

OmniSense-Dual -- Navigation Vest Suite for People with Eye Disability

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1. Introduction

Pedestrians in urban and campus environments frequently share space with bicycles, e-scooters, cars, and other pedestrians. Unlike drivers, pedestrians typically lack rear-view awareness tools, and distractions (headphones, phones) further reduce situational awareness. Meanwhile, navigation often requires looking at a phone or listening to voice guidance—both attention-demanding and sometimes unsafe. Our device addresses these gaps by combining 8-ways hazard sensing with clearly separated, non-visual and non-auditory haptic feedback for navigation and warnings.

1.1 Problem

Pedestrians frequently experience unprotected blind spots in urban and campus environments, where fast-approaching objects from behind or diagonal directions are often noticed too late, particularly on shared paths and narrow sidewalks. Situational awareness is further reduced when pedestrians use headphones or smartphones or move through crowded environments, which degrade both auditory and visual perception and make nearby hazards more difficult to detect. In addition, navigation itself imposes a cognitive burden, as pedestrians must frequently check maps or listen to voice guidance, diverting attention from their surroundings. Audio-only navigation can also be problematic for visually impaired users who already rely heavily on auditory cues, further increasing the risk of missing environmental hazards.

1.2 Solution

We propose OmniSense-Dual, a dual-wearable system providing both hazard awareness and hands-free navigation through spatially separated haptic feedback.

The system consists of:

1. A waist-mounted module that performs environmental sensing, computation, navigation processing, and navigation haptic feedback.
2. A head-mounted module dedicated exclusively to hazard alerts through directional vibration.

The key design decision is to separate **feedback** channels:

- Head feedback = hazards only
- Belly feedback = navigation only

This separation ensures that users can instantly distinguish between danger warnings and navigation instructions.

The waist module uses mmWave radar and distance sensors to detect approaching objects around the user, while navigation instructions are provided through gentle vibration cues corresponding to turning directions. Hazard warnings are delivered through directional vibrations on the headband, allowing users to quickly perceive the direction of danger.

The solution aims to improve pedestrian safety and reduce cognitive load while supporting hands-free navigation in campus and urban environments.

1.3 Visual Aid

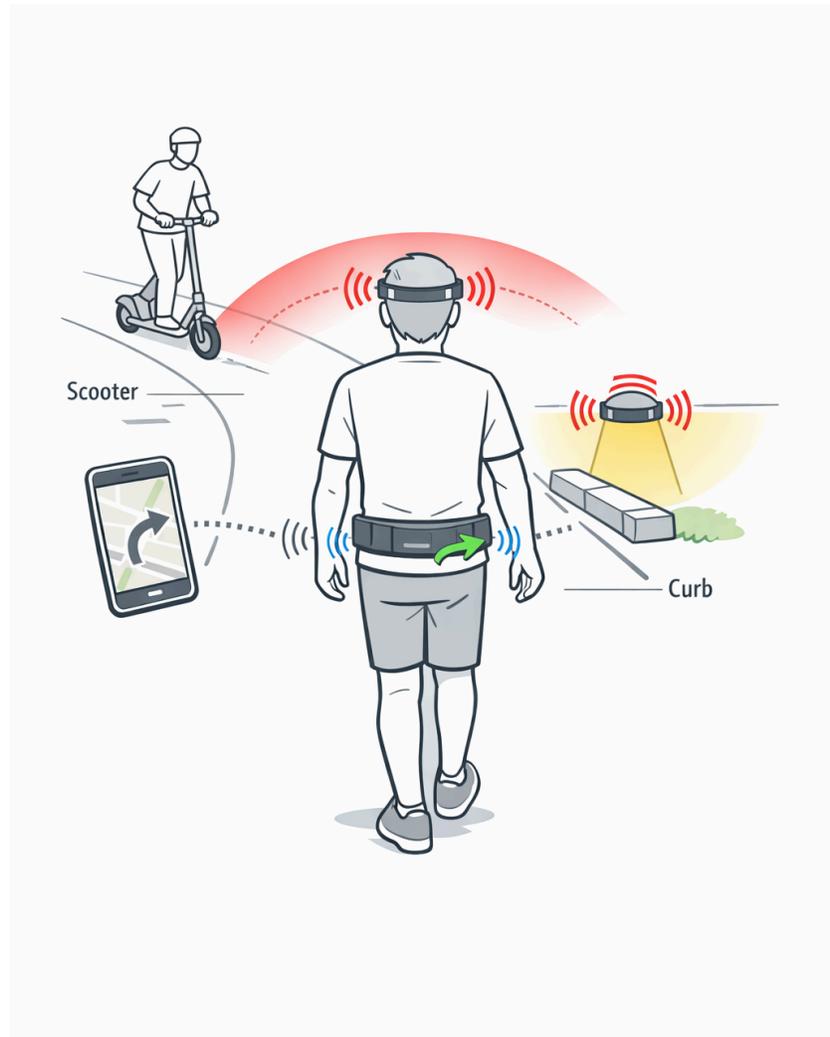


Figure 1. OmniSense-Dual operation example showing navigation cues delivered through waist vibrations while hazard alerts from approaching vehicles or obstacles are communicated via directional head-mounted vibrations.

Figure 1 illustrates the operational concept of the OmniSense-Dual pedestrian safety and navigation system. A user walks while wearing a waist-mounted sensing and navigation module together with a head-mounted hazard alert module. The waist module continuously monitors the surrounding environment using embedded sensors while receiving navigation instructions from a connected smartphone application. Navigation cues are delivered through gentle vibrations on the belt, guiding the user in the desired direction without requiring visual attention to the phone.

At the same time, hazards such as a fast-approaching scooter from behind or obstacles in the walking path are detected by the sensing system. When a hazard is identified, the head-mounted module produces directional vibration feedback corresponding to the location of the danger. This allows the user to quickly perceive where the threat is coming from without needing to look around or rely on audio warnings.

The figure also demonstrates the key design principle of OmniSense-Dual: navigation guidance is delivered only at the waist, while hazard alerts are delivered only at the head. This separation ensures that users can intuitively distinguish between movement instructions and safety warnings, improving situational awareness while walking in shared urban environments.

1.4 High-level requirements list

1. Safety Requirement: The system shall detect approaching hazards (bicycles, e-scooters, pedestrians) with $\geq 90\%$ recall at distances ≥ 5 meters and provide directionally accurate haptic alerts to the user's head module, ensuring 8-way coverage through dual-plane sensing (belly and head modules).
2. Navigation Requirement: The system shall provide hands-free, non-visual navigation guidance with $\geq 85\%$ turn accuracy through the belly haptic interface, maintaining heading deviation $\leq 10^\circ$ during straight-line navigation, with update latency $\leq 200\text{ms}$ from position change to haptic feedback.
3. Channel Separation Requirement: The system shall maintain distinct and unambiguous feedback channels where the head module exclusively provides hazard alerts and the belly module exclusively provides navigation cues, achieving $\geq 90\%$ user classification accuracy between hazard and navigation signals to prevent confusion during simultaneous alerts.

2 Design

2.1 Block diagram

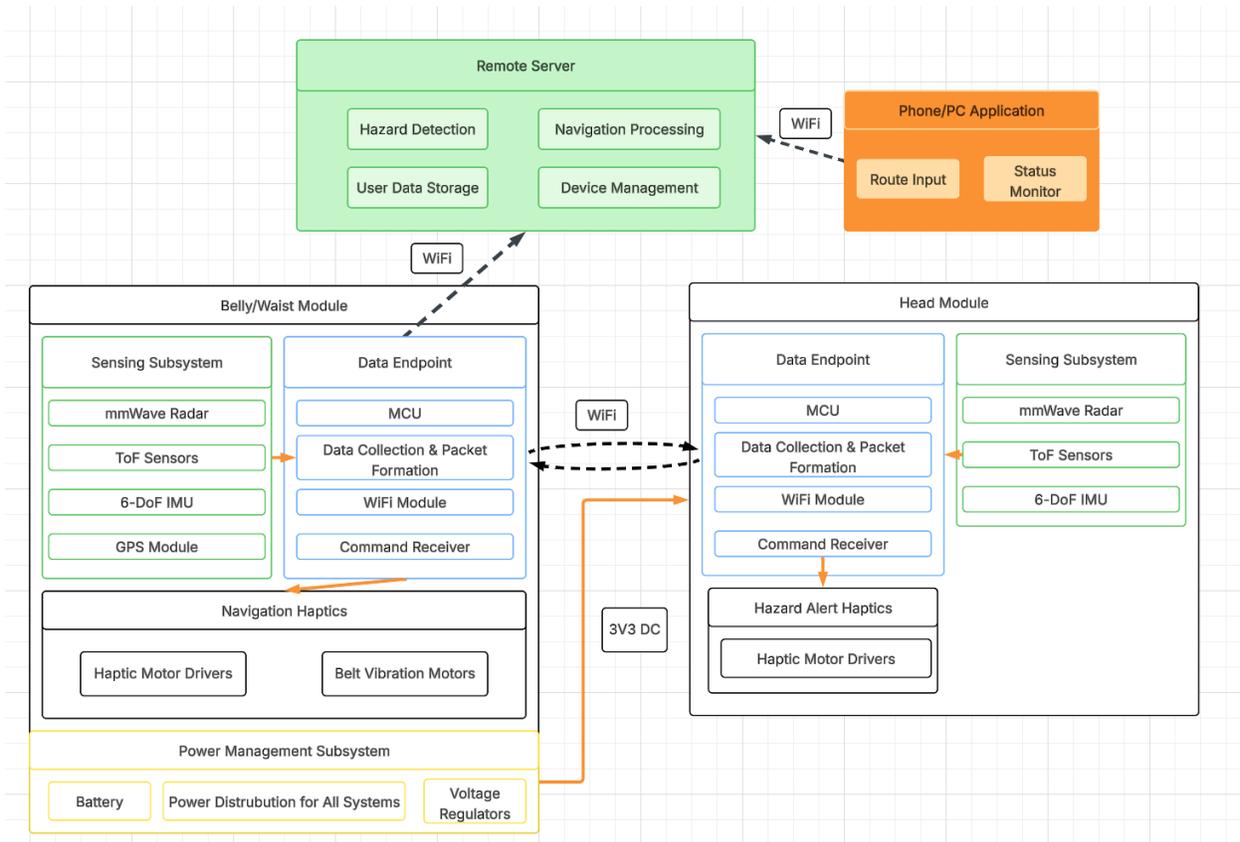


Figure 2. The Block Diagram of OmniSense-Dual system

The OmniSense-Dual system is composed of two coordinated wearable modules, a centralized power management subsystem, and two external computing components. Together, these elements form an integrated assistive navigation and hazard detection system that enables real-time environmental sensing, wireless communication, and haptic feedback.

The Belly/Waist Module functions as the primary navigation unit. Its sensing subsystem includes mmWave radar, multiple Time-of-Flight (ToF) sensors, a 6-DoF IMU, and a GPS module to collect obstacle distance, motion, orientation, and positioning data. The data endpoint subsystem, consisting of an MCU, data collection and packet formation logic, a WiFi module, and a command receiver, aggregates and formats sensor data for wireless transmission while also receiving control instructions. The module provides directional navigation guidance through belt-mounted vibration motors driven by dedicated haptic motor drivers, allowing intuitive spatial feedback to the user.

The Head Module serves as the upper-level hazard alert unit. It integrates mmWave radar, ToF sensors, and a 6-DoF IMU to detect obstacles and environmental hazards at head level. Similar to the waist module, it contains an MCU-based data endpoint with packet formation, WiFi communication, and command reception capabilities. The head module focuses on rapid hazard notification through localized haptic motor drivers, enabling immediate awareness of potential dangers.

A centralized Power Management Subsystem supplies regulated power to all electronics in the system. It includes a battery, power distribution circuitry, and voltage regulators to ensure stable and safe operation of sensors, microcontrollers, wireless modules, and haptic drivers across both wearable modules.

Externally, a Phone or PC application provides the primary user interface for route input and system status monitoring. The wearable modules communicate wirelessly with this application to transmit sensor data and receive navigation commands. An optional remote server supports higher-level processing, including hazard detection refinement, navigation computation, device management, and user data storage. Wireless communication among the wearable modules, the user application, and the remote server enables coordinated, real-time navigation guidance and hazard alert functionality.

2.2 Subsystem Overview and Requirements

2.2.1 Waist Module Control Subsystem

The Waist Module Control Subsystem serves as the primary sensing, processing, and coordination unit of the OmniSense-Dual system. This subsystem is responsible for collecting environmental data from the sensing subsystem, packaging sensor data for wireless transmission, receiving commands from external devices, and generating navigation haptic feedback. Based on processed navigation inputs and hazard data, the control subsystem determines directional guidance outputs and commands the belt vibration motors accordingly.

The subsystem is centered on an ESP32-S3 MCU operating at 240 MHz. Sensor interfaces include:

- mmWave radar via UART
- ToF sensors via I2C (400 kHz bus)
- IMU via I2C
- GPS via UART

Sensor data are sampled at defined rates:

- ToF: ≥ 20 Hz
- mmWave: ≥ 10 Hz
- IMU: ≥ 50 Hz
- GPS: ≥ 1 Hz

The MCU aggregates sensor data into timestamped packets and executes navigation logic. PWM outputs (≥ 200 Hz) drive vibration motors via dedicated haptic drivers.

Requirements	Verification
The subsystem shall sample all connected sensors at their defined frequencies and form structured timestamped data packets with $<5\%$ packet loss over 5 minutes of continuous operation.	<ul style="list-style-type: none"> ● Log sensor timestamps over 5 minutes. ● Count expected vs actual packets. ● Demonstrate packet loss $\leq 5\%$. ● Provide serial log and packet count table.
The subsystem shall receive navigation commands from the Phone/PC application and activate the corresponding belt motor within ≤ 200 ms (measured from command reception interrupt to motor PWM output).	<ul style="list-style-type: none"> ● Send command from application. ● Measure time between WiFi interrupt and PWM activation using oscilloscope. ● Record 10 trials. ● Demonstrate average latency ≤ 200 ms.
Each navigation command (left/right/forward/stop) shall activate only the intended motor(s) with no unintended activation. Cross-activation error rate must be $<5\%$ over 40 command trials.	<ul style="list-style-type: none"> ● Issue 10 commands per direction. ● Measure motor voltage outputs. Confirm correct motor activation. ● Provide confusion matrix table.
The subsystem shall maintain continuous wireless connectivity at distances up to 10 m indoors with $<2\%$ packet loss over 5 minutes.	<ul style="list-style-type: none"> ● Place device at 2m, 5m, 10m. ● Log packet reception statistics. ● Provide packet loss vs distance table.

2.2.2 Head Module Control Subsystem

The Head Module Control Subsystem is responsible for upper-body hazard detection and localized hazard alerts. This subsystem collects environmental data from head-mounted mmWave radar, ToF sensors, and IMU modules. The MCU processes this data, forms packets for transmission, and receives hazard alert commands from either the Waist Module or Remote Server.

The primary function of this subsystem is to provide immediate hazard notifications through dedicated haptic motor drivers positioned on the head module. These alerts correspond to detected back or frontal obstacles.

Sensor inputs:

- mmWave radar (UART)
- ToF sensors (I2C)
- IMU (I2C)

The MCU executes hazard detection logic based on:

- Distance threshold (≤ 5 m)
- Relative velocity (approaching objects)
- Obstacle persistence (>100 ms)

Hazard direction mapping activates the corresponding head-mounted motor.

Requirements	Verification
The subsystem shall detect obstacles within 5 m with $\geq 90\%$ detection recall across 30 controlled trials per obstacle type.	<ul style="list-style-type: none"> ● Perform 30 trials per obstacle type. ● Record detection outcomes. ● Provide confusion matrix.
Hazard alert motor activation shall occur within ≤ 150 ms from obstacle detection flag generation.	<ul style="list-style-type: none"> ● Trigger obstacle. ● Measure delay between detection event and PWM signal. ● Provide oscilloscope screenshot.
Obstacle direction classification shall be correct $\geq 90\%$ of trials across 30 multi-directional tests.	<ul style="list-style-type: none"> ● Place obstacle front/left/right. ● Record activated motor. ● Provide accuracy percentage.
Head and Waist modules shall exchange packets continuously at ≥ 10 Hz for ≥ 5 minutes without disconnection.	<ul style="list-style-type: none"> ● Log packet exchange rate. ● Provide timestamp log.

2.2.3 Sensing Subsystems

The Sensing Subsystems are responsible for detecting environmental obstacles, motion, and spatial orientation. These subsystems include mmWave radar for long-range detection, ToF sensors for short-range depth measurement, and 6-DoF IMUs for motion tracking. The Waist Module additionally integrates GPS for global positioning.

Requirements	Verification
The system's processed distance estimate (sensor + filtering + MCU processing) shall have $\leq \pm 5\%$ error for objects between 0.5 m and 2 m.	<ul style="list-style-type: none"> ● Measure ground truth with tape. ● Log processed output. ● Compute percent error. ● Provide table of 10 test distances.
The system shall reliably detect moving obstacles within 5 m with $\geq 90\%$ detection success.	<ul style="list-style-type: none"> ● Move object toward device. ● Log detection events. ● Provide detection rate vs distance plot.
Orientation estimation shall drift $\leq 5^\circ$ over 60 seconds when stationary.	<ul style="list-style-type: none"> ● Log yaw angle over 60 s. ● Compute drift. ● Provide angle vs time graph.
The integrated navigation heading system shall maintain $\leq 10^\circ$ heading error during 20 m straight walk trials outdoors.	<ul style="list-style-type: none"> ● Walk straight path. ● Compare measured heading vs ground truth. ● Provide deviation statistics.

2.2.4 Navigation and Hazard Haptics Subsystem

The Navigation & Hazard Haptics Subsystem is responsible for providing intuitive tactile feedback to the user. The waist module delivers directional navigation cues through multiple belt vibration motors, while the head module provides localized hazard alerts.

Requirements	Verification
Navigation and hazard motors shall operate simultaneously without voltage drop >5% on either module.	<ul style="list-style-type: none"> ● Activate both systems. ● Measure rail voltage. ● Confirm $\leq 5\%$ sag.
Motor current shall not exceed manufacturer-rated value $\pm 10\%$ under peak duty cycle.	<ul style="list-style-type: none"> ● Measure peak current with multimeter. ● Compare with spec.
Distinct vibration patterns must achieve $\geq 90\%$ user classification accuracy in 10-user test (20 trials each).	<ul style="list-style-type: none"> ● Conduct blind classification test. ● Provide accuracy statistics.

2.2.5 Wireless Communication Subsystem

The Wireless Communication Subsystem enables real-time data exchange between the Waist Module, Head Module, Phone/PC Application, and Remote Server. Communication is implemented through WiFi modules integrated into each wearable device.

Requirements	Verification
Sensor packets shall transmit at ≥ 10 Hz $\pm 10\%$ tolerance.	<ul style="list-style-type: none"> ● Log timestamps. ● Compute frequency.
Command packet bit error rate shall be 0% over 100 command transmissions.	<ul style="list-style-type: none"> ● Send known command pattern. ● Compare received vs expected.
System shall detect communication loss within ≤ 2 seconds.	<ul style="list-style-type: none"> ● Disable WiFi. ● Log detection time.

2.2.6 Power Management Subsystem

The Power Management Subsystem is responsible for supplying regulated and stable power to all electronics in both wearable modules. It includes a rechargeable battery, power distribution circuitry, and voltage regulators for required rails (e.g., 3.3V and 5V).

Requirements	Verification
Voltage regulators must maintain 3.3V and 5V outputs within $\pm 5\%$ tolerance.	Measure output voltage under no-load and full-load conditions using multimeter.

The system must operate continuously for at least 3 hours on battery power.	Fully charge battery and record runtime under normal operation until cutoff.
Battery protection must cut off power below a safe voltage threshold.	Gradually discharge battery and verify system shuts down at defined cutoff voltage.

2.2.7 Phone/PC Application Subsystem

The Phone/PC Application Subsystem provides the primary user interface for route input and device monitoring. It communicates wirelessly with the wearable modules to send navigation instructions and receive status data.

Requirements	Verification
Navigation commands shall be delivered with $\geq 98\%$ success rate over 100 transmissions.	<ul style="list-style-type: none"> • Send 100 commands. • Log successful receptions.
Application shall update connection status within ≤ 2 seconds of device disconnection.	<ul style="list-style-type: none"> • Power off device. • Measure status update time.

2.2.8 Remote Server Subsystem

The Remote Server Subsystem provides software-level processing for hazard detection refinement, navigation computation, device management, and user data storage. It supports more computationally intensive algorithms that may exceed onboard processing capability.

Requirements	Verification
Server-processed hazard/navigation outputs shall match locally processed results within $\pm 5\%$ deviation.	Upload test dataset and confirm processed output is returned correctly.
End-to-end server communication latency must be < 500 ms.	Send sensor packet to server and measure total round-trip response time.
Server must securely store user data.	Upload test data and confirm successful storage and retrieval.

2.3 Physical Design



Figure 3. OmniSense-Dual Wearable System Overview



Figure 4. Waist Module Internal Hardware Layout

The physical design of OmniSense-Dual focuses on wearable integration, sensor coverage, modular electronics packaging, and user comfort. The system consists of two wearable components: a waist-mounted module responsible for environmental sensing and navigation feedback, and a lightweight headband module dedicated to directional hazard alerts.

The waist module is designed as a belt-mounted enclosure positioned at the lower back, allowing central placement of the control electronics while distributing sensors around the user's torso. Distance sensors and radar modules are positioned circumferentially along the belt to provide near 360-degree coverage at torso level. Vibration motors are distributed around the belt to generate directional navigation cues corresponding to left, right, forward, or stop commands. The enclosure houses a custom PCB containing the ESP32 microcontroller, I2C multiplexers, sensor connectors, motor driver interfaces, and battery pack. Internal wiring is routed to minimize strain and electromagnetic interference, while maintaining accessibility for debugging and maintenance.

The head module is implemented as a lightweight adjustable headband with embedded vibration motors positioned at key angular locations around the head. This configuration enables localized hazard alerts corresponding to the direction of detected obstacles. The head module prioritizes minimal weight and compact form factor to reduce user discomfort during extended use.

The enclosure design emphasizes durability and ergonomic comfort. The waist enclosure is compact and positioned to avoid restricting arm swing or torso movement. Mounting hardware and strap materials are selected to distribute weight evenly while preventing slippage during walking. Ventilation considerations are included to prevent heat buildup from electronics and battery components.

Figures 3 and 4 provide high-level conceptual illustrations of the intended system configuration and internal organization. These figures are provided to communicate the overall design intent and the spatial arrangement of components. They are not exact representations of the finalized PCB layout, enclosure geometry, or wiring implementation. The final mechanical dimensions, connector placement, and routing may vary based on fabrication constraints and iterative testing.

Overall, the physical design integrates sensing hardware, processing electronics, and haptic feedback mechanisms into a compact and wearable assistive system while maintaining modularity for future refinement.

2.4 Hardware Design

The OmniSense-Dual waist module hardware is implemented as a custom PCB that integrates sensing interfaces, wireless communication, and haptic control into a compact wearable form factor. The board is centered around an ESP32-S3-WROOM-1 module, which provides the primary microcontroller, WiFi connectivity, and processing capability required for real-time sensor fusion and navigation logic. All sensors and haptic drivers interface directly with the ESP32 through dedicated communication buses, enabling synchronized data acquisition and deterministic control of feedback outputs.

Power for the waist module is supplied by a rechargeable lithium battery. The PCB includes power distribution circuitry to regulate and distribute stable voltage rails to the ESP32, sensors, and haptic drivers. A regulated 3.3 V rail powers the MCU and I²C devices, while higher-current paths are provided for vibration motors. Local decoupling capacitors are placed near each major IC to reduce noise and maintain voltage stability during transient motor activation. The power system is designed to support continuous operation during normal walking use without excessive voltage drop or brownout under peak load conditions.

The ESP32 interfaces with environmental sensors including mmWave radar, multiple Time-of-Flight (ToF) sensors, an IMU, and a GPS module. UART connections are used for radar and GPS communication, while I²C buses are used for ToF sensors and the IMU. To support multiple identical I²C devices that may share fixed addresses, two TCA9548A I²C multiplexers are implemented on the PCB. These multiplexers allow individual channel selection and isolation, ensuring reliable communication even with multiple identical sensors connected simultaneously. This architecture improves scalability and fault isolation within the sensing subsystem.

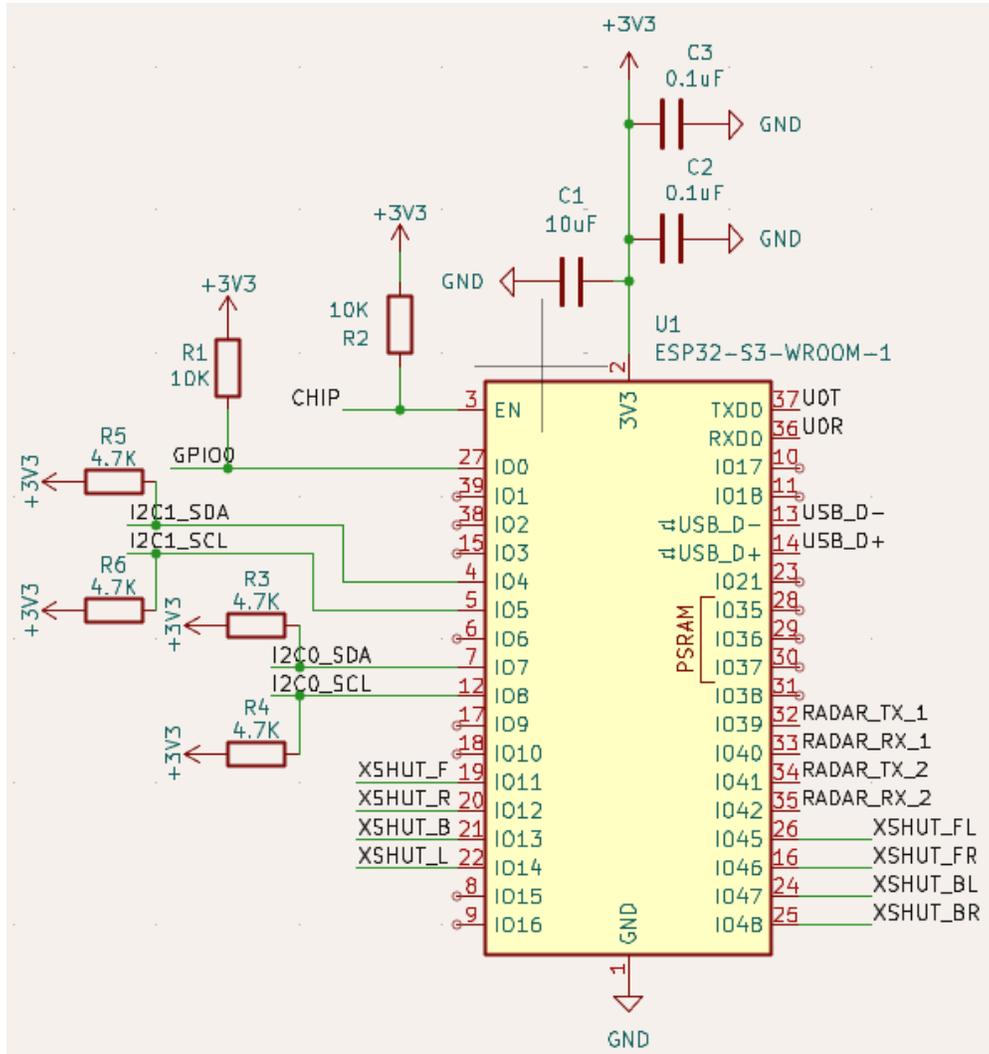


Figure 5. ESP32-S3 PIN allocation

Each ToF sensor is connected through a dedicated header that includes power, ground, I²C lines, and an individual shutdown control signal. This allows deterministic startup sequencing and address assignment during system initialization. The IMU and GPS modules are connected via standard header interfaces to allow modular replacement or debugging if required. All sensor connections operate at 3.3 V logic levels to maintain compatibility with the ESP32.

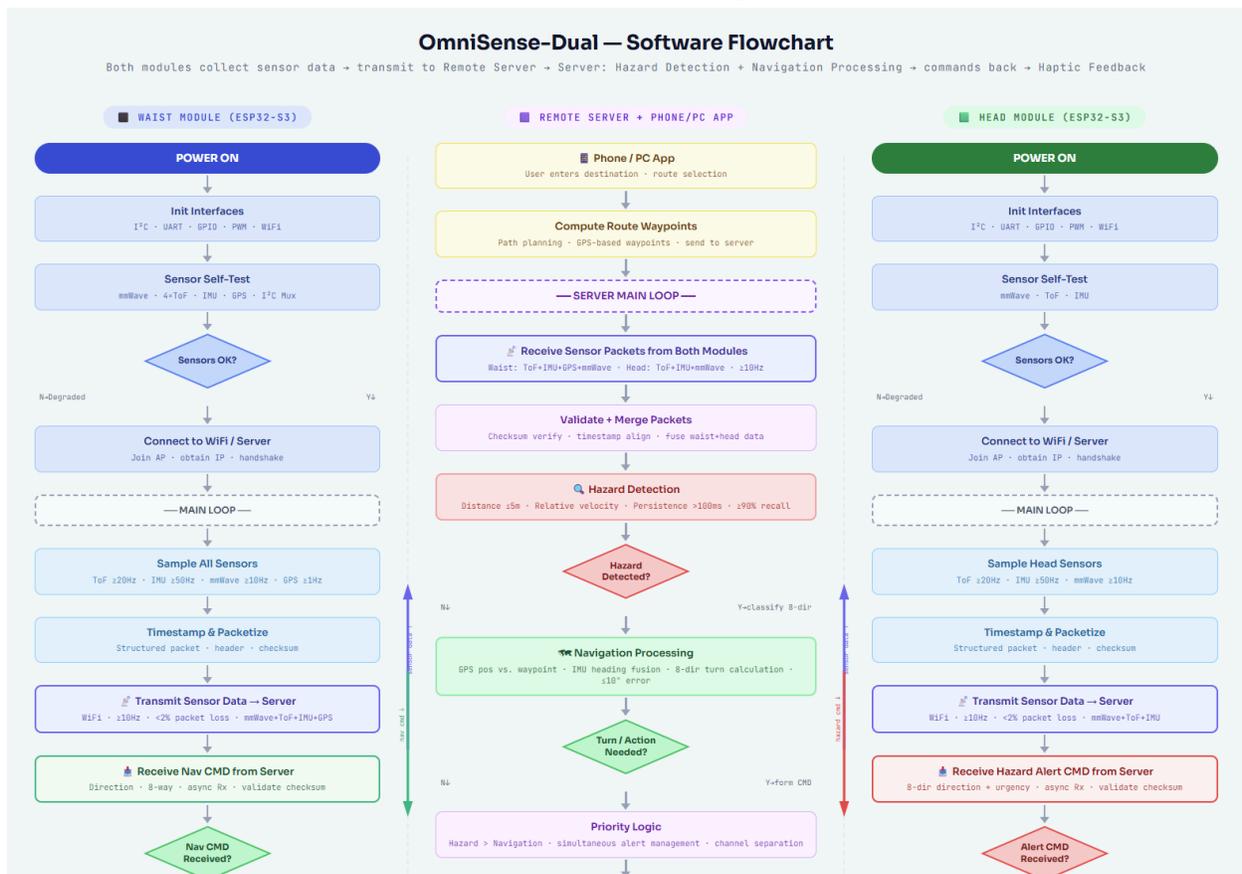
The navigation haptics subsystem is implemented using multiple vibration motor driver interfaces distributed around the belt. Each driver is controlled via the ESP32 using I²C or PWM signals depending on configuration. The PCB provides dedicated headers for these drivers, ensuring consistent power delivery and signal integrity. The layout separates motor power traces from sensitive signal lines to reduce electrical noise coupling during motor activation. This ensures reliable sensor communication even when multiple motors are activated simultaneously.

A USB-C connector is included on the PCB for firmware programming and serial debugging. The USB data lines are routed directly to the ESP32, and the required configuration resistors are implemented to ensure proper device detection when connected to a host. This interface enables rapid firmware iteration and system diagnostics during development and testing.

The overall PCB layout prioritizes modularity, noise isolation, and serviceability. High-current motor traces are widened to support peak activation loads, while signal traces for I²C and UART communication are kept short and routed away from motor switching paths. Ground planes are used to improve signal integrity and reduce EMI. Connectors are arranged to allow clean cable routing around the waist enclosure, supporting wearable integration without excessive strain on solder joints.

Together, the hardware design enables reliable sensor acquisition, low-latency navigation feedback, and stable wireless communication within a compact wearable system. The modular interface approach also allows future expansion or sensor replacement without major redesign of the core control board.

2.5 Software Design



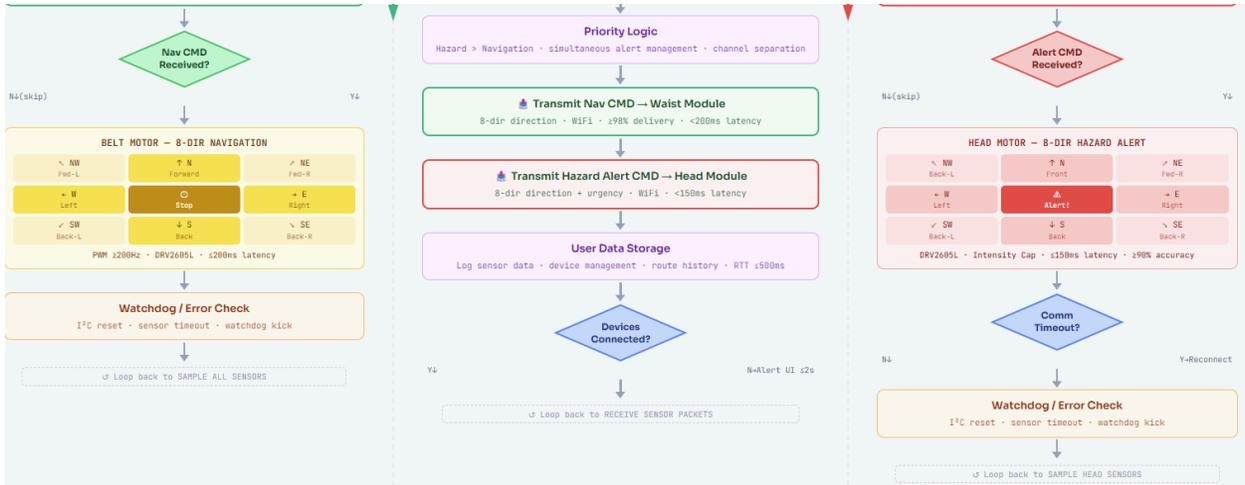


Figure 6. Software Workflow

The ESP32-S3 firmware on both the Waist and Head modules begins with a structured initialization routine at power-on. All communication interfaces — I²C, UART, GPIO, PWM, and WiFi — are configured with predefined parameters, and each sensor is individually probed through device identification or register validation. If any sensor fails this self-test, the system flags the fault and continues in degraded mode rather than halting, ensuring robustness during real-world deployment. Once all checks pass, the module connects to the WiFi network and handshakes with the Phone/PC application before entering the main operational loop.

Inside the main loop, all sensors are sampled at predefined rates suited to their purpose. The IMU runs at ≥ 50 Hz for smooth heading and orientation estimation, the ToF sensors at ≥ 20 Hz for short-range depth measurement, the mmWave radar at ≥ 10 Hz for longer-range moving object detection, and GPS at ≥ 1 Hz for outdoor positioning. Each reading is immediately timestamped and stored in structured data objects. The Waist Module then performs sensor fusion entirely on-device, combining IMU data to estimate the user's heading and walking direction, ToF and mmWave data to build a 360-degree spatial proximity map around the torso, and GPS data to track progress along the navigation route.

Both modules run hazard detection locally on the ESP32-S3 without requiring the server. The firmware applies threshold-based and persistence-based logic to the fused sensor data — a hazard candidate is triggered when an object enters the proximity zone at ≤ 5 m, but must persist across multiple samples for more than 100 ms before an alert is issued, suppressing false positives from transient noise or brief reflections. Once confirmed, the hazard is classified into one of 8 compass directions. The Head Module independently evaluates its own head-level sensors using the same logic, optimized for motor activation within ≤ 150 ms. When the Waist Module confirms a hazard, it forwards the directional alert to the Head Module via WiFi for immediate haptic output.

Navigation is handled on a completely separate channel from hazard detection, enforcing the system's dual-channel design principle. The Phone/PC application computes the required turn direction by comparing the user's current GPS position and IMU heading against the planned route waypoints, then sends a structured directional command — one of 8 directions — directly to the Waist Module over WiFi. The Waist Module decodes the command and maps it to the corresponding belt vibration motor pattern. If a hazard alert is active simultaneously, it takes priority, and navigation feedback is suppressed until the hazard clears, guaranteeing that safety-critical information is never blocked by a routine navigation cue.

The system maintains two entirely separate haptic output channels. The belt motors on the Waist Module deliver navigation cues only, driven by PWM signals at ≥ 200 Hz through DRV2605L motor drivers with end-to-end latency within ≤ 200 ms. The headband motors on the Head Module deliver hazard alerts only, with directional vibration corresponding to one of 8 hazard directions and latency within ≤ 150 ms. Vibration intensity is capped on both channels to avoid startling the user. Channel separation is a core system requirement — users must be able to distinguish head from belt feedback with $\geq 90\%$ accuracy in a blind classification test, even when both channels fire simultaneously.

All communication between modules and the Phone App runs over WiFi. Sensor status and synchronization packets are exchanged between the Waist and Head modules at ≥ 10 Hz, while navigation commands are received asynchronously from the Phone App. Every packet includes a header and checksum for integrity validation, and malformed packets are discarded. The firmware monitors for communication timeouts and automatically attempts reconnection if packet exchange stops, preventing permanent disconnection during brief signal loss. The Phone App updates its connection status within ≤ 2 seconds of any device disconnection.

The firmware also includes several layers of self-recovery to allow continuous operation without manual intervention. A watchdog timer detects main loop stalls and triggers a controlled reset. If the I²C bus becomes unresponsive due to a sensor lockup, the firmware runs a bus recovery sequence without a full system reboot. Individual sensor timeouts are detected and logged, and stale data is discarded so it cannot influence hazard evaluation. Finally, the Remote Server is an optional component for computationally intensive tasks that exceed on-device capability — when enabled, it can perform refined hazard filtering or complex navigation path calculations and return results to the devices, with round-trip latency monitored and kept within ≤ 500 ms. The wearable modules operate fully without it.

2.6 Tolerance Analysis

A major technical challenge of OmniSense-Dual is ensuring that hazard detection and alert delivery occur early enough for a user to react safely, even under varying environmental

conditions such as sensor occlusion, reflective surfaces, and interference. To demonstrate feasibility, a worst-case closing scenario is analyzed and compared against the system latency budget.

Consider a user walking at approximately 1.5 meters per second while a scooter approaches from behind at 6 meters per second. The relative closing speed is therefore approximately 7.5 meters per second. If the system detects the hazard at a distance of 5 meters, the time to collision is equal to distance divided by relative velocity, which gives 5 divided by 7.5, or approximately 0.67 seconds.

The system is designed so that total end-to-end latency remains below 250 milliseconds. This latency includes sensor sampling, hazard evaluation, wireless transmission, and vibration motor activation. Subtracting this processing delay from the available time to collision leaves approximately 0.42 seconds for user reaction. This remaining time provides a practical margin for the user to perceive the haptic alert and take corrective action such as stopping or stepping aside.

Even if detection range is reduced due to environmental effects, the system still maintains feasible timing margins. For example, if detection occurs at 4 meters instead of 5 meters, the time to collision becomes approximately 0.53 seconds. After subtracting 0.25 seconds of system latency, approximately 0.28 seconds remain for user response. Although reduced, this margin still allows immediate hazard awareness for fast-approaching objects.

To improve reliability in challenging environments, the system combines mmWave radar sensing with short-range distance sensors. Radar provides robustness to lighting and detects moving objects effectively, while distance sensors validate proximity and reduce false triggers. The software further enhances reliability using filtering and persistence logic, requiring hazards to exceed defined thresholds across multiple samples before issuing an alert. This multi-sensor approach maintains detection performance even in the presence of reflections or temporary occlusion.

To experimentally validate this analysis, controlled motion trials will be conducted. During each trial, timestamps will be recorded at three key events: hazard detection within firmware, alert command generation, and motor activation. The delay between detection and motor activation will be measured using serial logging and oscilloscope verification of the motor drive signal. The measured latency will then be compared against the 250 millisecond requirement.

For each trial, the available reaction margin will be calculated as time to collision minus measured system latency. The system will satisfy the safety timing requirement if the reaction margin remains positive and greater than 0.25 seconds in at least 90 percent of trials conducted at the required detection distance. This experimental validation confirms that the implemented

hardware and software meet the timing assumptions established in the analytical model and that the system can provide timely hazard alerts under realistic operating conditions.

3. Cost and Schedule

3.1 Cost Analysis

Description	Manufacturer	Quantity	Extended Price	Link
ESP32-S3-WRO OM-1-N8	Espressif	2	\$64.00	Link
DFRobot C4001 24GHz mmWave	DFRobot	4	\$56.00	Link
VL53L1X ToF Sensor Breakout	Aceirmc	16	\$86.70	Link
SparkFun ICM-20948 9DoF IMU Breakout	SparkFun	2	\$44.00	Link
GPS Module		1		
TCA9548A 8-Channel I ² C Multiplexer Breakout	DORHEA	2	\$20.00	Link
DRV2605L Haptic Motor Driver Module	DORHEA	16	\$247.68	Link
Cylindrical ERM Pager Motor 7×25 mm, 3V, wired	Generic	16	\$336.00	Link
3.7V 3000 mAh LiPo Battery	YDL	2	\$25.00	Link
BQ34Z100EVM Battery Fuel		2	\$0	

Gauge				
MCP73831T LiPo Charger Module	Adafruit	2	\$13.90	Link
TPS63020 Buck-Boost Regulator Module	Jessinie	2	\$20.00	Link
JST-PH 2.0 mm Connector Kit	CQRobot	2	\$26.00	Link
SMD Resistor & Capacitor Assortment	Ipudis	2	\$60.00	Link
Pin Headers 2.54 mm	Envistia	2	\$12.30	Link
USB-C SMD Connectors	Skweawert	2	\$12.50	Link
JLPCB 2-layer PCB fabrication		2	\$0.00	
HC-SR04 Ultrasonic Sensors		2	\$0.00	

3.2 Schedule

Week	Task	Person
Feb 23 - Mar 1	Design Review sign-up opens; PCBWay Round 1 order audit	Everyone
	Finish and submit Design Document	Everyone
	Freeze interfaces + sensor placement; finalize haptic	Jiateng, Alex, Simon

	mapping; order long-lead parts	
Mar 2 - Mar 8	Design Review: present architecture + requirements; incorporate instructor/TA feedback	Everyone
	PCBWay Round 2 order audit	Jiateng
	Start/continue PCB design (waist + head) and schematic review; begin firmware scaffolding	Jiateng, Alex, Simon
Mar 9 - Mar 15	Breadboard Demo: demonstrate core sensing or haptics on prototype wiring	Everyone
	PCBWay Round 3 order audit	Jiateng
	Integrate sensor drivers (ToF/IMU/GPS/mmWave) + basic haptic output demo	Simon, Alex, Jiateng
Mar 16 - Mar 22	Spring Break: light progress only.	Everyone
	Finalize PCB files + send for fabrication; continue firmware integration/testing as available	Jiateng, Alex, Simon
Mar 23 - Mar 29	PCBWay Round 4 order audit	Jiateng
	Bring-up first PCB(s) if arrived; solder + smoke-test power rails; verify I ² C mux + haptic drivers	Jiateng, Alex
Mar 30 - Apr 5	Individual progress reports	Everyone

	End-to-end integration: sensing → hazard decision → head alert; navigation cue pipeline from phone	Simon, Alex, Jiateng
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4. Ethics, Safety, and Societal Impact

4.1 Safety Concerns

The OmniSense-Dual system, a battery-powered wearable with multiple sensors and haptic drivers, presents several critical safety considerations across electrical, battery, mechanical, and human factors domains.

1. Electrical Safety

The primary electrical risks stem from potential short circuits, improper LiPo charging, connector failures, and transient current spikes generated by the vibration motors. A fault in the wiring or a short could lead to component damage, overheating, or, in severe cases, user burns. Given that the device is body-worn, critical mitigation strategies include ensuring robust electrical isolation, securing all wiring, and implementing reliable power regulation.

2. Battery and Fire Hazard

The system uses single-cell Lithium Polymer (LiPo) batteries. The main fire risk is LiPo thermal runaway, which can be triggered by overcharging, puncturing, or a short circuit. High simultaneous current draw from haptic actuation could also cause localized overheating in power regulators or circuit traces. Therefore, safe charging circuits, current limiting, appropriate enclosure design, and thorough thermal validation are essential before any user testing.

3. Mechanical and Wearability Safety

As the system is worn at both the waist and head, mechanical hazards must be addressed. These include sharp enclosure edges, potential pinching points from straps, exposed moving parts (vibration motors), and poorly strain-relieved cables that could break and expose conductors. For the head module, maintaining comfort and stability is paramount to prevent user distraction or discomfort during movement.

4. Human Factors Safety (Haptic Feedback and Distraction)

The risk here involves the haptic alerts themselves. Overly intense or too frequent vibrations could startle or confuse the user, especially if the cues for navigation and for hazards are not distinctly separated. Confusing feedback could lead to unsafe actions, such as stepping into traffic or freezing in place. To prevent this, the system must strictly cap haptic intensity and maintain clear "channel separation".

4.2 Ethical Concerns

Accuracy and Reliability of Guidance

The device provides safety-critical information: obstacle direction/urgency and navigation cues. If hazard alerts are missed (false negatives) or if navigation cues are wrong, users could be guided into unsafe situations. Following the principle in professional engineering ethics to prioritize public safety and avoid misleading performance claims, we must clearly communicate limitations (sensor blind spots, GPS unreliability indoors, unusual environments) and validate performance with measurable tests.

Accessibility and Inclusive Design

The target users may have different levels of tactile sensitivity and may wear different clothing (which affects vibration perception). The system must allow configuration (intensity levels, pattern choice, left/right mapping), and the feedback scheme must be easy to learn. Additionally, the device must not assume the user can rely on audio confirmation—OmniSense-Dual must remain functional without requiring hearing. Ethical design also includes minimizing stigma: the device should be discreet and comfortable so users are not discouraged from using it in public.

Privacy and Security

OmniSense-Dual may use GPS and communicate wirelessly (phone ↔ waist, waist ↔ head). Location and movement data can be sensitive: if logged or transmitted insecurely, it could expose personal routines and whereabouts. There is also risk of spoofing or interference (malicious or accidental) causing incorrect cues. Therefore, we should minimize stored data, avoid collecting personally identifiable information by default, and ensure the wireless link is authenticated and robust.

4.3 Regulatory and Standard Compliance

To address the safety and ethical concerns above, OmniSense-Dual must align with relevant standards and best practices, including:

- **IEEE / ACM Codes of Ethics** — prioritize public safety, transparency about limitations, and avoidance of harm.
design_document1
- **FCC Part 15 (unlicensed transmitters)** — ESP32 BLE/Wi-Fi operation must not cause harmful interference and must accept interference.
design_document1
- **Battery safety best practices** — safe LiPo charging, overcurrent protection, insulation, and enclosure safety to reduce burn/fire risk.
- **Accessibility considerations (ADA-aligned principles)** — while ADA may not directly regulate a student prototype, we will follow accessibility best practices: adjustable intensity, clear cue mapping, and safe/comfortable wearability.

4.4 Mitigation of Ethical and Safety Risks

The OmniSense-Dual system is designed to improve pedestrian safety and situational awareness in environments where pedestrians share space with bicycles, scooters, and vehicles. Because the system directly influences user behavior in potentially hazardous environments, ethical and safety considerations must be addressed carefully during both development and deployment. According to the IEEE Code of Ethics, engineers are required to prioritize public safety, avoid misleading claims, and design systems that minimize risk to users and society. To align with these principles, the project avoids presenting the device as a replacement for user awareness; instead, it is intended only as an assistive tool. Documentation and user instructions will clearly communicate system limitations so that users do not become overly dependent on the device.

Several safety concerns arise from both hardware design and system operation. The system uses rechargeable batteries and wearable electronics, which introduce potential risks such as overheating, electrical faults, or discomfort during prolonged wear. These risks are mitigated by using regulated power circuits, proper battery protection modules, and safe enclosure designs that prevent direct exposure to electrical components. Vibration motors are also limited in intensity to avoid discomfort or distraction that could itself create unsafe situations. During development and testing, all hardware will follow standard laboratory safety practices to protect team members from electrical hazards and mechanical failures.

Potential misuse must also be considered. For example, users might rely entirely on the system and pay less attention to their surroundings, or the device could be incorrectly used in environments beyond its sensing capability. To reduce these risks, the system design emphasizes conservative hazard detection thresholds and encourages users to maintain normal situational awareness. Furthermore, the system does not collect or transmit personally identifiable data, reducing privacy concerns associated with wearable sensing devices. Sensor data are processed locally and used only for real-time hazard detection and navigation guidance.

From a societal perspective, the system has the potential to positively impact urban mobility and accessibility by helping pedestrians navigate safely and by providing additional assistance for visually impaired users. As cities adopt more micro-mobility solutions such as scooters and bicycles, conflicts between pedestrians and vehicles are expected to increase. A wearable awareness system can help reduce accidents and improve coexistence on shared paths. Economically, the system leverages relatively low-cost sensors and consumer electronics, making future deployment feasible for broader populations. Environmentally, the device has minimal impact beyond standard consumer electronics usage, though responsible disposal and battery recycling practices should be encouraged.

Overall, OmniSense-Dual aims to enhance public safety while respecting ethical responsibilities, minimizing risks to users, and supporting safer and more inclusive pedestrian environments.

5. Reference

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