

PATH: PROXIMITY AWARENESS THROUH HAPTICS

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1 Introduction

1.1 Problem

According to the World Health Organization, at least 2.2 billion people worldwide live with a near or distance vision impairment. For those who are blind or have severe low vision, independent travel depends heavily on the white cane, which remains the most widely used mobility aid because it is inexpensive, lightweight, foldable, and reliable. Its core limitation is coverage: the white cane reliably extends ground-level obstacle and drop-off detection to only about 1.2 meters of reach and cannot detect obstacles at the trunk or head level. This leaves the user's upper body exposed to protruding and overhanging hazards such as tree branches, signage, open cabinet doors, wall-mounted fixtures, and vehicle mirrors, none of which a ground-swept cane will catch.

The consequences are serious and well documented. In a survey of roughly 300 visually impaired individuals, Manduchi and Kurniawan found that 13% experienced head-level injuries more than once per month, and 23% of those head injuries required medical attention. To cope, 43% of cane users reported changing their walking habits, moving more slowly or holding an arm up to shield their head, which trades away walking efficiency and confidence for protection. These are not minor inconveniences; they cause real injury, discourage independent travel, and erode the autonomy the cane is meant to preserve. The problem also has an economic dimension: electronic travel aids exist but have seen minimal adoption because of high cost, low information content, and limited reliability, so most users are left with the same coverage gap. A low-cost attachment that adds torso- and head-height awareness to a cane a user already owns directly targets an underserved public-health and accessibility need.

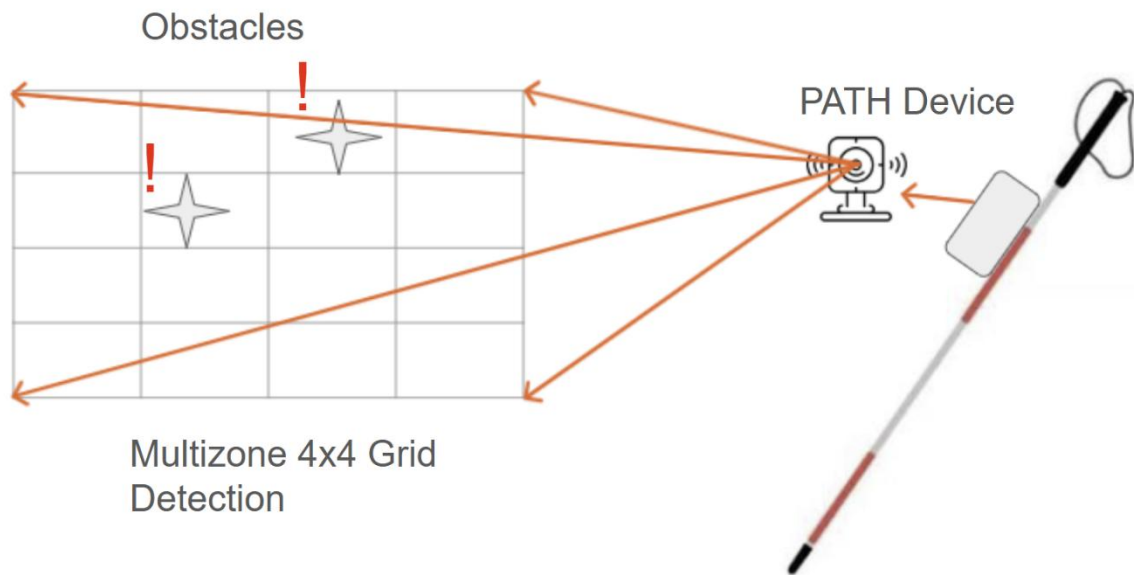
1.2 Solution

To address the coverage gap left by the white cane, we propose an obstacle-warning attachment that mounts to a standard cane and gives the user directional, distance-scaled haptic feedback about obstacles at torso and head height. Two coin vibration motors sit on the handle, one on the left and one on the right. The motor on the side of an approaching obstacle vibrates, and both vibrate together when the obstacle is straight ahead, so the cue itself points toward the hazard rather than just signaling that something is out there. Vibration strength scales with proximity: the closer the obstacle, the stronger the vibration.

The sensing that drives this comes from a multi-zone time-of-flight sensor paired with a 9-DoF IMU. We use the STMicroelectronics VL53L5CX in 4×4 resolution, giving 16 independently ranged zones across a 45° by 45° field of view (about 11.25° per zone), and the BNO086 IMU, which runs sensor fusion on-chip and outputs a filtered orientation estimate. The processor uses the BNO086's pitch to decide which rows of the ToF grid correspond to torso and head height and shifts that active window as the cane's angle

changes while walking, so the detection band stays locked on the upper body instead of drifting into the ground or the sky. This orientation-compensated depth mapping is what lets the device stay accurate during normal cane motion, and the multi-zone grid is what lets it tell the user which direction a hazard is on, something single-sensor commercial canes cannot do.

1.3 Visual Aid

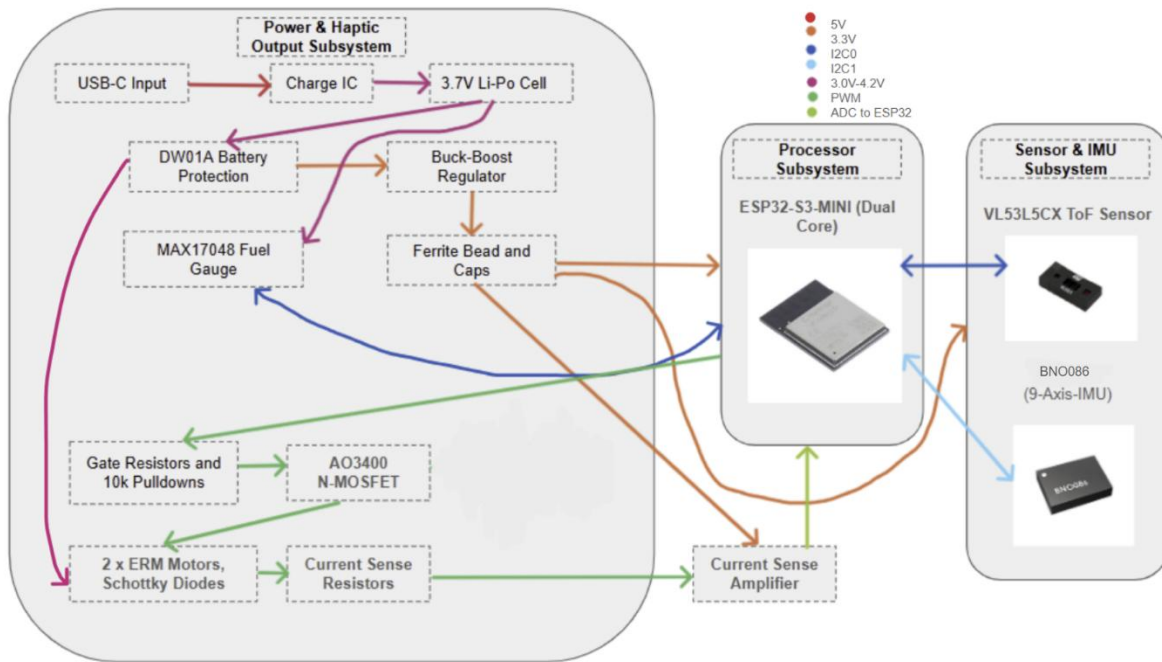


1.4 High Level Requirements List

- The device must detect obstacles up to 2 meters ahead and correctly identify whether each is on the left, right, or center in at least 90% of trials, holding that accuracy across cane tilt angles from -15 to $+15$ degrees (vertical) and cane sweep of 50 degrees/second.
- The device must deliver directional haptic feedback whose vibration strength scales with obstacle distance, completing the full path from sensor reading to motor activation in under 100ms.
- The device must run for at least 3 hours of continuous use on a single battery charge and warn the user before the battery is depleted.

2 Design

2.1 Block Diagram



2.2 Subsystem Overview

2.2.1 ToF Sensor & IMU Subsystem

The ToF sensor and IMU subsystem is the main “eye” of the entire architecture. It is the subsystem that detects obstacles ahead and provides orientation context and data needed for calibration for the processor. VL53L5CX Time-of-Flight sensor with 63 degrees diagonal field of view, or 45-degree x 45-degree square field of view will be used as the ToF sensor. It will be in 4x4 resolution mode, so each zone would have about 11.25-degree x 11.25-degree of coverage. For the IMU, BNO086 9-DoF sensor will be used. The IMU comes with a built in SH-2 sensor hardware and firmware, providing good level of filtering against physical noise on the gyroscope and the accelerometer. Both components communicate with the ESP32 via I2C bus. ToF Sensor will utilize the I2C0 channel and the IMU will utilize the I2C1 channel of ESP32 as they both primarily communicate via I2C protocol.

2.2.2 Processor Subsystem

The processor subsystem is the brain of the device and the only block that connects to every other subsystem. It is built around an ESP32-S3-MINI-1-N8 module surface-mounted on the custom PCB. Its role is to convert raw sensor data into directional haptic output in real time. The VL53L5CX's data-ready hardware interrupt triggers the ESP32 to read the latest 4x4 (16-zone) depth frame over I2C, and the

ESP32 also reads the BNO086's fused pitch. Using that pitch, it dynamically selects which vertical rows of the ToF grid to treat as the active detection window, keeping coverage locked at upper-body-to-head height, the region the cane itself does not protect. It then collapses the active zones into left, center, and right sectors, finds the closest valid return in each sector, and maps that distance to a PWM duty cycle for the corresponding motor (closer obstacle equals higher duty cycle equals stronger vibration). In parallel it samples each motor's current-sense line on its ADC to detect a stalled or disconnected motor, and polls the MAX17048 fuel gauge over I2C to drive the low-battery haptic warning. Because sensor fusion is offloaded to the BNO086, the ESP32's real-time work is limited to frame reads, row selection, sector classification, and PWM updates, which keeps the end-to-end response well inside the latency budget.

Interfaces (quantitative):

- Power in: 3.3 V $\pm$ 5% from the power subsystem, module draw on the order of 80 mA active (confirm by measurement; higher during BLE bursts if the extension is built).
- I2C: two buses at 400 kHz, 3.3 V logic. ToF on I2C0, BNO086 on I2C1, so IMU clock-stretching cannot stall ToF traffic; fuel gauge shares a bus.
- Interrupts: 2 digital 3.3 V inputs (ToF data-ready, BNO086 interrupt).
- Reset: 1 GPIO driving the BNO086 reset line for clean startup.
- PWM out: 2 LEDC channels, 3.3 V, $\sim$ 20 kHz (above audible range), 8-bit or better duty resolution, to the two MOSFET gate stages.
- ADC in: 2 channels sampling motor current-sense during drive.
- USB: native USB for programming and debug.

2.2.3 Haptic (Motor) Subsystem

The haptic subsystem provides directional feedback to the user through vibration. Two coin vibration motors are mounted on the handle, one on the left and one on the right, so the side that vibrates indicates the side an obstacle is on, with both vibrating for an obstacle straight ahead. Each motor is driven through its own low-side MOSFET switching stage, and the processor controls the vibration strength by adjusting the PWM duty cycle so that closer obstacles produce stronger vibrations. A flyback diode protects each switching stage from the voltage spike the motor produces when it turns off. Each motor also has a current-sensing path so the processor can detect a stalled or disconnected motor during operation.

2.2.4 Power Subsystem

The power subsystem is responsible for providing stable, regulated power to the rest of the device. The main source of power is a single rechargeable lithium polymer battery, which is recharged over USB-C through a battery charging IC. A protection circuit sits on the battery to guard against over-charge, over-discharge, and short circuits. The battery voltage is regulated to 3.3V by a buck-boost switching regulator, which supplies the processor, sensors, and motor drive. A buck-boost regulator is used rather than a standard buck because the battery voltage falls below 3.3V as it discharges, and the

buck-boost maintains a stable output across the full range. A fuel gauge IC monitors the battery over I2C so the processor can warn the user when the charge is low.

2.3 Subsystem Requirements

2.3.1 ToF Sensor & IMU Subsystem Requirements

- The system must use the VL53L5CX ToF sensor to detect forward obstacles out to at least 2.0 meters in standard indoor lighting (like the ECEB 3rd floor), continuously reporting multi-zone distance arrays to the ESP32-S3 over the I2C0 bus via hardware data-ready interrupts.
- The firmware must classify obstacles at upper-body to head height into left, center, right, and overhead detection sectors with at least 90% accuracy, and it must drive the corresponding ERM motor/motors(left, right, or both for center obstacle) with a PWM duty cycle that scales with obstacle proximity (closer = increasing duty cycle).

Obstacle Location	Triggered Motor
Left	Left
Right	Right
Center	Both

- The system must read real-time orientation data from the BNO086 IMU over the I2C1 bus and use it to select the active rows of the ToF sensor's 4x4 grid. It must maintain at least 90 percent correct obstacle classification across a vertical tilt range of -15 degrees to + 15 degrees and cane sweep angular velocities up to 50 degrees/second.

2.3.2 Processor Subsystem Requirements

- The processor must activate the correct motor's PWM output within 100 ms of receiving the VL53L5CX data-ready interrupt.
- The processor must sample each motor's current-sense line on its ADC during operation and correctly distinguish a healthy motor from a stalled or disconnected one.

2.3.3 Power Subsystem Requirements

- Must drive each motor independently with PWM intensity that scales with obstacle proximity as shown in the table below.
- Must protect each MOSFET from inductive spikes and keep motors off during power-up.
- Must detect a stalled or disconnected motor through current sensing.
- Must actuate the correct motor within the 100 milliseconds response budget.

Obstacle Distance	Approx Vibration Strength (PWM Duty)
< 0.5m	~100% (strongest)
0.5 to 1.0 m	~70%
1.0 to 1.5 m	~45%
1.5 to 2.0 m	~20% (gentlest)

2.4 Tolerance Analysis

2.4.1 Tilt Compensation Tolerance Analysis

One point of risk in our design is the reduction of the VL53L5CX's resolution from 8x8 to a 4x4 grid, as this limits tilt compensation to discrete row selection and makes it less continuous. Since our requirement aims to maintain a locked detection window across a tilt range of -15 to +15 degrees, it needs to be analyzed whether a limited number of discrete row-selection states can adequately cover this range of tilt while keeping the detection band within an acceptable margin of upper-body to head height at each angles.

Components (Variables)

- FOV: Vertical FOV of the VL53L5CX: ~45 degrees
- N: Number of rows available = 4
- Theta: Angular width per row = 11.25 degrees
- R: Required tilt range to compensate -15 to +15, total 30 degrees
- D: Distance to the obstacle used to evaluation (1m and 2m)

Number of discrete states required to take into account the tilt

$$\text{Number of states} = R/\theta = 30/11.25 \sim 3 \text{ states}$$

Based on this, the firmware must implement at least 3 distinct pitch states across the +-15 degree range (tilted up, down, neutral).

Worst case quantization error

Since 3 states evenly divide the 30-degree range, each state spans 10 degrees, which makes the worst case angular error of 5 degrees.

Now, converting this into physical vertical offset:

$$\text{At 1.0m: offset} = 1.0 \times \tan(5 \text{ degrees}) = 8.7\text{cm}$$

$$\text{At 2.0m: offset} = 2.0 \times \tan(5 \text{ degrees}) = 17.5\text{cm}$$

Using a 2-row active detection window instead of just one two provides overlap margin, the physical detection height at each range (1m and 2m) is:

$$\text{At 1.0m: offset} = 1.0 \times \tan(11.25 \text{ degrees}) = 39.8\text{cm}$$

$$\text{At 2.0m: offset} = 2.0 \times \tan(11.25 \text{ degrees}) = 79.6\text{cm}$$

As shown by this, the worst-case quantization offset represents around 20 percent of the active detection height at distances 1m and 2m. This means that the detection window retains a lot of the overlap with the target upper-body to head height target even in worst case scenario of -15 or +15 degree tilt, and therefore shows that the 4x4 resolution with the VL53L5CX is feasible.

2.4.2 Latency Tolerance Analysis

Another important aspect of the high-level requirement to be verified is the 100ms system latency requirement. This takes into consideration things like the sensor refresh timing and human reaction timing, and it must be determined whether the resulting latency will leave sufficient physical distance between the user and a detected obstacle to allow a safe response.

Components (Variables)

- T_Frame : Worst case wait time for the next ToF frame at 60Hz, $1000/60 = 16.7ms$
- Sys_Time : Stated system latency requirement, 100ms
- $React_Time$: Estimated human reaction time, approximately 200ms
- $Walk_Speed$: Around 1.4m/s
- $Detect_Distance$: Minimum guaranteed detection range, 2.0m

Calculating the total delay and distance traveled,

$$Total = T_Frame + Sys_Time + React_Time = 16.7 + 100 + 200 = 316.7ms$$

$$Distance_Traveled = Total \times Walk_Speed = 0.317 \times 1.4 = 0.44m$$

$$Distance_Remaining = Detect_Distance - Distance_Traveled = 2.0 - 0.44 = 1.56m$$

With the conservative full system latency measure plus the estimated human reaction time yields about 1.56m of clearance before reaching the obstacle's original position. This demonstrates that the 100ms latency goal is feasible with a good amount of safety margin.

2.4.3 Battery Tolerance Analysis

The 3-hour runtime is a high-level requirement, so we verify it here by estimating total current draw and dividing it into the battery capacity.

Known values: Battery capacity: 1500 mAh (single-cell Li-Po, low end of our range)

Component current draws at 3.3V:

- ESP32-S3 (active, BLE off, processing): ~80 mA
- VL53L5CX ToF sensor (continuous ranging): ~40 mA
- BNO086 IMU: ~10 mA
- Fuel gauge and passives: ~2 mA

- ERM motors: ~75 mA each at full drive, but duty-cycled

Motor current

The two motors are the variable load. At full drive each pulls about 75 mA, so both together draw about 150 mA. But the motors only run when an obstacle is present and their strength scales with PWM duty cycle, so they are not on continuously. We assume an average combined motor duty of 30% during active use, which gives an average motor current of:

$$150 \text{ mA} \times 0.30 = 45 \text{ mA}$$

$$\textbf{\textit{Total average current:}} 80 + 40 + 10 + 2 + 45 = 177 \text{ mA}$$

$$\textbf{\textit{Runtime:}} \text{ Battery life} = \text{capacity} / \text{average current} = 1500 \text{ mAh} / 177 \text{ mA} \approx 8.5 \text{ hours}$$

Worst case (motors at 100% continuously)

$$80 + 40 + 10 + 2 + 150 = 282 \text{ mA} \qquad 1500 \text{ mAh} / 282 \text{ mA} \approx 5.3 \text{ hours}$$

Even in the worst case where both motors run at full strength continuously, which should not happen in normal use, the device runs for over 5 hours. Under realistic use the runtime is roughly 8.5 hours, comfortably above the 3-hour requirement. This also leaves margin for the buck-boost regulator's conversion efficiency (around 90%), which slightly reduces usable capacity but does not threaten the requirement.

3. Design Verification

Each subsystem will be tested independently before integration to confirm it meets its requirements. The tests below focus on the power and haptic subsystems.

3.1 Power Subsystem

The power subsystem will be verified for stable regulation, charging, and runtime.

3.1.1 Regulation

We will load the 3.3V rail with a programmable electronic load or fixed resistors while sweeping the input from a bench supply across the full cell range of 4.2V down to 3.0V, and measure the output on a multimeter and oscilloscope. The rail must stay within 3.3V $\pm$ 0.1V across that entire range, which confirms the buck-boost holds regulation where a plain buck would drop out.

3.1.2 Charging and Protection

We will charge a depleted cell over USB-C and confirm the charge IC brings it up correctly and terminates at the right voltage. We will then verify the protection circuit by simulating over-discharge and short conditions and confirming it disconnects the cell.

3.1.3 Runtime and Fuel Gauge

We will run the fully assembled device under normal sensing and haptic load and time how long it operates on a single charge, confirming it meets the 3-hour target. We will also compare the fuel gauge's reported state of charge against measured battery voltage to confirm the low-battery warning triggers before the device shuts off.

3.2 Haptic (Motor) Subsystem

The haptic subsystem will be verified for intensity control, protection, fault detection, and response time.

3.2.1 Intensity Scaling

We will command a sweep of PWM duty cycles and measure vibration output, confirming that strength increases with duty cycle and that a nearer simulated obstacle never produces weaker vibration than a farther one. This confirms the monotonic distance-to-strength behavior.

3.2.2 Fault Detection

We will read the current-sense output on the ADC under three conditions: a healthy motor, a disconnected motor, and a stalled motor held in place. Each condition must produce a distinct, correctly classified current reading in firmware.

3.2.3 Response Time

We will trigger an obstacle and use an oscilloscope to measure the time from the ToF data-ready interrupt to the motor drive signal going active, confirming it stays under the 250 ms budget.

The verification here targets each subsystem requirement directly, so if you drop or change a requirement, drop the matching test. If the proposal only needs the sections through Ethics, hold this for the design document instead.

3.3 Processor and Sensor & IMU Subsystem

The processor, Sensor & IMU subsystem will be verified for response latency, tilt-compensated row selection, and sector classification with proportional output. Each test targets one of the three processor requirements above.

3.3.1 Response Latency

We will trigger an obstacle in front of the sensor and use an oscilloscope to capture the VL53L5CX data-ready interrupt line and the motor PWM line at the same time. The time from the interrupt going active to the PWM signal going active is the end-to-end processing latency. We will repeat this over 20+ triggers and confirm every measurement stays under 100 milliseconds. We will timestamp the end-to-end events and measure the time in total.

3.3.2 Tilt-Compensated Row Selection

We will mount the assembled unit on a cane and tilt it through pitch angles from -15° to $+15^\circ$ against a reference protractor or digital angle gauge, with a fixed target held at upper-body height. We will log the pitch the processor computes from the BNO086 alongside the reference angle, and log which ToF rows the processor selects as active. The system must read real-time orientation data from the BNO086 IMU over the I2C1 bus and use it to select the active rows of the ToF sensor's 4x4 grid. It must maintain at least 90% correct obstacle classification across a vertical tilt range of -15 degrees to +15 degrees and cane sweep angular velocities up to 50 degrees/second.

3.3.3 Sector Classification and Proportional Output

We will place a target in the far-left, center, and far-right of the field of view at stepped distances from 0.25 m to 2.0 m. At each position we will confirm the processor drives the correct motor (both motors

for a center target) in at least 90% of trials, and we will measure the PWM duty cycle on the oscilloscope to confirm it increases as the target moves closer, following the intended distance-to-strength mapping.

3.3.4 Minimum Distance Sensing

We will place upper-body to head height obstacles at distances of 4m, 3m, 2m, and 1m from the device (Will be measured accurately with tape measures). The device should start sending haptic feedback to the device starting at a distance of at least 2m.

3.3.5 Motor Fault Detection

We will read the current-sense output on the processor's ADC under three conditions: a healthy motor running normally, a motor with its lead disconnected, and a motor physically held stalled. Each condition produces a distinct current signature, normal running current, near-zero current when disconnected, and elevated stall current when held, and the test passes if the firmware correctly classifies all three across at least 20 trials each, verifying the second requirement.

4. Costs

4.1 Parts

Table 1 Parts Costs

Part	Manufacturer	Retail Cost (\$)	Bulk Purchase Cost (\$)	Actual Cost (\$)
Li-Ion cell (LP103450)	Jauch Quartz	17.1	14.23	17.1
MCP73831 charge IC	Microchip	0.76	0.75	0.76
BQ29700 protection IC	Texas Instruments	0.61	0.43	0.61
MAX17048 fuel gauge	Analog Devices	4.61	3.5	4.61
TPS63020 buck-boost regulator	Texas Instruments	5	3.8	5
USB4085-GF-A USB-C receptacle	GCT	0.91	0.77	0.91
USBLC6-2SC6 ESD protection	Slkormicro	0.4	0.25	0.4
ESP32-S3-MINI-1-N8	Espressif	3	2.4	3
VL53L5CX ToF sensor	STMicroelectronics	8.77	6.5	8.77
BNO086 IMU	CEVA / Hillcrest	15.79	9.41	12
ERM coin motors (2x)	Vybronic VC1026B002F	1.96	1.8	3.92
AO3400A MOSFET (2x)	Alpha & Omega	0.52	0.32	1.04
B5819W Schottky diode (2x)	NextGen	0.09	0.09	0.18
CRM1206 sense resistors (2x)	Bourns	0.4	0.2	0.8
INA181A1 sense amp (optional)	Texas Instruments	0.44	0.31	0.44
Passives (gate resistors, pulldowns, ferrite bead, decoupling caps)	Various	~4.00		4
Total		\$64.36	\$44.76	\$63.54

5. Conclusion

5.1 Accomplishments

By the end of the project we expect to have a working cane attachment that detects obstacles at torso and head height and conveys their direction to the user through the handle. Specifically, we aim to demonstrate reliable left, center, and right obstacle classification out to 2 meters, tilt-compensated sensing that holds the detection band at upper-body height as the cane angle changes, distance-scaled vibration feedback delivered within our latency target, and closed-loop motor fault detection. Meeting these would show that precise directional obstacle awareness can be added to a standard white cane in a low-cost, retrofittable form.

5.2 Uncertainties

The main uncertainty is whether the tilt compensation holds up under the constant motion of a cane in use, since a swinging cane produces acceleration that can corrupt the orientation estimate. We are relying on the IMU's fused output to reject this, but the real-world reliability will need testing. A second uncertainty is the vibration mapping, since ERM coin motors do not respond linearly to duty cycle and have a minimum spin-up threshold, so the distance-to-strength curve will require tuning against the actual motors. Finally, mounting the vibration pads so the cue transfers clearly to the user's hand without the two motors' vibrations blurring together is an open question we will resolve through testing.

5.3 Ethical considerations

Our device is a mobility aid for visually impaired users, so the governing principle is the first canon of the IEEE Code of Ethics, holding the safety, health, and welfare of the public paramount, and the parallel obligation in the ACM Code of Ethics to avoid harm and to be honest and trustworthy. The most important ethical duty here is honest representation of what the device does. It supplements a white cane by warning of torso- and head-height obstacles the cane misses; it does not replace the cane, and it is not a navigation system. We will state that limitation plainly in any documentation, will not overstate the detection accuracy, and will report the measured limits of the system honestly, including the conditions under which it can miss an obstacle, so that no user treats it as a primary means of travel or develops a false sense of safety. This directly reflects the IEEE Code's requirements to be honest in claims and to acknowledge and correct errors, and the ACM Code's emphasis on giving comprehensive and thorough evaluations.

The main safety-linked ethical risks are the lithium battery and the user's physical dependence on the device while walking, both addressed in the safety section through dedicated battery protection, a fail-safe scope that always leaves the cane functional, and honest testing of reliability. If the BLE phone extension is implemented, it introduces a data and privacy consideration: any location or usage data exchanged with the phone must be minimized and handled transparently, consistent with the ACM Code's respect for privacy, so we will keep that link to the minimum data needed for the crossing-awareness feature and store nothing beyond it.

In terms of societal impact, existing obstacle-detecting smart canes are expensive, which puts them out of reach for many of the people who would benefit most, and adoption of electronic travel aids overall remains low. By retrofitting onto a standard white cane with low-cost, off-the-shelf parts, our device aims to make upper-body obstacle awareness affordable and accessible, supporting independent mobility for a group that current commercial products underserve. Making a safety benefit available at low cost is itself an ethical goal, aligned with the professional responsibility to use engineering skill for the benefit of society.

5.4 Safety

The single largest hazard in this project is the lithium-polymer battery. Lithium cells can enter thermal runaway from overcharge, over-discharge, external short, or physical damage, so the power design treats that as a primary constraint rather than an afterthought: the MCP73831 enforces a proper constant-current/constant-voltage charge profile with termination, a BQ29700 protection IC guards against overcharge, over-discharge, and short-circuit conditions, and a USBLC6-2SC6 provides ESD protection on the USB-C input. The applicable standards are IEC 62133-2 (safety of portable sealed lithium secondary cells), UL 2054 (household and commercial battery safety), and UN 38.3 (transport, relevant whenever the prototype leaves the lab). During development we will follow the ECE 445 lab's lithium-handling rules: charging in a LiPo-safe container, never charging unattended, and inspecting cells for swelling or damage before use (see the course Safety Guidelines for the exact policy and cite it here).

The second concern is specific to an assistive device: because a visually impaired user may come to rely on it, a failure is a safety issue, not just a bug. The design fails safe by construction. The device augments the white cane and never replaces it, so the cane tip still handles ground-level detection and a complete electronics failure degrades to an ordinary cane rather than leaving the user with nothing. The fuel gauge drives a distinct low-battery warning so the user is alerted before the device dies mid-walk, and the current-sense path lets the firmware detect a stalled or disconnected motor instead of silently going dark. We also deliberately scope the device to obstacle warning only; it does not tell the user when to step off a curb or cross a street, because a wrong instruction there could put someone in traffic. All spatial information is presented for the user's own judgment, never as a command.

Electrically the device is low-risk. It runs from a single Li-Po (about 3.0 to 4.2 V) and 3.3 V logic, so there is no realistic shock hazard, and the only mains exposure is through a certified USB-C wall adapter. The PCB is fully enclosed so the user never contacts live traces. Thermally, the charge IC, the TPS63020 regulator, and the motor-drive MOSFETs are the heat sources; because the device is hand-held, we will verify under worst case (both motors driven while charging) that the enclosure surface stays below the roughly 48 °C continuous-contact limit in IEC 62368-1. The enclosure will use rounded edges and secure adhesive mounts so nothing loosens into the user's palm. If the optional BLE phone extension is built, its 2.4 GHz radio falls under FCC Part 15 Subpart C, and using the pre-certified ESP32 module keeps us compliant without separate certification. Finally, development itself carries risk: soldering and hot-air rework require ventilation, eye protection, burn awareness, and hand-washing given leaded solder, and all battery work follows the lab protocol above.

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