LightSight: Real-time obstacle detection to assist wheelchair navigation

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Introduction

Problem Statement

An individual with a brain injury has difficulty navigating their home in a manual wheelchair due to impaired vision.

Engineering Objective

Noting the difficulties associated with wheelchair navigation, and the added challenges of visual impairment, we seek to design, build, and deliver an assistive device to improve quality of life and mobility for Client X.

Target Audience

Individuals with any degree of visual impairment who use a manual wheelchair.

Purpose of Document

This document will provide a synopsis of the project with the aim of encouraging reproducibility. The proliferation of this document is paramount to expanding the reach of the device and its benefit to manual wheelchair users. Contained within are descriptions of the issue at hand, existing solutions, and through documentation of our process to build a more robust detection system.

Market Research

The Braze Mobility sensor is a blind-spot detection device designed for wheelchair users (pictured on the right) (Braze Mobility, 2020). The device alerts the user when something is within the adjustable danger zone, which ranges from one to four feet away from the wheelchair. An auditory, visual, and mechanical alert system is all available for use through an external device that is accessible to the user. On this device, there is 180° horizontal coverage and 55° vertical coverage. This device is small and adaptable for a variety of wheelchairs and has prices starting at $2,255 each (Braze Mobility, 2021).

The Braze Mobility Sensor

LUCI is an attachment-based smart technology that is made to fit on existing wheelchairs. It uses stereo vision, infrared, ultrasonic, and radar data in order to provide a warning for both drop-offs and potential collisions. The LUCI device connects to the cloud and is compatible with smart devices such as Amazon's Alexa and Google Assistant. It is also able to be attached to the seats and the wheels of current wheelchairs. LUCI falls into the price range of around $8500 per device (LUCI, 2021). A wheelchair equipped with the LUCI technology is pictured on the right (LUCI, 2020).

The LUCI Sensor

The Whill Model A Wheelchair

The Whill Model A is an adapted wheelchair that allows users to more easily avoid obstacles in new environments. This device combines responsive mouse control and electromagnetic braking to quickly avoid obstacles. The electromagnetic brakes are also able to stop on an incline. Additionally, it can be remotely driven from an iPhone with a range of 12 miles. For users not remotely driving, the on-chair control can be used by the left or right hand. This wheelchair can clear obstacles up to 3 inches in height and is all-wheel drive. This device has a charging time of eight to nine hours. While this wheelchair does work to avoid obstacles, it is unable to alert the wheelchair user or use obstacle detection. This device is priced at $6,999 (Whill Inc, 2021). A Whill Model A wheelchair is pictured on the right (Whill Inc., 2016).

The SenseStat® Wireless Obstacle Detection System is a wireless, stand-alone system designed to allow truck drivers to detect objects they may not be able to see fully when reversing. While not designed specifically for wheelchair users, the device may be mounted onto any vehicle by the user. The device features wireless backup sensors with a detection range of 0.22 ~ 2.5 meters. Additionally, the device has a communication module that provides both visual and auditory cues to the user to communicate the proximity of any obstructions. This device retails for $432.47 (Rear View Safety, 2022). The

SenseStat® Wireless Obstacle Detection System

Phoenix iWheelchair

SenseStat® System is pictured on the right (Rear View Safety, 2022).

The Phoenix iWheelchair is an adapted wheelchair that is designed to reduce the impact when the user comes in contact with an obstacle. This wheelchair is light in weight and includes an adjustable center of gravity allowing for more agility and stability. The wheelchair also includes electronic braking, power assist, and impact resistance. The main issue with this wheelchair comes from the main goal in the design which is to reduce the impact of hitting an object rather than detecting an object and eliminating impact altogether. It also does not have a function that allows for the user to be alerted in case of impact (Phoenix I Wheelchair, 2021).

The next competitor is the Brigade Backsense: Blind Spot Detection device, which is designed for larger vehicles to be able to easily sense their potential obstacles. This device is meant to target specific areas which are known to be harder for large vehicles to be able to see and through the use of ultrasonic and infrared sensors, is able to detect both stationary and moving obstacles. Along with all of that, this device has a large angular range allowing for objects to be detected well in advance. One major issue with this product in terms of being used for wheelchair detection is the fact that it is really only designed for use by large-scale vehicles. Not only does this cause large and bulky parts, but on a larger scale, the sensor is less specific, which can cause issues for detecting smaller objects. The interface is also not accessible to users with visual impairments (Radar Obstacle Detection, 2022).

Brigade Backsense: Blind Spot Detection

Preliminary Designs

Preliminary designs for this project included a camera-based detection system, a sonar-based system, and a mapping system which uses LiDAR and ultrasound sensors.

Design Concept #1

The wheelchair will be fitted with two Raspberry Pi Camera Module 5MP 1080p Webcam OV5647 Sensors. One is aimed parallel to the arm rests, and one aims perpendicularly to the lower portion of the seat. This detects objects in front of the user as well as any drops or bumps below the user (such as stairs). The design includes two vibrating armrest pads, which direct the user left or right to avoid any detected obstacles.

Real-time object detection on the parallel camera can be accomplished through the "You Only Look Once" (YOLO) method. The approach employs a trained Deep Convolutional Neural Network (CNN) to segment and perform classification on individual camera frames at upwards of 45 frames per second (Redmon et al., 2016). General object detection libraries and pretrained models exist for the purpose of developing YOLO networks (*Ultralytics/Yolov5*, 2022), enabling the possibility of utilizing transfer learning; however, further data relevant to the client's environment must be obtained and manually curated for further training.

Design Concept #1 Drawing

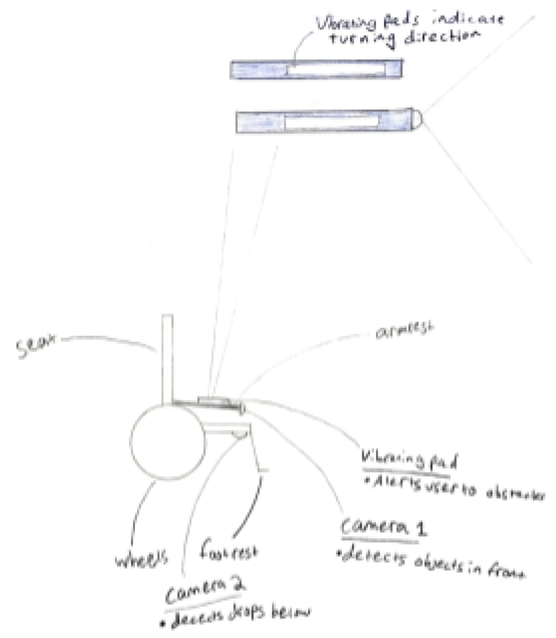

Figure 1: Diagram of a camera-based analyzation and vibration system output

Two additional buzzer modules would be attached to the arm rests to alert the wheelchair user to any objects detected in the path of motion. They would direct the user left or right to avoid any detected obstacles. Although the initial design uses a simple model where the arm rest vibration indicated a turn in its respective direction, this could be reprogrammed according to client specifications or requests.

Design Concept #2

Ultrasonic sensors are one of the sensors that can be utilized to measure objects within a close range of ten meters (Burnett, 2021). The type of sensor emits and receives acoustic waves, above human hearing. By measuring the time it takes for the wave to travel back to the receiving end of the sensor, the distance between the sensor and the nearby obstacle can be determined. At its greatest sensitivity, the spread of the wavelengths emitted by an ultrasonic is nine degrees. This means that specificity of the objects that are detected further out decreases. At four feet, any object that is within fifteen inches of the plane perpendicular to the sensor will be detected. Though at a location that is within a foot of the sensor, objects are only detected within roughly a four inch range (Sedgwick, 2012). Thus, sonar sensors are beneficial for detecting the general proximity of objects further out, and multiple sonar sensors could be used upfront to generate an image of where objects specifically are. In the above design, unobstructed clampable sonar sensors are attached to the wheelchair’s arms. The sensors can be used to refer to the general locations of an object by vibrating the wheel rail aligned with the object at different vibrations based on the object's proximity, which can either be in front of or behind the wheel chair. In addition, ultrasonic sensors or infrared sensors, which use infrared waves instead of acoustic waves, can be positioned under the wheelchair at angles in order to detect changes in the elevation of the floor in front of and behind the wheelchair. An additional buzzer module would be attached to alert the wheelchair user of this specific obstruction by creating a series of beeps. The communication and information processeing relies on a microcontroller, such as an arduino or a raspberry pi that can make decisions based on the information from the sensors.

Design Concept #2 Drawing

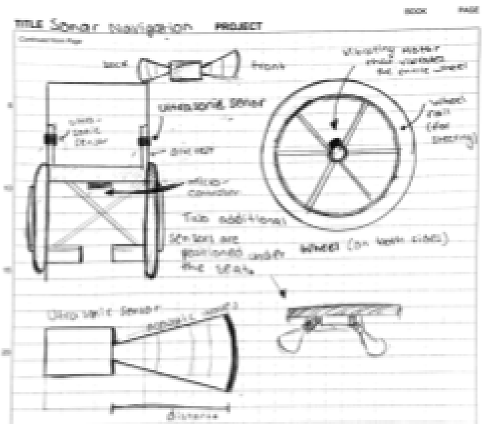

Figure 2: Sensor and subcomponent drawings of an ultrasonic-based sensor system on a wheelchair.

Design Concept #3

This proposed design relies on TFmini-S LiDAR sensors, HC-SR04 Ultrasonic sensors, and a processor, such as a raspberry pi to create a 3d map of the space in front of and behind the wheelchair. The lidar sensor, and all the electric componentry except for the vibrating pads, placed on the left and right side of the wheel chair's seat, can be mounted on a board directly under the seat of the wheelchair. The design incorporates lidar sensors, which have a max sensing range of 12 meters. Each lidar sensor is mounted between each foot rest, so that its view is not obstructed. Each mini lidar sensor can be attached to a servo motor that pivots up and down 45 degrees to create a topographical scan of the environment. If an object is within a certain range, pads beneath the wheel chair will vibrate at different frequencies based on the proximity of that obstruction. A series of LED lights on the armrests could be used to accompany this. Like the previous design, ultrasonic sensors are only required to measure depressions in the ground with decreased specificity. And, this subsystem in each of the designs would use alerts from a buzzer module to discern for depressions in the ground.

Figure 3

Design Concept #3 Drawing

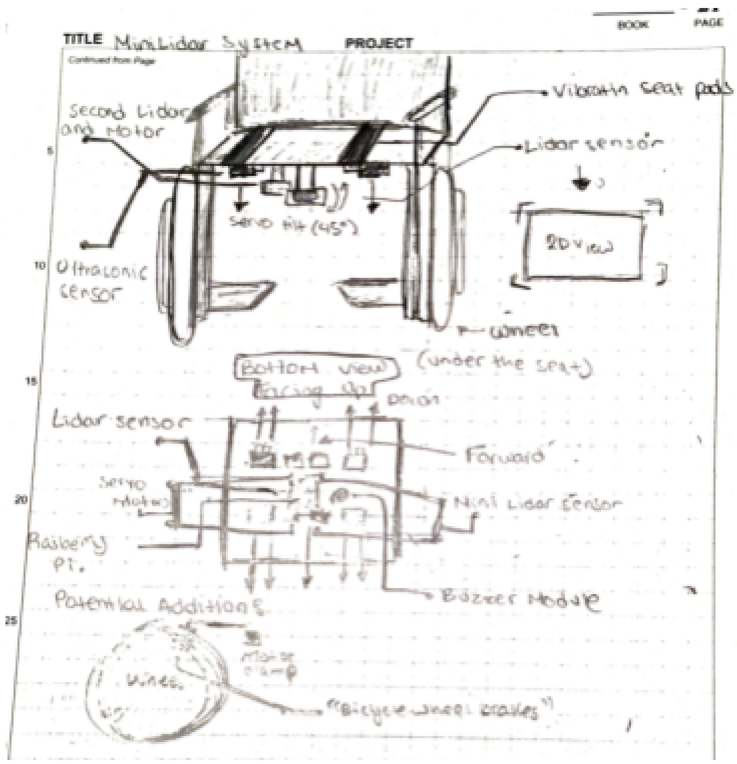

Figure 3: Diagram of the electronic componentry and its attachment to the wheelchair.

In all designs, we had identified certain pros and cons, but made the decision that due to the amount of data needed to train a computer vision model, a camera-based system would not be feasible. Additionally, a system which used solely sonar sensors would only be able to detect obstacles that were close, and thus sonar alone was not viable. Finally, we saw that ultrasonic and LiDAR sensing would be quite promising, but cost was prohibitive and topographic mapping would require knowing Client X's environmental layout. To combine the best parts of our solutions, we decided to utilize sonar and LiDAR to detect a wide range of obstacles.

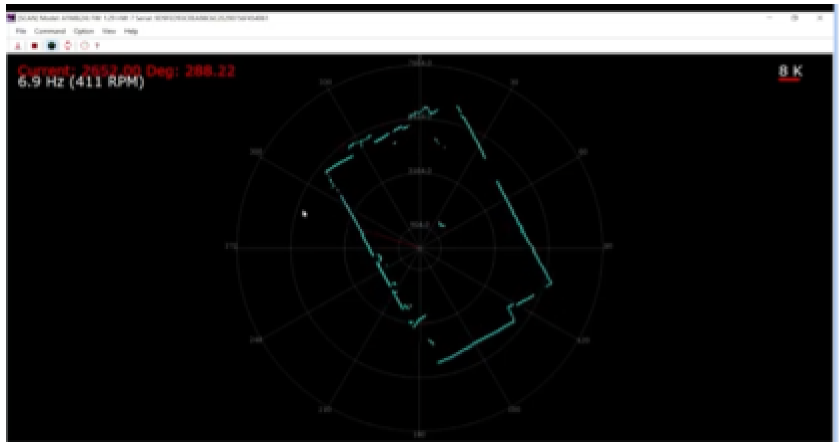

Figure 4: Map of Mass Academy math room, generated by LiDAR sensor.

Building

To begin building the device we first completed testing of the sonar and LiDAR sensors. The sonar sensor was connected to an Arduino Uno and placed in proximity to an obstacle. Readings were monitored in the Arduino IDE and detection range was set at 35 centimeters. The LiDAR sensor was run by a Python program on a Raspberry Pi 4 and detected walls in the Mass Academy math room. The sensor ran using the parameters of 750 units of vision and a 45° input angle. The initial testing of the sonar and LiDAR sensors act as our proof of concept: a sensor array can detect obstacles in a given environment.

The next step was to procure vibration modules and connect them to the output from the sensors. The buzzer modules were soldered to elastic wristbands and wired to the Arduino Uno. Upon obstacle detection the buzzer modules produce a vibration to alert the user.

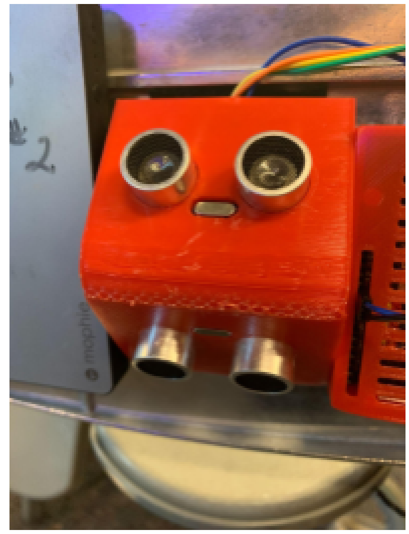

Figure 5: Sonar case

To attach the sonar sensors to the wheelchair we 3D printed a sonar case. This case was attached to the bottom of the foot rest of the wheelchair using velcro tape. This increases the versatility of our device because these sensors can be moved and gain additional zones of vision. The buzzer modules were soldered to FitBit elastic wristbands so that the user can easily place them on their wrists. The wristbands contain 3D printed chambers that store the buzzer modules and are labeled “L” and “R,” to indicate the side of the wheelchair where the wristband is located.

Figure 6: Left wristband

Implementing the LiDAR sensor proved difficult due to the sensor’s range of motion. The LiDAR utilized the gpiozero and rplidar libraries to write Python code which activated the buzzer modules when reading < 750 units between 45-90 deg for right bracelet and 270-315 deg for left bracelet for widened view of surrounding walls/tall obstacles. We tried to utilize a stepper motor, in addition to a 3D printed sensor platform, to tilt the LiDAR sensor and expand the field of view. The stepper motor was unable to receive enough power to efficiently tilt the LiDAR sensor, and the data from the tilting sensor was difficult to interpret.

Instead, we used a stationary platform to attach the LiDAR sensor above the user's head. The mount contains a wooden block and 3D printed stand for the LiDAR to rest on. PVC pipe and 3D printed components make up the vertical part of the mount. The mount was secured to the wheelchair using two 3D printed components for the handles of the wheelchair that could suspend a ⅜ of an inch threaded rod going across them. This allows the device to be easily adapted to other wheelchairs, because the mount can be slid on and affixed to the chair with little effort.

Figure 7: LiDAR mount

The entirety of the sensor apparatus can be controlled with battery packs which are located on the bottom of the left footrest and on the vertical attachment of the LiDAR mount.

Testing

Testing protocol was the same for each prototype. The MAMS Math room was utilized as a sort of obstacle course, with chairs tipped over and tables shuffled in a particular order that allowed just enough space for the wheelchair to navigate from the door to the whiteboard. Between designs, the layout of the room was identical, to avoid changing environments. The person testing the system was blindfolded to ensure that they could rely only on system-specific sensory cues to navigate their environment. They were given two minutes to navigate to their endpoint, and while they completed this task, the number of collisions and number of avoided collisions were counted and recorded.

Design Study #1: Sonar Testing

Purpose:

The purpose of this study was to analyze the accuracy of the HC-SR04 Ultrasonic sensors in obstacle avoidance.

IV: The constants were the environment setup (8 obstacles), wheelchair width, wheelchair height, and the range at which the sonar would activate (50cm). The changing independent variable was the person who was in the wheelchair. Data was collected for 6 individuals, each of whom navigated the environment blindfolded, under two conditions, which represent the boolean independent variable, first with no sensors, and second with the sonar attached.

DV: Number of collisions per two minutes

Materials:

- HC-SR04
- Arduino Uno
- Wires
- Portable rechargeable battery
- 3d-printed watch face
- Buzzer Module

Raw Data:

# Collisions / 2 minutes: No Sensor (control)	# Collisions / 2 minutes: Sonar Only
15	3
20	7
13	3
13	5
20	6
14	4

Qualitative Tests:

It was noted that the vast majority of collisions occurred on the right side of the individual, due to the fact that for the purpose of testing, one Sonar sensor was attached to the left footrest. In the final prototype, this would be addressed by attaching a symmetrical sensor onto the right footrest.

Analysis:

Results yielded that with one sonar sensor attached, the number of collisions per 2 minutes was reduced by over 70%, which was considered to be a successful display of the efficacy of the HC-SR04 Sonar sensor in obstacle detection and avoidance.

Conclusions:

The HC-SR04 Sonar sensor provides a viable detection system, able to reduce the number of collisions by 70% or more on average. The primary drawback is the limited range of detection, which will be addressed in future prototypes by attaching a similar setup to the right side.

Design Study #2: Testing the LiDAR

Qualitative Tests:

A qualitative test was first performed on the LiDAR to obtain the best settings for the sensor. The purpose of this test was to evaluate the consistency of the LiDAR sensor at different settings of activation ranges and angles.

IV (Qualitative): activation range (mm), activation angle ranges.

DV (Qualitative): consistency of objects detected (wall, column, person, bookshelf)

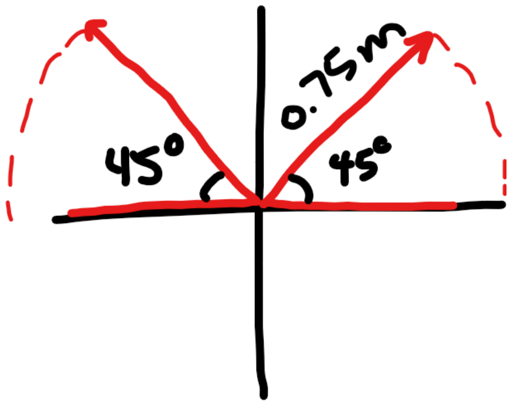

Figure 8. Optimal configuration.

Results: a qualitative evaluation found that an activation range of 45 degrees on either side and 0.75 m activation range was the optimal configuration.

Purpose: to establish a proof-of-concept for the functionality of the LiDAR sensor as an individual subsystem.

IV: use of LiDAR

DV: number of collisions

Materials:

- Slamtec RPLIDAR A1
- Raspberry Pi 4B
- PVC Pipe

Raw Data:

~~	# of Collisions	
Participant	No Sensor	With LiDAR
A	15	6
B	20	8
C	13	9

D	13	7
E	20	6
F	14	10

Analysis:

LiDAR is shown to have lowered the number of collisions, as demonstrated by a t-test with a p-value less than 0.01. However, the average number of collisions using LiDAR is greater than that of sonar. We attribute this observation to the fact that the LiDAR was mounted five feet above the ground—consequently, ground-level obstacles, such as chairs and desks, could not be sensed.

Conclusions:

Upon considering the active ranges of the LiDAR sensor, it proves to be a viable sensor for 0.75m ranges, which functions in a 360-degree range.

Design Study #3: Full Prototype Testing

Purpose:

The purpose of this design study was combining both the sonar and LiDAR subsystems, and testing the functionality of our intended device as a whole. Specifically, the functionality and user experience with enhanced feedback. Feedback that included the detection of obstacles perpendicular to the bottom forward facing half of the wheelchair, and feedback regarding the detection of walls and larger obstacles 360 degrees around the wheelchair above the head of the wheelchair user. The design study was also intended to examine the combined functionality of the detections systems, and the functionality of the combined electrical outputs, which upon examination necessitated the need for diodes in the parallel wiring for each bracelet between the arduino and the raspberry outputs for obstacle detection. The diodes in the parallel wiring prevented the electrical grounding of the outputs from either the LiDar or the sonar sensors, allowing for the combination of the two subsystems.

IV: The changing independent variables in this design study were the individuals part of the testing in the wheelchair. The controlled variables in the study included a constant path with the same obstructions for a two minute time period for measuring the total number of collisions, the positioning of the sonar sensors and Lidar on the same wheelchair, and the sensitivity of the sensors to nearby obstacles.

DV: The dependent variables in the study were the total measured collisions for the different wheelchair users that tested the functionality of the device without any vision. The purpose of the dependent variables was for a comparative analysis that could determine the efficiency of having two sonar sensors and the combined LiDar sensor, which could be concluded with an analysis via a T-test.

Materials:

- ⅜ in. Threaded rod and nuts
- 3d-printed handle mounts for LiDar
- 3d-printed PVC mount
- HC-SR04
- Arduino Uno
- Wires
- 3d-printed watch face
- Buzzer Module

- Slamtec RPLIDAR A1
- Raspberry Pi 4B
- PVC Pipe

Raw Data:

No Sensor (control)	Sonar + LiDAR (final prototype)
15	3
20	2
13	4
13	2
20	2
14	3

Qualitative Tests:

The quantitative test revealed interesting patterns with regards to user behavior and associated qualitative data. Behavior that was characterized by tendencies to slow down upon the detection of objects, such as the pole in the center of the math room via the LiDAR sensor, and chairs at the base of the wheelchair via the sonar sensors. Though quantitative in nature it was qualitatively noticeable that users took less time and quickly navigated around the obstructions compared to the design study with just a sonar sensor.

Analysis:

Results yielded a drop in collisions of over 83% on average, when compared to the control. In addition, a 43% percent drop when compared to sonar only, and a 65% drop when compared to LiDAR only.

Conclusions:

The final prototype, which combined LiDAR and sonar, provides a viable and safe alternative to the sonar-only or LiDAR-only systems.

Data Analysis

In order to determine the statistical significance of the collected data a series of student's t- tests were performed. First, each individual design study/ iteration of the prototype was analyzed in comparison with the control data, collected with no sensors at all. Each of the prototypes had a highly significant difference from the control (**$p < 0.001$). Our final prototype, including both LiDAR and sonar sensors, reduced the number of collisions by almost 80%. In addition, the t-tests performed between the final prototype and LiDAR and sonar only iterations showed that the final prototype was most effective in reducing the number of collisions.

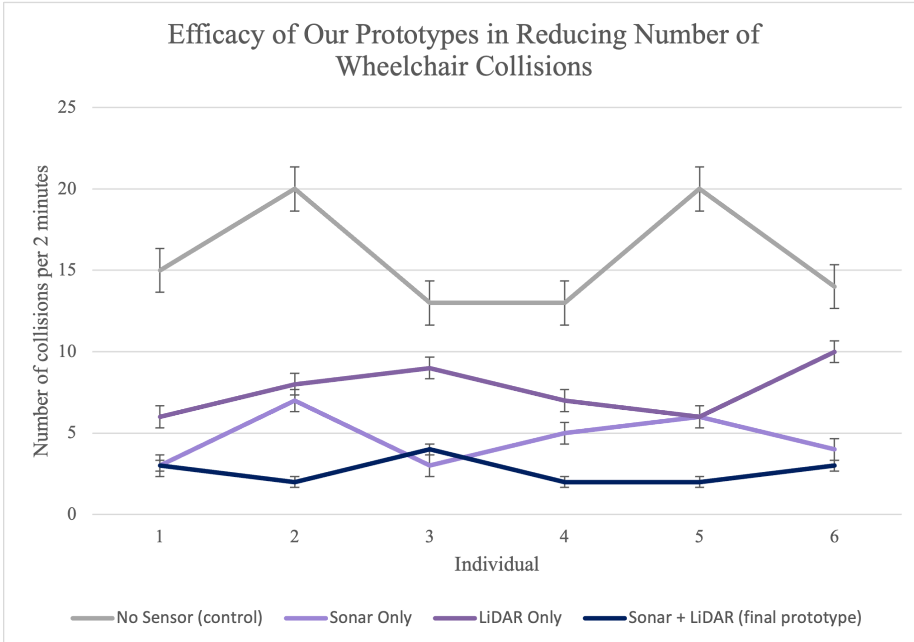

Figure 1: Iterations of prototyping and number of collisions for each. Significant p values for each prototype in comparison with control. Complete system had highly significantly less collisions (**$p < 0.01$).

Decisions Based on Testing

After initial testing, it was decided that the use of a single portable and rechargeable battery for both sonar sensors would be more effective than the use of two separate batteries. This would prove to reduce both the overall cost and weight of the device. Additionally, a diode was connected within the wire traveling from the battery to the LiDAR. It was discovered that when a command issued from the Arduino connected to the sonar sensor to trigger the vibration module, a majority of the current from the battery was traveling back up to the Raspberry Pi rather than to the vibration module. This prevented the module from producing a vibration powerful enough to alert the user of a detected obstacle. The diode prevents current from traveling to the Raspberry Pi, which allows for a more noticeable vibration. The diode still allows for current to travel down from the Raspberry Pi to each vibration module. The directional control enables our device to operate effectively.

Engineering Matrix

Requirement	Level	Type	Verison 1 - SONAR Only	Verison 2 - LiDAR Only	**Verison 3 - SONAR and LiDAR**
The device must be able to sense obstacles within a 1.5 meter range directly in front of the wheelchair.	1	functional	pass	pass	pass
The device must be capable of alerting visually impaired individuals.	1	functional	pass	pass	pass
The electronic system shall detect drops (ie. stairs, curbs, etc.) greater than 2" under the wheelchair in its front and back.	1	functional	fail	pass	pass
The device must be able to sense obstacles three-quarters of the way up from the floor to the top of the wheelchair.	2	functional	fail	fail	fail
The device shall propose a safe alternative path to the user before the object is incidentally detected.	2	functional	pass	pass	pass
The device shall be functional in dark conditions.	2	functional	pass	pass	pass
The device shall be able to notify the user in at least two ways (ex. sound and vibration)	2	functional	fail	fail	fail
Must sense 360° around the user.	2	functional	fail	pass	pass
The apparatus will be capable of providing a range of information to the user regarding the scope of the space between them and environmental obstacles.	3	functional	fail	fail	fail
The device will contain a remote alert system capable of notifying others in a separate environment about a detected collision.	3	functional	fail	fail	fail
The device shall scan and map the surrounding environment in three dimensions to assist with alternative route navigation.	3	functional	fail	pass	pass
The device will allow the user to program the range and type of information relayed to them.	3	functional	fail	fail	fail
The device must be able to attach to the wheelchair.	1	physical	pass	pass	pass
The device shall use a rechargeable energy source.	1	physical	pass	pass	pass
Wires and electric parts will be protected and waterproof.	2	physical	pass	pass	pass
The apparatus shall weigh less than 5lbs.	2	physical	pass	pass	pass
The device will be integrable with manual wheelchairs different from the client's.	2	physical	pass	pass	pass
The total price of the device must not exceed 125 USD, excluding already obtained and borrowed materials.	1	cost	pass	pass	pass
The user must be physically capable of operating a manual wheelchair.	1	user	pass	pass	pass
The device shall include a user manual detailing the operation and capabilities of the apparatus.	1	documentation	pass	pass	pass
The device will include documentation specifying the design, materials, and data collection/analysis.	1	documentation	pass	pass	pass
The device shall include figures/diagrams regarding its installation.	1	documentation	pass	pass	pass

Conclusion and Discussion

Final Device Summary

The final prototype effectively integrates the use of both SONAR and LiDAR sensors along with vibration modules in order to relay information back to the user. The SONAR sensors are located on both the left and right footrests of the wheelchair to scan the ground for any floor level objects. The LiDAR sensor is mounted between the handles and is positioned so that the sensor is able to scan for higher objects and altitude changes without being blocked by the user's head. All sensors are wired and connected to two separate vibration modules, which correspond to both the left and right side of the chair and are encompassed by a 3D printed shell attached to a watch wristband. The user attaches each vibration module to the appropriate wrist and is able to move freely in their environment. The wrist attachment will vibrate when an object is within 50 centimeters of the footrest, or when there is an altitude drop greater than 2 inches. However, these distances are able to be modified by the user to fit the configuration and needs of their specific wheelchair.

Future Work

To further optimize the device there are a variety of improvements which can be made. By placing a sonar sensor on the back of the wheelchair, the device would gain an additional field of vision. This would help make backing up more safe. Additionally, we would like to control the strength of the vibration to represent obstacles which are further or closer to the chair. For example, an object within a couple centimeters would produce a string vibration, whereas one a foot or two away would vibrate less strongly. In an effort to further improve the safety of our user we would look to implement push notifications to a loved one, via text, to indicate that the user has potentially been in a collision. Finally, we will add a type of path generation which will sense the obstacles in the general area and guide the user through the obstacles in their path. This would help to reduce the amount of obstacles that the user collides with as well as reduce the time it would take for the user to change their path once an obstacle is detected.

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Appendix

Cost of Materials

Item	Supplier	Catalog #	Quantity	Unit Cost	Total
Slamtec RPLiDAR A1	Already in possession	-	1	-	-
HC-SR04 Ultrasonic Sensor	Already in possession	-	3	-	-
Raspberry Pi Model B+	Already in possession	-	1	-	-
Wires, Sauter, Electrical Tape, 3d printing filament	Already in Possession	-	1	-	-
Mini Vibration Motors DC 3V	Tatoko	-	1 pack (20 pcs)	$14.99	$14.99
Digital Servo Motor	Already in Possession	-	1 set(4-pack)	-	-

20800mAh Compact Rechargeable Battery for Raspberry Pi	PiShop.us	-	1	$24.95	$24.95
Buzzer Module	Tatoko	-	1 Pack (10pcs)	$10.69	$10.69
Arduino Nano	Already in Possession	-	1	-	-
Arduino Uno	Already in Possession	-	5	-	-
Raspberry Pi 4 *Analyzing the necessity over the Model B+*	Soon to be in Possession (Borrowed)	-	1	-	-
					50.63

Tools

- Soldering Iron
- Ender V2 3D Printer
- Screws and Drill Bits
- Wirestrippers
- Scissors
- Hot Glue
- Duct Tape
- Band Saw
- Caliper
- Ruler
- Voltmeter
- Multimeter
- Arduino IDE
- Fusion 360
- Python 3.9

Relevant Materials

- Arduino Uno
- Arduino Nano
- Raspberry Pi 4
- Buzzer Modules
- Fitbit Wristbands
- Wheelchair