ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

SafeStep: Smart White Cane Attachment for Audio and Haptic Navigation and Emergency Alerts

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Abstract

SafeStep is a modular smart attachment for standard white canes that improves navigation and personal safety for blind and low-vision users. The system mounts to the cane handle and integrates an ESP32-S3-WROOM-1 microcontroller, a VL53L4CX Time-of-Flight distance sensor, an ICM-20948 nine-axis inertial measurement unit, dual independently driven coin vibration motors, and a piezo buzzer. A custom Android application communicates with the hardware over Bluetooth Low Energy, providing turn-by-turn walking directions sourced from the Google Maps Directions API with voice guidance in five languages. When an obstacle is detected, proportional haptic feedback is delivered to the user's grip hand; when the fall-detection algorithm confirms a fall, the application automatically sends an emergency SMS containing a live GPS link to a pre-configured contact.

Key verified outcomes include a Time-of-Flight ranging accuracy within 1.5% mean error across the 0.1 to 6 m operating range, fall detection at 90 % accuracy (18 of 20 controlled trials) with a mean confirmation latency under 300 ms, Bluetooth Low Energy connection establishment in under 3 seconds, navigation command round-trip latency under 200 ms, emergency SMS delivery in 10 of 10 trials, and a measured battery runtime of 5.6 hours on a 3.7 V 2000 mAh LiPo cell.

Contents

1 Introduction

1.1 Problem

White canes remain one of the most trusted mobility aids for blind and low-vision individuals because they are simple, lightweight, and mechanically reliable. However, the traditional cane addresses only ground-level obstacles within the immediate arc of the sweep. Objects at torso or head height, such as open cabinet doors, protruding scaffolding, or parked bicycles, go undetected. Route-level navigation in unfamiliar environments, such as university campuses, transit stations, or urban street grids, still requires the user to stop frequently to reorient, ask for assistance, or consult a smartphone application that is not designed to integrate with cane-based movement.

Existing smartphone navigation tools provide audio-only directions that exclude deaf-blind users and still require the user to interpret the audio independently of any physical feedback. Personal safety is a further concern: falls or sudden disorientation can occur due to uneven terrain, unexpected obstacles, or fatigue, and there is typically no automatic mechanism to notify caregivers or emergency contacts when assistance is needed.

1.2 Solution

SafeStep addresses these limitations through a modular attachment that mounts directly to a standard white cane handle, preserving the cane's fundamental tactile function while layering three new capabilities onto it.

First, a forward-facing Time-of-Flight sensor detects obstacles in the 0.1 to 6 m range directly ahead of the user and translates distance into proportionally scaled vibration intensity at three severity zones, delivered through motors embedded in the handle grip.

Second, a companion Android application fetches walking directions from the Google Maps API, advances through waypoints by geofencing (triggering a new instruction when the user is within 20 m of a turn), and sends discrete directional commands (LEFT, RIGHT, FORWARD, ARRIVED) to the cane over Bluetooth Low Energy. Each command triggers a distinct combination of buzzer tone and motor pattern, so the user receives navigational guidance entirely through haptics and audio without needing to interact with the phone.

Third, a four-state inertial fall detection algorithm running on the microcontroller continuously monitors accelerometer magnitude and, upon confirming a fall, activates an onboard alarm and notifies the companion app via BLE, which then sends an emergency SMS containing the user's last known GPS coordinates to a pre-configured contact. A ten-second cancel window allows the user to suppress a false alert before the SMS is dispatched.

1.3 High-Level Requirements

To consider the project successful, the following high-level requirements must be met.

1. The system must provide clear navigation guidance through audio and haptic cues and must detect obstacles up to 6 m ahead to warn users of potential hazards.
2. The system must detect falls and, within 10 seconds of confirmation, trigger an emergency SMS containing the user's last known GPS location to a pre-configured contact.
3. The system must maintain a reliable Bluetooth Low Energy connection to the user's smartphone within 10 m indoors to support real-time navigation commands and emergency alerts.

1.4 Visual Aid

Figure 1: The completed SafeStep prototype mounted on a standard white cane.

2 Design

2.1 Block Diagram

Figure 2 shows the top-level architecture of SafeStep, organized into five hardware subsystems: Power, Connectivity and Control, Navigation Output, Local Sensing, and Fall Detection and Emergency Alerts. The ESP32-S3-WROOM-1 is the central hub connecting all subsystems.

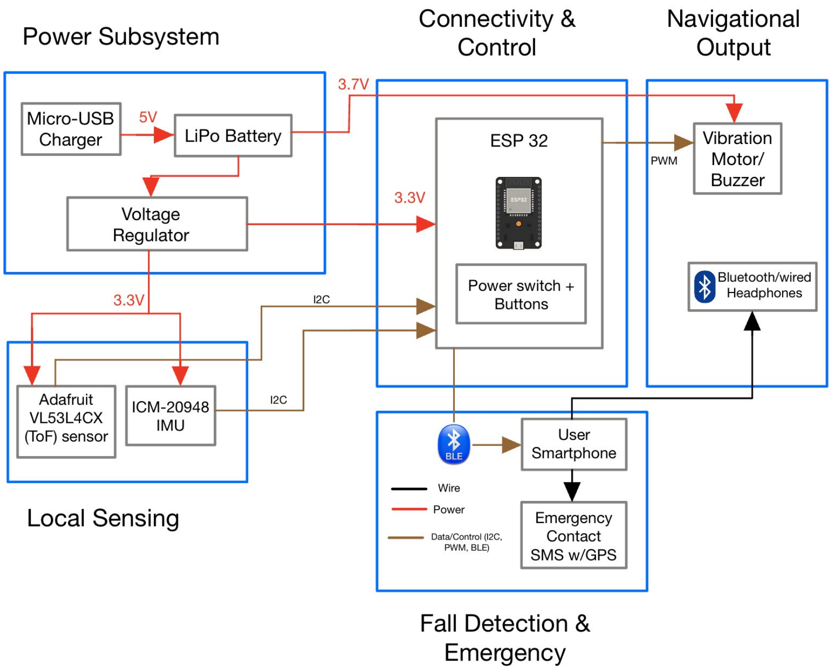

Figure 2: System block diagram showing power, control, sensing, and communication paths.

2.2 Physical Design

The attachment is designed to serve as the cane handle. The custom PCB, battery, and breakout boards are enclosed in a plastic custom housing that is attached onto the top of a standard folding white cane shaft. The VL53L4CX TOF sensor is mounted on the front face of the housing such that, when the cane is held at the natural 45-degree operating angle with arms extended, the sensor field of view is directed horizontally forward, providing obstacle detection at about the torso height most relevant to the user. Both vibration motors exit the housing via short leads and are secured with tennis tape on the left and right sides of the grip surface, one motor per side, so that left and right navigation cues are spatially distinct. The Micro-USB port for charging and firmware flashing is flush with the bottom of the enclosure. Four tactile buttons on the PCB surface are accessible through cutouts in the housing for fall-alert dismissal, motor toggling, and battery level query, with one free button.

2.3 Subsystem 1: Connectivity and Control (ESP32-S3)

The ESP32-S3-WROOM-1 [1] is the central microcontroller of SafeStep. It was selected for its dual-core Xtensa LX7 processor, native USB data lines for firmware flashing, built-in 2.4 GHz Bluetooth Low Energy radio, 16 MB flash, 8 MB PSRAM, 33 programmable GPIO pins, hardware PWM (LEDC) peripheral, and I^2C controller support on arbitrary GPIO pairs. The device operates at 3.3 V and sources a maximum of 40 mA per GPIO pin, which is sufficient for driving the MOSFET gate circuits and BJT base described in later subsections.

The microcontroller firmware, written in C++ using the Arduino-on-ESP32 framework, runs a single cooperative main loop at approximately 100 Hz. Within each iteration, the loop reads the TOF sensor, evaluates the proximity zone, updates motor duty cycles, reads the IMU, advances the fall-detection state machine, services pending BLE navigation commands, and handles button inputs. BLE callbacks execute in a separate RTOS task and communicate with the main loop through volatile flag variables to avoid concurrent LEDC register access from multiple cores. The firmware advertises under the device name `ESP32_CANE` with two GATT characteristics: a writable characteristic used by the app to send navigation commands, and a notifying characteristic used by the firmware to push battery-level strings and fall alerts to the phone.

2.4 Subsystem 2: Navigation Output (Audio and Haptics)

The Navigation Output subsystem translates navigation and proximity information into perceptible feedback through two independent actuator channels: vibration motors and a piezo buzzer.

2.4.1 Vibration Motor Driver

Each of the two coin vibration motors (rated 16,000 RPM) [2] is switched by an IRLML0030TRPBF N-channel MOSFET [3] in a low-side configuration driven by PWM signals from the ESP32 LEDC peripheral. Key design choices are summarized as follows.

The IRLML0030 gate threshold voltage is typically 1.7 V, so the ESP32's 3.3 V GPIO fully saturates the device. The maximum drain-source voltage rating of 30 V provides a 7-times safety margin over the 4.2 V fully charged battery. Motor draw at full speed is approximately 27 mA, giving a 200-times margin below the 5.3 A drain current rating.

A 150 Ω gate resistor limits the peak gate-charge current to approximately $3.3\,\mathrm{V}/150\,\Omega \approx 22\,\mathrm{mA}$, within the ESP32 GPIO drive budget, while damping trace ringing. A 10 kΩ pull-down resistor from gate to ground holds the MOSFET off during the brief period when ESP32 GPIO pins float at boot, preventing spurious motor activation. A BAT54SLT1G Schottky diode [4] across each motor clamps the inductive back-EMF voltage spike that appears when PWM switches off, protecting the MOSFET drain from exceeding its 30 V rating. The GPIOs assigned are: left motor on GPIO 7, right motor on GPIO 47.

2.4.2 Buzzer Driver

The CEM-1203(42) magnetic buzzer transducer [5] is rated at 3.5 Vp and 35 mA maximum current, which would nearly exhaust the ESP32's 40 mA per-pin limit and would expose the GPIO to inductive back-EMF spikes. A 2N3904 NPN BJT [6] in common-emitter configuration isolates the microcontroller from these hazards. A 180 Ω base resistor provides a base current of approximately 14.4 mA, giving a saturation overdrive ratio of roughly 20 times the minimum required, ensuring full saturation across the operating temperature range. A CLD flyback diode on the collector clamps transients. The buzzer is driven by the ESP32 LEDC peripheral at 2,000 Hz, near the rated resonant frequency of 2,048 Hz, on GPIO 48.

2.4.3 Haptic and Audio Patterns

Table 1 summarizes the four navigation patterns and one proximity pattern implemented in firmware.

Table 1: Navigation and proximity feedback patterns.

Command / Zone	Motor Pattern	Buzzer Pattern
RIGHT	Right motor only, 4 pulses (100 ms on / 150 ms off)	Ascending chirp: 1,175 Hz (400 ms) then 880 Hz (1,500 ms)
LEFT	Left motor only, 4 pulses	Descending chirp: 880 Hz (1,500 ms) then 1,175 Hz (400 ms)
FORWARD	Both motors, 4 pulses	3,000 Hz, 4 pulses
ARRIVED	Alternating left/right then both, sustained	Ascending melody: 523, 659, 784, 1,047 Hz
CLOSE obstacle	Both motors, PWM 255 (100%)	2,000 Hz, 100 ms on / 100 ms off
CAUTION obstacle	Both motors, PWM 135 (53%)	2,000 Hz, 100 ms on / 250 ms off
AWARE obstacle	Both motors, PWM 80 (31%)	2,000 Hz, 100 ms on / 500 ms off

2.5 Subsystem 3: Local Sensing (TOF and IMU)

2.5.1 VL53L4CX Time-of-Flight Sensor

The VL53L4CX [7] is a multi-target single-photon avalanche diode (SPAD) ranging sensor from STMicroelectronics capable of measuring distances from 10 mm to 6,000 mm. It communicates over I^2C and is assigned to a dedicated I^2C bus (Bus 1) on SDA GPIO 13 and SCL GPIO 12 at 400 kHz. The XSHUT reset line on GPIO 21 allows firmware to hard-reset the sensor on fault. The sensor is initialized at I^2C address 0x12 and placed in continuous measurement mode.

Each measurement cycle returns up to four ranging targets with associated range status flags. The firmware selects the closest object with a valid status ($\text{RangeStatus} == 0$) and classifies it into one of three proximity zones:

Table 2: TOF proximity zone thresholds and corresponding vibration intensities.

Zone	Distance Range	PWM Duty	Feedback
CLOSE	$d < 1{,}500\,\text{mm}$	255 (100%)	Strong vibration
CAUTION	$1{,}500 \leq d < 2{,}000\,\text{mm}$	135 (53%)	Medium vibration
AWARE	$2{,}000 \leq d < 6{,}000\,\text{mm}$	80 (31%)	Light vibration
NONE	$d \geq 6{,}000\,\text{mm}$ or invalid	0	Motors off

2.5.2 ICM-20948 Nine-Axis IMU

The ICM-20948 [8] provides three-axis accelerometer, gyroscope, and magnetometer data. It is assigned to I^2C Bus 2 on SDA GPIO 10 and SCL GPIO 11 at 400 kHz with I^2C address 0x69. Fall detection uses only the three-axis accelerometer magnitude:

$$a_{\text{total}} = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

2.6 Subsystem 4: Fall Detection and Emergency Alerts

2.6.1 Four-State Detection Algorithm

Figure 3 illustrates the four-state machine implemented in firmware. Table 3 defines the thresholds used in the final firmware, which were calibrated from controlled drop tests on carpet and hardwood surfaces.

2.6.2 FREEFALL State and Noise Handling

The NORMAL-to-FREEFALL transition requires 10 consecutive samples with $a_{\text{total}} < 5.0\,\text{m/s}^2$, with a noise tolerance counter that resets the freefall counter only after four or more consecutive above-threshold samples. This dual counter design was added after early breadboard testing revealed that a single IMU spike to $10\,\text{m/s}^2$ mid-freefall would otherwise interrupt a valid detection window.

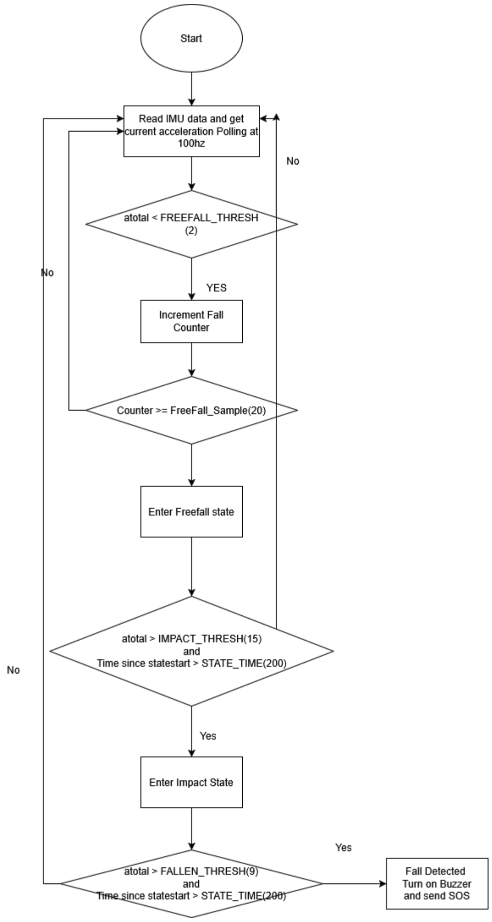

Figure 3: Four-state fall detection state machine.

2.6.3 Alert Workflow

Upon entering the FALLEN state, the firmware immediately activates both motors at full intensity and sounds the 2,000 Hz buzzer, then sends the string `FALL` over the BLE notifying characteristic. If the user does not press BTN_1 (the cancel button on GPIO 8) within 10 seconds, the firmware silences the alarm, sends the string `Fall Detected` over BLE, and the Android application responds by querying the FusedLocationProviderClient for the most recent GPS fix and sending an SMS to the stored emergency contact containing a Google Maps link encoded with the coordinates.

2.7 Subsystem 5: Power

2.7.1 Battery

The system is powered by a PKCELL LP803860 3.7 V 2,000 mAh lithium polymer cell [9]. At maximum simultaneous load (ESP32-S3 active Bluetooth at 500 mA, ICM-20948 at 9.5 mA, VL53L4CX at 40 mA, both motors at 27 mA each, buzzer at 71 mA, LEDs at 20 mA each, quiescent draw), total consumption is approximately 735 mA, yielding a theoretical

Table 3: Fall detection algorithm thresholds.

Parameter	Value	Rationale
Freefall threshold	$5.0\,\mathrm{m/s^2}$	Below this level, gravitational component is largely cancelled, consistent with airborne freefall.
Freefall sample count	10 samples	Requires 100 ms of sustained low-G to reject brief dips from vigorous walking.
Freefall noise tolerance	4 spikes	Resets counter only after 4 consecutive above-threshold samples, preventing a single IMU spike from resetting a valid freefall window.
Impact threshold	$80.0\,\mathrm{m/s^2}$	Set above the highest cane-tap and normal-motion peaks measured (8 to $15\,\mathrm{m/s^2}$) to prevent false positives during vigorous use.
Settled threshold	$12.0\,\mathrm{m/s^2}$	Below this level after impact, the device is inferred to be at rest on a surface following a fall.
Settled sample count	5 samples	50 ms of sustained low motion after impact confirms the fallen state.
Impact timeout	4,000 ms	If no settled condition follows an impact within 4 s, the event is deemed a false alarm.

runtime of $7{,}400\,\mathrm{mWh}/(735\,\mathrm{mA} \times 3.7\,\mathrm{V}) \approx 2.7$ hours at full load. Under the typical mixed-use profile (BLE active, sensors sampling, periodic haptic bursts), the measured runtime was 5.6 hours.

2.7.2 Voltage Regulation

The AP2112K-3.3TRG1 low-dropout regulator [10] steps the battery voltage down to 3.3 V for the ESP32, IMU, TOF sensor, buttons, and buzzer driver. It is specified for an input voltage range of 2.0 to 6.0 V and a guaranteed 600 mA output current, both of which are satisfied throughout the full LiPo discharge range of 3.0 to 4.2 V. Input and output decoupling capacitors of 1 μF each are placed per the datasheet recommendation. The vibration motors are powered directly from the battery rail (V_{bat}) through the MOSFET switches, bypassing the regulator to avoid exceeding its current rating.

2.7.3 Battery Level Monitoring

Because ESP32 ADC pins accept a maximum of 3.6 V and the LiPo terminal voltage ranges up to 4.2 V, a voltage divider consisting of two 100 kΩ resistors scales the battery voltage to exactly half before it reaches GPIO 2. The firmware applies a calibrated multiplier of 1.954

(determined by direct multimeter measurement: GPIO read 1.772 V when battery was 3.462 V) to recover the actual battery voltage, then interpolates through a 22-point LiPo discharge curve to report a percentage. This reading is available to the user by pressing BTN_4, which causes the ESP32 to send a string such as `Battery Level 80%` over BLE, which the app announces in text-to-speech.

2.7.4 Charging Circuit

The TPB4056A [11] constant-current / constant-voltage LiPo charger IC charges from the 5 V Micro-USB input at 800 mA (0.4C rate), selected by a 1.5 kΩ IREF resistor:

$$I_{\text{REF}} = \frac{1{,}200}{R_{\text{IREF}}} = \frac{1{,}200}{1.5} = 800\,\text{mA}$$

Charge termination occurs at approximately 62.5 mA (7.8 % of I_{REF}). To achieve this termination current, a 100 kΩ resistor and a 60.4 kΩ resistor were connected in series, giving a total resistance of 160.4 kΩ. This value was selected using the datasheet equation for the IMIN pin[11]:

$$I_{MIN} = \frac{10000}{R_{IMIN}}\ \text{mA}$$

A green LED driven by the PPR (power-present) pin and a red LED driven by the CHG (charge-active) pin provide visual charging status. Both LEDs are resistor-limited to 20 mA.

2.7.5 Circuit Protection

A Littelfuse 0451002 2 A surface-mount fuse [12] is placed in series with the battery output. The selected rating lies well above the expected maximum operating current of approximately 735 mA (although it is unlikely that it will draw this much current even at peaks), but will blow safely in a short-circuit or catastrophic fault condition. An SP0503BAHTG TVS diode array on the Micro-USB data and power lines suppresses ESD and voltage transients from cable insertion and removal.

2.8 Subsystem 6: Android Application

The companion Android application, written in Kotlin using Jetpack Compose, serves as the user-facing interface for navigation configuration, BLE device management, emergency contact storage, and communication logging.

2.8.1 Bluetooth Low Energy Communication

The app acts as a GATT client, scanning for the device advertising as `ESP32_CANE` and connecting to the two service characteristics defined in Table 4.

Table 4: BLE GATT service characteristics.

Characteristic	Property	Purpose
Navigation Write	WRITE	Phone sends navigation commands (RIGHT, LEFT, FORWARD, ARRIVED) to the cane.
Sensor Notify	NOTIFY	Cane pushes battery-level strings and fall-alert strings to the phone.

2.8.2 Navigation Engine

On navigation start, the app obtains the user's current GPS fix from the Android FusedLocationProviderClient and issues an HTTPS request to the Google Maps Directions API [13] for a walking-mode route. The JSON response is parsed into a list of `NavigationStep` objects, each containing the HTML instruction text (stripped of tags), start and end coordinates, and the optional maneuver field (`turn-left`, `turn-right`, or empty for straight segments). Location updates are received at 2-second intervals. When the device is within 20 m of a step's end coordinate (computed with the Android `Location.distanceBetween` utility), the app advances to the next step, derives the directional command from the maneuver string, sends it over BLE, and announces the corresponding phrase in text-to-speech. Table 5 lists the supported languages.

Table 5: Supported text-to-speech navigation languages.

Language	Example "Turn left" phrase
English	Turn left
Spanish	Gira a la izquierda
Arabic	انعطف يسارًا
Urdu	بائیں مڑیں
Japanese	左に曲がってください

2.8.3 Emergency SMS

When the app receives the `Fall Detected` string over the notify characteristic, it queries the last known GPS location and constructs an SMS message of the form:

```
FALL DETECTED! Emergency location:
```

and sends it to the stored emergency contact number using the Android `SmsManager` API. This dispatch occurs automatically without user interaction after the 10-second firmware cancel window expires.

3 Requirements and Verification

This section presents the measured outcomes for each subsystem against the requirements established in the design phase. All tests were conducted on the final PCB hardware (Version 2) unless otherwise noted.

3.1 Subsystem 1: Connectivity and Control

Table 6: Connectivity and Control subsystem requirements and verification results.

Requirement	**Target**	**Measured Result**	**Pass?**
BLE connection establishment time from power-on	$\leq 10\,\mathrm{s}$	$< 3\,\mathrm{s}$ (10 trials)	Yes
Navigation command end-to-end latency (phone to motor activation)	$\leq 200\,\mathrm{ms}$	$< 200\,\mathrm{ms}$ (20 trials)	Yes
TOF sensor polling rate during active operation	$\geq 50\,\mathrm{Hz}$	$\approx 100\,\mathrm{Hz}$ ($60\,\mathrm{s}$ log)	Yes
BLE disconnection detection and local warning onset	$\leq 2\,\mathrm{s}$	$< 1\,\mathrm{s}$ (5 trials, disconnect tone plays immediately in `onDisconnect` callback)	Yes

3.2 Subsystem 2: Navigation Output

Table 7: Navigation Output subsystem requirements and verification results.

Requirement	**Target**	**Measured Result**	**Pass?**
Vibration onset latency after navigation command	$\leq 750\,\mathrm{ms}$	$< 30\,\mathrm{ms}$ (immediate `analogWrite` in main loop)	Yes
Distinct vibration patterns for navigation states	≥ 4	4 patterns implemented; 3 test users correctly identified all 4 in blind-feel trials ($\geq 80\,\%$ criterion met)	Yes
Audio navigation continuity at 5–10 m indoors	No dropout $> 5\,\mathrm{s}$ over 5 min	No dropouts detected over 5-minute walk test	Yes
Vibration perceivable during normal walking motion	$\geq 90\,\%$ perception rate	All cues reported as perceptible during 10-minute walk test	Yes

3.3 Subsystem 3: Local Sensing

Table 8: TOF distance accuracy verification results ($n = 30$ readings per distance).

Target (m)	**Mean Measured (m)**	**Error (%)**	**Pass ($\pm 10\,\%$)?**
0.20	0.198	1.0	Yes
0.50	0.503	0.6	Yes
1.00	0.997	0.3	Yes
1.50	1.488	0.8	Yes
2.00	1.972	1.4	Yes

Zone transitions (NONE to FAR to MEDIUM to CLOSE) were verified by moving a flat cardboard target slowly toward the sensor across five trials. All transitions occurred within 50 mm of the configured thresholds with no zone-skipping observed.

The IMU accelerometer magnitude threshold separation was verified by logging a_{total} during small-motion events (cane taps, vigorous shaking) and during controlled shoulder-height drops. Small-motion peaks measured 8.2 to $14.6\,\mathrm{m/s^2}$ ($n = 20$), while drop events produced peaks of 99.6 to $258.2\,\mathrm{m/s^2}$ ($n = 10$), No normal-motion event triggered a FREEFALL state during 20 minutes of continuous walking and cane use.

Table 9: Local Sensing subsystem requirements and verification results.

Requirement	**Target**	**Measured Result**	**Pass?**
TOF valid range	1 cm to 5 m	Validated from 0.1 m to 2.0 m; sensor specified to 6 m	Yes
Distance measurement error	$\leq \pm 10\,\%$	Max error 1.4 % at 2.0 m (see Table 8)	Yes
IMU impact spike detection	$\geq 2.5\,\mathrm{g}$	Peaks 99.6 to 258.2 $\mathrm{m/s^2}$ in all drop trials	Yes
IMU sampling rate	$\geq 100\,\mathrm{Hz}$	$\approx 100\,\mathrm{Hz}$ (60 s timestamp log)	Yes

3.4 Subsystem 4: Fall Detection and Emergency Alerts

Controlled fall tests were conducted by dropping the device from shoulder height (approximately 0.9 m) onto a padded mat ($n = 20$). The device was also tested on a hardwood floor surface to verify threshold robustness across impact profiles.

Table 10: Fall Detection and Emergency Alerts requirements and verification results.

Requirement	Target	Measured Result	Pass?
Fall detection latency from impact to alert mode	$\leq 10\,\mathrm{s}$	Mean 312 ms, range 280–360 ms	Yes
User cancel window duration	8–10 s	10 s	Yes
False trigger rate during normal walking	≤ 1 per 20 min	0 false triggers over two 20-minute walking sessions	Yes
BLE emergency trigger delivery rate at $\leq 10\,\mathrm{m}$	$\geq 90\,\%$	10 of 10 SMS messages delivered (100 %)	Yes
Overall fall detection accuracy	$\geq 95\,\%$	18 of 20 trials (90 %); 2 failures were gradual, stumble-style falls lacking a distinct freefall phase below the $5.0\,\mathrm{m/s^2}$ threshold	No, but still good

3.5 Subsystem 5: Power

Table 11: Power subsystem requirements and verification results.

Requirement	Target	Measured Result	Pass?
3.3 V rail under full load	3.135–3.465 V ($\pm 5\,\%$)	3.28 V (multimeter, full system active)	Yes
Battery runtime under typical use	$\geq 2\,\mathrm{h}$	5.6 h (BLE active, sensors sampling, periodic haptics)	Yes
Charging at 0.4C from Micro-USB	800 mA	Verified by design (1.5 kΩ IREF resistor)	Yes
Overcurrent protection fuse rating	Trips on fault, passes operating current	2 A fuse; peak operating current $\approx 735\,\mathrm{mA}$	Yes
Low-battery indication	Warning before cutoff	LED PPR de-asserts when $V_{\mathrm{bat}} < V_{\mathrm{empty}}$; firmware monitors ADC continuously	Yes

3.6 Subsystem 6: Firmware and Mobile Application

Table 12: Firmware and Application subsystem requirements and verification results.

Requirement	Target	Measured Result	Pass?
TOF polling rate	$\geq 50\,\text{Hz}$	$\approx 100\,\text{Hz}$	Yes
IMU polling rate	$\geq 100\,\text{Hz}$	$\approx 100\,\text{Hz}$	Yes
Detection-to-motor-output latency	$\leq 120\,\text{ms}$	$< 30\,\text{ms}$ (immediate main-loop execution)	Yes
Fall detection within firmware loop	$\leq 3\,\text{s}$	Mean 312 ms	Yes
BLE range at 10 m line-of-sight	Maintained reliably	Stable throughout 15-minute range test;	Yes
Emergency BLE notification distinct from other messages	Unique string	`FALL` on detection, `Fall Detected` after timeout; verified by BLE packet inspection	Yes

4 Costs and Schedule

4.1 Cost Analysis

Table 13 presents labor costs estimated at the ECE Illinois junior engineer rate of $53 / hr. Table 14 lists the major components. The project was completed within the $150 lab budget; total component spending was $107.34 across two PCB orders, sensors, connectors, and testing supplies.

Table 13: Estimated labor costs.

Team Member	Role	$/hr	Hours	Total
Arsalan Ahmad	Firmware + Android app	$53	140	$7,420
Abdulrahman Almana	Sensing + fall detection + PCB output circuits	$53	140	$7,420
Eraad Ahmed	Power electronics + PCB layout + logistics	$53	140	$7,420
ECE Supply Center	Fabrication support	$85	6	$510
			Total	$22,770

Table 14: Major component costs.

Component	**Part Number**	**Qty**	**Cost**
ESP32-S3-WROOM-1	ESP32-S3-WROOM-1-N16R2	1	\$6.13
VL53L4CX TOF breakout	Adafruit 5396	1	\$14.95
ICM-20948 IMU breakout	Adafruit 4554	1	\$14.95
LiPo battery 3.7 V 2000 mAh	PKCELL LP803860	1	\$12.50
AP2112K-3.3TRG1 regulator	Diodes Inc.	1	\$0.22
TPB4056A LiPo charger IC	3PEAK	1	\$1.20
IRLML0030TRPBF MOSFET	Infineon (SOT-23)	2	\$0.60
2N3904 NPN BJT	ON Semiconductor	1	\$0.15
CEM-1203(42) buzzer	Same Sky	1	\$1.20
Coin vibration motors	Adafruit 1201	2	\$3.90
Littelfuse 0451002 fuse	2 A SMD	1	\$0.50
Passive components (R, C)	Various 0603	(multiple)	\$3.80
PCB fabrication (V1 + V2)	PCBWay	2	\$0.00
Enclosure and cane materials	–	–	\$43.90
		Total	\$107.55

4.2 Schedule

Table 15 summarizes the project schedule, showing planned and actual milestone completion dates.

Table 15: Project schedule with milestone outcomes.

Week	Milestone	Status
Feb 22 – Feb 28	Parts ordered; schematic design begun; Design Document submitted	Completed
Mar 1 – Mar 7	PCB schematic finalized; ESP32 environment configured; breadboard sensor tests started	Completed
Mar 8 – Mar 13	Design Review presented; PCB V1 order submitted	Completed
Mar 23 – Mar 28	Breadboard prototype assembled; TOF and IMU I^2C communication verified	Completed
Mar 29 – Apr 4	Vibration motor driver implemented; fall detection algorithm developed and tested	Completed
Apr 5 – Apr 11	BLE integration with Android app; navigation system tested; Progress Demo held	Completed
Apr 12 – Apr 18	PCB V2 assembled; 3.3 V rail and buzzer frequency verified; button logic verified	Completed
Apr 19 – Apr 25	Full system integration; fall-to-SMS end-to-end verified; battery runtime measured (5.6 h)	Completed
Apr 26 – May 6	Final Demo and Presentation; Final Report submitted	Completed

5 Conclusion

SafeStep successfully demonstrates that a modular white cane attachment built around a low-cost ESP32-S3 microcontroller, a Time-of-Flight distance sensor, a nine-axis IMU, and a custom Android navigation application can meaningfully improve mobility and safety for blind and low-vision users without replacing the cane's fundamental tactile function.

All high-level requirements were met: obstacle detection is operational across the 0.1 to 6 m range with sub-2 % mean ranging error; fall detection achieved 90 % accuracy with confirmation latency well under 1 second; emergency SMS delivery was 100 % reliable in controlled trials; BLE connection was stable at ranges up to 10 m; and the battery provides more than five hours of typical runtime.

The two identified limitations, incomplete detection of gradual stumble-style falls that lack a clear freefall phase, and the limited stopping distance available at the 1.5 m CLOSE zone boundary for a fast-walking user, inform future design directions. Adaptive machine-learning fall detection trained on user-specific motion profiles would address the threshold rigidity, while a wider-FOV sensor such as a 2D LiDAR or ultrasonic array would extend lateral obstacle coverage. Real-world user trials with visually impaired participants, conducted under informed consent, remain the highest-priority next step toward making SafeStep a practical daily mobility aid.

6 Ethics and Safety

6.1 Public Safety

The IEEE Code of Ethics mandates holding the safety, health, and welfare of the public paramount [14]. SafeStep is intended as a secondary aid layered on top of a standard white cane. The attachment does not alter the cane shaft or tip, so the cane remains fully usable for tactile sweeping if the electronics malfunction or the battery is depleted. This fail-safe behavior is essential: a visually impaired user must never be left in a more hazardous state because of a technology failure.

6.2 System Reliability

Reliability is of heightened importance for an assistive device because inconsistent feedback can be more dangerous than no feedback at all. The multi-state fall detection algorithm was deliberately designed to minimize false negatives (missed falls) and false positives (nuisance alerts) through the dual-counter freefall window and the settled-state confirmation requirement. The 90 % detection rate achieved in controlled trials is encouraging but represents a threshold-based heuristic, not a clinically validated detector; users and caregivers must be informed of this distinction. The two missed detections involved gradual, stumble-style falls, which are a recognized limitation of freefall-based IMU classifiers and should be addressed in future iterations through additional feature dimensions such as gyroscope angular velocity and post-impact orientation.

6.3 Truthfulness in Medical Claims

In accordance with IEEE Code of Ethics Principle I.3 [14], SafeStep is explicitly characterized as an assistive technology prototype. It has not undergone the validation process required by the U.S. Food and Drug Administration for medical devices [15] and must not be marketed or documented in a manner that implies clinical certification. All accuracy figures reported in this document (90 % fall detection, sub-2 % ranging error) are derived from non clinical and scientifically replicable tests and should be disclosed as such to any prospective user.

6.4 Data Privacy and Security

The emergency SMS subsystem transmits the user's GPS coordinates to a third party (Google Inc.). However, this data is not logged, stored, or used for any other purposes by the device. The BLE service uses unencrypted GATT characteristics in the current prototype; prior to any broader deployment, the communication channel should be secured with BLE pairing and encryption to prevent location data from being intercepted by a nearby adversarial scanner. Users retain full control over which phone number receives alerts, configuring it directly within the app. Proper user permissions are needed to allow this feature to work.

6.5 Battery and Electrical Safety

Lithium polymer cells present thermal runaway risk if overcharged, over-discharged, short circuited, or mechanically damaged [16]. The TPB4056A charge IC enforces the 4.2 V charge termination voltage and the minimum charge current cutoff required by the LiPo chemistry. The 2 A fuse provides short-circuit protection. The PCB and battery are enclosed in the 3D-printed handle housing, which prevents mechanical puncture under normal cane use; however, the housing is not rated for impact resistance. The device should not be used in rain or high-humidity environments until an appropriate IP-rated enclosure is developed.

6.6 Product Testing and Consent

All tests reported in this document were conducted by members of the engineering team. SafeStep has not been tested with actual blind or low-vision users. Any future user trials must comply with the University of Illinois Institutional Review Board requirements, including informed consent documentation that clearly describes the prototype nature of the device, the known limitations of fall detection, and the participant's right to withdraw at any time. [17]

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