Smart Baby Buggy

Final Report

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Abstract

Visually impaired parents face multiple issues when taking their babies out, as pushing a baby buggy while having to use a cane is a difficult and inconvenient task. They often resort to pulling the baby buggy behind them while using their cane to scan their surroundings, looking for obstacles and braille bumps (small bumps on the pavement or floor of public places that help the Visually Impaired navigate the urban environment). This practice is cumbersome and dangerous for both the parent and the baby. The smart baby buggy aims to solve this by using an integrated sensor-feedback system to guide them. It allows parents to push the baby buggy safely, avoiding the main hazards to the user in a quick and reliable manner. This will hopefully improve the quality of life for visually impaired parents and encourage them to take their children out on the buggy, now that the process is made simpler and safer for them.

The integrated system is composed of 6 ultrasound sensors that enable the user to detect obstacles in the immediate vicinity of the buggy (in the front and sides). A LiDar sensor is additionally used at the front to detect obstacles at a longer range to guarantee additional safety. All this data is then sent to the processing unit, where it is processed and used to drive vibrating motors that will provide haptic feedback to the user. This will convey information about position and proximity of the obstacles by varying intensity and frequency. Finally, a mobile app for both Android and iOS were also developed. The app uses a machine learning model to detect changes in terrain such as curbs and braille bumps, this information is then sent to the user as audio cues via an earpiece. This ensures that the user stays on the pavement and is informed about pedestrian crossings ahead.

Contents

Introduction

According to the Registered Blind and Partially Sighted People, England 2016-17 publication, there are 19,495 visually impaired persons on the register who are aged 18-49 [1]. A large proportion of this age group consists of new parents but currently there are no viable solution that allows visually impaired parents to push their baby or child in a buggy safely outside.

People who suffer from sight loss use a walking cane to probe a radius around them as a means of locating obstacles in their path of travel. The difficulty increases exponentially for visually impaired parents when they struggle to find a balance between pushing their buggy with one hand while using their walking cane on another. Swivel wheels may be an advantage to normal users of the baby buggy as they enable easy rolling of the buggy. However, these wheels pose a serious disadvantage to visually impaired parents as it makes it harder for steering and manoeuvrability - especially when using only one hand. As a result, most visually impaired parents tend to pull their buggy behind them, so that they can easily detect obstacles ahead of them with their walking cane. Whilst commonly used, this method leads to the child being positioned behind the parent and limits their reaction in cases when the child is in danger, which is a clear safety concern.

The Baby Buggy Project was initiated by Ramona Williams, the founder of Eyes for Success London, as she realized the severity of this problem and approached Imperial College London to help her address it.

Project Aims

The aim of the project is to develop a hazard awareness system consisting of an integrated system of motors and sensors.

The four main aspects stated in the PSD specifications are as follows [2]:

Functionality & performance, usability, safety & security and life, reliability & maintenance.

1) Functionality & performance: The sensors must be able to detect obstacles with a surface area larger than 50cm^2 at distances under 1m in front of the buggy and 20cm along the sides. It must also be able to measure a minimum change in height of 10cm as well as detect braille bumps that are 20cm away. Users will then be provided with sensory feedback in real-time whenever an obstacle is detected as specified above.

2) Usability: The final design should be user friendly and easy to understand and assemble. It must also be compatible with different baby buggy models.

3) Safety & security: The electrical equipment must be protected against wet weather conditions so that the user will not be susceptible to electric discharge or any prototype malfunctions. Moreover, the feedback system should not interfere with the user's other senses.

4) Life, reliability & maintenance: The accuracy of the prototype must be ensured to minimize errors in detection, such as giving false positives.

The importance of this project is highlighted by the fact that while visually impaired parents have various methods they employ to ensure overall safety, each of the methods has its own drawbacks and currently there is no technology available on the market that addresses this problem.

Objectives

With the aims of the project defined above, the project will then be broken down to several stages and teams will be formed to ensure a smooth development process. This project management structure is represented by a Gantt Chart (Appendix A).

Definition of Sensor and Feedback System Functionality

Considering user and technical requisites, the initial design will be split into two main parts and two groups will be formed - sensory detection and feedback system. The former should include testing a range of sensors for obstacles, braille bump and curb detection and the latter utilizing vibration motors as a form of haptic feedback output to the user upon detection of input from the sensory system. Multiple drafts of system design will be made to ensure these features are progressively upgraded to satisfy user requirements. In addition to functionality of the individual systems, components should also be specifically designed to improve ergonomics and user interface as well as to be able to fit in the limited space available on the buggy. Finally, the circuitry of the systems will be simulated using OrCAD Capture before being physically implemented.

Functionality and Data Interpretation

The individual systems will be tested empirically for viability before being integrated together as one complete product for final testing. This will include testing for detection of obstacles, user feedback, range of operation, and power consumption. Sensory output will be interpreted using a simple program to show clear characteristic input detection and analysis will be done by a graph plot included in the code of the program at the end of supplied input. Feedback for braille bump and curb detection will be assessed using an in-app program which will be able to indicate performance of detection in terms of percentage success rate. Haptic feedback testing will consist of exploring various haptic languages to ensure the best user satisfaction.

Processing unit and Programming Language

Following thorough research, it was determined that the optimal processing units for such a system are either the Arduino or the Raspberry Pi. The appropriate processing unit will then be used as the foundation for the prototypes of the obstacle and feedback system. The programming language used will depend on the processing unit, with the Arduino and Raspberry Pi demanding the use of C and Python respectively. With regards to braille bump and curb detection, a mobile phone will be used through the development of an app which uses machine learning to detect input. The processing language for the app will be Java for Android and Swift for the iOS version.

Usability and Compatibility

Focus groups will be conducted with the help of Eyes for Success and potential visually impaired users will be asked to provide their feedback thus ensuring the usability of the prototype as well as its compatibility to multiple users. Additionally, the possibility of using prototypes on different brands and designs of buggies will also be explored.

Power source

Throughout the stages of the prototype development, the power requirements of the prototype will be identified such that an ideal power source can be determined. Keeping in mind that infants will be occupying the buggy, the power ratings must be low to ensure safety of the toddler in addition to the user. Collectively, the power source should be able to sustain the prototype with a desirable battery life.

Final Design

Upon finalization of the system design, prototype circuit schematics will be produced and simulated on OrCAD Capture. Then, the circuit will be created on a breadboard to ensure expected operation. Finally, printed circuit boards (PCB) implementing the same circuitry will be produced. Casings and mounts for the respective systems will be a combination of purchasing of basic materials and 3D printing.

Public Demonstration and User Feedback

As discussed previously, before the completion of the final prototype, user feedback from targeted focus groups from Eye for Success will be obtained and after refining the prototype, the final prototype will be demonstrated publicly. Feedback from all the public usage/demonstration of the prototype will help in optimizing the system for peak performance.

Requirement Definition

1. **Functionality and Performance**
    a. Obstacle Detection - Able to detect obstacles with a surface area larger than $50cm^2$ at distances under 1m in front of the buggy and 20cm to the sides.
    b. Depth detection - Able to measure a change in height of minimum 10cm as well as detect braille bumps at 20cm away.
    c. Feedback to the user - Provide user with sensory feedback whenever an obstacle is detected as specified above.
    d. Storage system - Secure the white probing cane and allow easy access to mobile phone.
    e. Visually impaired Identifier - Identifying the user as visually impaired with a sign.

2. **Size and Weight**
    a. Lightweight - Should not account for more than 20% of the buggy's weight, limited to 2kg.
    b. Compact - Should not account for more than 15% of the buggy's dimensions.

3. **Usability, Interface and Ergonomics**
    a. User friendly - Device should be easy to understand and quick to assemble.
    b. Storage - The prototype shall not impede the folding of the buggy.
    c. Compatible - Easily integrated to different buggy models.
    d. Comfortable - Feedback should not cause discomfort to the user.

4. **Safety & Security**
    a. Maintain the baby buggy's safety specification - Attachments should not affect the safety standards of the buggy.
    b. Isolated electrical system - The electrical system shall not endanger the baby or the user.
    c. Water resistance - Protection of electrical equipment against wet weather conditions.
    d. Feedback system does not obstruct senses - The feedback system should not interfere with the user's senses (particularly hearing).

5. **Life, Reliability and Maintenance**
    a. Battery Life - The whole system should last for a minimum of 4 hours, for every full charge.
    b. Lifespan - Prototype operational for a minimum of 1 year (under responsible usage).
    c. Maintenance - Modular design, system should not be compromised or rendered unusable due to individual faulty or worn components.
    d. Accuracy - Minimise the errors in detection (such as false positives) of the prototype.

6. **Cost**
    a. Affordable - Overall cost of the prototype, excluding the buggy, should not exceed £300.

Technical Requirements

1. **Software:**
    a. A machine learning model that can consistently identify both Braille bumps and Drop-off points. The model must also classify the terrain ahead within 1 second.
    b. Code for obstacle detection for Ultrasound Module (Arduino) should use small processing power.
    c. Code for the obstacle detection with the LiDar should be used with Arduino, utilizing the libraries made available by the provider. Due to the faster readings, more processing power will be needed, thus requiring the usage of an Arduino Mega or superior.

2. **Hardware:**
    a. Vibrating Motors should not overheat causing discomfort to the user.
    b. Vibrations from vibrating motors must not affect the baby.
    c. Rechargeable battery.
    d. Voltage regulated at 5 Volts to power Arduino and Vibrating motors.
    e. Power source must have the capacity to output 2A to the circuit.
    f. Front sensors capable of obstacle detection in the range of 0 to 5 meters.
    g. Side sensors must have enough sensing ability to detect obstacles in the range of 0 to 2 meters.
    h. Sensors must be able to function normally regardless of terrain.

3. **Physical:**
    a. Materials for the grips around vibrating motors:
        i. Breathable
        ii. Elastic (dampen the vibrations)
    b. Materials for the casing of the LiDar sensor:
        i. Waterproof
        ii. Clear
    c. The casing for the LiDar must be held securely to the bottom of the buggy and capable of withstanding the constant vibrations due to the terrain.

Background Research

To optimize the research necessary to design a functional smart baby buggy, separate teams were created focusing on two different aspects of the project: Sensory detection and Feedback system. Additionally, research was conducted to identify user requirements and guide the design of the project.

1. Sensory Detection

In terms of sensory detection, research was conducted to examine the compatibility of a variety of readily available sensors for this project.

- Infrared
- Ultrasound
- Rotation of a single sensor
- Light Detection and Ranging (LiDar)
- Image recognition

Sensor/ Factors	Range	Accuracy	Hazard detection	Cost
Infrared	10-80 cm	Gets distorted heavily when exposed to external noise	No	Low
Ultrasound	20-200 cm	Thicker, "furry" clothing such as jumpers and coats tend to provide diminished reflection of ultrasound waves	No	Low
Rotation of a single sensor	20-200 cm	Has the same issues with the stationary Ultrasound sensor used and even lower accuracy due to rotating element	No	Mid
Light Detection and Ranging (LiDar)	40m	Good coverage (360 degree) and instantaneous response	No	High
Image recognition	20-60cm	Gives false positive sometimes	Yes	Mid

Infrared Sensors:

Infrared sensors have a range of 10-80 cm [3], which means it only permits the detection of close obstacles. In addition, infrared distorts heavily when exposed to external noise. These two factors result in a level of inconsistency and risk that is unacceptable when considering the safety of the baby.

Ultrasound Sensors:

HC-SR04 ultrasound sensors were tested and proven to be consistent within a range of 20-200 cm [4] [5], in alignment with the requirements set. A notable drawback of ultrasound sensors for this application is that thicker, "furry" clothing such as jumpers and coats tend to provide diminished reflection of ultrasound waves. This results in weak returning signal and hence unreliable measurements of distance.

Single rotating sensor:

One sensor is not enough to cover 180 degrees. Rotating the sensor solves the problem but greatly increases the probability of errors occurring. An alternate solution is to use an array of multiple sensors, which will be easier and produces the same effect while increasing reliability.

Light Detection and Ranging (LiDar):

LiDar is a time of flight sensor that measures distance by emitting laser pulses to a target and measuring the reflected laser pulse [6]. A device that could be used is "Sweep" by Scanse, which is a rotating LiDar device with a detection range of 40m that is able to capture readings of a 360 degrees radius. The maximum sampling rate is 1000Hz with up to 10 complete turns per second [7]. The swift and precise reading from the LiDar would ensure optimal hazard detection in all angles. Furthermore, the range provided by the LiDar greatly outperforms ultrasound. This will be of great benefit especially for the front sensing, which requires longer distance readings for improved security [8].

Image recognition:

The white probing cane plays a big role in helping the Visually Impaired detect hazardous road terrains. It aids in the identification of braille bumps, which signifies the path available as well as pedestrian crossings. At the same time, the walking cane also helps notice a drop-off when walking on the pavement. Ultrasound and LiDar sensors fail to detect terrain patterns such as braille bumps.

Both Android and iOS apps were created, to detect curbs, pavements and braille bumps using image recognition. For this, a machine learning model was incorporated to differentiate between the terrain patterns, using a live feed through the phone’s camera. The overall precision of the machine learning model is 80.1%. The accuracy of the app increases to 87% when only the factors that affect the Visually Impaired most, braille bumps and curbs, were considered.

2. Feedback System

To design the feedback system, research was conducted by accessing various publications on the internet and interviewing experts, such as engineers from smrtGRiPS (a company that produces systems relevant to this project) [9]. This information was distilled, and the three most intuitive and user-friendly potential systems were identified.

- Braille Display
- Audio feedback
- Haptic feedback

Braille Display:

Braille is by far the most common tactile writing system used by visually impaired people. When tackling a similar problem, a group of MIT students utilized a Braille Display Module that was able to effectively convey information to the user about their surroundings [10]. This was initially selected as the prime feedback system because the technology was already in the market and it would be time conserving for this project. However, this method was ruled out due to two facts. Firstly, reacting to the Braille Display Module is not instantaneous even for the most experienced Braille user, which introduces a safety risk in cases of emergency such as having to make quick adjustment to avoid crashing into a moving obstacle. Secondly, as this is a tactile method, one hand of the user will be required to translate what is displayed on the Display Module, while the other hand will be pushing on the buggy. Controlling a buggy with one hand is dangerous and potentially life-threatening for the baby [11].

Audio Feedback:

Audio feedback was identified as one of the most intuitive ways to relay information regarding obstacle position and distance to the user. It is also an effective method of warning the user of immediate hazards, such as road crossings or curbs. However, the effectiveness of this approach is limited as visually impaired users often utilize audio navigation systems to guide them through the city. It was considered that multiple auditory inputs could confuse the user's senses and cause disorientation. Hence, it was not chosen as the main source of feedback.

Haptic Feedback:

Incorporation of wearable technologies like shoes, gloves and belts was considered as it allows for non-intrusive haptic feedback. A potential approach that was examined was the use of a belt with vibration motors attached that would be worn by the user. The final design is based on a similar concept, the placement of vibration motors on the handle that provide a user-friendly experience [12, 13].

3. User Requirements

An initial meeting was set up between the group and Ramona Williams, who first came up with this project, to gain further insight on the difficulties she faces and the needs she hoped the project would address. A workshop was conducted for the team to better understand how it felt to be visually impaired and hence, to determine the requirements of the target audience.

Final Design

I. Overview

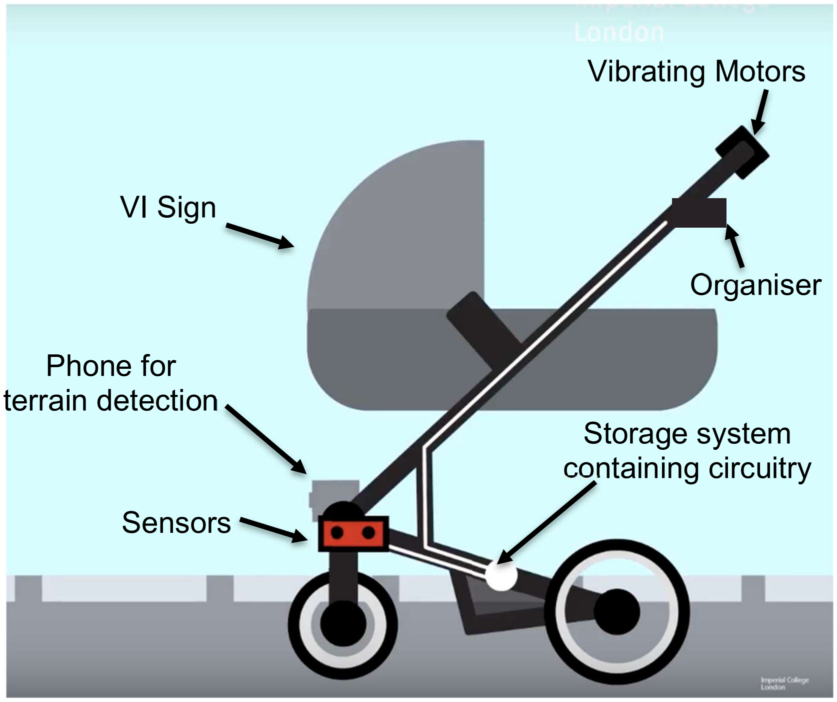

Figure 1. Overview of Final Design (Illustration) [14]

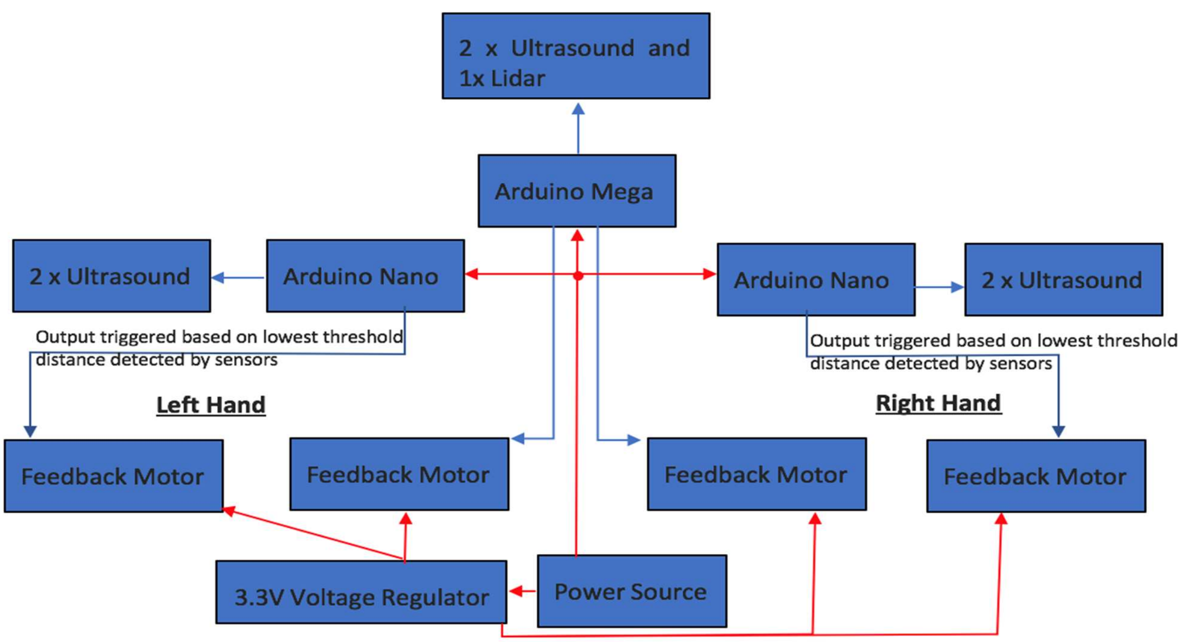

Figure 2. Overview of Final Design (Flowchart)

Figure 1 shows the overview of the prototype and figure 2 shows the flowchart of how the prototype functions. A power source provides the power required to drive all components. Two ultrasound sensors are used at either side of the buggy to track obstacle distance. The program takes in distance values from both sensors, finds the minimum and if it is subthreshold, it will trigger an appropriate output. Similarly, on the front, there are two ultrasound sensors and one LiDar sensor that detect the distance of obstacles, compare their values and trigger the appropriate output. Figures 3 and 4 below show the actual final prototype on the buggy.

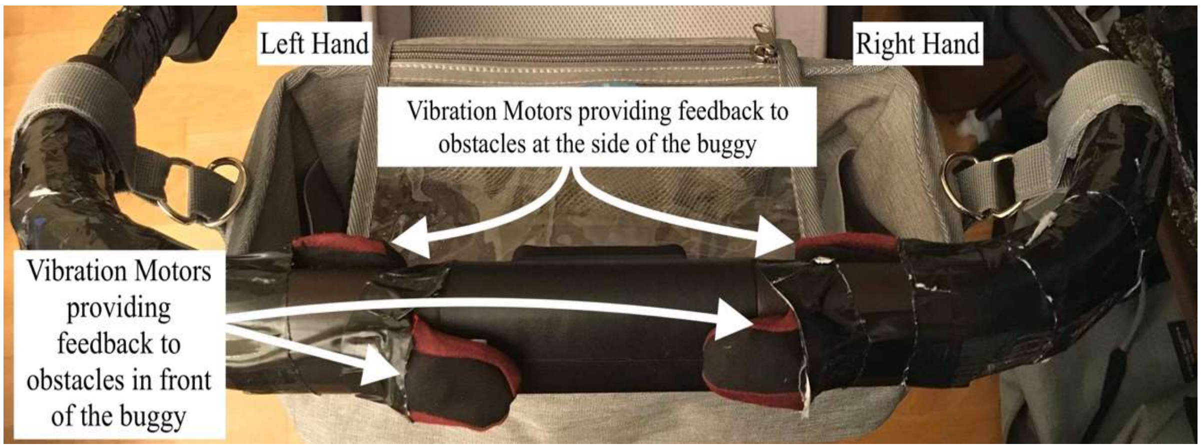

Figure 3.

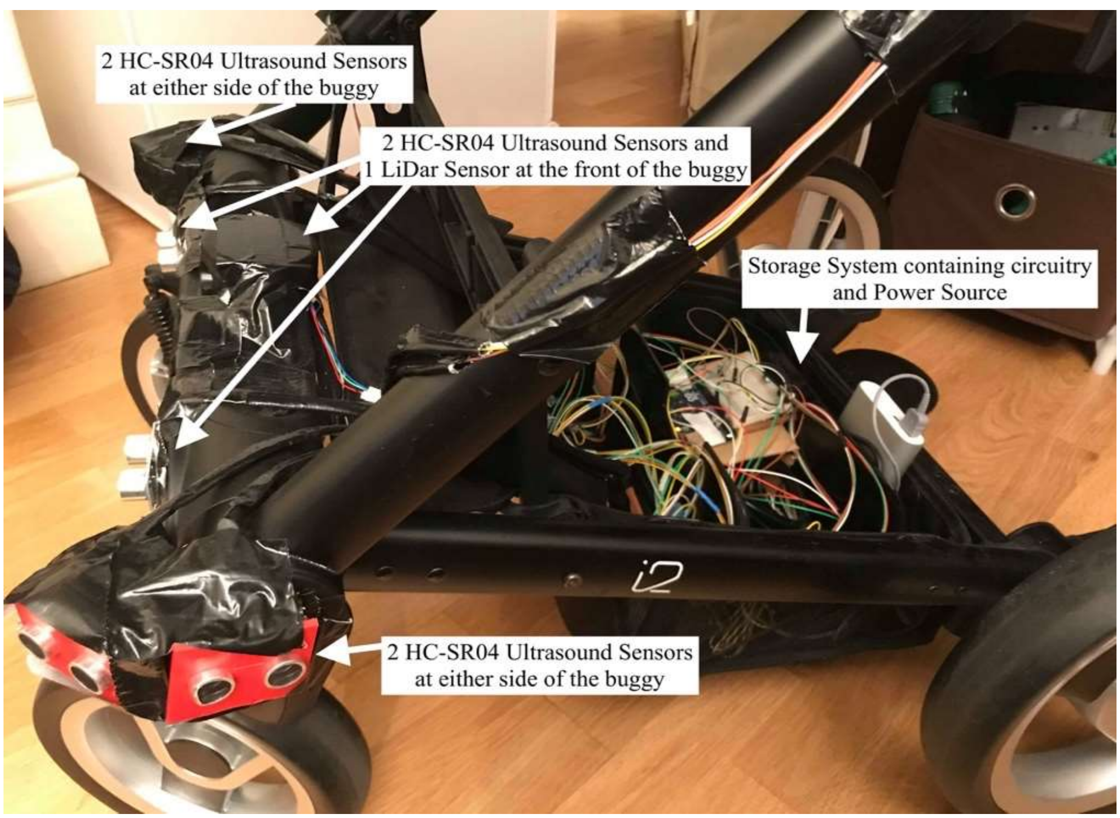

Figure 4.

II. Mechanical Design

1. Storage system

Figure 5.

Figure 6.

The circuit and processing units were stored in plastic boxes in order to maintain order over the wiring and provide protection. Figures 5 and 6 show the plastic boxes used to store the circuitry and the wiring in a compact manner to ensure neatness and unexposed wires. These boxes were stowed at the bottom of the buggy as can be seen on the images above.

2. Organizer

Figure 7. [15]

Figure 8. [15]

A grey organiser bag (figures 7 and 8) is attached to the buggy at the handles for additional storage space. This bag is especially useful for the easy access of the user's mobile phone and white cane.

3. **Ultrasound Casing**

Figure 9.

One of the main concerns that surfaced during the initial stages of prototype development was the fragility of the ultrasound sensors. To solve this, a CAD file of the casing for ultrasound sensors was designed using Autodesk Fusion 360, which was later 3D printed. 3D printing was preferred over other manufacturing methods due to its versatility, availability and low cost. The final ultrasound casing is shown in figure 9.

4. **Handle Sleeve for vibrating feedback motor**

The vibrating motors were put into sleeves to dampen the vibrations and eliminate the risk of electric discharge injuring the user. A dampening material called “Sorbothane” was used in the making of vibration sleeves. Multiple layers of Sorbothane were fitted into the sleeve after the dimensions of the sleeve were taken. The vibrating motors and Sorbothane sleeve were then glued together and attached onto the handle of the baby buggy.

III. Hardware

1. **Arduino (Control Module)**

A total of 2 Arduino Nano and 1 Arduino Mega were used. The use of the Arduino platform is justified due to its compact size in addition to easy and quick prototyping. The Arduino Nanos were easily soldered onto stripboards to create a neater and more reliable circuit. The choice of using an exclusive “Arduino-only” circuit, facilitated the design process, since the whole system could then be programmed using exclusively the C programming language. The first trials were programmed using a mix of Raspberry Pi and Arduino, however, the use both Python and C concurrently proved unnecessary complication. This led to a decision to use only Arduino in the final prototype. An additional advantage of Arduino, is its large online community and abundance of open source libraries to interface a variety of hardware.

2. Sensors

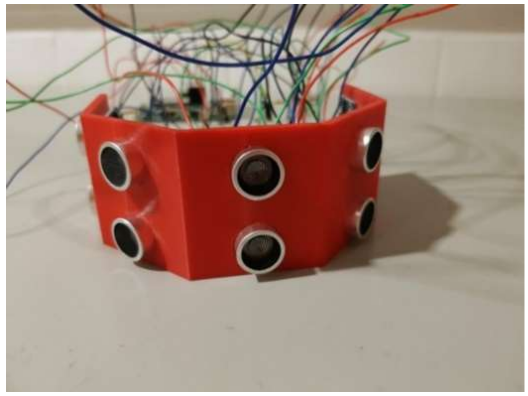

Figure 10. Initial prototype for testing HC-SR04 sensors

In the Final Design of the prototype, a total of 6 HC-SR04 Ultrasound Sensors and 1 LiDar were used. The ultrasound sensors were primarily used for detection of obstacles to the sides of the buggy and the LiDar sensor primarily used for detection of obstacles in front.

The HC-SR04 sensor was chosen due to its affordability, availability and its ability to detect obstacles reliably. Additionally, it only requires a small current of 15mA to function and has a reliable effective range of 20-200cm. Its small compact size results in a 30-degree angle of coverage, but this was easily compensated by using more sensors for wider coverage. For example, figure 10 is a cascade of 5 HC-SR04 sensors used in the initial testing stages that covered a 180-degree range.

Trials with infrared sensors were conducted during the early stages of the project. This technology was later abandoned due to unreliability and limited effective range.

LiDar was used to detect obstacles in front of the buggy. LiDar is a detection and ranging sensor that measures distance by illuminating the target with pulsed laser light and measuring the backscattered or reflected light pulses. Differences in laser return times and wavelengths can then be used to make a digital representation of the target [16]. SparkFun Electronics were generous to sponsor the project and provide the Scanse Sweep 360 Degree Scanning LiDar, allowing the team to experiment with a more accurate sensor.

The Scanse Sweep LiDar has an effective range of 40m, an adjustable sample rate and rotation frequency (10 rotations per second, sampling rate of 1000Hz) and a low 450mA current requirement. These specifications result in the LiDar sensor giving an accurate representation of the 2-D plane. During the lab tests, it was found that prolonged use of the rotating LiDar causes the motor to overheat and temporarily stop functioning. This issue was overcome by detaching the LiDar from the rotating mount and using it as a fixed sensor, resulting in loss of 360-degree coverage. This decision was justified as the LiDar could be used only to detect obstacles to the front, while ultrasound sensors could be used to cover other directions.

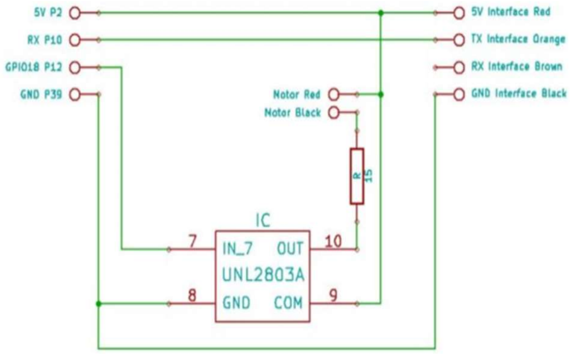

Figure 11.

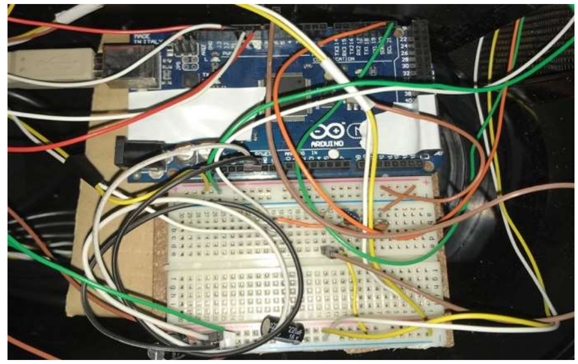

Figure 12.

Figure 13.
Side sensors (Ultrasound sensors in red)
and front sensors (Ultrasound sensors and LiDar in blue and black)

Figure 11 shows the OrCAD Schematic of LiDar. Figure 12 shows a picture of the circuitry of LiDar. Figure 13 shows the final design of the sensors mounted on the buggy. Two HC-SR04 ultrasound sensors were mounted on each side of the buggy and the front of the buggy was mounted with 2 HC-SR04 sensors and 1 LiDar sensor. The overall set up allows elimination of blind spots and provides optimal obstacle detection. A copy of the codes for the sides and the front are included in the references [17] [18].

3. Vibrating Motors

Figure 14. Vibrating Motor (Rb-See-403) [19]

2mm mini vibrating disk motors, shown in Figure 14, were chosen to provide haptic feedback to the user. This is due to their affordability, small size and vibration intensity. A copy of the datasheet is attached in the references section [20].

3V are required for the motors to function, which is easily provided using a 5V power bank. The strength of the vibrations can be modulated, which is incorporated in the final haptic language code. An increasing intensity indicates that an obstacle is drawing nearer. In addition, the size of the motors allows for convenient placing on the buggy handle and does not cause discomfort for the user.

The final product consists of two motors on each hand, placed at a large enough distance to each other that vibrations are isolated, and no overlap is experienced. In terms of position, one motor is situated where the user would place their thumb and the other where the user's other fingers would be placed. This placement was found to be optimal, as it allows the user to easily distinguish which motors are vibrating. It also enables the user to comfortably hold and push the buggy around.

The motors vibrate according to the input received from the sensors and provide the user information about their surroundings through a haptic language that can be easily understood.

4. Power Source

A portable USB power bank of output 2.1A was sufficient to drive the whole circuit. A portable charging source provides convenience and aligns with the PSD specifications for the prototype to use rechargeable batteries. Moreover, the large capacity of readily available power banks allows the system to run for at least 4 hours.

5. 3.3V Voltage Regulator

Figure 15.

The vibration feedback motors require an input of 3V. The rest of the circuit requires an input of 5V. To ensure that only one power source is used and to prevent overheating and failure of the vibration motor, a voltage regulator is implemented. The specification sheet of the voltage regulator is included in the reference section [21]. The circuit for the voltage regulator is shown in figure 15.

6. Combined Circuit

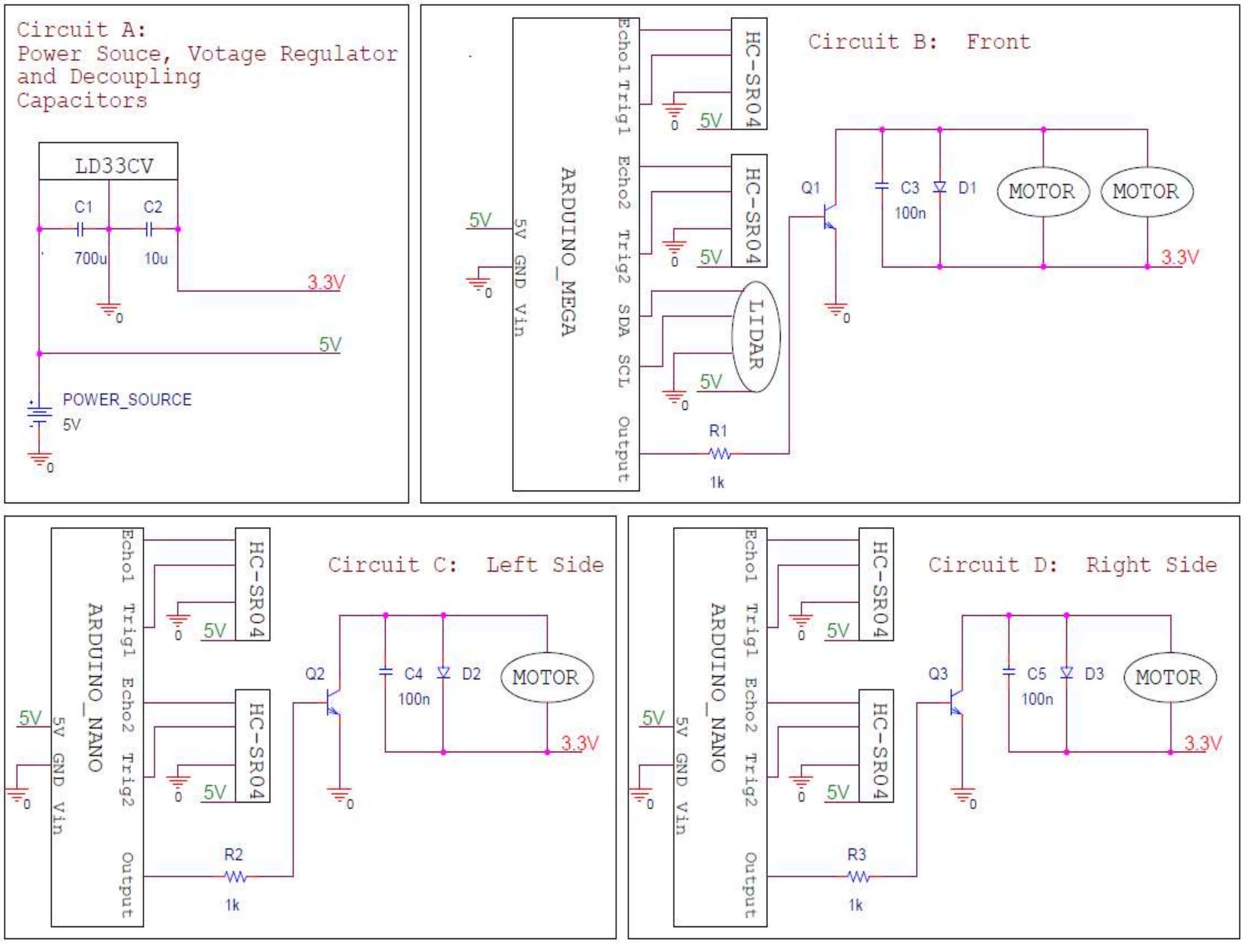

Figure 16. OrCad Schematic of combined circuitry

Figure 16 shows the complete circuit design consisting of four blocks.

Circuit A is made up of the power source, an external power bank (20,000mAh, 5V at a maximum of 2.1A) that creates the 5V rail, the LD33CV voltage regulator (outputs 3.3V at a maximum of 0.8A) that creates the 3.3V rail and two decoupling capacitors to eliminate AC distortion on both the 3.3V and 5V rail.

Circuit B consists of an Arduino Mega powered directly by the 5V rail, two HC-SR04 ultrasound sensors, and a LIDAR sensor powered by the 5V rail, two vibrating disc motors powered by the 3.3V rail and a transistor circuit that controls the motors. Note that the Arduino is powered through the 5V pin thus bypassing its internal regulator and allowing the use of a 5V power source, whereas otherwise more than 6V would be necessary for consistent operation.

When one of the sensors detects an obstacle at a subthreshold distance, this distance is converted through an experimentally determined function into frequency and a 5V square wave of this frequency is outputted, resulting in the motor vibrating at this frequency. Given that the vibration intensity decreases with frequency, this is an effective way of conveying the obstacle distance to the user.

In case multiple sensors detect a subthreshold distance, the distances are compared, and the smallest dominates and is used as input to the motors. As the current output of the Arduino is low, a transistor is required to drive the motors. The transistor works as a voltage-controlled switch, thus the low current capability 5V square wave outputted from the Arduino is effectively converted into a 3.3V higher current capability square wave across the motors.

Finally, a protection circuit consisting of a capacitor and a fly-back diode is connected in parallel to the motors.

Circuits C and D each consist of an Arduino Nano powered by the 5V rail (again note that the internal regulator is bypassed), two ultrasound sensors as well as a vibrating motor along with its control and protection circuits. The operation is the same as in Circuit A with the exception that there is no LIDAR unit and there is only one motor.

Thus, in the complete circuit there are 4 motors each operating at under 100mA (a combined 400mA at full load) which means that the 0.8A maximum current at the 3.3V rail is enough to safely power the motors. Additionally, there are 1 Arduino Mega, 2 Arduino Nanos, 6 HC-SR04 ultrasound sensors and 1 LiDar unit (a combined current draw of less than 1A at full load), which means that the 2.1A of the power supply is clearly enough to drive the system even at its maximum load (1.4A).

Finally, the 20,000mAh capacity of the battery suggests that the minimum battery life is 20/1.4 = 14 hours (in practice the average current draw is 1A, resulting in an expected battery life of 20 hours).

7. Braille bump and Curb Detection

Image processing and a machine learning model were used through an Android/iOS mobile application. The camera on the phone takes a live video feed of the terrain and attempts to classify each frame into one of the following categories: braille bumps, curbs or pavements. If the frame belongs to one these categories, a positive response is registered, and the user is notified accordingly.

The background behind machine learning is to recognize the pattern within an image so that it can reliably process and categorize it. To start, a set of training images must be supplied to train the machine learning model. A sample size of one hundred photos of braille bumps, curbs and pavements was fed into the model. The images were tagged, labelled and categorized manually into braille bumps, curbs and pavements respectively.

The machine learning model was created on the Microsoft Azure platform. To illustrate, the platform would interpret the images in figure 17 and 18 below as follows:

Figure 17.
Braille bumps consisting of repeating raised patterns [22]

Figure 18.
Curbs consisting of a straight line with contrasting edges [23]

The application can compare the live video feed in real time with the machine learning model and thus there is virtually no time delay in the detection of potential hazards.

The android application was created using Android Studio and coded in Java. Similarly, the iOS application was developed in Swift using XCode as an environment. Both applications have three main functions, camera activity, classifier, and results view. The functions are described in figure 19 below.

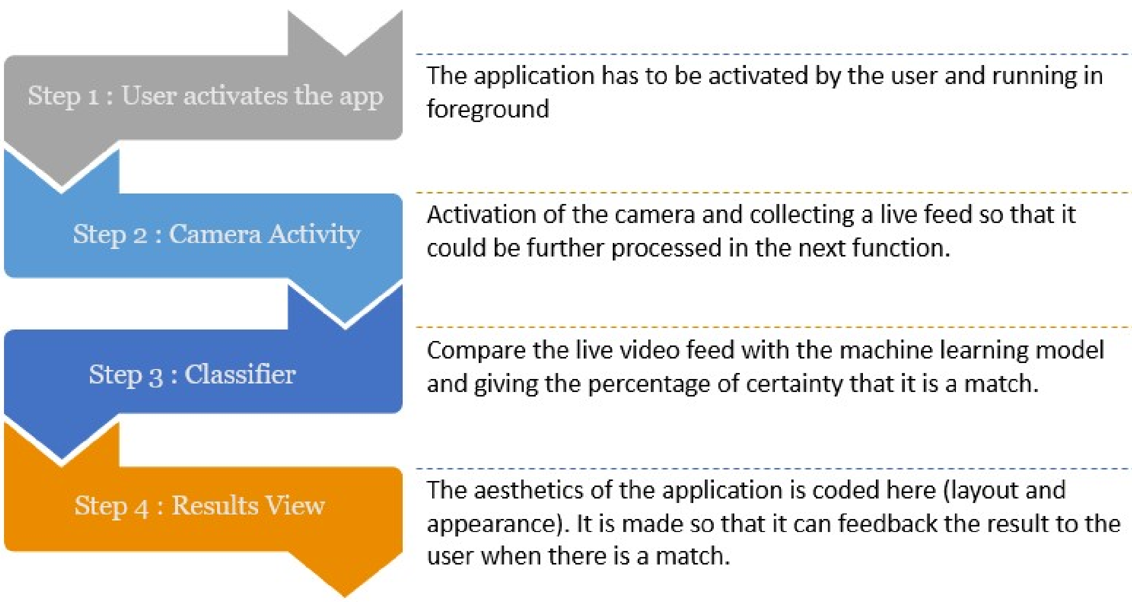

Figure 19. Braille bump and Curb Detection Flowchart [24]

Whenever there is a match, the application will be able to alert the user by sound. The team decided to implement audio feedback as the default way of alerting the user of changes in the terrain, to avoid confusion with obstacle detection which is conveyed through haptic feedback.

8. Feedback Language

Regarding the development of the feedback language, the aim was to create an intuitive haptic language that would provide enough information of the surroundings (direction and distance of an obstacle) and that would be easy to understand for the user.

Initially, three vibrating motors were placed on each handle and two languages were developed.

Language A:

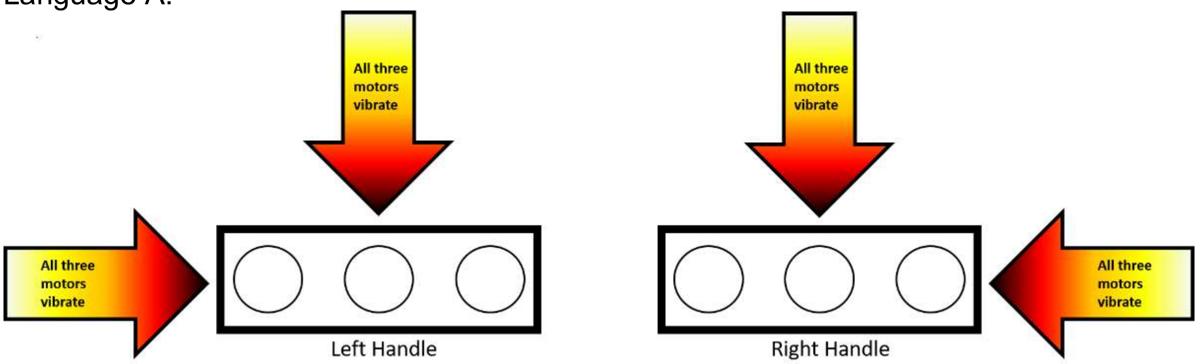

Figure 20.

In figures 20, 21 and 22 the intensity of vibration is represented by the colour gradient. The first language shown in figure 20 was developed with simplicity being the main significance. When an obstacle approached from the left or right, the whole left or right handle respectively would vibrate; and when something would approach from the front, both handles would simultaneously vibrate. However, this language provided little information of the surroundings: the user had limited sense of directionality. Language B was developed as a result and took advantage of the three motors on each handle to give a sense of where the obstacles were coming from.

Language B:

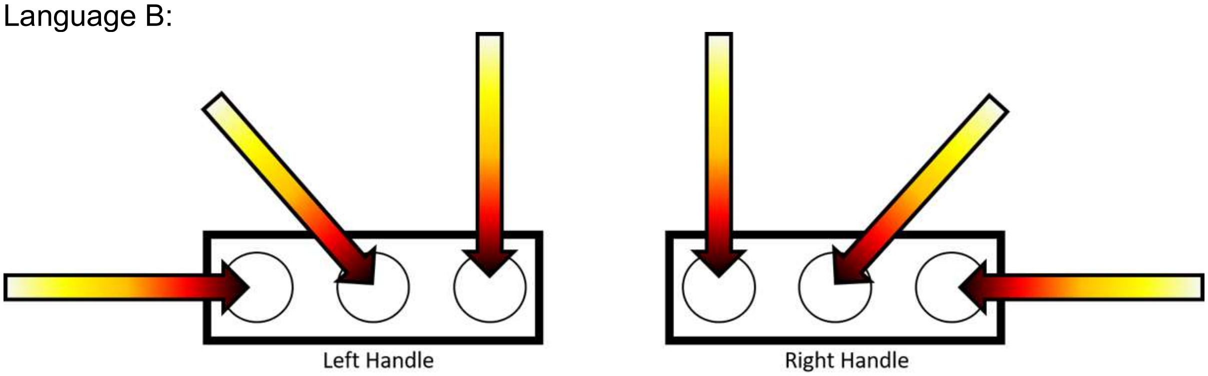

Figure 21.

While the second language (shown in figure 21) could provide more information, it was still unsatisfactory as the vibrations were very confusing due to excessive overlap. Therefore, a third language was developed: a language complex enough to convey sufficient information to the user yet at the same time simple enough to not saturate the user's senses.

The final feedback language was developed with only two vibrating motors on each handle, to simplify the integration of information. To avoid confusion regarding the origin of the vibrations, the two motors indicating the centre were placed on top of the handles (for the thumbs) and the two others indicating left and right were placed underneath (for the index).

Final Language:

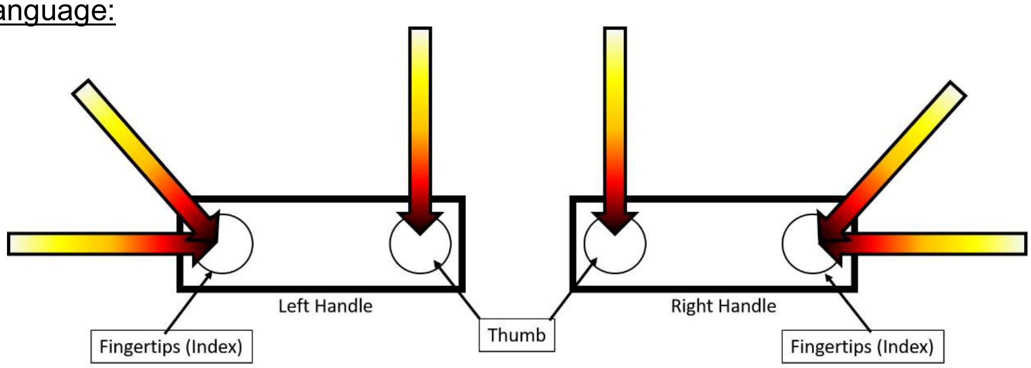

Figure 22.

The motors vibrating under the user's thumbs would provide information of obstacles in front of the buggy while the motors felt by the fingertips provide information of obstacles on the sides of the buggy. After testing this language (figure 22), it was found that vibrations on the fingertips, rather than on the palm of the hand, were much easier for the user to process (location and intensity of vibration). Participants could navigate through obstacles with relative ease when this language was implemented.

IV. <u>Software</u>

For the HC-SR04, LiDar sensors as well as the vibrating motor feedback, code was written in C to comply with the Arduino specifications. For simplicity's sake, the flow chart, shown in figure 23, was created summarizing the main functionality of the program.

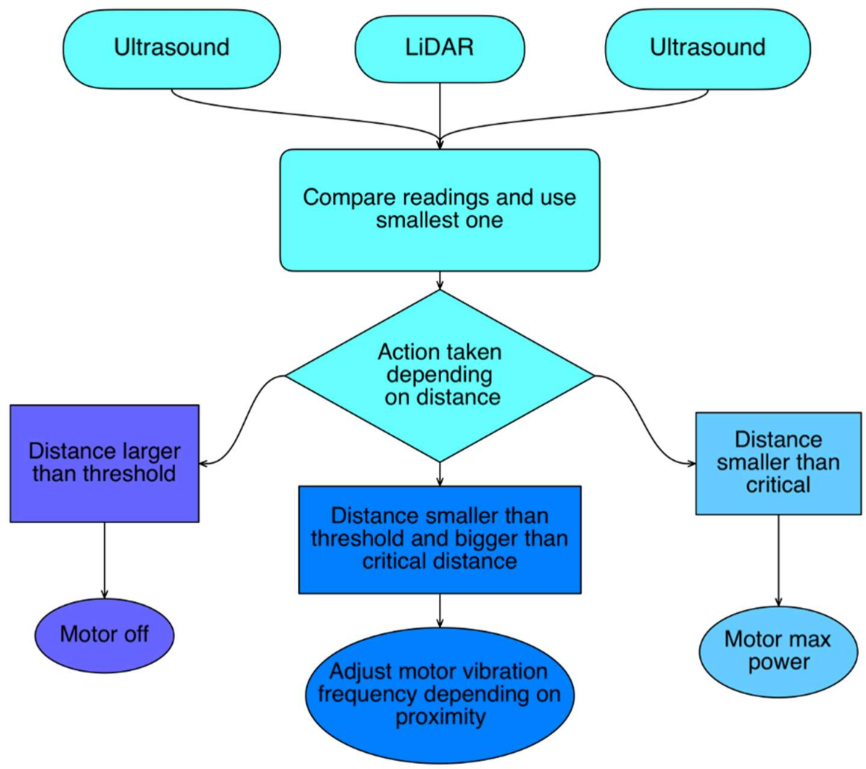

Figure 23.

The braille bump and curb detection application were coded in Java. The Android app was developed using Android Studio, while the iOS app was developed in Swift and using XCode as the environment, which was provided by Apple. The working of both apps has already been described in previous sections.

A more detailed flow chart for the sensor and haptic feedback operation can be found in Appendix D.

Testing and Evaluation

I. Field Testing

1. Sensor Testing

To test the sensors, an obstacle course was set up. The PSD specifications were such that obstacles needed to be detected 20cm to the side of the buggy and 100cm to the front of the buggy. The testing was carried out such that at least two instances of obstacles being at the threshold distance and below were recorded. (i.e. 50cm and below for the side of the buggy as well as 100cm and below for the front of the buggy)

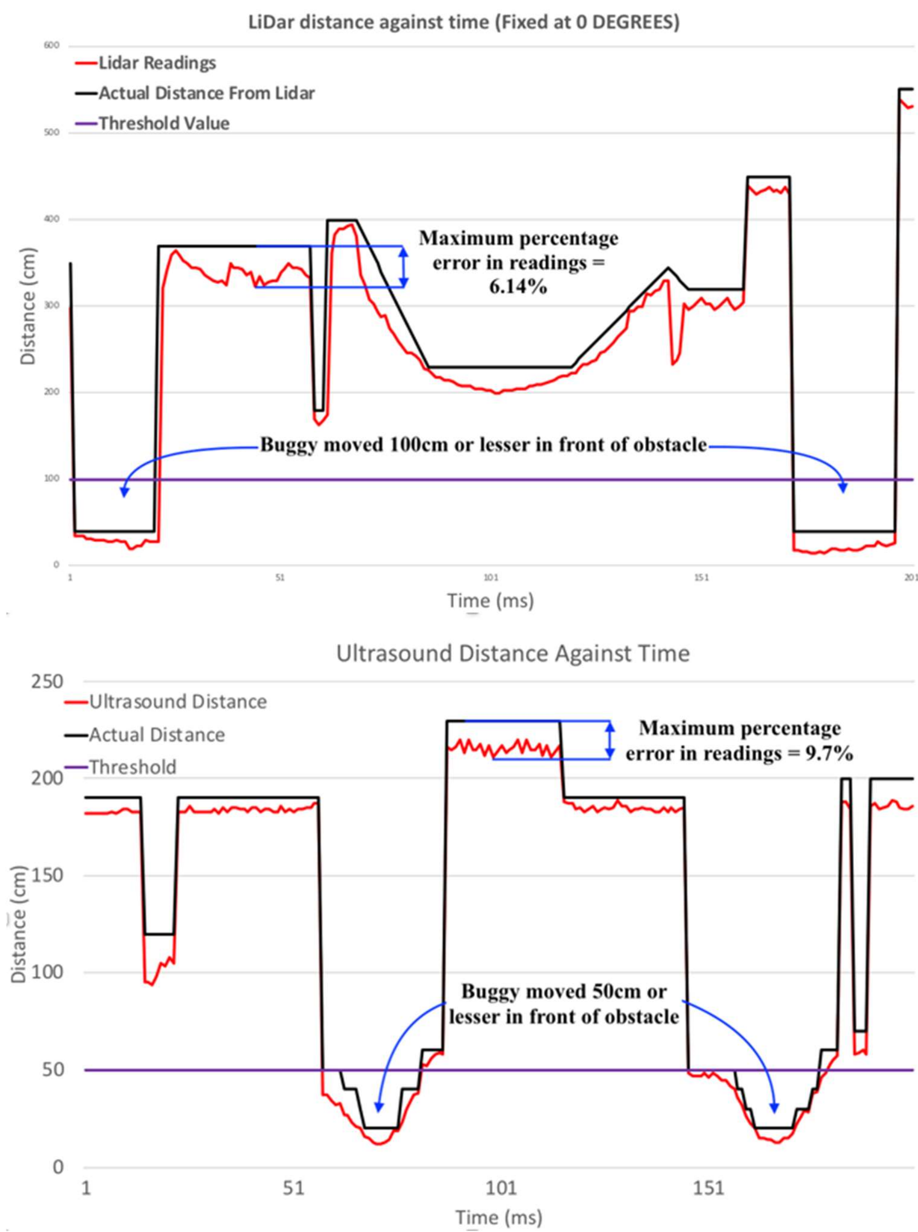

Figure 24. [24]

Figure 24 shows the results from testing the sensors in an obstacle course. The LiDar sensor was able to detect an obstacle 100cm or less to the front of the buggy and the ultrasound sensor was able to detect obstacles 50cm or less to the side of the buggy. The LiDar sensor had a 6.14% maximum error in readings, while the ultrasound had 9.7%. The maximum percentage error readings were calculated using the ratio of the maximum difference between the recorded and actual distance to the actual distance.

2. Braille and Curb Detection

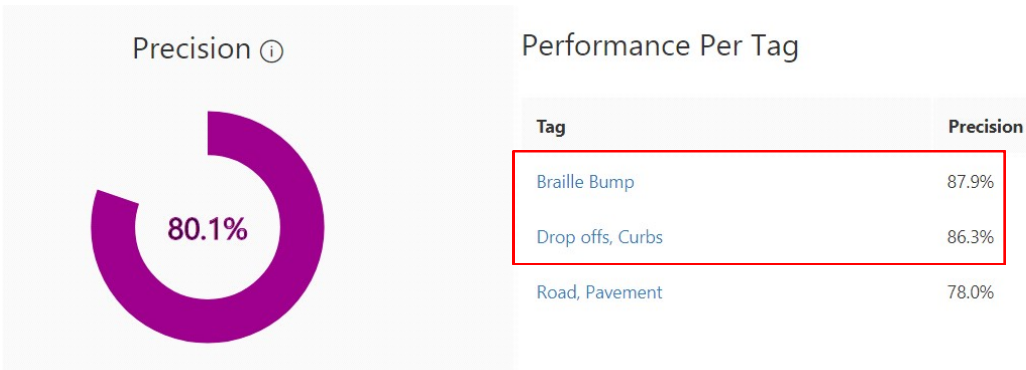

Figure 25. VI app accuracy [24]

An overall accuracy of 80% was achieved using the training set of data, as shown in figure 25. The accuracy of the model implies that it will be able to identify and distinguish between braille bumps, drop-offs and pavements. When looking at the components crucial for the safety of the Visually Impaired (braille bumps and curbs), the overall accuracy improves to 87%. This could be further improved by having a larger set of training data.

To improve the reliability of the machine learning model, photos taken at different orientations and lighting conditions were also included. Figures 26 to 29 below show the tests results. The machine learning model does not consider factors such as color and relies exclusively on pattern recognition.

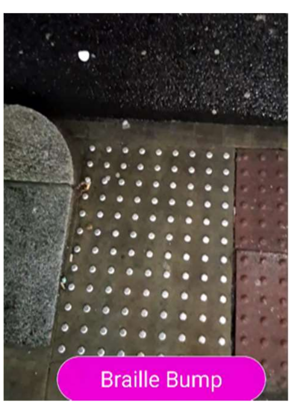

Figure 26. [25]

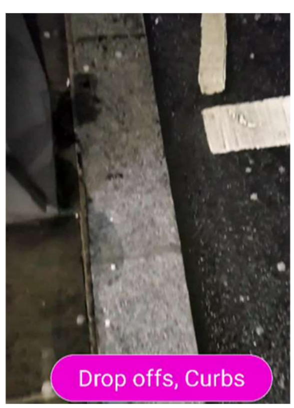

Figure 27. [25]

Figure 28. [26]

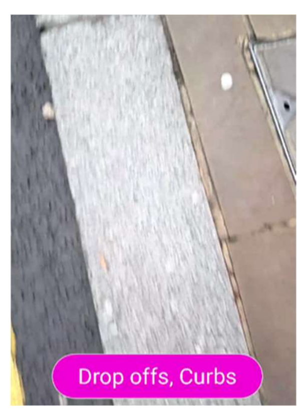

Figure 29. [26]

3. Motor testing

Tests were initially conducted in the lab by using a set of pre-determined inputs to the feedback system after the vibrating motors were attached to the sleeve. This was done to ensure that the motors vibrated according to the language that was programmed on Arduino and to check if the vibrations could be felt clearly. After the lab tests were done, the feedback system was then placed on to the buggy and connected to the sensor system. An obstacle course was then set up and the feedback system was then tested to ensure that it worked in tandem with the sensors and that the language was understandable. Field tests were subsequently conducted along the corridors and around the university campus.

II. Lab Testing

To determine the intensity of the motor vibration as a function of frequency, the sound emitted by one of the motors was measured. This was made using a microphone attached to a motor responding to square waves of amplitude 3V and varying frequency within the range used in the project (0 to 25 Hz).

The amplitude of the sound emitted by the motor was plotted against the period of the square wave. Then the amplitude was normalised, dividing the amplitude by the maximum amplitude found (which was at 0 Hz), and plotted against the period as shown in figure 30. Finally, the gain $(20\log(A_{norm}))$ in dB of the amplitude was plotted vs frequency in a logarithmic scale as shown in figure 31.

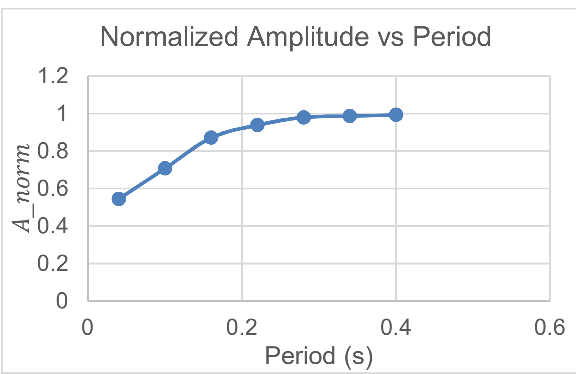

Figure 30.

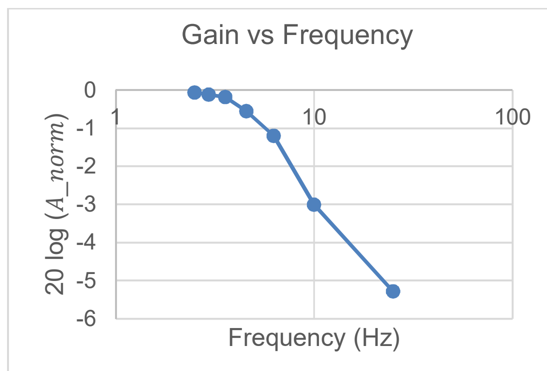

Figure 31.

Having determined the response of the vibrating motor experimentally, the appropriate function for the relation between obstacle distance and signal period at the sides of the buggy was derived $(\mathrm{period} = 0.001 \times 0.16 \times (91 - \mathrm{distance})^2)$. Similarly, the appropriate function which describes the relation between obstacle distance and signal period at the front of the buggy was determined $(\mathrm{period} = 0.001 * 4 * (200 - \mathrm{distance}))$. Both graphs are plot as shown in figures 32 and 33.

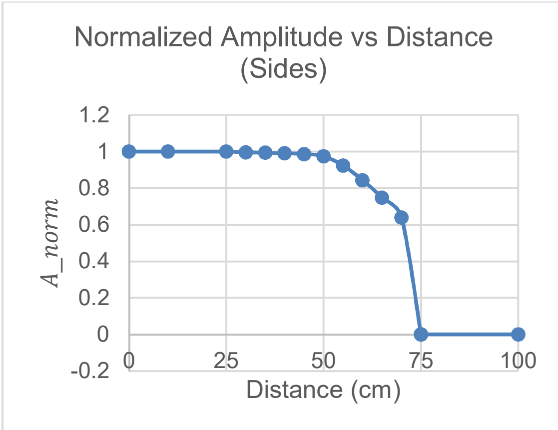

Figure 32.

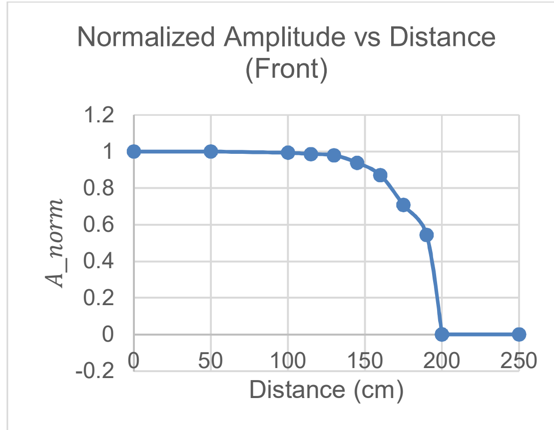

Figure 33.

As the human haptic response if often logarithmic it is useful to also plot the gain (defined as before) against the distance.

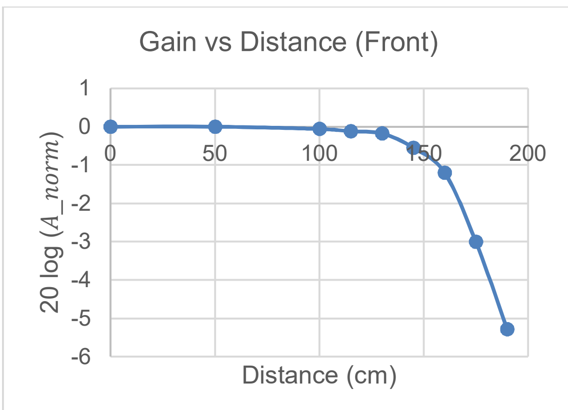

Figure 34.

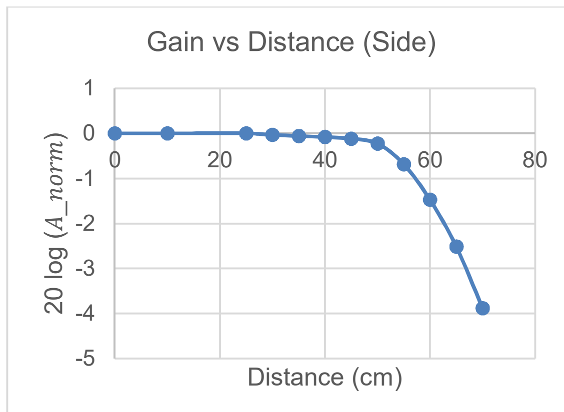

Figure 35.

In both plots (figure 34 and 35) there is an exponential increase in haptic feedback as the object moves closer, with a threshold of 200cm for the front and 75cm for the sides (after which the haptic feedback disappears). The critical value is set at 50 cm on the front and 25cm on the sides (under critical, motors will vibrate continuously at maximum intensity).

This indicates that effectively, the user will use the amplitude (strength) of vibration to determine the distance to an obstacle in three different stages. For the distances which are far away, the user will easily notice the approach of the obstacle due to the vibration intensity difference (notice the slope on the latter part of the curve). After that, the differences in intensity become smaller and the user is just made aware that he is getting closer to the obstacle. In the final stage, the obstacle is already dangerously close, lower than the critical distance, and the frequency will drop to zero, making the motors vibrate constantly with maximum intensity.

III. Electrical Testing

1. Power supply

A fully charged portable bank of 20,000 mAh capacity was connected to the circuit and left to run until it fully ran out of power. The time taken for this was approximately 14 hours and 38mins. This surpassed the PSD specifications of 4 hours that was initially planned for.

2. Soldered circuit boards

The circuit was soldered onto stripboards to protect against the possibility of components coming loose and the disconnection of wires. Testing continuously ensured build quality, schematic adherence as well as short circuit avoidance. The figures below depict the stripboard with soldered components (figure 36) as well as the final version of the stripboard where additional electrical tape was placed above the components to improve insulation and mechanical stability (figure 37).

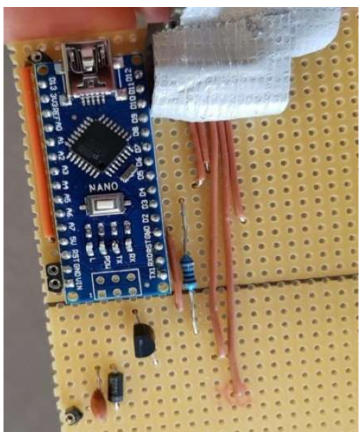

Figure 36.

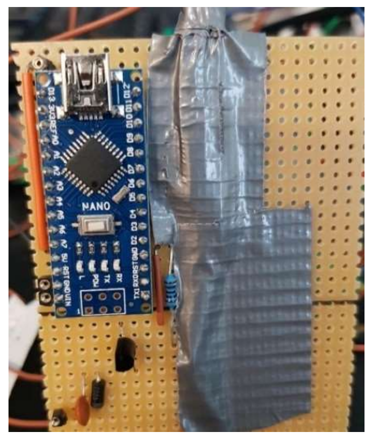

Figure 37.

IV. User Feedback

Figure 38. [14]

Feedback for the final prototype was obtained during demonstration day. The project was also showcased during the Imperial Festival, which provided an opportunity to gauge the public's reactions. Overall the prototype received positive feedback, with users and especially the Visually Impaired reporting a positive and user-friendly experience.

After a one-minute demonstration on the operation of the system given by team members, the audience was tasked with navigating an obstacle course. Simulation glasses were given to the users, allowing them to experience different types of visual impairment and act as test subjects. Many users felt that the language was intuitive, and successfully completed the task.

Notably, visually impaired users were particularly good at navigating the obstacle course, due to their heightened sense of touch. Other users were slower to identify the position of the obstacles, owing to a difficulty in distinguishing which motor was vibrating. Given enough time, the majority of users adapted to the haptic language and successfully completed the task.

A common complaint among those that were unsuccessful was that the strength of the vibrations was excessive, an issue that could be dealt with on subsequent iterations of the design. While the testing environment was not particularly conducive to concentration, as it was noisy and crowded, it does accurately reflect the real-life conditions in which the system will be used.

Our interaction with Ramona Williams, shown in figure 38 trying out the baby buggy, allowed for an in-depth case study. After a very short time she began to intuitively respond to the haptic language. In addition, she was pleased with the convenient placing of the motors on the handle of the buggy as well as its overall comfort and ease of use. At times, she faced difficulties navigating crowded environments, as experienced during demonstration day. Ramona also expressed her concern regarding the placement of the smartphone in the buggy, as it requires proximity to the floor for the mobile app to function correctly. While this temporary placement is far from optimal, the next iteration of the system should contain a camera module, transmitting a live video feed of the terrain to the user's smartphone safely placed in a holder on the handle.

In the future, a focus group consisting of visually impaired parents exclusively could be set up to obtain further feedback from the product's target audience.

V. Evaluation Matrix

User Requirements	PSD Specifications	Test Results	Pass/Fail
Obstacle Detection	Able to detect obstacles with a surface area larger than $50cm^2$ at least a distance of 1m in front of the buggy or 20cm from the sides of the buggy.	Obstacles detected at a maximum distance of 2m from the front, 75cm at the sides. Final product surpasses initial specification requirement.	Passed
Hazard Detection (Drop-Off)	Able to detect drop-offs from 20cm away.	Was able to detect drop-offs from 30cm away.	Passed
Hazard Detection (Braille Bump)	Able to detect braille bumps from 20cm away.	Was able to detect braille bumps from 30cm away.	Passed

User Requirements	PSD Specifications	Test Results	Pass/Fail
Feedback to User	Provide user with sensory feedback whenever there is an obstacle detected within the detectable range.	Haptic feedback language was clear and able to give user information about obstacles including its direction.	Passed
Storage System	Secure the white cane and allow easy access to mobile phone for navigation purposes.	Storage system stores the cane and has a mobile phone compartment that can be easily accessed.	Passed
Visually Impaired Identifier	Identifying the user as visually impaired with a sign.	Signage through a universal visual impairment clue that is large enough to be seen by pedestrians.	Passed
Lightweight	Should not account for 20% of the buggy's weight, with maximum weight of 2kg.	Total weight of system is around 1-2kg and does not add significant weight to buggy.	Passed
Compact	Should not account for 15% of the buggy's dimensions.	Components are small enough to be tucked neatly into storage system without any significant protruding components and affecting functionality.	Passed
User Friendly	Device should be easy to understand.	Haptic language is intuitive and easy to understand, according to user feedback obtained.	Passed

User Requirements	**PSD Specifications**	**Test Results**	**Pass/Fail**
Compatibility	Easily integrated to different buggy models.	The circuitry was stored in a portable case that was placed under the buggy. The sensors and motors were attached to the buggy using tape and a sleeve respectively. This would allow the whole system to be transferred to another buggy, although it would be inconvenient. The finalized system would make use of finer methods for integration in other buggies.	Failed
Comfort	Feedback should not cause discomfort to the user.	Vibrating motors on handles are dampened, so user is not overwhelmed by strength of vibrations.	Passed
Safety Specification	Attachments should not affect the safety standards of the buggy.	Does not affect the standard operations of the buggy and does not make the buggy's weight exceed the weight limit.	Passed
Isolated electrical system	The electrical system should not endanger the baby or the user.	Wires are insulated and neatly taped using insulating tape. No exposed ends. Main circuitry is kept away from baby and user in secure storage compartments.	Passed
Water Resistance	Electronics are to be kept in water resistance containers that have passed the IP54 test to protect against wet weather conditions.	Did not conduct IP54 test to check if the containers are completely water-resistant.	Failed
Feedback does not obstruct user's other senses	The feedback system should not interfere with the user's senses, particularly hearing, as users may require hearing for navigation purposes.	Feedback mostly vibrational, does not interfere with other senses of the user. Audio feedback is not overbearing, used only for major concerns, to indicate road crossings or drop-offs. Necessary to maintain user's safety.	Passed

User Requirements	PSD Specifications	Test Results	Pass/Fail
Battery Life	System should last for 4 hours for every full charge.	Able to last a maximum of 14 hours and 38minutes using a 20000 mAh power bank. Rechargeable.	Passed
Lifespan	Prototype operational for a maximum of 1 year. (under responsible usage)	Vibrating motors and sensors can last for about 1 year, according to sensor and motor datasheets.	Passed
Maintenance	The system has a modular design, and individual components can be easily removed and replaced. Individually faulty and worn out components does not affect the whole system.	The system does not have a modular design, as individual components are soldered onto the circuit board and hence, cannot be easily removed and replaced. In the event of individually faulty and worn out components (i.e. vibrating motors, ultrasound sensors), the whole system would still function, due to the fact that the buggy has multiple side and front sensors.	Failed
Accuracy	Minimise the errors in detection of the prototype.	The HC-SR04 Ultrasound sensors have an accuracy of 90.29%. The LiDar sensor has an accuracy of 93.86%. The Braille bump and Curb detection application has a cumulative precision of 80.1%.	Passed
Affordability	Overall cost of the prototype, excluding the buggy, should not exceed £300.	The total cost of the prototype is £473.28 (including the cost of the LiDar). However, the LiDar sensor can be replaced by ultrasound sensor and this will reduce of the cost of the prototype by £320.21, totalling to £153.07. However, this will result in a less reliable system in terms of accuracy and range of distance detected.	Failed

Discussion

I. Limitations

The aim of this project was to create a proof of concept, by designing and testing a system that keeps visually impaired users safe while operating a baby buggy. The limitations of the prototype could be broadly categorized as follows:

Hardware
The focus was on functionality and not precision, thus the parts chosen for the project were inexpensive, mass-produced and readily available on the market. Using lower quality components means diminished reliability and lifespan.

Current technology
The technology for an affordable, portable LiDar unit that is compact enough to be mounted onto a buggy is currently not as developed, readily available, and reliable. The field of machine learning is improving rapidly, and improved models could be trained to better meet the requirements.

Component Degradation
The components will undergo wear and tear and their performance will degrade over time. For example, after a large number of cycles, the voltage the battery is capable of producing will decrease to a level below the Arduino operating voltage, which will result in system failure.

Extensive testing must be conducted to determine the product lifespan, and at which point it will be deemed as non-functional. From there, a proposal for the replacement of parts or changing the entire system could be recommended to the user.

Cost
One of the criteria of the project was to keep the cost of the prototype low to guarantee that it will be affordable to a large audience. Therefore, compromises were made in the performance of components to reduce cost.

Time Constraint
The main limiting factor to the optimization of the design was the tight time constraints. The time afforded for the completion of a prototype, from project inception in mid-October to the showcase in late March, was insufficient to complete all aspects of the system necessary for production. Within a larger timeframe, improvements could be made to the design.

II. Improvements

1. Functionalities

Ultrasound
Two potential approaches could be implemented to increase the effectiveness of the array of ultrasound sensors. One approach would be to utilize fewer sensors of wider coverage thus simplifying the circuit and code and minimizing the probability of failure, due to the use of fewer components. Alternatively, a larger number of sensors could be used, providing redundancy and thus minimizing the effect the failure of an individual sensor would have to the overall functionality of the system.

LiDar
The LiDar unit used was initially mounted onto a rotating element that allows for a 360-degree coverage of the surroundings. However, due to overheating issues it stopped working during the prototype testing stage. A functional rotating LiDar sensor would provide the system with improved accuracy, range and reduce the number of sensors necessary to meet the specifications.

Mobile app
Currently the accuracy of the machine learning model stands at 87% for braille bump and curb detection. This could potentially be improved with a larger training set of photos. Other objects of interest (e.g. potholes) could also be included into the model to improve the coverage of hazards.

For the prototype, the model is built on a mobile application. It could potentially be integrated onto a central CPU that processes data input from other sensors as well. Standalone cameras could be connected to the CPU for the live feed of the terrain.

2. **Feedback System**

Haptic language
The use of two vibrating motors on each side of the handle to provide feedback to the user limits the amount of information that could be provided to the Visually Impaired. With the inclusion of additional vibrating motors, a more specific direction at which the obstacle is approaching could be conveyed to the user.

Another language could be developed, specifically adapted for indoor use of the buggy. This could be toggled by the user depending on their environment. This language would use smaller threshold distances, which will ensure feedback is given only when necessary. This would hopefully resolve the issue of vibrations being overwhelming in crowded environments and hard to distinguish.

Vibrating motors
The improvement for the haptic language would need to be coupled with an improved vibration absorption system. In the event where the vibrations cannot be isolated, the user will not be able to pinpoint which vibrating motor is activated.

The current feedback system relies on reducing the frequency of the vibration to increase its intensity. Ideally, the frequency and intensity of the vibrating motors should operate independently from one another. This would allow the team to come up with a haptic language that will be able to convey much more information to the user.

However, implementing more vibrating motors and a more complex haptic language comes with a drawback. There will be the risk of oversaturating the user with information. The current language is intuitive and easy to understand without the need for training.

3. Design

Bluetooth
Incorporating a Bluetooth module will reduce the amount of wires used. This would prevent circuit failure in the event the wires get damaged or disconnected due to collisions. This would increase the reliability of the prototype as well as increase its safety, as less circuitry is exposed.

Compatibility
Currently, components are attached to the buggy using duct tape. In the future, universal mounts could be incorporated. The complete system could be implemented as a single component and be easily attachable to multiple buggy types.

Water Resistance
The system could be placed in a water-resistant casing (at least IP54).

Mechanical Protection
Protruding sensors could be placed in improved protective cases.

Conclusion

The aim of the project is to develop a baby buggy that detects and provides feedback on the position of obstacles and hazards to visually impaired parents. Through the showcase as well as Imperial Festival, the proof of concept has been successfully demonstrated. The prototype was well received by the public, and especially the Visually Impaired who are the target audience.

The four main aspects mentioned in the PSD are:

1. **Functionality & performance**: the prototype exceeded the specifications stated in the PSD. It can detect obstacles with a surface area of $50cm^2$ at 2m in front of the buggy and 75cm to the sides. Changes in height can be detected at a minimum of 30cm away for both braille bumps and drop-offs/curbs.
2. **Usability:** the specifications were met. Based on the feedback received from the showcase and Imperial Festival, users were able to navigate around obstacles with a short one-minute explanation from the team. Visually impaired users adapted even faster and were better at navigating due to their elevated senses.
3. **Safety & security:** the specification was not met. While the components were electrically insulated, none of them were water resistant.
4. **Life, reliability & maintenance:** the accuracy of the prototype in detecting obstacles and hazards is at a functional level.

As mentioned in the discussion, due to various reasons such as hardware, current technology, cost and time constraint, the team was only able to create a prototype. The prototype serves as a proof of concept to show the potential of this project. The main constraint faced in this project was time.

To bring this project to a commercial level several improvements must be made, in terms of functionality, feedback and design. The system should be fully integrated in a single circuit that could be easily installed on buggies with different designs. It would also implement an improved language that would convey more detailed information. Furthermore, input from the sensors and the camera could be combined to give the user a superior representation of their surroundings unachievable with a white cane.

The team will continue to work on the project over summer as an Undergraduate Research Opportunities Programme. There will also be the possibility of it being continued either as a third-year project or a new batch of second year students taking over this project.

This project has garnered attention from the public through several avenues. It was mentioned in the World Economic Forum by the President of Imperial College and also featured in media outlets such as the BBC, Huffington Post and Imperial College website. People from several parts of the world have expressed interest in the project, and there is the possibility of a collaboration with buggy manufacturers to tap into their expertise and bring the project forward.

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Appendices

Appendix A – Project Management

Our team consists of 10 members: Georgios Gryparis, Iani Gayo, Kenzo Togo, Kwayne Teo, Wen Hau Lim, Paul Courty, Pei Shi Lim, Rachel Tan, Samuel Martin Frias, Shaokai Hong. The team is then further split into three further teams to ensure simultaneous progression in all aspects of the project.

Sensor team – Pei Shi Lim, Samuel Frias, Kwayne Teo, Wen Hau Lim
Feedback team – Iani Gayo, Georgios Gryparis, Kenzo Togo, Paul Courty, Rachel Tan
Braille and Curb detection – Shaokai Hong

Tasks were allocated on a meeting to meeting basis to achieve goals set on Gantt Chart.

Figure 39. Gantt Chart

Figure 39 above represents our Gantt Chart. Green cells represent the feedback team, red cells represent the sensor team, blue cells represent Braille and Curb Detection team and orange cells represents everyone.

Figure 40 below shows the project plan including the start date, number of days of each task and the deadlines.

Project: Baby Buggy for Visually Impaired			
Task	**Start Date**	**Duration (days)**	**Deadlines**
Project Starts			
Background Research	9-Oct	17	
PSD Specifications Definition	26-Oct	4	30-Oct
Concept Generation	30-Oct	14	
Early Calculations	13-Nov	7	
Initial Prototyping	20-Nov	13	
Concept Selection	3-Dec	1	
Detail Design	4-Dec	14	
CHRISTMAS BREAK	18-Dec	14	
Final Design of Prototype	15-Jan	7	22-Jan
Prototype Manufacture	21-Jan	30	
Lab and Field Testing	26-Feb	14	
Poster Writing	5-Mar	7	12-Mar
Final Assembly	12-Mar	9	21-Mar
Report Writing	5-Mar	105	18-Jun
Project Ends	18-Jun		

Figure 40.

Appendix B – Risk Management

This should focus on the foreseeable risks associated with the design of the device. An example is given below.
Each risk/failure should be listed in the "Detailed Risk Analysis" below. Describe the failure and possible resulting effects; rate the probability of its occurrence, the severity, and the probability to detect the failure. Describe preventing measures and rate the failure again.

Examples of possible hazards are listed below (based on ISO14971):

Examples of energy hazards	**Examples of biological and chemical hazards**	**Examples of operational hazards**	**Examples of information hazards**
Electromagnetic energy Line voltage Leakage current enclosure leakage current earth leakage current patient leakage current Electric fields Magnetic fields **Radiation energy** Ionizing radiation Non-ionizing radiation **Thermal energy** High temperature Low temperature **Mechanical energy** Gravity falling suspended masses Vibration Stored energy Moving parts Torsion, shear and tensile Force Moving and positioning of pilot **Acoustic energy** ultrasonic energy infrasound energy sound	**Biological** Bacteria Viruses Other agents (e.g. prions) Re- or cross-infection **Chemical** Exposure of airway, tissues, environment or property, e.g. to foreign materials: acids or alkalis residues contaminates additives or processing aids cleaning, disinfecting or testing agents degradation products medical gasses anesthetic products **Biocompatibility** Toxicity of chemical constituents, e.g.: allergenicity/irritancy pyrogenicity	**Function** Incorrect or inappropriate output or functionality Incorrect measurement Erroneous data transfer Loss or deterioration of function **Use error** Attentional failure Memory failure Rule-based failure Knowledge-based failure Routine violation	**Labelling** Incomplete instructions for use Inadequate description of performance characteristics Inadequate specification of intended use Inadequate disclosure of limitations **Operating instructions** Inadequate specification of accessories to be used with the device Inadequate specification of pre-use checks Over-complicated operating Instructions **Warnings** of side effects of hazards likely with re-use of single-use medical devices **Specification of service and maintenance** Ideally, the only maintenance made by the user would be that of recharging the battery of the device. In case of damage or malfunction, the device would be replaced or fixed, but rather than by the user, by an IT service.

Critical Risk Priority Number

During the risk analysis, each risk or failure is analysed and rated with respect to its severity (S), probability of occurrence (O), and detection rate (D). The rating for each of the three aspects ranges from 1 (low security risk/failure, low probability of occurrence, high detection probability) to 10 (severe injuries or death, high probability of occurrence, no/low probability for detection). The product out of these three ratings is called Risk Priority Number (RPN). In case, the RPN is greater than a critical threshold, preventing measures are required in order to reach a final RPN below or equal to the critical threshold by means of reasonable and justifiable security measures.

Define a critical threshold in this section here – we recommend a critical **RPN threshold of 75**.

In case, the risk is greater than the critical threshold the risk **must clearly be mentioned** in the “declaration of agreement” signed by the pilot and involved staff.

Factors of the Risk Priority Number (RPN)

Find below a recommendation how to rate occurrence, severity, and detection. The “Risk Priority Number before” is a mathematical product of the numerical Severity- (S), Occurrence- (O), and Detection-Ratings (D) obtained before applying any preventing measures to reduce the likelihood for dangerous incidents, thus: **RPN before = (S1) x (O1) x (D1)**. This “RPN before” should be set to prioritize items that require additional quality planning or action.

The “RPN after” is a mathematical product of the numerical Severity- (S), Occurrence- (O), and Detection-Ratings (D) obtained after applying the preventing measures to reduce the likelihood for dangerous incidents, i.e. **RPN after = (S2) x (O2) x (D2)**. The “RPN after” has to be equal or below the predefined threshold in order to guarantee safe use of the part/element/device.

Preventing measures are mechanisms that prevent the cause of the failure mode from occurring or that detect the failure and stop the application before an incident can happen. It could also reduce the severity by e.g. designing softer and rounder edges. Preventing measures could include specific inspection, testing or quality assurance procedures; selection of other components or materials; de-rating; limiting environmental stresses or operating ranges; redesign of the item to avoid the failure mode; monitoring mechanisms; performing preventative maintenance; or inclusion of back-up systems or redundancy. [27]

S – Severity

Rating S	Criteria: Severity of effect	Consequence	Treatment
10	Death	-	-
9	Quadriplegia	Life-long medical care necessary / coma / permanent damage	Hospital stay
8	Amputations, paraplegia, blindness, deafness, traumatic brain injury (severe), fourth-degree burns	Life-long medical care necessary / coma / permanent damage	Hospital stay
7	Complex fractures, open fracture, inner injuries, traumatic brain injury (severe), third-degree burns	Permanent damage possible	Hospital stay
6	Gash, fractures, torn muscles, articular cartilage injury, traumatic brain injury (moderate), second-degree burns	Permanent damage possible	Hospital stay
5	Gash, fractures, torn muscles, articular cartilage injury, traumatic brain injury (mild), second-degree burns	Reversible injury	Hospital stay or ambulant treatment
4	Severe cuts, severe scratches, severe contusions, strains, first-degree burns	Reversible injury	Ambulant treatment or self-treatment
3	Minor cuts, minor scratches, minor contusions, stiff muscles, tension, blisters, excoriations, sickness, first-degree burns	Discomfort during application up to three days after application	Self-treatment
2	Slight sickness, pressure marks	Discomfort	-
1	No harm	-	-

O – Occurrence

Rating O	Criteria: Probability of occurrence
10	Occurs or may occur very likely during every use of the session
9	Occurs or may occur likely during every use of the session
8	Occurs in 1 of 5 sessions (less than once a day)
7	Occurs in 1 of 10 sessions (less than once a day)
6	Occurs in 1 of 50 sessions (less than once half a month)
5	Occurs in 1 of 100 sessions (less than once a month)
4	Occurs in 1 of 500 sessions (less than once half a year)
3	Occurs in 1 of 1000 sessions (less than once per year)
2	Occurrence very unlikely
1	Occurrence nearly impossible

D – Detection

Rating D	Criteria: Likelihood of detection by design control
10	No chance of detection
9	Very remote chance of detection
8	Remote chance of detection
7	Very low chance of detection by indirect methods (hardware or software)
6	Low chance of detection by indirect methods (hardware or software)
5	Moderate chance of detection by indirect methods (hardware or software)
4	High chance of detection by indirect methods (hardware or software)
3	High chance of detection by direct or indirect methods (hardware/software)
2	Direct and indirect detection: Hardware or software
1	Direct detection: Hardware or safe software (category 4, performance level e)

Risk Analysis

Assembly	Failure & Effect	S1	O1	D1	RPN before	Preventing measures	S2	O2	D2	RPN after
Circuitry of Feedback	Direct exposure to electrical components in handle grips. – user discomfort risk of electrocution	4	3	5	**60**	Exposed wires are covered using highly insulating materials around handle. Wires and electrical systems are kept in a case away from infant. [Decreases S]	1	3	5	**15**
Vibrating motors	Vibrations from the motors can be felt from the cradle and have nauseating effect to the infant.	3	10	N/A	**30**	Using rubber grips to dampen the vibrating effects. [Decreases S]	2	10	N/A	**20**
General circuitry	Overheating of components esp. motors. – user injuries and risk of damaging device	4	3	9	**108**	Holes are added to the rubber grips wrapped around the motors. Ventilation to allow dissipation of heat and reduce discomfort. [Decreases S&O]	2	2	9	**36**
Connection between sensors and feedback	Breakage of data transmission from sensors to vibrating motors. – user can't receive any information from the surroundings, risk of endangering the infant's safety	4	2	9	**72**	Bluetooth connection between sensors and vibrators are not being used due to consistent disconnection of Bluetooth modules. Wires are used instead, connecting the sensors and vibrating motors. [Decreases S]	2	2	9	**36**
Sensor	Failure to measure any obstacle ahead of respective sensors	1	2	5	**10**	Device is programmed to report to the user by a distinct pattern of vibrations to the motors. [Decreases D]	1	2	1	**2**
Power supply	Battery failure causing malfunction	1	3	7	**21**	Power indicator installed [Decreases D]	1	3	4	**12**

Appendix C – Ethics

The main purpose of this project was to provide a better gauge of the Visually Impaired's surrounding and reducing the risk of any potential hazards closing in. It is of utmost importance to cater for their needs and to have special considerations for them. The smart baby buggy group participated in a workshop held by Ramona to have a better understanding of the limitations faced by visually impaired parents, while getting useful feedback on how the product should be designed to provide intuitive output to the user. Some of the ethical issues faced were: .

Human Trials
Multiple user trials were done on Bioengineering Demo Day and Imperial Festival. Most users gave insightful comments and felt the feedback system were really intuitive and easy to get used to. Concerns on the long-term effects of vibrations were brought forward as well. It is unclear as of what the side effects of long-term exposure of vibrations towards the visually impaired parent and the baby are, but the potential risks and ways to reduce it are described in the risk analysis (Appendix B). Animal trials are not considered as the product is meant for humans, not animals.

Honesty and Integrity
The idea and execution of prototype are solely the group's brainchild, although codes were taken from open source libraries and altered slightly to meet the project's specific requirement (e.g. threshold of minimum safest distance, varying vibrating frequency by different distance above threshold).

Openness
It is crucial to make the background research and the system functionality as open and transparent as possible. Therefore, during Demonstration Day and Imperial Festival, members of the group clearly explained the functions of our system to the public as well as warning them about the potential inaccuracy and dangers arising from it.

Carefulness
Repeated trials on obstacle course were being carried out to ensure reliable results. During soldering of circuit board, use of a voltmeter to ensure part by part that the circuit is sound. Initial advice was sought from mentor Dr. Radcliffe regarding sensors during brainstorming.

Respect for colleagues
The team demonstrated great teamwork skills, as each idea presented by individuals were listened to and taken into great consideration. In addition, constructive criticisms were provided throughout the progression of the project. Respect for each other was clearly demonstrated in this sense.

Objectivity
Project decisions were not compromised by any bias, conflict of interest and or influenced by external circumstances.

Respecting Intellectual Property
Care was taken to ensure intellectual property was respected at all stages of the project.

Responsible Publication

Research results and trials will be made publicly available and the team will be held accountable for the completeness and accuracy of the report. All sources of funding and institutional affiliations have been clearly stated in the report.

Social Responsibilities

This project was done solely for the benefit of the Visually Impaired. In the event this were to develop into a business, a balance will be made considering the benefit of society and individual gain.

Overall, the group believes to have adhered to all the important ethical aspects of this project.

Appendix D – Manufacture

The manufacturing of the final product can be broken down into 4 main segments, preliminary tasks, code debugging, assembly and testing.

The preliminary tasks included soldering the two individual Arduino Nanos to separate strip boards as well as preparing a breadboard for the Arduino Mega. This was done once the circuit was working on a breadboard before soldering it onto different stripboards. PCBs were not printed out due to the time constraint that the group faced in this project.

Once the circuit was completed, the Arduino's code was tweaked and further improved to make sure that the maximum vibration threshold was well in range. Codes were further modified to eliminate noise and decrease the inconsistent vibrations. When the codes were running smoothly, the strip boards were glued to 2 black chassis which were placed in the storage basket under the baby buggy. The last stage was to further modify the baby buggy and improve certain aspects of it, while testing it out in the real-world environment.

3D printed case for Ultrasound Sensors
A CAD file of the casing for the 5 ultrasound sensors was made using "Autodesk Fusion 360". The ultrasound transmitter and receiver have the same dimensions (diameter 2.6cm). This CAD file was then 3D printed. However, during assembly, the group realized that this design was not ideal as the side bars will give out false readings to the Arduino, causing inconsistent vibrations. Figure 41 and 42 show the various viewpoints of the casing.

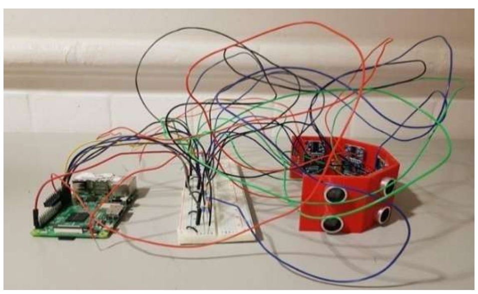
Figure 41. Side view of casing

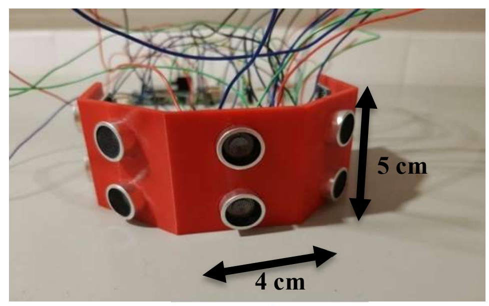

Figure 42. Front view of casing

The position of the Ultrasound sensors was then readjusted as shown in figure 43 to 45. Two Ultrasound sensors were fitted on each side (45° to each other), giving the baby buggy an upwards of 180° detection range. The casing from the previous design was cut out and attached to each pair of side Ultrasound sensors to provide protection if the Visually Impaired hits an obstacle accidentally.


Figure 43. Side view of sensors


Figure 44. Side view of sensors


Figure 45. Front view of sensors

The vibrating motors were put into sleeves to dampen the vibrations as well as to eliminate the risk of electric discharge. A dampening material called “Sorbothane” was used in the making of vibration sleeves, shown in figure 46. Multiple layers of Sorbothane were fitted into the sleeve after the dimensions of the sleeve were taken. The vibrating motors, Sorbothane and sleeve were then glued together and attached onto the handle bar of the baby buggy, shown in figure 47.

Figure 46. Vibrating motors sleeves

Figure 47. Vibrating motors sleeve on buggy

Wiring

Firstly, the dimensions for the storage basket under the baby buggy were measured (350mm by 300mm) and suitable casings (325mm by 125mm) were purchased. The stripboards were then taped to the sides of the chassis, ensuring tidiness and avoiding confusion during troubleshooting, as seen in figure 49. The wires from the vibrating motors and sensors connecting to the Arduinos in the chassis were duct taped along the side bars of the buggy, as shown in figure 48.

Figure 48. Side view of buggy

Figure 49. View of Chassis

The figure below describes the LiDar and Ultrasound sensor system and the integration of haptic feedback through the vibration motors (Figure 50).

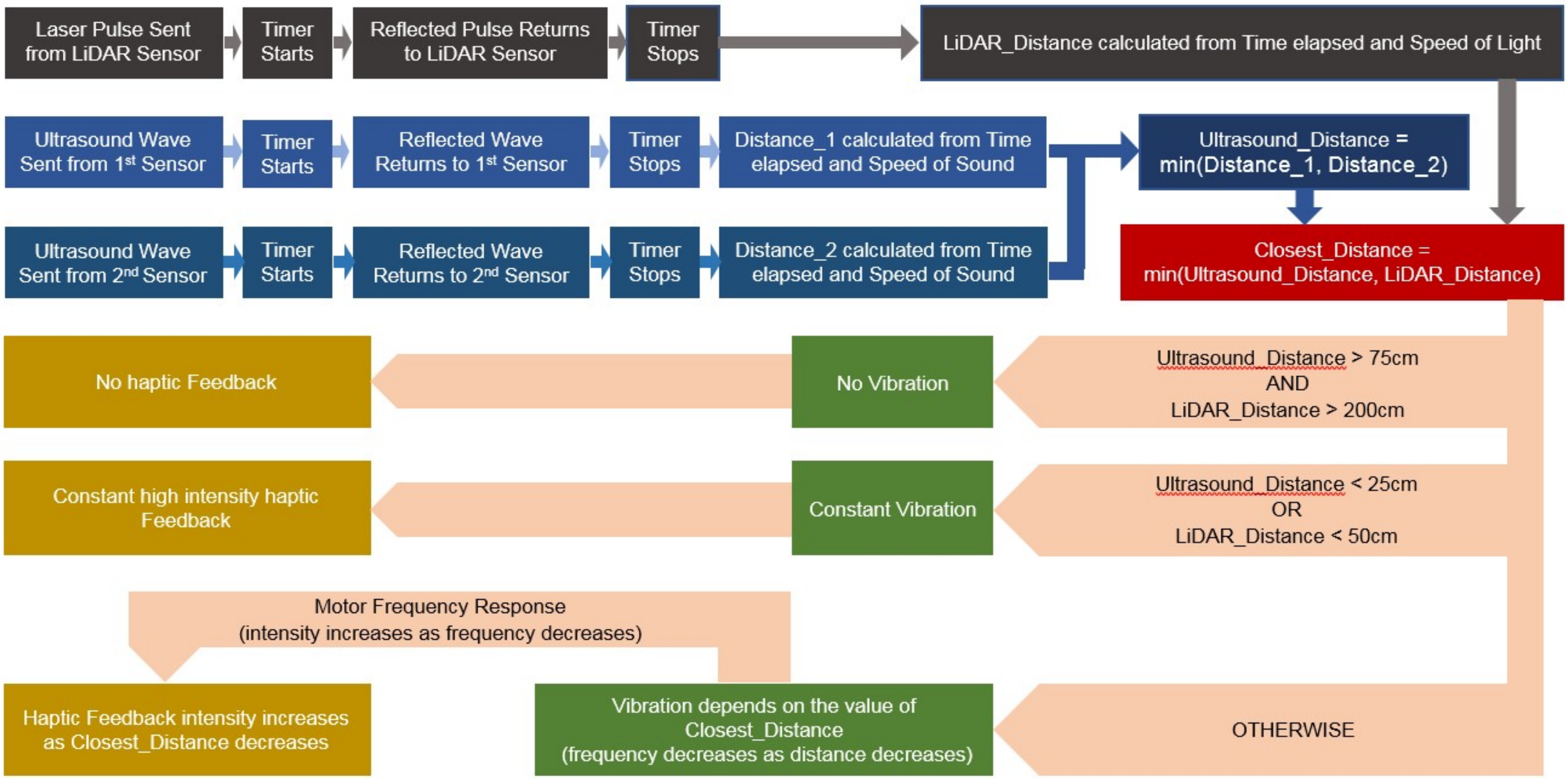

Figure 50. Extended Flow Chart of Sensor system

Appendix E – Bill of Materials

Item	Description	Part Number	No. of unit	Cost per unit	Total Price
1	Ultrasonic Module HC-SR04 Distance Sensor	HC-SR04	10	£1.25	£12.50
2	120 Pieces Breadboard Jumper Wires 40 Pin M/M	-	1	£4.99	£4.99
3	Baseball Acrylic Clear Display Case	-	1	£7.82	£7.82
4	Velcro Brand All Purpose Straps	-	1	£4.91	£4.91
5	2mm Mini Vibrating Disk Motors	-	10	£0.90	£9.00
6	D-Line Cable Tidy Unit	-	1	£16.00	£16.00
7	Octopus Tripod Phone Holder	-	1	£9.99	£9.99
8	2mm Vibrating Disk Motor	RB-See-403	20	£0.90	18.00
9	VPM2 Vibrating Disk Motor	RB-Sbo-46	2	£3.06	£6.12
10	Shoulder Strap pads protector for backpacks	-	1	£7.99	£7.99
11	Sorbothane Damping Film	-	3	£13.25	£39.75
12	Cycling gloves- light silicone gel pad	-	1	£4.99	£4.99
13	Super-stick holder for rollator (Cane holder)	-	1	£6.02	£6.02
14	Pram organizer storage bag	-	1	£14.99	£14.99
Total					£163.07

Table E1: Bill of materials and cost breakdown for the target system.
NOTE: Materials acquired from College resources and sponsorships rather than purchased are not included and are listed in Appendix F.

Appendix F – Sponsorships and Institutional affiliations

1) 1 Scanse 360 Sweep LiDar by SparkFun Electronics
2) Use of laboratory and equipment by Imperial College London
3) 2 Baby Buggy models, Evo and i2 by Mutsy
4) Microsoft Azure for Machine Learning Model

Appendix G – Acknowledgements

We would like to thank our supervisors, Dr. Firat Guder and Dr. Ian Radcliffe for their support and guidance with throughout this year. We extend our gratitude to Paschal Egan and Niraj Kanabar for their assistance with all electronics-related parts of our project. We are also grateful to smrtGRiPS for giving us advice related to feedback systems.

We appreciate Ramona Williams and her active involvement in our project.

Finally, we are thankful to Mutsy, SparkFun, and Microscoft Azure for their financial support towards the development of our project.

Appendix H – Nomenclature

LiDar	Light Detection and Ranging
VI	Visually Impaired
IP	International/ Ingress Protection Marking (Degree of Protection)
PSD	Product Specification Document
USB	Universal Serial Bus