DEVELOPMENT AND TESTING OF AN OBSTACLE DETECTION SYSTEM FOR ROLLING WALKERS

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ABSTRACT

Objective: The purpose of this report is to outline the methods taken to design a prototype to reduce the risk of falling in elderly citizens who use assistive rollators. This was developed by evaluating common disabilities for elderly citizens and identifying a need to reduce the chance of falling in this demographic. From this problem identification, four concepts were evaluated using qualitative and quantitative methods to select a single concept to proceed with through successive design phases.

Methods: The design included a system of range, force and movement sensors that work in conjunction to warn the user of any hazards that are detected in front of a mobile rollator. Force and accelerometer sensors were implemented to reduce false alarms and improve usability and versatility among the senior target market.

Validations: The tests conducted through the design phases include: walking tests to adapt the product to multiple gait types; object resolution tests to create a relationship between object size versus distance; FSR tests to calibrate the force sensor to varying grip strengths; and landscape surface tests to evaluate the devices usability on multiple surface types.

Conclusions: The final prototype is able to detect objects greater than 7258mm^2 at a range of 0.9m in front of the device to allow for ample stopping time based on demographic reaction times. It met engineering specifications and was successful in detecting objects when in use, and could be improved upon through further size minimization, improving battery life, and continuous optimization on different topography.

I. INTRODUCTION

Falls in elderly individuals are common and severe: “More than 30% of people over 65 years of age fall each year and in half of the cases falls are recurrent. About one in ten falls results in serious injuries such as hip fracture, other fractures, subdural hematoma, or traumatic brain injury” (Dionyssiotis, 2012). There are many extrinsic and intrinsic factors that cause or prevent falls in elderly individuals. The impact from falls typically increase the probability for more falls in the future, immobility or potential hospitalization.

There are many environmental and motor conditions that determine a human’s ability to prevent a fall during daily activities. Extrinsic factors include: light level, number of stimuli, visibility, and challenging terrain (weather, ice, water or any obstacles). Intrinsic factors include: mental degeneration, executive control, reaction time, attention level, state of preparation, information processing time, muscle atrophy, and motor unit response time; all which are negatively influenced by aging. Falling in elderly individuals is primarily due to these intrinsic and extrinsic factors overlapping and becoming more prominent.

With preliminary research across a variety of disabilities (Figure 1), there was a clear need for an effective strategy to decrease the risk of falling in elderly individuals. Falling prevention was considered through common modalities of elderly people walking. Rollators were determined to be a common use of support for elderly individuals performing daily tasks; however, a decrease in attention (with a downward gaze towards the feet rather than the floor in front), and a heavy reliance on the rollator for weight support creating a difficulty in balance and postural response when they faced an unexpected obstacle. Both a decrease in activation of the visual cortex and differences in balance typically found in elderly individuals were considered when designing a system to detect objects ahead of time to allow the user more time to react appropriately. This preliminary research led to the problem statement:

“To design a non-invasive device to decrease the risk of falling for elderly citizens that use rollators.”

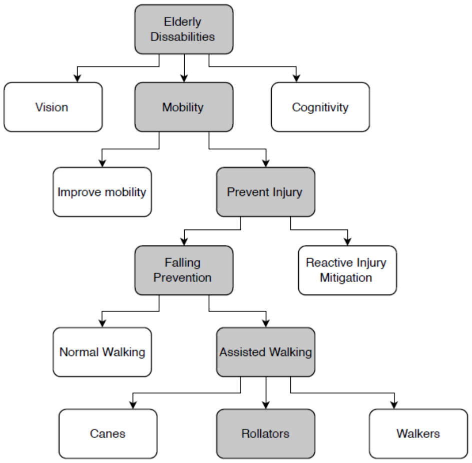

Figure 1. Morphological Analysis; exploring disabilities in the elderly, and determining a clear problem statement

II. Discussion

A. Product Design Requirements and Constraints

The final prototype was a range-finding system mounted on a rollator, which notified the user of any potential tripping hazards in their path of motion, while providing ample time to stop, or change direction. The design utilised ultrasound sensors, in conjunction with an accelerometer and force-resistive sensor, to detect both user motion as well as obstacles of a within a predetermined size range. Together, these formed a system that would detect when the user was physically using the rollator, and notify the user if potential tripping hazards were detected.

For testing, the prototype was mounted on a Hugo Fit 6™ rollator, an affordable and easily available commercial model (Figure 2). System integration onto the rollator was not a design goal, as the final commercialised product is intended to be a unique rollator model, and not a retro-fit. Thus, design development in this prototyping stage focused primarily on circuit design, and code logic.

Figure 2. Image of the Hugo® Fit 6 Rollator, with coordinate axes.

Key Design Constraints

The requirements of the target demographic, and the design's classification as a medical device, heavily influenced the development of key design constraints. A demographic census was performed with a sample of elderly customers at Cherryhill Village Mall and at St. Joseph's Hospital in London, Ontario. The customer requirements obtained from this research included:

- Safety (for users and surrounding bystanders)
- Universality across all rollator products
- Must not impede normal function of a rollator

From this information, functional design specifications were extrapolated to include:

- Warning the customer of any height changes in terrain that increase the risk of falling
- Warn the customer of hardware failures or low battery
- Must detect obstructions of a minimum distance that reflects a common reaction time found in elderly individuals

Engineering Specifications

Based on the customer requirements and functional design specifications above, engineering specifications were developed to outline the constraints of a conceptual product. The engineering specifications include:

- Must weigh under 5 lbs
- Must detect at least 0.32 m in front of the rollator
- The battery life (if applicable) must last 24 hours
- Water resistant up to IP24 (water spray from any direction - rain, splash, snow, spills) (Sensors One, 2018)
- Functional within a temperature range of -20 to 30˚C (For use outside across Canada common temperature range)

Human Factors Considerations

The abilities and constraints of the target demographic were extremely important in the development of the prototype. Generally, ageing increases simple reaction time (SRT) in humans (Figure 3). The extrinsic and intrinsic factors influencing a user's ability to prevent a fall significantly influence premotor (PMT) and motor (MT) time; these both add up to quantify the reaction time of an individual. PMT is the processing time in the brain before a seen movement occurs. PMT usually involves intrinsic brain functions affected by degeneration due to age which play a part in falling prevention. These include: cognitive impairment of attention, visuomotor control, working memory, and decision making. MT is the time for the beginning of the movement to start to the end. This may include weight transfer times/balance ability, impaired quadricep/hamstring ratio, strength, or history of falling. PMT highly determines reaction time (RT), (KIN 4482, 2017).

Slower reaction times are shown with decreased activation of the occipital and frontal lobes. Visual activity decreases in elderly individuals who: primarily have poorer eyesight, usually focus their attention downwards at their feet, or away from relevant surrounding. These decrease an individual's ability to detect and react appropriately to relevant obstacles (KIN 3480, 2017). Components in the frontal lobe detect and resolves processing conflicts, allows for task goals to be maintained in working memory, and orients the attention with

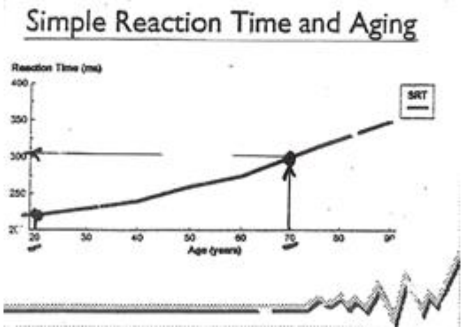

Figure 3. Simple Reaction Time and Aging: Graph demonstrating the simple reaction time increase to approximately to 300ms for individuals 70 years of age (KIN 4482, 2017).

the stimulus present. Frontal lobe volume decreases with age, which may decrease their ability to prevent falling (Peters, 2006). These disturbances are seen in Figure 3; the decreases in frontal and occipital lobe activity reflect an increase in SRT from 225ms to 300ms from ages 20 to 70 respectively.

Calculation of minimum sensor distance: Choice reaction time reflects the ability for an elderly individual to stop when seeing an obstacle. Choice step reaction time (CRT) accounts for more than one choice. This results in a longer time for the person to react to the multiple stimuli; mimicking more closely to a real-life scenario. The psychological refractory period is defined as the delay in response with multiple conflicting stimuli. Multiple choices may interfere in the proper response selection and response execution in a falling situation of an elderly individual (KIN 3480, 2017).

In order to calculate minimum reaction time required for the target demographic (Figure 4), maximum PMT and MT of fallers were added together to find the maximum reaction time (Wang, 2016). The highest-risk adult walking time of 32.22s was recorded to gain the maximum distance it would take for an elderly person (age > 65) to stop moving (Yamada, 2011).

$$Reaction\ Time = PMTmax + MTmax$$

$$Reaction\ Time = (456.00 + 25.37)ms + (814.29 + 10.42)ms$$

$$= 1.30608s$$

$$\frac{\text{High} - \text{risk elder walking time}}{\text{Distance}} = \frac{\text{R}eaction\ Time}{(Distance\ to\ stop\ moving)}$$

$$\frac{(21.57 + 10.65)s}{10m} = \frac{1.30608s}{m}$$

$$Distance\ for\ high - risk\ elderly\ person\ to\ stop\ moving = 0.31986592m$$

Figure 4. Calculations performed to ascertain demographic reaction time and minimum stopping distance.

A distance of 0.32m was calculated to represent sufficient reaction time of object detection to an appropriate response. Considering a factor of safety of 3; 0.9m minimum will be used to include the increases of reaction time that results from: the time sensitivity of object recognition, sensor signal transmission to the human ear and the variability amongst people.

B. Conceptual Design Development and Evaluation

Concept Description and Breakdown

Following the establishment of customer and engineering constraints, multiple conceptual designs were generated to solve the proposed problem. The designs were qualitatively evaluated, and the top-rated designs were sketched and further evaluated using concept design methods, as explored in the following section.

Concept 1, Wheel Elevation Sensor: The proposed design would incorporate a single wheel sensor on the front of the rollator in order to detect abrupt or sudden changes in height when the user is in motion. This system would be able to decrease the risk of falling for seniors since it would send a warning response to the user to deter them from continuing walking if a sharp drop or steep incline is detected.

Concept 2, Four-Wheel Sensor System: This design worked by retrofitting four individual sensors to the base of each wheel, to ensure that height remains in a proper range when the rollator is in use. The system would ensure that all four wheels remain on the ground at all times, and if the rollator were about to tip, the device would send a response to the user to warn them of the hazard to prevent further falling.

Concept 3, Forward/Down Elevation Sensor: This design would work by incorporating a system with multiple sensors that can detect height elevations at a proposed distance in front of the rollator while it is in motion. This would decrease the risk of falling because it would continuously be scanning the topography in front of the rollator for any sudden height changes or objects that could be a hazard to the user while walking.

Concept 4, Retractable Stabilizing Arms: This design would work by incorporating a gyroscope that would initiate retractable arms to stabilize the walker when a major tilt is detected in the rollator. This would decrease the risk of falling by continuously running the gyroscope when the walker is in motion and allowing the safety arms to initiate if the rollator detects a tilt greater than the nominal range.

Concept Selection

A decision matrix found in the Appendix was used to compare the various concepts to the customer and engineering requirements and select a single one to further develop.

Concept 3, the Forward/Down Elevation Sensor, was heavily weighted towards safety for the user, and was ultimately the preferred design. The rejected concepts had limitations in their ease of use, ease of transport, or safety. Concept 3 not only scored highest on the decision matrix when compared to a datum, but was deemed practical and achievable based on the scope and constraints of the project. The proposed sensors would provide a non-invasive way to detect elevation changes that may be a hazard and could be incorporated with various additional circuit components to provide feedback to the user.

C. Product Generation

Circuit design and integration

On the final prototype, the sensor and actuator elements on the physical circuit build were selected with prototyping versatility in mind. An Arduino Uno (with an ATMega328P microcontroller) was selected as the prototyping board, due to its ease of use and plethora of supporting documentation.

Hazard detection dictated the selection of a vision sensor, which would be able to detect objects in the operating path of the rollator, and that would be able to pair with a feedback component to notify the user of an obstacle.

However, the likelihood of false alarms triggering, especially if the user was not physically using the rollator system, were high. Minimisations of false alarms was thus a high priority in further product development.

Sensor Selection

A number of sensors were commercially available for distance detection and are primarily differentiated by the technology they use. Ultrasound (US) sensors use pulsing sound waves to detect obstacles in the wave path, with the reflected wave determining the distance from the sensor. Infrared (IR) sensors emit and subsequently detect light pulses within a certain wavelength, again using reflection time to ascertain range. Since the vision detection of a potential hazard is the primary design goal, sensor selection focused primarily on reliability and versatility. Therefore, a number of commercially available sensors underwent a comparison Go/No-Go matrix to determine the best component for design integration (Table 1).

The HC-SR04 proved to be the most viable option for the prototype vision system. While the sensors were all considered based on size and weight, cost and beam spread were major factors that contributed to eliminating certain products. The Lidar Lite v3 was a relatively good choice, however its unit cost of $129.99CAD made it too expensive for this application. The Sharp GP2Y0A02YK0F used a higher current to operate, and common reviews described its functionality with highly reflective surfaces to be unsatisfactory. Comparing the remaining US sensors, similar functionality led the most cost-effective option to be the chosen sensor for the prototype. The HC-SR04, with a unit cost of $3.95CAD, detection range of 400cm, and 15° beam spread made it an ideal choice for the range specification determined.

In order to reduce false triggering of the detection system, a simple force resistive sensor was integrated into the rollator handle, in order to initiate user notification only when the user is physically using the rollator. An Interlink 402 sensor (AdaFruit, 2018) was selected, due to its low price, and adequate force detection range. Since the force detection system did not need to discern between different types of user, a more accurate sensor was not necessary.

To further reduce false triggering, rollator motion was also used to ascertain user presence. An LSM9DS1 9-DOF (AdaFruit, 2018) IMU sensor was selected, due to its functionality as an accelerometer, gyroscope, and magnetometer. This trifecta of functionality allowed for a diverse range of possible solutions towards accurately detecting user motion, and when coupled with the affordability of the sensor, was key in making it the most viable option.

Space Minimization, Routing and Integration

Even with the need for an adaptable prototype, space minimization was a priority, with all of the US sensors, IMU, and Arduino being connected to a single standard breadboard as a base. The system circuitry was integrated around the central controller, with the power supplied to the breadboard rails coming from the 5Vout and GND pins on the Arduino. Signal and power lines for the sensors were routed to match the configuration and location needs of the sensor leads, minimizing line length and connection issues through signal dissipation. Feedback emitters for user notification; LEDs and a DC vibration motor. The FSR and US sensors, as well as the feedback DC vibration motor, were positioned off the main board and secured directly to the rollator; this required longer lead wires routed along the rollator frame. Additionally, the DC motor required a separate power source due to high current draw; necessitating the integration of a MOSFET for power control. A wiring diagram of the circuit can be found in the Appendix.

Code and Logic

The final code for the device was developed around the US sensors used for object detection. An important part of this process was to develop a program that only detected and offered feedback to users when absolutely necessary. From a system perspective this meant implementing an IMU to detect motion and an FSR sensor to detect user presence. This input data would control when the system notifying the user of detection. Code samples and block diagrams can be found in the Appendix.

The code written for the device started with the inclusion of multiple libraries and defined functions. These files allowed for proper communication and functionality of the different chip and sensor components within the system. Next in the code the different input and output pins used on the Arduino were assigned and labelled to match the pin connections on the circuit. The last part of the program's initial declarations

TABLE I
RANGE SENSOR SELECTION

Range Sensor	Reference	Type	Range	Cost	Beam Spread	Power Usage	Weight	Size
Sharp GP2Y0A02YK0F	A	IR	NO-GO	GO	GO	NO-GO	GO	GO
HRLV-MaxSonar-EZ4	B	US	GO	NO-GO	NO-GO	GO	GO	GO
Lidar Lite v3	C	IR	GO	NO-GO	NO-GO	GO	GO	NO-GO
HC-SR04	D	US	**GO**	**GO**	**GO**	**GO**	**GO**	**GO**

Table 1. A Go-NoGo analysis of various range sensors. The HC-SR04 Ultrasonic Range sensor proved to be the most viable option. Sensors considered were the; [A] Sharp GP2Y0A02YK0F Long Range Infrared Proximity Sensor (Sparkfun, 2018); [B] HRLV-MaxSonar-EZ4 Ultrasonic Range Finder (Sparkfun, 2018) [C] Lidar Lite v3 (Sparkfun, 2018); [D] HC-SR04 Ultrasonic Sensor (Sparkfun, 2018).

comprised of defining all the global variables used in the main code block. Variables that required global initialization were assigned starting values at this point as well

After the initial inclusions and declarations, a void function named *setup()* was declared to contain all the setup code required to initialize the sensors and chips being used in the code's main block. This function block was not part of the main loop and only ran once during the initial run of the program. The first part of this section consisted of initializing the digital Arduino pins for their respective functions as inputs and outputs. The pins set here included the trigger (output) and echo (input) pins from each US sensor, as well as the LED and motor feedback pins (output). Following this, serial communication was started and connection with the IMU was established. Once the IMU was connected and setup to measure movement the void setup function was ended.

At this point in the program all the pins, and sensors being used have been initialized and setup. The remaining section of the code will be the main program loop. This will consist of processing the input data from the IMU and FSR, as well as pulsing the ultrasonic sensors, and processing the data to send the appropriate feedback response. Proceeding from the void setup function the code's main block gets declared as a void function called loop. The first section of code found within loop consists of function calls to acquire the reading from the IMU. Once the IMU chip is set to read, a sensing event is created to gather data from the board's sensors. This data is received as an array containing sensor data regarding acceleration, magnetism, gyro, and temperature. In order to extract the data relevant to the code's functionality a variable called *AccelX1* was used to store only the acceleration in the x-axis. Since the system is only intended to detect while in motion along this axis it was the only data needed from the IMU.

In addition to needing to know whether the device is in motion, the system also used an FSR sensor to detect user presence through force exerted on the device handle. After obtaining an acceleration reading from the IMU the next step in the code was to acquire the force reading from the sensor. In order to do this a variable called *FSRreading* was used to store the analog sensor reading. To actually pull the reading an Arduino function called *analogRead()* was called with the *FSRPin* as an input parameter.

With the acceleration and force data sampled the next step for the code was to analyze the data and use logic statements to control the system functionality. The first part in this section involved setting threshold values for the devices stop-time, motion start-time, and jerk magnitude. Respectively, these variables were named *jcount*, *icount*, and *jerk_thres*. Although the IMU reading provided the system with the device's acceleration, the motion detection algorithm for the system utilized the device jerk (rate of change in acceleration) to determine motion instead. Jerk is calculated in the code based on the absolute difference in acceleration between each loop iteration. This is done after the parameter thresholds get set. Jerk is calculated and saved to the variable *dx* all in one line. This was done by using the C function *fabs()* to take the absolute value of the difference between the current acceleration value, *AccelX1*, and the previous value, *AccelX2*. The next part in the code takes the calculated and set threshold for jerk and uses if statements to control two variables, i and j, that track motion and stopping counters. The moving and stopping counters keep track of the occurrence of two possible events; a moving event or a stopping event. The first if statement checks to see if the calculated system jerk, *dx*, is greater or equal to the value set for the variable *jerk_thres*. If the statement is evaluated as true then the code considers that to be a movement event, increases the motion counter *i* by one, and resets the stopping counter *j* to zero. If the statement is false the code considers that to be a stopping event. In this circumstance there is an else statement that increments the stopping counter *j* by one. The counters *i* and *j* allow the system to track movement events and consecutive stopping events. At this point the previously set thresholds *icount* and *jcount* are used with if statements to set the system in detect mode or rest mode. The first statement checks for stop mode by seeing if *j* is greater than *jcount*. If the statement is true then the system is considered not to be in motion. As a result *i* gets reset to zero and the feedback pins *LEDPin* and *MotorPin* are turned off. In the next statement *i* is compared with *icount* to see if the system is in motion. In addition to this, related by a boolean *AND* condition, *FSRreading* is compared to the force threshold to see if the user is present. If both conditions are met the whole statement is considered true, the system is determined to be in motion with the user present, and the system is set to detect mode. Within detect mode all the coding for the ultrasonic sensor sampling, distance data analysis, and feedback response can be found. This is where the system operations are enabled allowing for object detection and feedback to be sent to the user.

Within this detect mode the US sensors are prepped for sampling by clearing their respective trigger pins. After this the sensors are activated one at a time by setting the trigger pin for a specified 15us which emits a sonic signal for that interval. The duration it takes for the signal to hit an object or the floor is acquired from the echo pin on the sensor and stored to a duration variable called *durationx* where *x* equals the sensor number. In between the sampling of each sensor is a 20us delay to ensure there is no cross talk from the previous signal interfering with the current sensor's echo pin. After all the sensors have been sampled and the durations are attained the distances detected can be calculated using the sensor duration reading and the speed of sound. The next section of the detect mode calculates the distance in centimeters read by the individual sensors. This is done by multiplying the duration value by the speed of sound and dividing by 2 to account for the signal traveling to the detection point and back. These distance values are saved in variables called *meas_distx* where again *x* equals the respective sensor number. The final part of the detect mode coding involved comparing the measured distance values with set distance thresholds to see if an object is in the path of the user. This was done with an if statement utilising or boolean logic to trigger a true condition if any of the measured distances fall below their threshold. In this situation one or more sensors have detected an object or potential obstacle in the user's path and the feedback response should be triggered. Within this statement, the feedback pins, *LEDPin* and *MotorPin*, are set high sending a voltage to the outputs causing the warning LED and tactic feedback motor to turn on. A 500ms delay was added to the response signal to give the feedback interval a longer length for a more stable signal and noticeable signal for the user. At this point in the code the current acceleration value is set as the previous value for the next iteration of the loop. This ends the main void loop function of the system code.

D. Product Evaluation

The final proposed solution to the problem statement met all of the engineering specifications. The prototype weighs less than 5lbs and is able to detect objects at a minimum distance of 0.32m in front of the rollator. The maximum distance the sensor successfully detects an obstacle of an anterior cross-sectional area of 7258mm^2 within a required range of 1.48m. An external battery life ensures the device would last over 24 hours to allow realistic use for the elderly individual. The prototype would be effectively covered to be water resistant up to IP24 which includes handling any splashes from any direction. Weather conditions will be tied into future testing and consideration to provide reassurance that the device will functionally operate properly under typical weather conditions in Canada: -20 to 30°C.

Accomplishing these engineering requirements still satisfied all of the customer requirements. The prototype is safe to use and is not impeded by the prototype. The system would be developed into a new rollator design as a full product in order to allow it to be easy to use for the elderly individual. The clear and non-invasive indication of a warning signal was successful with a subtle vibration in the right handle and an illuminating LED indicator. A different warning signal would be implemented if it reached the market to warn the user of a low battery or any hardware or software failures.

WALKING TESTS (WT)

Since the implementation of an IMU was to remove the incidences of false alarms, the Walking Test (WT) was designed to fully map the range of accelerations the LSM9DS1 IMU would detect, and to ascertain which parameters were relevant in defining whether the device was experiencing motion. Four gaits were analysed as part of the test, each representing typical walking styles found in the specified target demographic.

Motor neuron deficits were amongst the most prevalent diseases in an elderly population (approximately 45.7%) (Al-Momani, 2006). Other common deficits in elderly individuals include: Parkinson's' disease producing a shuffle gait, muscle atrophy due to a broken bone from osteoporosis causing decreased postural control, and typical muscle imbalances from an aging body (Berg, 1992).

A breakdown of gait classes are detailed below. Graphs of acceleration data can be found in Appendix Testing, Iterative Parameter Testing, Walking Tests.

Reference [A], Motor Neuron Deficit Gait: Muscle imbalances are classified by significant motion in the x, y and z planes. Decreased executive control and motor neuron abilities are clearly demonstrated by the need to generate greater correctional movement in x and y. The variation of z-acceleration shows instability in the core, resulting in much superior and inferior movement. Greater decrease in core strength greatly deteriorates an elderly person's ability to control balance during daily walking gait.

Reference [B], Shuffle Gait: This gait relies heavily on the rollator because of the atrophic muscles demonstrated by the feet dragging on the floor. This shows more reliance on a stable ground to prevent falling, with high vertical force from the subject onto the rollator. This reliance on the rollator to support weight results in a low z-axis acceleration variation. This gait type may be seen in individuals with Parkinson's disease, which may result in poor balance and posture. A rapid spike is visible when the rollator is shifted forward by the user in the x direction, with the user shuffling to catch up to the rollator. Acceleration data for this gait class shows very high acceleration in the x-axis. A rapid spike in x acceleration is visible when the rollator is shifted forward by the user, with the user shuffling to catch up to the rollator. Due to the shuffle, y-acceleration is minimal, due to the slow motion of the user.

Reference [C], Limping Gait: Atrophic muscles or previous stroke incidents may cause overall slower movement, which may cause a muscle imbalance in a lower extremity and result in a cautious walking style. Acceleration data for this gait demonstrated significant z-axis acceleration, as well as x and y acceleration due to a muscle imbalance in the affected limb.

Reference [D], Typical Aging Gait: An individual with this gait would walk at a slower but more consistent velocity, demonstrating minimal acceleration in all axes. This walking style is common in individuals who have experienced aging with a typical slowing in neuron activity.

(WT) Testing Setup

The IMU was secured to the rollator, and oriented carefully for the x-axis to be pointing in the forward direction. No visible obstacles were present on the flat, indoor floor. Subjects walked for at least one 13m straight length, and then executed a 180° turn. The subjects' x, y and z accelerations were recorded. Code and recordings of this test can be found in Appendix, Code.

(WT) Results

The greatest accelerations in all of x, y, and z axes were observed in the Motor neuron deficit gait (Reference A). Smallest accelerations recorded were generally found in the

TABLE II
WALKING TEST

Reference	Gait Class	Absolute Acceleration X Max	Min	Mean	Absolute Acceleration Y Max	Min	Mean	Absolute Acceleration Z Max	Min	Mean
A	Motor Neuron Deficit	4.78	0.01	1.05	2.45	0.00	0.31	12.01	7.25	12.01
B	Shuffle	2.74	0.02	1.03	0.85	0.00	0.079	11.52	8.94	9.78
C	Limp	2.62	0.02	1.03	1.58	0.00	0.28	11.55	8.61	9.77
D	Typical Aging	2.53	0.04	1.05	0.89	0.00	0.11	10.85	8.37	9.78

Table 2. This table lists the results for the Walking Test, and details the absolute acceleration values detected across four different gait types, each emulating a gait the target demographic may use.

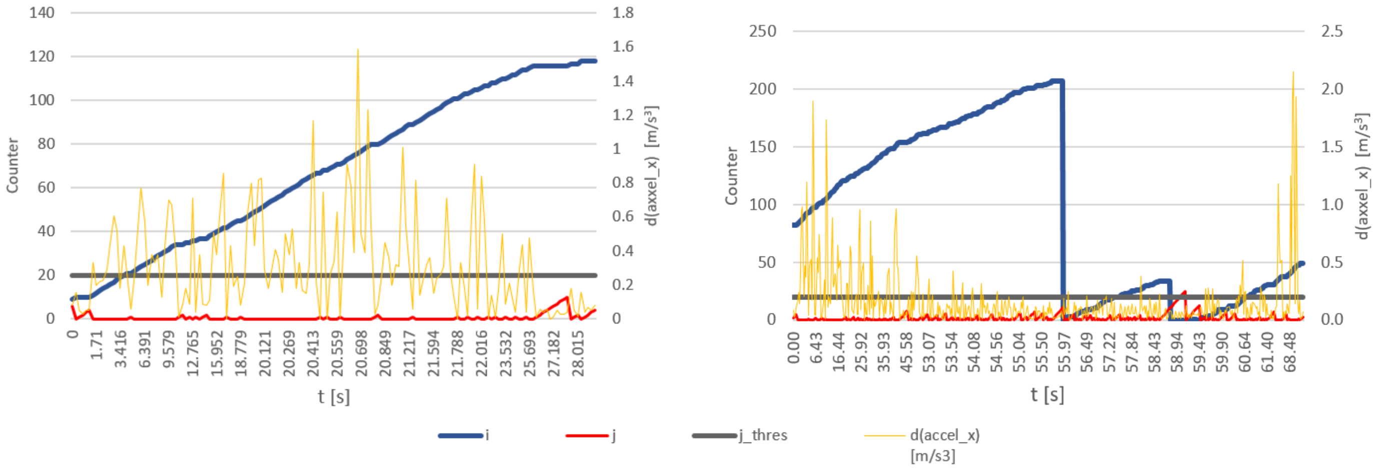

Figure 5. Plots of jerk, and i-j counters against time. Comparison of two different gaits, and whether they trigger a stop-time function, shutting off ultrasonic sensor readings. This feature was being tested as battery-saving method, as well as a method to reduce false alarms when the user was not in motion.
Different walking gaits: (A) Motor Neuron Deficit, with a dragging right leg; (B) Shuffle, with rapid x-acceleration. This data was generated through the *Walking Test* and demonstrated the need to calibrate accelerometer sensitivity based on user walking speed. Additionally, it established the efficacy of utilizing two counters for both stop-time (j) and motion-time (i), to reduce instances of false alarms.

Shuffle gait (Reference B). These gaits defined the extreme acceleration cases expected from our target demographic.

X-acceleration, being the acceleration in the direction of user propagation, proved to be the most valuable parameter for determining intentional user motion. Spikes in y-acceleration, while common and periodic in certain gaits, did not indicate user intent. The mean of z-acceleration remained relatively constant for most users, making its use as a logic parameter redundant.

Variations in acceleration data were found to be extremely high, proving difficult to narrow down to general values that could control notification feedback to the user. The LSM9DS1 sensor proved to be very sensitive, and minute orientation changes could cause non-negligible acceleration values in the x and y axes. Additionally, slight variations in motion were frequently detected, even if the user was attempting to simulate an immobile case. These issues with sensor calibration led to the implementation of jerk as the primary logic parameter, instead of acceleration.

Analyzing jerk, the rate of change of acceleration with respect to time, removed the need for a gyroscope in the system design. Since the change in acceleration in a certain axis is not affected by orientation (assuming the object did not move out of plane), the jerk in the x-direction gives a parameter value that can be used to determine whether the rollator is experiencing adequate axial motion. When moving forward up an inclined ramp the system x-axis becomes tilted to be parallel with the incline and direction of forward motion. As a result, the acceleration in this tilted axis develops an offset that is a product of gravity acting against the direction of motion which is now partially in the z axis. When looking at the change in acceleration the offset gets eliminated and because of this the thresholds for motion detection can remain the same when walking on flat ground or a slope.

(WT) Motion Bias

The parameters set for detecting stop-time and motion-time for the final design iteration were heavily biased towards assuming the rollator was in motion. Since the device is meant to be commercialised from a medical or assistive perspective, it needed to err towards the side of safety in the logic parameters. The device accepts extremely small jerk values as an indication of motion. These jerk values were parameterised by analysing the trigger of *icount* and *jcount* variables in the code logic. The jerk values analysed were of the aforementioned Shuffle [B] and Motor Neuron Deficit [A] gaits, the two extreme gaits encompassing the target demographic. As seen in Figure 5, Plot [A] demonstrates very little triggering of a 'stopping event', the ideal situation if the user is actually in motion. However, Reference [B] triggers at least three stopping events (where the US sensors do not read data), even while the user is in normal forward motion. Reference [B] indicates the lower limit of *jcount* parameters and ensures that the prototype does not potentially endanger the user.

OBSTACLE RESOLUTION TESTING (ORT)

Tripping hazards for users had to be properly defined in-terms of their dimensions, and the HC-SR04 sensor's ability to detect the relevant objects needed to be quantified. Common objects that were tested can be found in Appendix, Iterative Parameter Testing, Object Dimension Tests.

The Obstacle Resolution Test (ORT) was designed to find the maximum distance away from the HC-SR04 sensor an obstacle of a given dimension could be. This experiment provided the relationship between maximum distance of the obstacle, and its frontal area (the projected view of the obstacle in the yz-axis).

The HC-SR04 sensor was placed parallel to the ground, and oriented towards an obstacle along the x-axis (an image of the testing setup can be found in Appendix, Iterative Parameter Testing, Object Dimension Tests. The distance along the x-axis from the sensor to the nearest point on the obstacle was measured manually, and the maximum distance ($\bar{x}$) was determined to be the point that the HC-SR04 sensor returned a stable value over time (Table 3).

Plotting the $\bar{x}$ values against frontal area resulted in a moderately close linear fit (Figure 6). This predictive relationship allowed us to appropriately set trigger parameters for the HC-SR04, based on the theoretical smallest obstacle that we determined could be a user hazard, using the equation below,

$$D = 0.0798 \cdot A + 909.38$$

where *D* is the maximum distance (mm) from the HC-SR04 sensor where a stable signal is detected, and *A* is the projected frontal area of the object (mm^2).

The smallest object that could constitute a tripping hazard was determined through trial and error, and had a frontal area 7258mm^2. This resulted in a predicted stable maximum distance of 1.48m.

TABLE III
OBSTACLE RESOLUTION TEST – OBJECTS LIST

Object	Projected Frontal Area [mm^2]	Maximum Distance [mm]
Concrete block	11432.26	1800
Foam Cylinder	3394.56	1500
Duct Tape	5994.46	1800
Screw Driver	683.49	750
Pen	1323.85	750
Mug	12166.32	1650

Table 3. This table lists the objects tested to ascertain the HC-SR04 sensor's resolution capabilities, based on its 15degree unidirectional beam spread, and the projected frontal area of the objects. Data from this table was used to generate Figure 6.

The minimum reaction time of a user in the target demographic had been previously determined to be 0.32m. Applying to this a Factor of Safety (FOS) of 3, resulted in a minimum detection distance of 0.96m. The minimum detection distance had an FOS of 1.54 when compared to the maximum distance capability for the smallest object (the worst case scenario), with FOS increasing as the object got larger at the same detection distance.

The final sensor orientation was determined based on the minimum detection distance of 0.96m.

(ORT) Potential sources of error

The accuracy of this experiment was limited; convex obstacles had points on their surface that were closer to the sensor than others. The HC-SR04 sensor was calibrated to note the closest obstacle point that returned a full, high-amplitude wave, and thus the returned value always had a tolerance determined by the radius of curvature of the convex surface. Additionally, the experiment had a low sample size (N), and thus may have had a high sampling error. The convexity and curvature of the object's frontal area, and the diffusivity of the returned sound wave was also not factored in significantly. Additionally, the experiment did not account for reflectivity of the object's surface.

Positioning of HC-SR04

The HC-SR04 US sensors were positioned to be able to accurately detect obstacles with a minimum frontal area of 7258 mm^2. The lateral positioning and height of the sensors were adjusted to be able to detect objects across the entire track-width of the rollator.

Positioning the HC-SR04 sensors too low in the z-axis caused significant issues with the return signal. Since the sensor only triggers a high signal when a return wave of significant

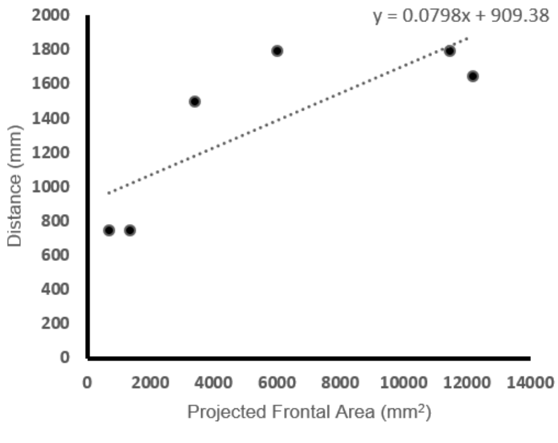

Figure 6. Projected Frontal Area as a function of Maximum Distance. This data was generated through the *Resolution Test* and yielded a linear relationship, which allowed for the prediction of maximum distance away from an HC-SR04 sensor an object of certain frontal area.

strength is detected, it relies on the initial pulse not being too heavily attenuated by the reflecting surface. Additionally, the angle at which the pulse wave meets the reflective interface determines how much of the wave is returned.

Initial positioning of the HC-SR04 sensors were on a lower cross-bar, allowing them all to be identically aligned in the y-axis. However, due to the 15° beam spread of the sensor, this resulted in object detection at a closer range than predicted, resulting in the user being too close to the object when it was actually detected, significantly reducing their available reaction time.

A change in the sensors' angle to detect at a further distance increased its angle of incidence to the ground surface, which on smooth surfaces resulted in a very weak return signal, and provided an untenable solution for object detection, since detection of the ground surface was meant to be the default distance for the sensors.

FSR Test

In order to ensure that the target demographic was capable of exerting adequate force on the integrated FSR, and that notification parameters were correctly calibrated, the sensory range of the FSR needed to be mapped. The FSR Test was designed to test four different grip cases, and measure the absolute force detected, as well as map the force to a raw analogue value to be used for conditional logic. A video of the test is contained in Appendix, Testing, Iterative Parameter Tests, FSR Force Tests, and results can be seen in Table 4.

TABLE IV
FORCE RESISTIVE SENSOR TEST

Grip Case	Force [N]	Raw Analog Value
Full Weight	50.0	984
Clenched hand	16.0	959
Relaxed hand	1.0	523
Barely Resting	<0	70

Table IV. This table lists the values detected by the force resistive sensor during the FSR Test. Four different grip classes were assessed, and all force values were compared to maximal grip strengths for the target demographic. (DTI Strength Report)

The force range for 60-80 year old users gripping a 30mm handle is 4.05 - 20.05 [N] (Table IV, (DTI Strength Report)). Since there was a clear disparity in FSR analog value between the Relaxed Hand case, and the Barely Resting case, it was ascertained that any analog value between 70 - 523 would be appropriate to signify user presence, since the force range of 0-1 [N] was well below the force capabilities of the target demographic. A logic condition value of 523 was initially selected and was reduced to 400 during final testing.

FINAL TESTING

Surface Testing

For older users living in long-term care facilities, or at home, maintaining independence is paramount. While the design of this sensing system was optimized for indoor use on surfaces such as wood or linoleum flooring, it was also tested on outdoor surfaces such as concrete paving and asphalt. Testing videos can be found in Appendix, Testing, Final Testing, Surface Tests.

Asphalt was found to be an uneven surface, with many potholes and major irregularities in elevation. Concrete was a more even surface, but still resulted in significant wave diffusion due to its dimpled surface. Indoor surfaces, while extremely regular in terms of elevation, had the potential to be too smooth, resulting in a very weak return signal. The smoother the ground surface, the longer the HC-SR04 sensor had to pulse to return a high signal, due to the high ratio of waves reflected away from the sensor, as opposed to back towards it. However, with dimpled, uneven, or rough surfaces, this would not be the case.

These property variations in the surfaces that the device operates on causes significant variations in the return signal received by the HC-SR04 sensors. The consistency of these sensors readings is paramount, as it dictates the triggering of the detection notification to the user.

These variations add more parameters to the rollators operation that need to be analysed and mapped. A further consideration for range capabilities of the design could be to detect drops in elevations as well, which would require more consistent accurate sensors.

Object Detection

The object detection capabilities of the device were tested across a range of obstacles, varying in their frontal area. The HC-SR04 sensor was capable of detecting every object at range =< 0.9m, although sensitivity decreased with decreasing object area. Geometry of the objects did not seem to affect detection significantly, verifying the device as a successful prototype for obstacle detection. Testing videos for obstacle detection can be found in Appendix, Testing, Iterative Parameter Tests, Parameter Calibration.

III. RECOMMENDATIONS

FUTURE HUMAN FACTORS CONSIDERATIONS

Moving forward, continuous testing is paramount for improved iterations. These tests include: optimizing data for hills/elevation, public space, subtle changes in terrain (such as ice, change in height in doorway or loose carpet) and objects that are unnecessary to identify (such as crowds of people) (Sollitto, 2017). Another approach is to universally retrofit to any common rollator to allow for the elderly to keep the rollator they trust and to save money (Tesi, 2013).

Walking Calibration Code

Since acceleration and jerk parameters are highly dependent on the user's walking velocity and style, an appropriate future consideration could be to execute a 'walking calibration function', to redefine sensor parameters to the specific user. By requiring the user to walk for 10 seconds, the system can ascertain control values for the user's acceleration and jerk ranges, thus adjusting stop-time and motion detection sensitivity appropriately to improve motion bias. If this test is completed upon rollator purchase, it could be performed in closed lab conditions, and if part of a rehabilitation regime, could be updated as the user's gait adapts.

This technology may be adapted to people beyond the population of the elderly including: people with neurological deficits, motor deficits, severe knee issues, or people with Multiple Sclerosis. To target these populations, looking at a six-minute walk data gathered by researchers will be paramount to determine how to optimize our technology to fit their needs to detect obstacles effectively. Six-minute walk data has been a well-trusted method to gather information of walking gait while recording motion data capture as they do at the Wolf Orthopaedic Biomechanics Lab at the Fowler Kennedy Clinic.

Size Minimization

If commercialised, this circuit could be significantly reduced in size. The prototype was developed using a breakout-board for the LSM9DS1 chip, and an Arduino Uno with an ATMega328P microcontroller. A subsequent prototyping stage should see these components embedded on a single-layer printed circuit board, in order to minimise the devices overall areal footprint. Since the ultimate goal of this technology is for integration into a rollator design, and not as an add-on attachment, the devices dimensions should be small enough to enable low-profile integration.

Further development considerations for size minimization could be:

- Programming the ATMega328P with the Arduino C code, removing the need for the entire Arduino shield. A pinout diagram detailing the pin changes is available in the Appendix.
- Integrating the LSM9DS1 chip onto the PCB significantly reduces areal footprint of the device.
- Miniaturization of the ultrasonic sensors would not be ideal. The HC-SR04 was selected based on its 400cm range, $3.95 cost, and availability for prototyping purposes. However, since sensor distance range has decreased to less than 100cm, a smaller sensor could be used in order to remain functional at this range and decrease overall size.
- Since the design has already been tested on a 16MHz clock, and the sample rate of data collection and processing is of paramount importance to detection and notification of obstacles, the implementation of an external clock is recommended. A quartz crystal oscillator (Sparkfun, COM-00536), similar to what is used on the Arduino Uno, along with two 22pF capacitors, could be used to accurately time the ATMega328P. While the ATMega328P has an internal clock, it is limited to 8Mhz, and is susceptible to temperature and voltage changes. Additionally, calibration of the internal ATMega328P clock cannot easily be achieved to within +/-1%, making an external timing solution much more stable. (Stack Exchange, 2018), (Sparksfun, 2018).

Further miniaturization of the power supply (voltage regulator) and capacitor selection could be achieved in future prototype iterations. Surface-mount capacitors and resistors should be used for final production design.

Battery Life

A smaller, more lightweight battery solution would be an ideal implementation in the next prototype iteration, since the power requirements of this design call for a minimum of a 24-hour continuous on-time. The continuous firing of the three HC-SR04 sensors in the circuit drain battery life very rapidly.

A measure implemented in this iteration was to turn off sensor pulsing when motion was not detected by the accelerometer. Further power usage reductions could be achieved by the decrease of the pulse amplitude emitted by the ultrasound sensor. Currently, the device has an operating range that is a mere 10% of the maximum range capabilities of the HC-SR04 sensor, indicating that the pulse amplitude should be adjusted to the device requirements. A reduction in pulse amplitude would decrease maximum range to the required level, reducing needless power draw and prolonging battery life.

Other options for reducing battery life include optimising motor rpm and motor size to provide the ideal feedback required for the target demographic, as well as using lower power LED strips.

Conclusion

The final product has demonstrated the ability to detect objects within the desired range in front of the rollator when it is in use. It has proven the ability to warn the user of hazards in minimally invasive way by illuminating LED indicator and through a subtle vibration in the right handle.

The product has met customer requirements of safe to use, does not impede the normal function of the rollator, and it can detect objects within its required range of 1.48 meters. While the system has been retrofitted to an existing rollator, if this product were go to market, it would be developed into a new rollator design to market as a full rollator product.

In addition to customer requirements, it has remained within engineering guidelines and specifications outlined above. It weighs less than 5lbs and can detect at least 0.32 m in front of the rollator. An external battery source was hooked up to the prototype that would allow it to be used systematically for 24 hours through a single charge. The prototype was not covered to allow for vision of circuit components for demonstration purposes, all components could be easily covered with protective housing to meet IP24 water resistance standards without impeding the function of the system. The system however was not tested in various temperature ranges to determine its usability between -20 to 30° C, this could be proven through future testing.

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