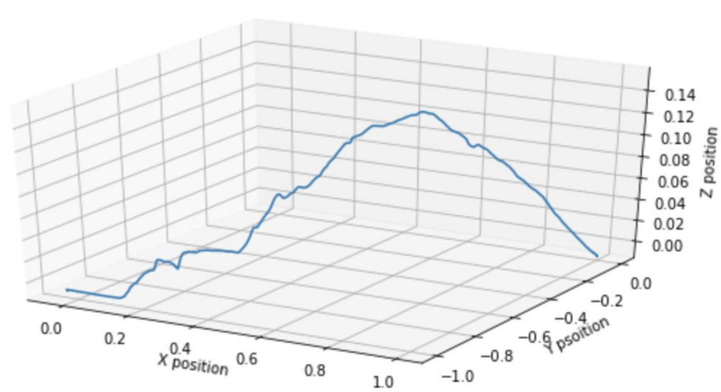


Figure 8

2.1.3 Experimentation and Evaluation

To test our implementation, we decided to collect some data by walking around and then tried to plot the walking trajectory using the aforementioned algorithms. For the purposes of testing, we used the phone's IMU to collect the data, and placed the IMU inside the pant pocket for the entire duration of the walk.

The ground truth trajectory looked as follows:

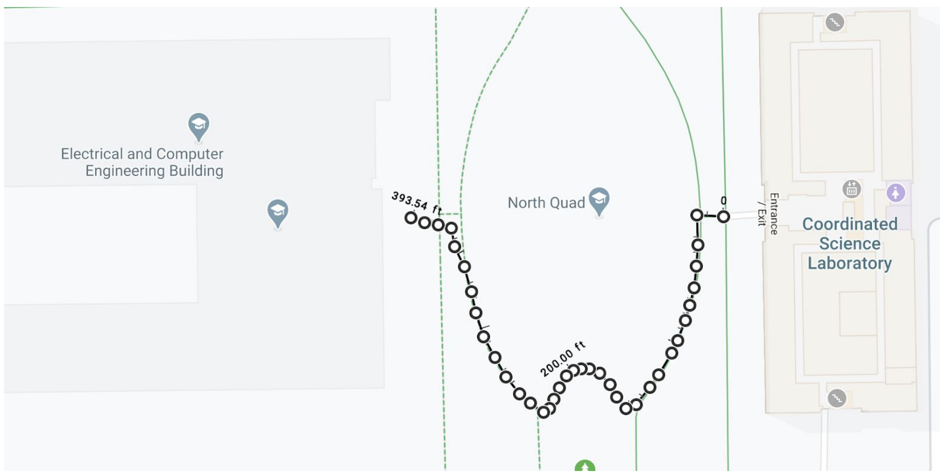


Figure 9
(The length of the trajectory is 393.54 ft)

The magnitude of the acceleration at each time-step is graphed as follows:

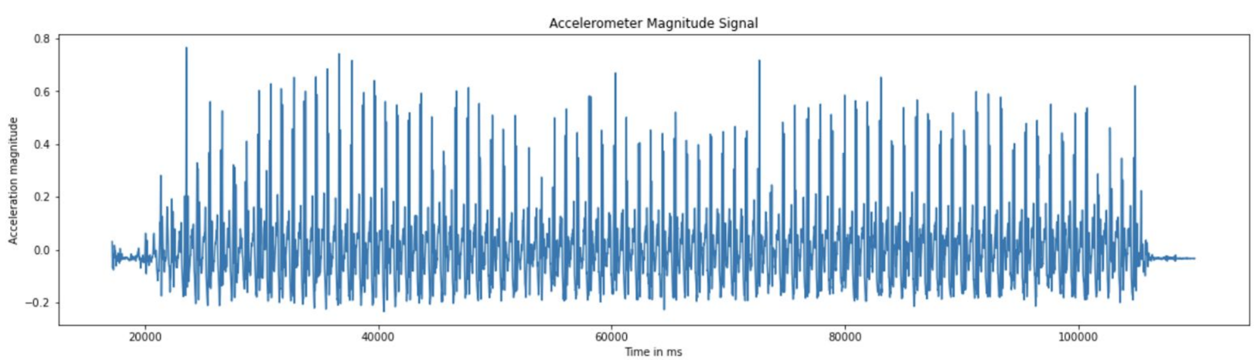


Figure 10

After passing the acceleration signal through a Low Pass Filter and smoothing the data, we get the following signal:

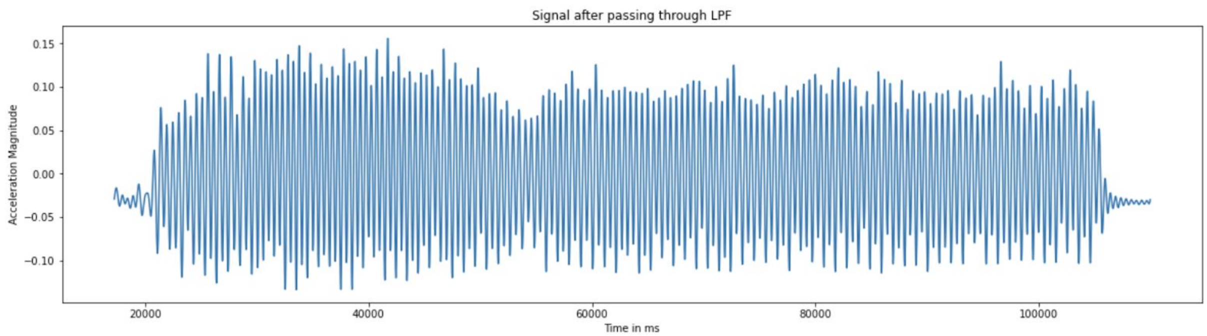


Figure 11

We perform peak detection on the smoothened data, and the number of peaks gives us the number of steps taken by the user.

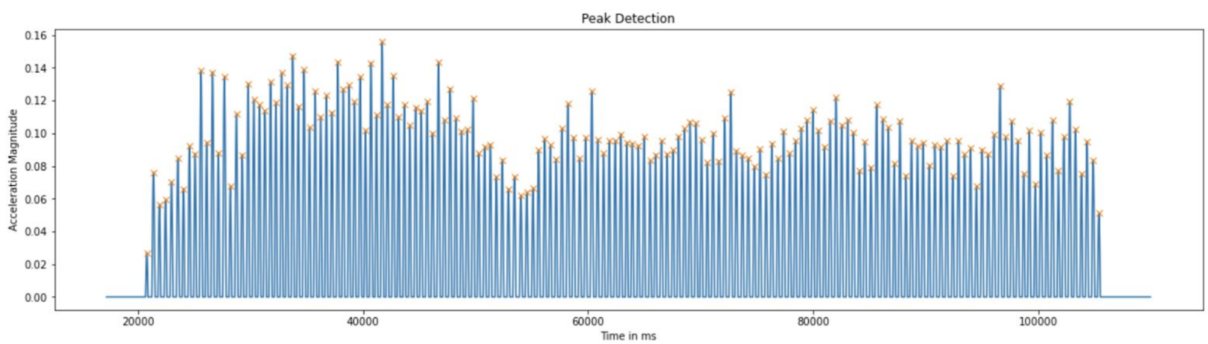


Figure 12

Our algorithm counted the number of steps taken to be 165.

After performing the necessary gyroscope integration and using it to track the walking direction at each step, we plotted the trajectory of the user as follows:

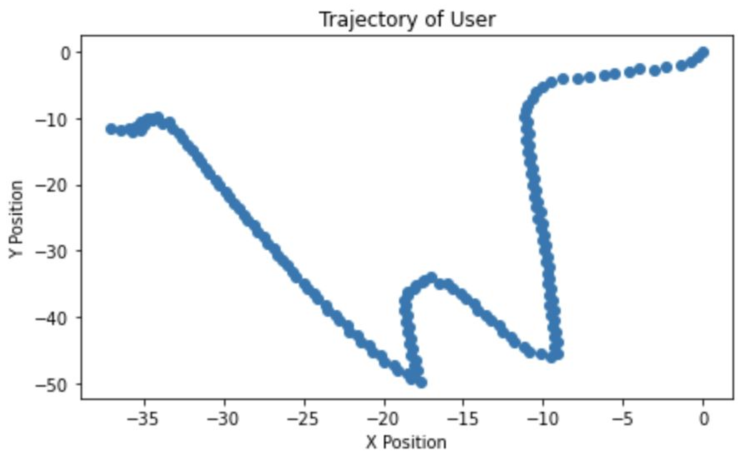


Figure 13

Assuming the average step length to be 2.4 feet and the number of steps calculated as 165, we get a total walking distance of $2.4 \times 165 = 396$ feet. The ground truth length of the trajectory is 393.54 feet. Therefore, our algorithm result is well within the tolerance of the system.

3. Conclusion

3.1 Implementation Summary

Given the less than ideal circumstances, we decided to focus on the software implementation side of things. Below is a summary of our procedures and observations in Section 2:

- We acquired data directly from an IMU in the various orientations we expect the user to be using the device in.
- Use a processing algorithm involving FFT, low pass filter and peak detection to count the number of steps.
- Integrating the gyroscope data, we were able to track the path of the user.
- Match up the algorithm output and the ground truth values to confirm the error margins of our algorithm.

The processing algorithm is the backbone of our project. The fact that our algorithm was able to get the correct number of steps within a range of +-1 every time as well as roughly the same path within a range of 3 feet is very significant as it bolsters the practicality of our device. To achieve the accuracy expectations for the overall project, it is important to make sure that our algorithm can handle every orientation of the IMU. After fine tuning various parameters to get the steps and path, our results are conclusive. We can ensure the robustness of the data pipeline through these conclusions and can guarantee that the device user can be tracked - the crux of the problem.

Anumay, being the one having an IMU in hand, was able to compile all the data in formats that would be easy to use for processing. Lakshya and Tanvi divided up the software implementation part, both figuring out algorithms that can be useful for our case. In the end, the implementation that we adopted had elements of both their works.

3.2 Unknowns, Uncertainties, Testing Needed

Given the constraints we were operating under, it was not possible for us to design and check every aspect of the project. The following points delve more into things that were left with uncertainty and details some scope for improvement -

- Access to the machine store would have been very useful for prototyping. We debated a few designs for our device but can only theorize what would be the most comfortable one for the user. Switch placement, curvature angles, surface material are all up for experimentation and we would have accomplished a “best-fit” design for our project.

- As for the software modules, we would have liked to do more rigorous testing and implement the other software modules that work in conjunction with the hardware. We are confident about the three test cases that we could implement but until we cover the entire space and outlier testing, it will be uncertain how well the algorithm generalises to all possible scenarios.

- The WiFi AP’s are not always expansive enough to cover the entire environment leaving us in a few “dark spots”. The plan was to test the environment for such spots and make sure to get them enough WiFi coverage and signal strength to accomplish reliable data transmission through the medium. This variable is easily covered through simple testing using our own phones.

3.3 Ethics and Safety

The biggest risk factor in our project is the Software subsystem. It is the “brain” of the project and it is imperative that it function correctly. It performs many critical functions which have been evaluated below :

- The subsystem determines the path that the person needs to take using the appropriate algorithms. If the algorithm is not efficient and/or correct, the person stands to lose a lot of time in the navigation and potentially enter unfamiliar environments.

- The software needs to understand the map of the place accurately to give directions. If navigating around a dangerous environment involving steps and other obstacles, it is crucial that the person is given the correct information regarding the path otherwise it could lead to injury.

- The location tracking function of the subsystem needs to be precise. The IMU data can have errors which the software needs to recognize. This needs to be detected such that the person can be warned of their deviation and don’t stray away from the ground truth path.

There are various concerns and things we need to keep in mind when we build this device from a safety standpoint, few of which have been elaborated:

- Individuals using this device are visually impaired and it might be difficult to get used to functionalities of the device and build trust. We recommend a helper who will be around the person for the first few uses and report inaccuracies, if any. This will help with the person being more confident in environments that have these devices.

- We are using a beeping mechanism to indicate the deviation from the path by the user. Often sensory nerves get more sensitive with age so the testing of this component will be conducted to make sure the pitch of the sound is not harmful to the ears and a researched value for frequency of the beep will be selected.

- Our project relies on wifi access points to keep the IMU data error from building up. We all face connectivity issues for whatever reasons and this device is not immune to those either. The benefit of having multiple access points is that even if one of the wifi networks is down, we can rely on the others to be functional enough and mitigate the error.

Our project also addresses various ethical issues that accompany this project. It accounts for the challenges that visually impaired people have to face when going about their routine.

- Since a very small subset of people face the challenge we are tackling, not enough people are working towards improving their lives. This project serves an attempt to popularize the struggles of people and promote more research in similar fields.

- In accordance with the IEEE Code of Ethics which states that we need to be honest and realistic about the claims made in the project, we are designing this project with a solid backing of research papers that have taken up similar experiments with very promising results.

- The IEEE Code of Ethics also states that we should seek and accept criticism of our work and to acknowledge and correct the errors. We realize that this project has a few moving parts which leads to an opportunity to optimize things and hence are willing to incorporate any constructive suggestion we get in the lifetime of the project. The errors expected will be stated clearly so that users are aware of situations and how to work around it [5].

We acknowledge the challenges we face ahead of us to make this project as safe for the user as is possible while also complying with the code of ethics specified by IEEE. We have procedures in place to help us achieve both such that we can guarantee the best experience for the individual.

3.4 Project Improvements

Our understanding is that this project is not perfect and we have identified a few channels for improvement. GIven a more ideal situation and a longer time duration on our hands, we would have worked on the following aspects of our project -

1) The fastest route is not always the best route. We recognize this principle as it is very relevant to our project. Currently, our project only has the capacity to calculate the shortest route within the environmental constraints and suggest it to the user. However, given the additional resource of time, we would like to expand the functionality of our device to include the calculation of various routes and suggest 2 or 3 of the most logical ones. This is a feature which is also utilised in Google maps which gives more than just a single route to get to the preferred destination. This additional feature will enhance the usability of our device and benefit the user.

2) An important characteristic of the device which can greatly impact the experience of the user is the physical feel of the device. Humans are very receptive to haptic feedback which is why phones take the shape they do and other things we touch in our daily lives. We were not able to conduct experiments into testing the physical design that we have proposed as any “furnished” product will require focus on tuning the physical traits. With more time on our hands, we would have bounced around a few designs involving various materials, shapes and the overall feel of the device to come up with the most user friendly version.

3) On the subject of making the device more user friendly, a great feature to have would be to make the device rechargeable. Currently, our design makes use of batteries which does not guarantee safety against a potential power loss during the use. We have considered using warning signs for low battery indications, but having a port for charging using USB-C/ MicroUSB cables would make the device way more practical for today’s world. We are seeing the emergence of charging stations in a lot of public places like subway stations, airports etc and making this device compliant to such environments adds to the comfort level of the user while handling this device.

4. First Project Progress

As a part of our initial implementation, we decided to focus on the hardware components and creating a physical prototype. We proceeded to build a circuit consisting of the toy car, hooked up to the arduino and a flex sensor connected to a breadboard. Further, we tested the functionality of the flex sensors to ensure the speed dependency on the resistance.

Figure 14

We tested whether the device at around 7mph, stops within the calculated time. It does stop and we calculated the speed Since the maximum allowed velocity is 7mph as described in the tolerance analysis

$$u_{max} = 7mph = 3.12928\ m/s$$

We use the formula:

$$\alpha = \frac{{v_{current}}^2}{2.5}$$

$$\alpha = \frac{(3.02)^2}{2.5} = 3.64816\ m/s^2$$

At this, the distance covered was 105m. These are both below the max and min as mentioned in the tolerance analysis.

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