

PATH: PROXIMITY AWARENESS THROUH HAPTICS

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Design Document for ECE 445, Senior Design, Fall 2026

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10/2/2026

Project No. 26

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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.

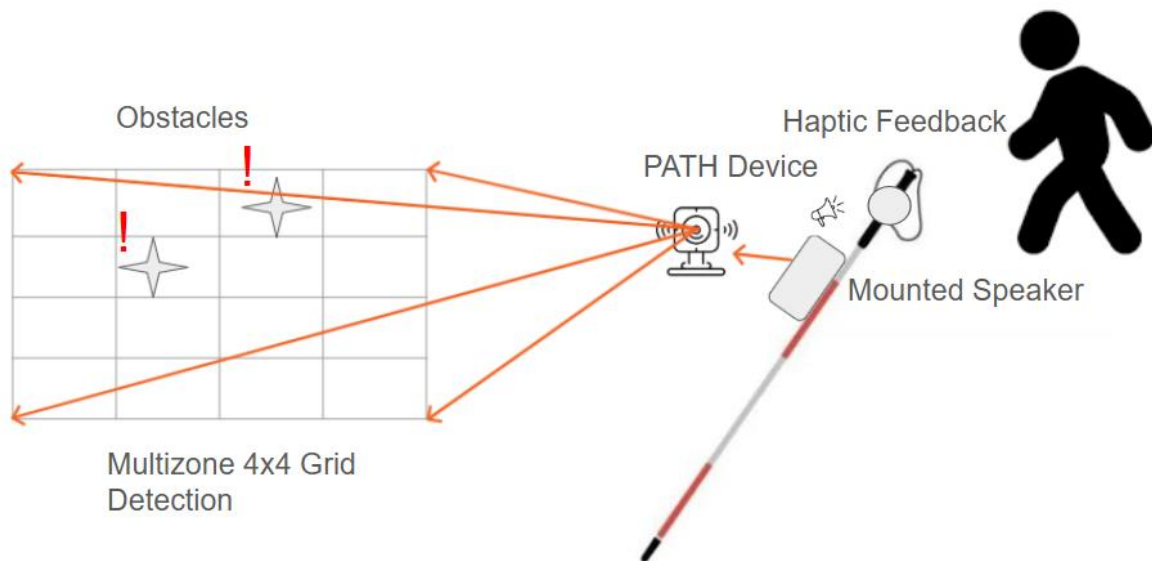
1.2 Solution

To address the coverage gap left by the white cane, we propose an obstacle-warning attachment that mounts to a standard cane and warns the user about obstacles at torso and head height using touch and sound together. A single coin vibration motor in the handle tells the user how close the nearest obstacle is. Vibration strength scales with proximity, so the closer the obstacle, the stronger the vibration. A small speaker on the device tells the user where the obstacle is, playing a short audio cue that identifies it as being on the left, on the right, or straight ahead. Splitting the two cues this way keeps each one simple to read, since the user feels distance through the handle and hears direction, rather than having to tell apart two vibration motors sitting a few centimeters apart on the same grip.

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

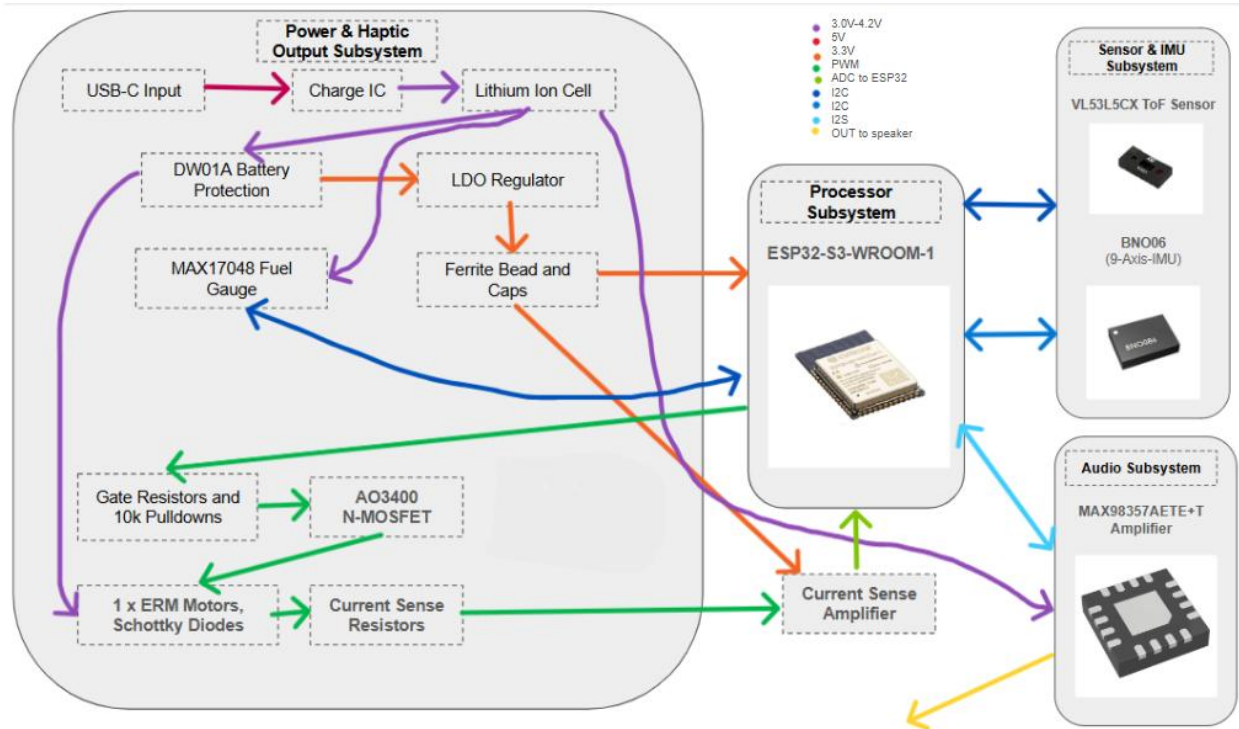


1.4 High Level Requirements List

- The device must detect forward obstacles up to 2.5 meters ahead and correctly identify them into low (closest to ground or at ground starting at around 2.0m from the device), medium (lower body to chest level), and high (upper body to head height, with head height starting at around 2.3m from the device) zone. If it is a continuous obstacle that spans multiple zones, then it will be classified as medium zone. The system must maintain at least 90 percent detection accuracy under normal walking and cane usage conditions (around 40 degrees cane sweep per second). To prevent false spatial feedback, the system must actively compensate for dynamic vertical cane pitches of +15 and -15 degrees, and ensure correct vertical zone classification of the obstacles.
- 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. In addition to the haptic feedback, the correct audio cue must be played at the same time as the vibration to match the audio cue with the haptic feedback (within 50ms of each other). This will give the user both distance and spatial information. The audio cue should also be activated in under 100ms, synced with haptic feedback.
- The device must run for at least 4 hours of continuous use on a single battery charge and must warn the user at least 10 minutes before the battery reaches the 3.4 V shutdown point.

2 Design

2.1 Block Diagram



2.2 Physical Design

All of the electronics except the battery, motor, speaker and power switch sit on one two-layer PCB, 75 mm by 65 mm, made from 1.6 mm FR-4 with 1 oz copper and an ENIG finish. The board mounts upright inside a 4 in by 5.5 in enclosure on four M3 standoffs, with the VL53L5CX at the board edge so it looks out through a window in the front of the box. The window must be at least 20 mm wide so the sensor's 45 degree field of view is not clipped. The ESP32-S3 antenna hangs past the top edge with no copper under it, so the ground pour doesn't block the radio.

Everything that leaves the board goes through a labeled connector, so the board can be removed without desoldering. The 18650 cell sits in a holder off the board and plugs into a JST-PH connector (J1, BATT + and -). The coin motor sits in the cane handle and runs back to the board on a two-wire lead (J2). The speaker connects at J6, and the panel switch on the outside of the box connects at J4. The USB-C connector (J3) overhangs the left edge to line up with a cutout in the box, so we can charge and reprogram without opening it.

Both layers carry a ground pour, with the bottom layer kept as unbroken as possible. Battery and USB power traces are 0.8 mm, the 3.3 V rails are 0.4 mm, the motor and speaker outputs are 0.5 mm, the USB pair is 0.25 mm, and signals are 0.2 mm. By IPC-2221, a 0.8 mm outer trace in 1 oz copper carries about 2 A for a 10 C rise, several times our worst-case battery current. Four test points (VBAT, 3.3 V,

GND, ISNS_MOT) support the verification tests. Surface mount parts are stenciled and reflowed, and through-hole parts are hand soldered.

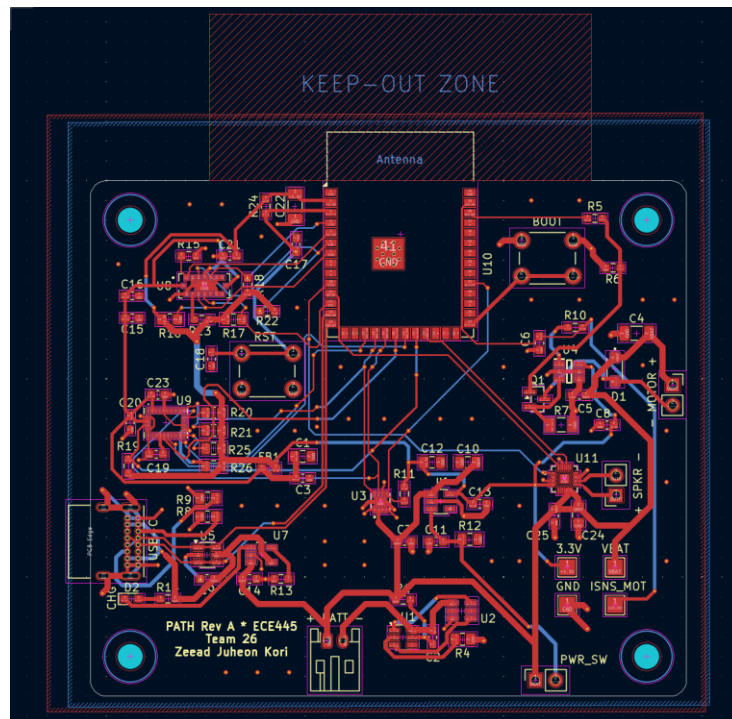


Figure 3. PCB Layout, Top and Bottom Copper

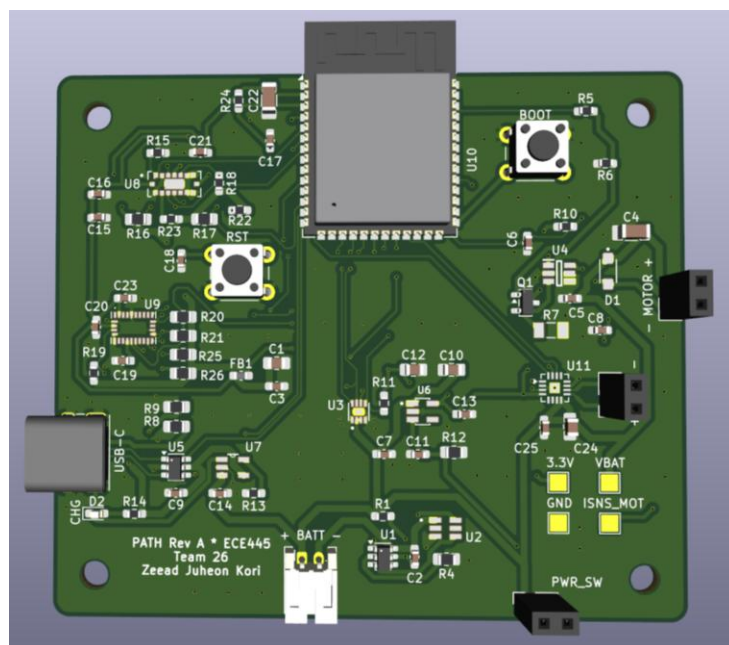


Figure 4. 3D Render of the PCB

2.3 Subsystem Overview

2.3.1 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.

2.3.2 Audio Subsystem

The audio subsystem consists of the max98357a t+ amplifier and CMS-30204-18L250 speaker. The speaker is wired externally from the PCB, and the amplifier is directly on the PCB. The amplifier communicates with the processor via its own I2S bus. The amplifier's OUTN and OUTP are connected to a 2-pin socket, and the socket is connected to the speaker itself. This system's purpose is to provide the user with correct spatial audio cue based on which height each obstacle is located at. Since the system uses a 4x4 resolution, each row will be divided into high, mid, and low sections. High row is meant to cover the upper body to head height level obstacles. Since the FoV is only 45 degrees, and with the sensor looking at the parallel direction to the ground, or slightly angled down, it will only truly detect the head level obstacles starting at the latest around 2.1m range. Same goes for the low row, it will only truly detect the ground level obstacles starting at the latest around 2.1m range. When it is truly detecting head level or ground level obstacles, it will beep twice. For other cases, there will only be one beeping (low, medium, high pitch) depending on where the obstacle is at. Table below shows the exact audio mapping. The table below represents the 4x4 resolution of the ToF sensor.

High pitch beep 2x High pitch beeps if it is true head level	High pitch beep 2x High pitch beeps if it is true head level	High pitch beep 2x High pitch beeps if it is true head level	High pitch beep 2x High pitch beeps if it is true head level
Medium pitch beep	Medium pitch beep	Medium pitch beep	Medium pitch beep
Medium pitch beep	Medium pitch beep	Medium pitch beep	Medium pitch beep
Low pitch beep 2x Low pitch beeps if it is true ground level	Low pitch beep 2x Low pitch beeps if it is true ground level	Low pitch beep 2x Low pitch beeps if it is true ground level	Low pitch beep 2x Low pitch beeps if it is true ground level

2.3.3 Processor Subsystem

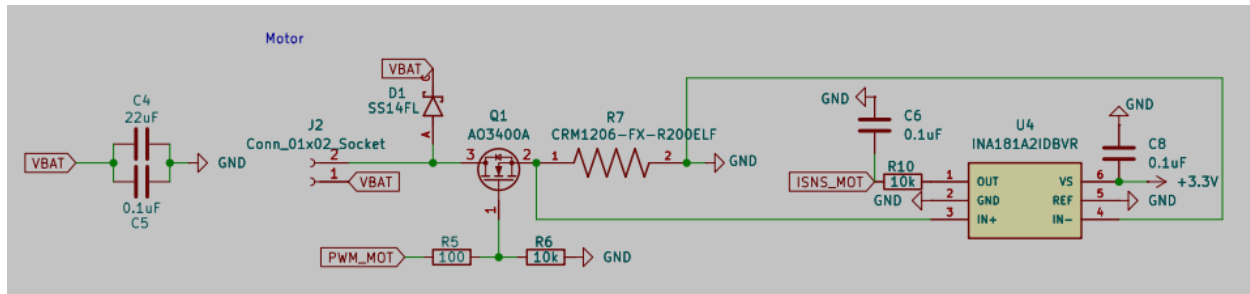
The processor subsystem is the brain of the device and the only block that connects to every other subsystem. It is built around an ESP32-S3- WROOM-1-N16 module surface-mounted on the custom PCB. Its role is to convert raw sensor data into directional haptic output in real time. The VL53L5CX's data-ready hardware interrupt triggers the ESP32 to read the latest 4×4 (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, ~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.

2.3.4 Haptic (Motor) Subsystem

The haptic subsystem turns the processor's PWM command into vibration at the cane handle and reports the motor current back so a stalled or disconnected motor can be detected. We reduced the design to a single 3 V coin ERM motor, which tells the user how close the nearest obstacle is through vibration strength, while the speaker handles the spatial cues. The motor connects to the PCB through J2.



The motor is switched on its low side by an AO3400A N-channel MOSFET. Its positive lead connects to VBAT and its negative lead to the drain, and the source returns to ground through the sense resistor. A low-side switch lets the ESP32's 3.3 V output drive the gate directly, since the source sits near ground. The AO3400A has a threshold of 0.65 to 1.45 V and at most 48 mΩ on-resistance at 2.5 V of gate drive, so it is fully on at 3.3 V. Conduction loss at 75 mA is $(0.075 \text{ A})^2 \times 0.048 \Omega = 0.27 \text{ mW}$. The motor runs from VBAT instead of 3.3 V so its pulsed current stays off the rail powering the ToF sensor and ESP32.

The gate is driven from IO2 through a 100 Ω resistor, with a 10 k Ω pull-down to ground. The series resistor limits peak GPIO current and damps ringing. The pull-down holds the MOSFET off while the ESP32 is in reset, booting, or switched off. IO2 is not a strapping pin on the ESP32-S3, so the pull-down doesn't affect boot. With about 1 nF of gate capacitance and 125 Ω of drive resistance, each edge takes about 0.3 μ s, under 1 percent of the 50 μ s period, for a switching loss of about $\frac{1}{2} \times 4.2 \text{ V} \times 0.075 \text{ A} \times 0.6 \mu\text{s} \times 20 \text{ kHz} = 1.9 \text{ mW}$.

The LEDC peripheral generates the PWM at 20 kHz, above hearing, giving $80\text{ MHz} / 20\text{ kHz} = 4000$ counts or 11 bits of resolution. The motor is rated for 3.0 V but a full cell is 4.2 V, so the firmware reads the cell voltage from the fuel gauge and limits duty to $D_{\text{max}} = 3.0\text{ V} / V_{\text{BAT}}$ (71.4% at 4.2 V, 88.2% at 3.4 V). Each strength level is a target average motor voltage, converted to duty with $D = V_{\text{target}} / V_{\text{BAT}}$, so the vibration stays the same as the battery drains. ERM motors won't start below a minimum voltage, so when starting from rest the firmware applies 3.0 V for 30 ms before dropping to the target.

An SS14FL Schottky diode across the motor, cathode on VBAT, gives the winding current a path when the MOSFET turns off, clamping the drain at about VBAT + 0.4 V (4.6 V at a full cell), far below the AO3400A's 30 V rating. A 22 μ F and 0.1 μ F capacitor next to J2 supply the pulsed current locally.

A 0.2 Ω , 1 percent resistor sits between the source and ground, and an INA181A2 (gain 50) measures across it with Kelvin connections. Its common-mode range goes down to -0.2 V, so it works for low-side sensing. At 75 mA the resistor drops only 15 mV. Current only flows through it while the MOSFET is on, so the amplifier output is a 20 kHz pulse train of height $0.075 \text{ A} \times 0.2 \Omega \times 50 = 0.75 \text{ V}$. A 10 k Ω and 0.1 μF filter ($f_c = 159 \text{ Hz}$) averages it, leaving at most 9.4 mV of ripple and settling in about 5 ms. The result goes to IO1 (ADC1, since ADC2 is shared with the radio). The averaged voltage is $V_{\text{ISNS}} = 10 \Omega \times D \times I$, so the firmware recovers $I = V_{\text{ISNS}} / (10 \Omega \times D)$. The firmware checks the motor during the 30 ms start pulse, where duty is highest. A healthy motor reads about 0.54 V at a full cell, an open motor reads near

0 V, and a stall reads higher because there is no back EMF. Below 20 mA is flagged as open, and above 1.3 times the measured healthy current is flagged as a stall.

Duty Table

Obstacle distance	Target motor voltage	Duty at 4.2 V	Duty at 3.4 V
Under 0.5 m	3.00 V	71.4%	88.2%
0.5 to 1.0 m	2.55 V	60.7%	75.0%
1.0 to 1.5 m	2.10 V	50.0%	61.8%
1.0 to 1.5 m	1.65 V	39.3%	48.5%
2.0 to 2.5 m	1.20 V	28.6%	35.3%

Haptic Interfaces

Net	From / to	Spec
VBAT	Battery to J2 pin 1	3.0 to 4.2 V, 75 mA typ
MOT_SW	J2 pin 2 to Q1 drain, D1	0 V on, VBAT + 0.4 V off
PWM_MOT	ESP32 IO2 via R5 to Q1 gate	3.3 V, 20 kHz, 11-bit, duty $\leq$ 3.0/VBAT
ISNS_MOT	U4 via R10/C6 to IO1, TP4	0 to 1.5 V, $V = 10 \Omega \times D \times I$
+3.3V	To U4	260 μ A max

2.3.5 Power Subsystem

The power subsystem charges a single 3.7 V, 2500 mAh 18650 lithium-ion cell from USB-C, protects it, reports its charge to the processor, and produces the 3.3 V rail for the ESP32-S3, sensors and current-sense amplifier. The motor and speaker amp run straight from the protected battery. Since the proposal, on our TA's suggestion we replaced the TPS63020 buck-boost with an AP2112K-3.3 LDO, replaced the BQ29700 with a DW01A and 8205A dual MOSFET, and added an external on/off switch.

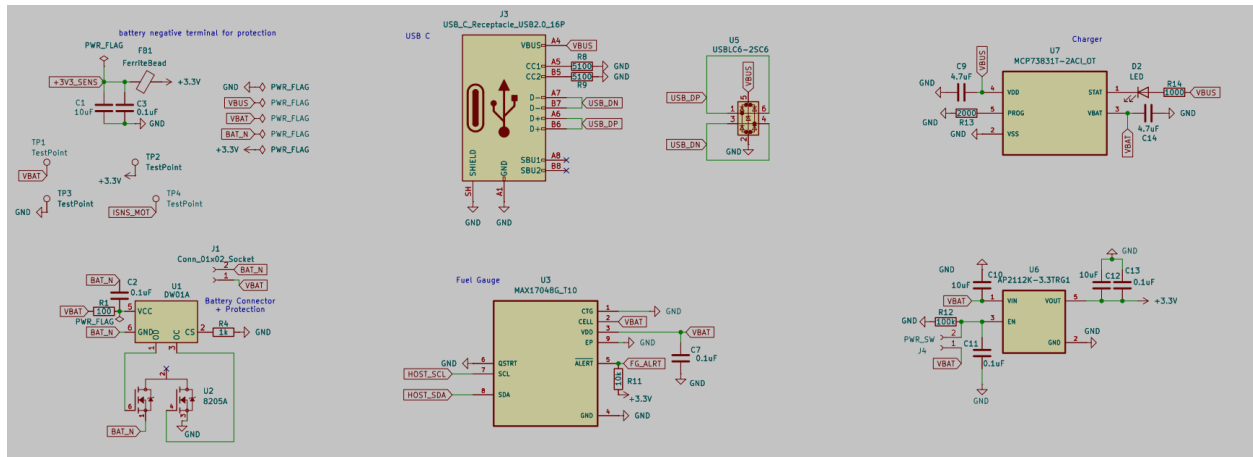


Figure 6. Power Subsystem Schematic

The USB-C connector is a GCT USB4085. Two 5.1 k Ω resistors on CC1 and CC2 identify the device as a sink, so any USB-C source supplies 5 V at default USB current (500 mA for USB 2.0), enough for the charger plus the 3 mA LED. D+ and D- go to the ESP32-S3's native USB for programming. A USBLC6-25C6 clamps ESD on D+, D- and VBUS to IEC 61000-4-2 level 4.

An MCP73831T-2ACI/OT charges with a constant-current, constant-voltage profile at $I_{\text{REG}} = 1000 \text{ V} / 2.0 \text{ k}\Omega = 500 \text{ mA}$, which is 0.2C for our 2500 mAh cell. It stops at $4.20 \text{ V} \pm 0.75\%$, trickle charges at 50 mA below 2.79 V, ends at 37.5 mA, and restarts below 4.05 V. A red LED driven from VBUS through 1 k Ω draws 3 mA while charging. The constant-current phase takes about $0.9 \times 2500 \text{ mAh} / 500 \text{ mA} = 4.5 \text{ h}$ plus about an hour of tail. As a linear charger, it dissipates $(5.0 - 3.6 \text{ V}) \times 0.5 \text{ A} = 0.7 \text{ W}$, and with 230 C/W it will thermally limit early, so we expect 6 to 7 hours for a full charge, which is fine for overnight charging. It has no power path, so a running load would keep it from reaching its 37.5 mA end-of-charge current, and the device is meant to be charged while off.

The protection uses a DW01A and an 8205A dual MOSFET in the cell's negative lead, so the cell minus (BAT_N) and board ground (GND) are separate nets joined only through the MOSFETs. The DW01A is referenced to BAT_N so it measures the real cell, and it senses current through the MOSFET drop on its CS pin. It disconnects above $4.30 \text{ V} \pm 50 \text{ mV}$, below $2.40 \text{ V} \pm 0.1 \text{ V}$, and on overcurrent at 0.15 V across the MOSFETs, which is $I_{\text{trip}} = 0.15 \text{ V} / (2 \times 25 \text{ m}\Omega) = 3 \text{ A}$. A short is cut off within 50 μs . Our worst-case current is under 0.4 A, where the MOSFETs drop only 20 mV.

A MAX17048 fuel gauge estimates state of charge without a sense resistor. It shares the IMU's I2C bus at address 0x36 and draws about 23 μA . The open-drain ALRT pin is pulled up through 10 k Ω to IO38. We set the SOC alert to 15 percent and VALRT.MIN to 3.40 V (register value $3.40 / 0.020 = 170$). The firmware warns at 15 percent or 3.55 V, whichever comes first, and shuts down at 3.40 V.

The 3.3 V rail comes from an AP2112K-3.3 (600 mA) with 10 μF in and 10 μF plus 0.1 μF out. An LDO's efficiency is $\eta = V_{\text{out}} / V_{\text{in}} = 3.3 / 3.75 = 88\%$ at the average cell voltage. The TPS63020 shows about 85 to 90 percent at our load, so it gave no runtime benefit while adding an inductor, about ten more parts, and megahertz switching next to the ToF sensor and the 15 mV sense signal. The LDO is quiet, has

65 dB of ripple rejection at 1 kHz, and is stocked in the eShop. The trade-off is that its worst-case dropout is about 180 mV at our 268 mA worst-case load, so it holds at least 3.2 V while $V_{BAT} \geq 3.38$ V. We shut down at 3.40 V, and only about 5 percent of capacity sits below that. Worst-case dissipation is $(4.2 - 3.3 \text{ V}) \times 0.268 \text{ A} = 0.24 \text{ W}$, a 44 °C rise at 184 °C/W.

The panel switch on J4 connects the LDO's enable pin to VBAT. A 100 k Ω pull-down turns it off when open, and 0.1 μ F filters noise from the external wires. The AP2112K turns on above 1.5 V and off below 0.4 V. Putting the switch on EN means it carries only about 40 μ A, the device still charges with the switch off, and the fuel gauge keeps tracking the cell. The off-state drain is about 31 μ A in total (DW01A up to 6 μ A, gauge 23 μ A, charger leakage under 2 μ A). The motor stays off through its gate pull-down.

A ferrite bead with 10 μ F and 0.1 μ F splits off +3V3_SENS for the VL53L5CX and BNO086, keeping the ESP32's digital and radio current spikes off the sensor supplies. To keep the drop under 100 mV at 145 mA, the bead's DC resistance must be under about 0.7 Ω .

The speaker is driven by a MAX98357A class-D amplifier (U11), which takes digital audio from the ESP32-S3 over three I2S lines (BCLK, LRCLK and DIN) and drives the speaker directly, so no separate DAC or output filter is needed. The amplifier runs straight from VBAT instead of the 3.3 V rail. It is rated for a 2.5 to 5.5 V supply, so the full 3.0 to 4.2 V cell range is in spec, and running from the battery gives it more output swing than 3.3 V would while keeping its current peaks off the LDO. Into an 8 Ω speaker the most it can deliver from a 3.7 V cell is about $V^2 / (2R) = 3.7^2 / 16 \approx 0.86 \text{ W}$, which at roughly 85 percent efficiency draws peaks of about 270 mA from the battery. That is well under the protection circuit's 3 A trip point, and because the cues are short the average draw stays near the 5 mA in the power budget. 10 μ F and 0.1 μ F decoupling capacitors (C24, C25) sit right at its supply pins to supply those peaks locally. The outputs are a bridge-tied pair (OUTP and OUTN), so neither speaker terminal connects to ground. They run on 0.5 mm traces to J6 and are kept short and away from the ToF sensor and the current-sense traces, since the filterless output switches at several hundred kilohertz. The SD_MODE pin is driven by the ESP32, so the amplifier is held in shutdown at under 1 μ A whenever the device is switched off or not playing a cue.

Power Interfaces

Net	From / to	Spec
VBUS	J3 to charger, ESD, LED	5.0 V $\pm$ 5%, up to 503 mA
USB_DP/DN	J3 via U5 to ESP32 pins 14/13	USB 2.0 full speed
VBAT	Protected cell to LDO, motor, amp	3.4 to 4.2 V in use, up to 0.4 A
+3.3V	LDO to ESP32, U4, pull-ups	3.3 $\pm$ 0.1 V, up to 300 mA
+3V3_SENS	FB1 to ToF, IMU	3.2 to 3.4 V, up to 145 mA
HOST_SDA/SCL	Gauge to ESP32 I2C1	400 kHz, address 0x36
FG_ALRT	Gauge to IO38	Open drain, active low, 10 k Ω pull-up
PWR_SW	J4 to LDO EN	Closed is on, open is off

OUTP / OUTN	U11 to J6 (speaker)	Bridge-tied class-D output, 0.86 W max into 8 Ω at 3.7 V
I2S (BCLK, LRCLK, DIN)	ESP32 to U11	3.3 V logic

2.4 Subsystem Requirements

2.4.1 ToF Sensor & IMU Subsystem Requirements

ToF Sensor & IMU Requirements & Verification

Requirement	Verification
The device correctly identifies obstacles into low (closest to ground or at ground starting at the latest 2m from the device), medium (lower body to chest level), and high (upper body to head height, with head height starting at the latest 2.3m from the device) zone. The system must maintain at least 90 percent distance and classification accurate across the range up to 2.5m.	3 obstacles will be placed. 1 obstacle will be at the ground level (low), about 2m away from the device. 1 obstacle will be a medium height obstacle (around 1m tall), with one placed at 1m mark and one placed at 2.3m mark to test different haptic feedback intensities. Lastly, one obstacle will be hung around neck-head height (around 170 – 175cm) about 2.3m away from the device. Successful detection is determined by the presence of a correct audio signal and haptic feedback intensity.
The system must maintain at least 90 percent distance and classification accurate across the range up to 2.5m and hold this accurate even when subjected to cane sweep of 40 degrees/second.	Run through the same verification as the one above, but this time with the cane sweeping at 40 degrees/second. Successful detection is determined by the presence of an audio signal and haptic feedback.
The system must be able to detect obstacles located up to 2.5 meters in a standard light setting (ECEB 3 rd floor).	Obstacles will be placed at 1m, 2m, and 2.5m mark down a hallway in the ECE building. Successful detection is determined by the presence of an audio signal and haptic feedback.
The system must dynamically adjust its ToF row classification mapping using IMU data to maintain at least 90 percent vertical zone classification accuracy when the cane is subjected to vertical pitches between +15 and – 15 degrees.	Place an obstacle on the ground level, about 1m away from the device. Tilt the device down 15 degrees. Make sure that the haptic feedback and audio feedback still corresponds to ground level obstacle (low zone) feedback. Do the same with a hanging object at height 170cm and 2.3m away from the device. Tilt the cane up 15 degrees. Make sure the feedback corresponds to the high zone feedback and not the mid zone.
If two objects are detected at same height level, the system must send PWM cycle corresponding to the closer object with at least 90 percent accuracy	Place 2 1m tall objects, one at 1m and one at 2m mark. Verify that the haptic feedback corresponds to the 1m haptic feedback and not the 2m.
If two objects are detected at different height levels, the system must send PWM cycle	Place 1m tall object at 1m and place ground level object at 2m mark. Verify that the haptic

corresponding to the closer object with at least 90 percent accuracy	feedback corresponds to the 1m haptic feedback with mid pitch beeping.
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2.4.2 Processor & Audio Subsystem Requirements

Processor & Audio Subsystem Verification

Requirement	Verification
The processor must activate the correct motor's PWM output within 100 ms of receiving the VL53L5CX data-ready interrupt.	Connect VL53L5CX's hardware interrupt pin to channel 1 of an oscilloscope. Connect ESP-32's PWM output pin going to the haptic motor to channel 2 of an oscilloscope. Put a 1m tall obstacle in front of the sensor and force a haptic response. Check on the oscilloscope that the time between CH1 interrupt and first CH2 PWM edge have less than or equal to 100 ms of period.
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	This will need to be first tested through a breadboard set up first. We will intentionally disconnect the connection to the motor and check if the processor is able to detect the fault.
The processor must trigger the haptic PWM output and the speaker's I2S output within 50ms of each other when a new obstacle is detected.	Connect ESP32's I2S data pin to channel 1 of an oscilloscope. Connect ESP-32's PWM output pin going to the haptic motor to channel 2 of an oscilloscope. Put a 1m tall obstacle in front of the sensor and force a haptic response. Check on the oscilloscope that the time between CH1 data pin and first CH2 PWM edge have less than or equal to 50 ms of gap.

2.4.3 Power & Haptic Subsystem Requirements and Verification

Power Requirements & Verification

Requirement	Verification
3.3 V rail within ± 0.1 V for VBAT 3.40 to 4.20 V and 0 to 300 mA load, ripple under 50 mV with the motor running.	Bench supply on J1 (1 A limit), electronic load or 11 Ω 2 W resistor on TP2. Step through 4.20, 3.90, 3.60 and 3.40 V at 0, 100 and 300 mA. Scope the ripple at TP2 with the motor on.
Charges at 500 mA $\pm 10\%$ before thermal limiting, stops at 4.20 ± 0.05 V, LED on only while charging, full charge from 3.4 V in under 8 h.	Real cell at 3.4 V, device off, USB power meter inline. Log every 10 min. Check the start current, the LED turning off, the cell voltage 10 min after, and the total time.
Disconnects above 4.30 ± 0.05 V, below 2.40 ± 0.1 V, and on a short, and reconnects after.	Bench supply in place of the cell (never the real cell), 1 k Ω load. Ramp up in 10 mV steps (pass 4.25 to 4.35), then ramp down (pass 2.30 to

	2.50). Short VBAT at 3.7 V for under 1 s. Pass if it cuts off within 1 ms and recovers.
Gauge VCELL within 20 mV of a multimeter, and ALRT fires within 1 s of crossing 3.40 V.	Step the supply from 4.2 to 3.4 V and compare against the multimeter. Scope IO38 while crossing 3.40 V.
Off-state drain under 50 μ A, motor off, and charging still works.	Microamp meter in series with the battery and switch off. Then plug in USB and check the LED.
Runs at least 3 h with the warning at least 10 min before shutdown.	Full charge, normal firmware, motor active about 30% of the time. Log to flash, not USB, since USB would charge the cell.
Box surface under 48 C and parts under 85 C during charging and worst-case use.	Charge 30 min with the box closed, then run the motor 30 min. Measure with a thermocouple or IR thermometer.

Haptic Requirements & Verification

Requirement	Verification
Average motor voltage within 0.1 V of the table target at every level, never above 3.1 V, for VBAT 3.4 to 4.2 V.	Bench supply on J1 at 4.2, 3.8 and 3.4 V. Command each level and measure DC across J2 with a multimeter. Pass if within 0.1 V and none above 3.1 V.
Vibration strength increases with each closer distance band.	Tape a phone running phyphox to the handle. Run each level 5 s, 5 times, and record RMS acceleration. Pass if it strictly increases.
Motor stays off (gate below 0.5 V) during power-up, reset, flashing, and with the switch off.	Scope on gate and MOT_SW. Toggle the switch 10 times, hold RST 10 times, and flash once. Pass if the gate never exceeds 0.5 V.
Drain stays below 10 V at every turn-off.	Strongest level at 4.2 V. Capture 20 turn-off edges at MOT_SW. Pass if the peak is under 10 V (expect about 4.6 V).
Calculated motor current within 10 mA of true current.	Multimeter in series with the motor. At 3.4, 3.8 and 4.2 V, compare against the firmware estimate over serial.
Healthy, open and stalled motor classified correctly in 20 of 20 trials each, within 1 s.	20 trials each with the motor normal, unplugged and held still. Log the result and its timing over serial.
Drive responds within 100 μ s of a PWM update.	Toggle a spare GPIO at the update and scope it against MOT_SW over 20 updates.

2.5 Tolerance Analysis

2.5.1 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:

$$\text{At 1.0m: offset} = 1.0 \times \tan(11.25 \text{ degrees}) = 19.9\text{cm}$$

$$\text{At 2.0m: offset} = 2.0 \times \tan(11.25 \text{ degrees}) = 39.8\text{cm}$$

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 tilt, and therefore shows that the 4x4 resolution with the VL53L5CX is feasible.

2.5.2 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, $1000/60 = 16.7\text{ms}$
- 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,

$$Total = T_Frame + Sys_Time + React_Time = 16.7 + 100 + 200 = 316.7\text{ms}$$

$$Distance_Traveled = Total \times Walk_Speed = 0.317 \times 1.4 = 0.44\text{m}$$

$$Distance_Remaining = Detect_Distance - Distance_Traveled = 2.0 - 0.44 = 1.56\text{m}$$

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.

2.5.3 FOV Tolerance Analysis

An important aspect of the high-level requirement to be verified is the geometric FOV limitations for identifying both the ground level and head height hazards. This analysis determines whether a fixed mechanical tilt provides sufficient vertical spread to detect high and low targets at safe distances.

Components (Variables)

- $SensorFOV$: Total vertical FOV of the ToF sensor, 45 degrees
- $HandleHeight$: 0.9m
- $MountTilt$: -3 degrees
- $TopEdgeAngle = 22.5 - 3 = 19.5$ degrees
- $BottomEdgeAngle = -22.5 - 3 = -25.5$ degrees
- $HeadHazard = 1.7\text{m}$
- $GroundHazard = 0.0\text{m}$
- **Calculating the head detection distance:**

$$Distance = \frac{1.7m - 0.9m}{\tan(19.5)} = 2.26m$$

- **Calculating the ground detection distance:**

$$Distance = \frac{0.9m}{\tan(25.5)} = 1.88m$$

With a minimal -3 degrees downward tilt, the sensor's top edge successfully detects a 1.7m overhead hazard starting about 2.26m away, while the bottom edge intersects with the floor at 1.88m. This demonstrates the angle of mount captures head-level and ground-level hazards within the maximum 2.5m range.

2.5.4 Battery Tolerance Analysis

The VL53L5CX datasheet gives 313 mW in continuous ranging at 3.3 V (about 95 mA, up to 130 mA), more than double the 40 mA assumed in the proposal. Because the 3.3 V rail comes from an LDO, the battery current equals the load current with no conversion efficiency on top.

Load	Typical (mA)	Worst (mA)
ESP32-S3	80	120
VL53L5CX	95	130
BNO086	10	15
Gauge, INA181, pull-ups	2	3
Motor (30% activity / always on)	22.5	75
Speaker amp	5	30
Total	214.5	373

We take 5 percent off the rated capacity for cell variation and aging. In the worst case we take another 10 percent, because the firmware shuts down at 3.40 V instead of draining the cell to 3.0 V.

$$C_{typ} = 2500 \text{ mAh} \times 0.95 = 2375 \text{ mAh}$$

$$C_{worst} = 2500 \text{ mAh} \times 0.95 \times 0.90 = 2138 \text{ mAh}$$

Runtime

$$t_{typ} = \text{capacity} / \text{average current} = 2375 \text{ mAh} / 214.5 \text{ mA} \approx 11.1 \text{ hours}$$

Worst case (motor at full strength continuously)

$$t_{\text{worst}} = 2138 \text{ mAh} / 373 \text{ mA} \approx 5.7 \text{ hours}$$

Even in the worst case the device runs nearly twice as long as the 3-hour requirement. The highest average current it can draw and still meet the requirement is

$$I_{\text{max}} = 2138 \text{ mAh} / 3 \text{ h} \approx 713 \text{ mA}$$

Low-battery warning time

The warning fires at 15 percent charge, and about 5 percent of the capacity is left below the 3.40 V shutdown, so about 10 percent remains between the warning and the shutdown. With 3 percent fuel gauge error, the worst-case leaves 7 percent.

$$t_{\text{warn,typ}} = 0.10 \times 2375 \text{ mAh} / 214.5 \text{ mA} \approx 66 \text{ minutes}$$

$$t_{\text{warn,worst}} = 0.07 \times 2138 \text{ mAh} / 373 \text{ mA} \approx 24 \text{ minutes}$$

Both are above the 10-minute requirement.

2.5.5 Current Sense Tolerance Analysis

The error sources are the sense resistor (1 percent), the INA181A2 gain error (1 percent) and offset (150 μV , or 7.5 mV at the output), and about 20 mV for the calibrated ESP32-S3 ADC.

During the start pulse at a full cell, $V_{\text{ISNS}} = 10 \, \Omega \times 0.714 \times 0.075 \text{ A} = 0.536 \text{ V}$.

The worst-case error is $\Delta V = 0.02 \times 0.536 + 7.5 + 20 = 38 \text{ mV}$, which is $\Delta I = 38 \text{ mV} / (10 \, \Omega \times 0.714) = 5.4 \text{ mA}$, or 7 percent. An open motor reads at most 27.5 mV (under 4 mA), well below the 20 mA threshold. At the gentlest level the error grows to 8.5 mA, which is why the fault check runs during the start pulse

3 Cost and Schedule

3.1 Cost Analysis

Labor

Partner	Hours	Labor cost
Kori (firmware, safety, cost/BOM, verification)	150	\$15,762
Zeead (haptic + power, PCB review, mechanical)	150	\$15,762
Juheon (schematic, PCB layout/review, firmware, orders)	150	\$15,762
Total labor	\$47,287	

Assumed starting salary \$87,429/yr (UIUC ECE average, AY24-25), giving an hourly rate of \$42.03, applied as rate x 2.5 x hours per the course formula.

Parts

Description	Manufacturer	Part #	Qty	Unit cost	Line cost
MCU module ESP32-S3-WROOM-1-N16	Espressif	ESP32-S3-WROOM-1-N16	1	\$3.50	\$3.50
Time-of-flight sensor	STMicroelectronics	VL53L5CXV0GC/1	1	\$7.00	\$7.00
9-axis IMU	CEVA / Bosch	BNO086	1	\$11.00	\$11.00
I2S audio amplifier	Analog Devices	MAX98357AETE+T	1	\$1.50	\$1.50
Battery fuel gauge	Analog Devices	MAX17048G+T10	1	\$2.50	\$2.50
Current-sense amplifier	Texas Instruments	INA181A2IDBVR	1	\$0.60	\$0.60
USB ESD protection	STMicroelectronics	USBLC6-2SC6	1	\$0.45	\$0.45
3.3V LDO regulator	Diodes Inc.	AP2112K-3.3TRG1	1	\$0.45	\$0.45
Li-Po charge controller	Microchip	MCP73831T-2ACI/OT	1	\$0.60	\$0.60
Battery protection IC	generic	DW01A	1	\$0.25	\$0.25
Dual MOSFET (protection)	generic	8205A	1	\$0.35	\$0.35
N-channel MOSFET (motor drive)	Alpha & Omega	AO3400A	1	\$0.25	\$0.25
Schottky diode (flyback)	generic	SS14FL	1	\$0.30	\$0.30
0.2 ohm current-sense resistor (1206)	Bourns	CRM1206-FX-R200ELF	1	\$0.50	\$0.50
USB-C receptacle (through-hole)	GCT	USB4085-GF-A	1	\$0.90	\$0.90
Tactile pushbutton (BOOT/RST)	generic	PTS645 (E-Shop)	2	\$0.20	\$0.40
Status LED (0603)	generic	LED 0603	1	\$0.15	\$0.15
Ferrite bead	generic	MI0805K400R-10	1	\$0.15	\$0.15
JST-PH 2-pin battery connector	JST	S2B-PH-K-S	1	\$0.50	\$0.50
2.54mm pin headers (motor/pwr/spkr)	generic	1x02 2.54mm	3	\$0.30	\$0.90

Capacitor 0.1uF	KEMET (E-Shop)	C0603C104K4RAC7867	15	\$0.10	\$1.50
Capacitor 4.7uF	KEMET (E-Shop)	C0603C475K9PAC7867	3	\$0.15	\$0.45
Capacitor 10uF	Murata (E-Shop)	GRM21BR61H106ME43L	4	\$0.20	\$0.80
Capacitor 1uF	KEMET (E-Shop)	C0603C105K9PAC7867	1	\$0.10	\$0.10
Capacitor 22uF	Samsung (E-Shop)	C0805C226K9PACTU	2	\$0.30	\$0.60
Resistor 100 ohm	generic	R 0603	2	\$0.10	\$0.20
Resistor 1k	Stackpole (E-Shop)	RMCF0805JT1K00 / 0603	2	\$0.10	\$0.20
Resistor 2k	generic	R 0603	1	\$0.10	\$0.10
Resistor 2.2k	Stackpole (E-Shop)	RMCF0805JT2K20	6	\$0.10	\$0.60
Resistor 5.1k	Stackpole (E-Shop)	RMCF0805JT5K10	4	\$0.10	\$0.40
Resistor 10k	Stackpole (E-Shop)	RMCF0805JG10K0 / 0603	5	\$0.10	\$0.50
Resistor 47k	generic	R 0603	4	\$0.10	\$0.40
Resistor 100k	Stackpole (E-Shop)	RMCF0805JT100K	1	\$0.10	\$0.10
ERM coin vibration motor	generic	10mm ERM	2	\$1.50	\$3.00
Speaker (small 8 ohm)	generic	8 ohm mini spkr	1	\$1.50	\$1.50
Single-cell Li-Po battery	generic	3.7V ~500mAh	1	\$8.00	\$8.00
Standard white cane (retrofit base)	generic	white cane	1	\$20.00	\$20.00
Enclosure / 3D-printed housing + mounts	self-service	PLA/PETG print	1	\$5.00	\$5.00
PCB fabrication (2-layer, small run)	JLPCB/PCBWay	custom	1	\$20.00	\$20.00
Total parts	\$95.70				

Unit costs are single-quantity estimates (Digikey/Mouser ballpark)

Machine shop labor

Estimated 2 hours at \$25/hour (enclosure/mounting; mostly 3D printed) = \$50.00. Confirm the ECE machine shop rate.

GRAND TOTAL (labor + parts + machine shop)	\$47,433
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3.2 Schedule

Week of	Primary tasks	Owner(s)
Sep 28	Finalize and submit Design Document (due Fri). Freeze schematic and complete PCB layout. (Round 1 PCBway order missed via TA, so first real order is next week.)	Kori (doc: processor/safety/cost/BOM); Juheon + Zeead (schematic, PCB layout, PCB review); Zeead (haptic/power doc sections)
Oct 5	Pass audit and submit Second Round PCBway order (Thu). Attend Design Review. Order E-Shop and Digikey/Mouser parts. Start firmware scaffolding and breadboard ToF + IMU over I2C.	Kori + Juheon (firmware start); Juheon + Zeead (PCB review); Juheon (PCB order); Kori (parts list); Zeead (breadboard bring-up)
Oct 12	Breadboard Demo. Teamwork Evaluation I (Wed). Third Round PCBway order available (Thu) if a board revision is needed.	All (demo); Juheon (PCB rev/order); Kori (eval)
Oct 19	Round-2 PCB arrives: assemble (solder) the board and bring up the power subsystem (charge, protection, 3.3V rail). Continue firmware.	Kori + Juheon (firmware); Juheon (assembly); Zeead (power bring-up); Kori (verification)
Oct 26	Sensor + MCU bring-up (frame read, BNO086 orientation, row selection, sector classification). Fourth Round JLCPCB order available (Thu) as final board option.	Kori + Juheon (firmware); Zeead (assist)
Nov 2	Haptic drive and current-sense motor fault detection working. Progress Demo. Individual Progress Reports due (Wed).	Zeead (haptic); Kori + Juheon (firmware); Kori (IPR)
Nov 9	Integrate subsystems (sensing + haptic + power) into one system. Tune latency to under 100 ms and tune the distance-to-vibration curve. Enclosure and cane mounting. Team Contract assessment (Fri).	Kori (integration); Kori + Juheon (firmware); Zeead (mechanical)
Nov 16	Mock Demo and Mock Presentation. Run full requirement verification (R&V) tests and fix gaps.	All
Nov 23	Fall Break — buffer for rework and retest only.	All as needed
Nov 30	Final Demo and Final Presentation. Video Assignment due (Fri).	All
Dec 7	Final Paper due (Wed). Lab checkout	All

Owner split: Kori = firmware, safety, cost/BOM, verification. Juheon = schematic, PCB layout, PCB review, firmware, parts orders. Zeead = schematic/PCB review, haptic and power subsystems, mechanical/enclosure.

4. Conclusion

4.1 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.

4.2 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 BNO086'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. Mounting the vibration pads so the cue transfers clearly to the user's hand without the two motors' vibrations blurring together is another open question we will resolve through testing. Finally, the audio amplifier and speaker that were added are a smaller unknown, since the useful volume range and its draw on the battery still need to be characterized.

4.3 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 reflects the IEEE Code's requirements to be honest in claims and to acknowledge and correct errors, the ACM Code's emphasis on thorough evaluation, and the course ethics guidelines on representing work truthfully.

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. A specific ethical choice is that the device does not instruct the user when to cross a street, because a wrong instruction in traffic could cause serious harm. If the BLE phone extension is implemented, it introduces a data and privacy consideration, so we will exchange only the minimum data needed for the crossing-awareness

feature and store nothing beyond it, consistent with the ACM Code's respect for privacy. We will also give credit for any external libraries or reference designs we use.

4.4 Safety

The single largest hazard in this project is the lithium-ion 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 and constant-voltage charge profile with termination, a DW01A protection IC together with an 8205A dual MOSFET 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, meaning charging in a fire-safe battery bag, never charging unattended, and inspecting cells for swelling or damage before use. We use a cylindrical 18650 cell from a major manufacturer, which has a steel case, a pressure vent and a current interrupt device, making it more tolerant of crushing and puncture than a pouch cell.

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 INA181 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 lithium-ion cell (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 AP2112K regulator, and the motor-drive MOSFET are the heat sources, and because the device is hand-held we will verify under worst case (charging, then the motor running at full strength) that the enclosure surface stays below the roughly 48 C continuous-contact limit in IEC 62368-1. A new consideration since the proposal is the added audio amplifier and speaker, so output level will be bounded in firmware to avoid any hearing risk. 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-S3-WROOM module keeps us compliant without separate certification. Finally, development itself carries risk, so 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.

4.5 Societal impact

The core public health and safety benefit is reducing upper body and head level injuries for people who are blind or have low vision. A standard white cane detects obstacles only at or near ground level, so protruding and overhanging hazards such as branches, signage, open cabinet doors, and vehicle mirrors are a recurring cause of injury, and surveys of cane users report head level collisions affecting a meaningful fraction of users more than once a month. Economically, the device uses low-cost, off-the-shelf parts and retrofits onto a cane the user already owns, which keeps the barrier to adoption low compared with the expensive smart canes on the market today. Socially and culturally, preserving independent mobility supports a user's ability to work, travel, and take part in public life without always depending on a sighted guide. Environmentally, the device is small and battery powered, so the main considerations are responsible end-of-life handling of the lithium cell and keeping the board and enclosure compact. Globally, vision impairment affects billions of people and is more common where access to assistive technology is limited, so a cheap retrofit aimed at the near-universal white cane has potential reach well beyond any single market.

4.6 Engineering standards

Several standards apply. The lithium battery, charging, and protection circuit fall under IEC 62133-2, UL 2054, and UN 38.3. IEC 61000-4-2 for the USB ESD protection and IPC-2221 for trace widths. Overall product safety, including the touch temperature of a hand-held device, follows IEC 62368-1. The charging input and connector follow the USB Type-C specification. The I2C bus shared by the ESP32-S3-WROOM, the VL53L5CX, the BNO086, and the MAX17048 fuel gauge follows the NXP I2C bus specification. If the Bluetooth extension is used, the 2.4 GHz radio in the ESP32 module falls under FCC Part 15 Subpart C, which the pre-certified module is designed to satisfy. Our professional conduct on the project is governed by the IEEE Code of Ethics and the ACM Code of Ethics and Professional Conduct.

4.7 Mitigation procedures

For the battery we will keep a short lab safety procedure and follow the course battery rules, meaning charging the cell in a fire safe battery bag, never charging unattended, inspecting cells for damage before use, and relying on the on-board DW01A and 8205A protection for overcharge, over-discharge, and short-circuit cutoff during operation. We will verify under worst-case load that the enclosure surface stays within the IEC 62368-1 touch-temperature limit. For the human interface, the device is designed to fail safe, augmenting the cane and never replacing it, with a low-battery haptic warning and

INA181-based motor fault detection so the user is never left with a device that has failed silently, and with the audio output level capped in firmware. Mechanically, the motor and board are mounted with strong adhesive and strain-relieved wiring, the enclosure uses rounded edges, and mounting is checked so nothing can work loose into the user's palm. For development, soldering and rework are done with ventilation, eye protection, and burn awareness, and all bench work with the battery follows the lithium-ion protocol above. Together these decisions protect both the user, whose safety depends on predictable behavior and a guaranteed fallback to the plain cane, and the developers, whose main risks are the battery and the soldering bench.

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