



A ROS 2-Based Wearable Navigation Architecture for Visually Impaired Users Using ToF and GNSS: A Proposed System and Evaluation Framework.

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ABSTRACT

Independent mobility remains a significant challenge for visually impaired individuals, particularly when transitioning between indoor and outdoor environments where the reliability of positioning technologies differs sharply. This paper presents a proposed wearable assistive navigation architecture that combines time-of-flight (ToF)-based indoor sensing with GNSS-based outdoor positioning, coordinated through a ROS 2 architecture distributed across smart glasses and a sensor-equipped smart shoe, with guidance delivered through an audio headset and shoe-mounted haptic motors. This is a conceptual, design-stage paper that presents the proposed system architecture, candidate hardware components, proposed ROS 2 node design, and a proposed evaluation framework for future assessment of localization accuracy, obstacle-detection performance, mode-transition reliability, and usability. No hardware has been fabricated and no experiments have been conducted at the time of writing; accordingly, this paper reports no quantitative results. All proposed measurements are intended for a future prototype-validation study. The primary contribution is a distributed ROS 2 architecture that integrates head-mounted ToF and visual sensing with shoe-mounted proximity, inertial, pressure, and haptic sensing to support context-aware indoor-outdoor navigation.

Keywords: assistive navigation; visual impairment; wearable computing; ToF sensing; GNSS; sensor fusion; ROS 2; haptic feedback

1. Introduction

Visual impairment affects several hundred million people worldwide and substantially limits independent mobility, particularly in unfamiliar or dynamically changing environments. Traditional aids such as white canes and guide dogs remain widely used, but their capabilities differ from those of sensor-based wearable systems in terms of long-range environmental perception, contextual scene understanding, and computational route guidance. Over the past decade, wearable assistive technology has advanced considerably, incorporating cameras, ultrasonic sensors, inertial measurement units (IMUs), and increasingly, artificial intelligence for object and scene recognition. However, most existing systems are optimized for a single operating context — either indoor obstacle avoidance or outdoor navigation — and rely on a single wearable form factor rather than a coordinated multi-device system.

A particular gap exists in seamless indoor-to-outdoor transition. Indoor environments are GNSS-denied and require alternative localization strategies, while outdoor environments benefit from GNSS but suffer from multipath errors near buildings and lack fine-grained obstacle information [1]. Systems that address only one of these regimes leave the user without reliable guidance when crossing between them, which is precisely when disorientation risk is highest, such as at building entrances, transit stations, and stairwells.

This paper proposes a wearable assistive navigation architecture that integrates indoor ToF-based structural sensing with outdoor GNSS positioning through a distributed ROS 2 framework. The architecture combines two coordinated wearable units: smart glasses for head-level perception, including ToF sensing, visual sensing, and orientation tracking, and a smart shoe for ground-level sensing, including proximity, inertial, pressure, and haptic feedback. A context-aware localization strategy is proposed to coordinate available sensing modalities during indoor-outdoor transitions. At the current stage, the system remains a conceptual design; candidate hardware components and software modules have been identified, but no physical prototype has been fabricated and no experimental validation has been conducted.

Contributions

1. **A distributed ROS 2 wearable architecture** that coordinates sensing, localization, navigation, and multimodal feedback across smart glasses and a smart shoe.

2. **A multimodal sensing configuration** that combines head-level ToF and visual sensing with shoe-mounted proximity, inertial, pressure, and haptic sensing for complementary environmental and ground-level awareness.
3. **A proposed context-aware indoor–outdoor localization framework** that considers GNSS quality, ToF-derived structural information, and foot-mounted inertial measurements during transitions between positioning environments.
4. **A structured evaluation framework** for future assessment of localization accuracy, obstacle-detection performance, indoor–outdoor mode-switch reliability, feedback latency, power consumption, and usability.

The remainder of this paper is organized as follows. Section 2 reviews related work. Section 3 describes the proposed system architecture and candidate hardware. Section 4 describes the proposed sensor-fusion and mode-switching concept. Section 5 presents a proposed evaluation framework, specifying what would be measured and how, once a prototype exists. Section 6 discusses the expected contribution and limitations, and Section 7 concludes the paper.

2. Related Work

Research on wearable assistive navigation for visually impaired users spans several overlapping directions: obstacle-detection glasses, smart footwear, ROS-based control architectures, and, more recently, indoor-outdoor sensor fusion.

2.1 Smart Glasses for Obstacle Detection and Scene Understanding

Recent systems increasingly combine perception, AI reasoning, and multimodal feedback. LidSonic V2.0 combined a LiDAR sensor, a servo motor, and an ultrasonic sensor for obstacle perception, paired with image-based obstacle classification [3]. More recent AI-glasses frameworks integrate object detection with language-model reasoning and haptic feedback [5]. Commercial systems such as .lumen use AI-based environmental perception together with audio and haptic feedback to support independent navigation for visually impaired users [6].

2.2 Smart Footwear for Ground-Level Sensing

IMU- and ultrasonic-sensor-equipped smart shoes have been investigated for obstacle detection and navigation assistance for visually impaired users [7]. Other smart-shoe systems have incorporated inertial sensors, Bluetooth Low Energy communication, and vibration-based haptic feedback to provide navigation instructions and proximity alerts [8]. These studies demonstrate the potential of footwear-based sensing as a complementary component of wearable assistive navigation systems.

2.3 ROS/ROS 2-Based Assistive Navigation Architectures

A representative prior system used a fuzzy-logic decision-support system on an embedded ROS-based controller to fuse ultrasonic sensor data from an eyeglass frame and a hand-worn accessory. Such architectures demonstrate the feasibility of ROS as a real-time coordination layer for multi-sensor BVIP systems [2], but predate ROS 2 and do not incorporate ToF-based indoor sensing or GNSS-based outdoor fusion.

2.4 Indoor-Outdoor Sensor Fusion for Wearable Localization

The most directly related recent work addresses seamless indoor-outdoor localization through GNSS-IMU fusion, dynamically switching between GNSS-dominant outdoor localization and neural-network-enhanced IMU dead reckoning indoors. This establishes indoor-outdoor context switching as an active research problem, but addresses the indoor gap through IMU dead reckoning rather than ToF-based mapping, and does not incorporate a coupled footwear sensing device [1].

2.5 Positioning of the Present Work

Based on the literature reviewed in this study, no directly comparable system was identified that combines ToF-based indoor localization, GNSS-based outdoor positioning, and a tightly coupled shoe-based sensing and haptic unit within a single ROS 2-based architecture [1]–[5]. This combination therefore represents the proposed research direction of the present work.

3. Proposed System Architecture

The proposed system consists of three coordinated hardware units — smart glasses, a smart shoe, and an audio headset — communicating through a ROS 2 framework. Figure 1 shows the overall architecture.

Figure 1. Proposed Wearable System Architecture

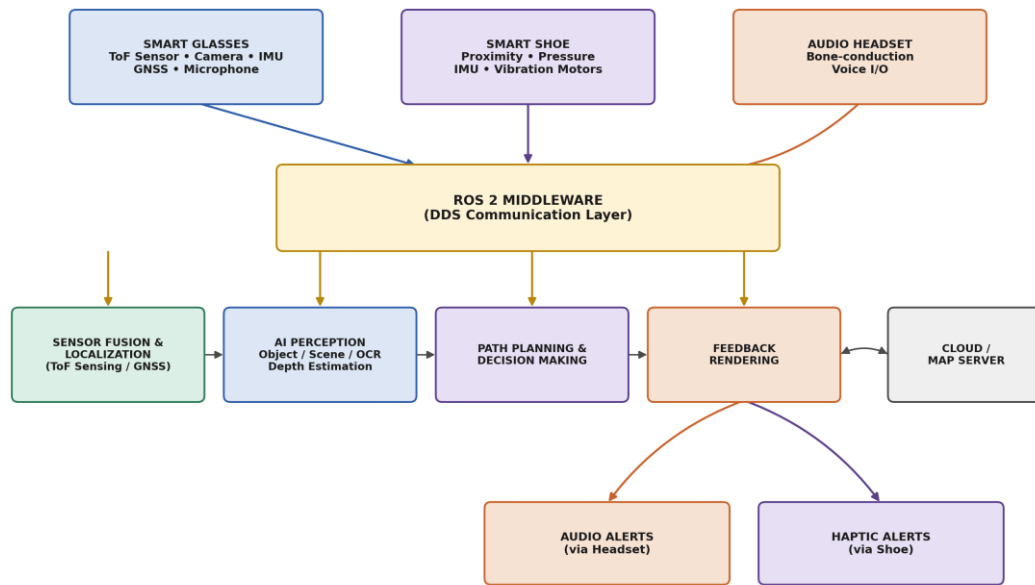


Fig 1 – Proposed wearable system architecture

3.1 Proposed Hardware Components

The following components are proposed for a future prototype and are summarized in Table 1; none have yet been procured or assembled. Note that a full spinning LiDAR is not selected for the proposed face-worn configuration because of its anticipated weight, power, and integration constraints ; the proposed design therefore uses a compact time-of-flight (ToF) sensor array on the glasses for indoor obstacle/structure sensing, referred to throughout as "ToF sensing" rather than LiDAR.

Table 1 – Candidate hardware components for future prototype implementation

Subsystem	Candidate Component	Purpose
Compute	Raspberry Pi 4/5 (8 GB) or Jetson Orin Nano	Runs ROS 2 nodes and onboard AI inference
Indoor sensing (glasses)	VL53L1X ToF sensor array	Compact indoor obstacle/structure sensing (proposed)
Camera	Raspberry Pi Camera Module 3	Object detection, scene understanding, OCR
IMU (glasses + shoe)	BNO055 / MPU6050	Orientation and motion tracking
Outdoor positioning	u-blox NEO-M8N GNSS module	Outdoor localization
Shoe proximity	VL53L0X / HC-SR04	Curb, step, and hole detection
Shoe pressure	FSR 402 sensors	Gait and balance monitoring
Haptic actuation	Coin vibration motors + driver IC	Directional obstacle/step alerts
Shoe MCU	ESP32	Shoe-side sensor handling, BLE link to glasses
Audio output	Bluetooth bone-conduction headset	Voice guidance without occluding ambient sound

3.2 Smart Glasses Unit (Proposed)

- ToF sensor array — indoor structure/obstacle sensing, proposed to support future indoor mapping
- RGB camera — object detection and scene understanding
- IMU — head-motion tracking and orientation
- GNSS module — outdoor positioning
- Microphone — voice command input

3.3 Smart Shoe Unit (Proposed)

- Ground proximity sensors — step, curb, and hole detection
- Pressure sensors — gait and balance monitoring
- IMU — foot motion tracking, usable for step-based dead reckoning
- Vibration motors — directional and event-based haptic feedback
- BLE module — data transfer to the glasses unit

3.4 Audio Headset (Proposed)

A bone-conduction or open-ear headset is proposed to deliver real-time voice alerts, turn-by-turn navigation commands, and destination guidance, chosen specifically to avoid occluding ambient environmental sound, which visually impaired users rely on for orientation.

3.5 Proposed ROS 2 Coordination Layer

A ROS 2 framework running on the onboard compute unit is proposed to coordinate all sensor and decision-making nodes, illustrated conceptually in Figure 2. This node graph represents the intended software architecture; it has not yet been implemented or tested.

Figure 3. ROS 2 Node and Topic Communication Graph

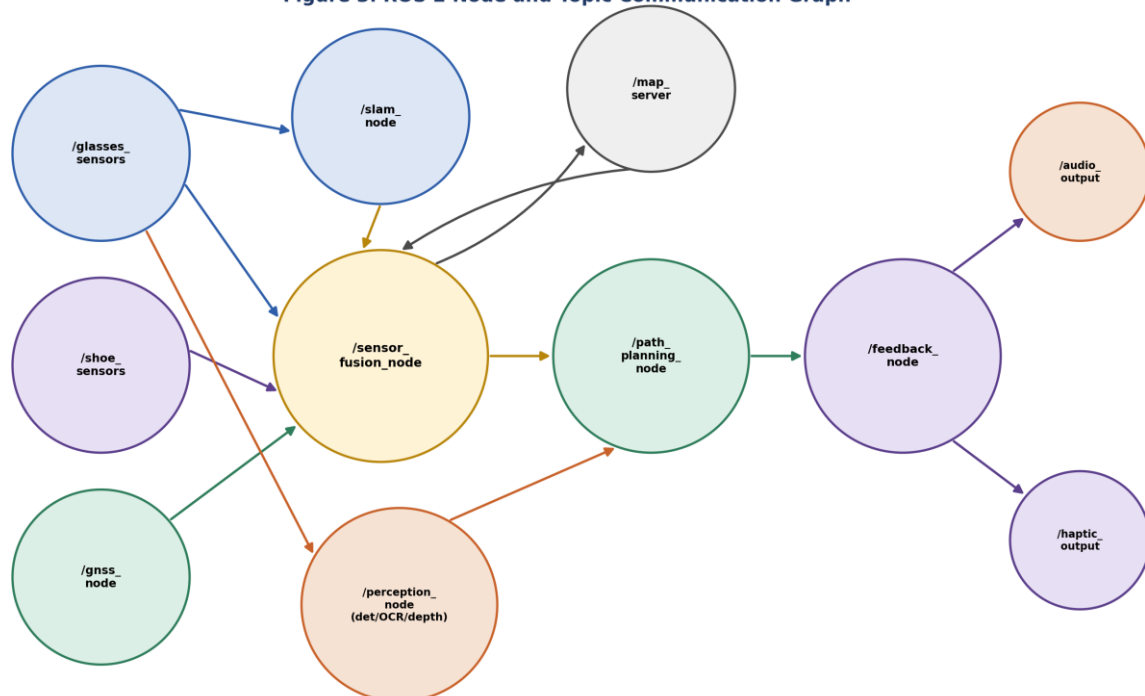


Fig 2 – Proposed ROS 2 node and topic communication graph (design concept, not yet implemented)

- Sensor-fusion node — intended to combine glasses and shoe sensor streams into a unified state estimate

- Localization node — proposed to use ToF-based indoor mapping (a future implementation may employ ToF-based SLAM) and GNSS-based positioning outdoors
- Path-planning and decision node — intended to compute safe headings and step-level guidance
- AI perception node — proposed for object detection, scene understanding, and text/sign recognition
- Feedback node — intended to render decisions as audio prompts and haptic patterns

4. Proposed Sensor Fusion and Indoor–Outdoor Mode Switching

The central proposed contribution of this work is a context-aware architecture for coordinating indoor and outdoor localization within a ROS 2-based wearable system, rather than a demonstrated or validated fusion algorithm. The concept, illustrated in Figure 3, is that an environment-classifier node would continuously evaluate GNSS signal quality (fix status, satellite count, HDOP) alongside ToF-derived structural cues to determine the current context. During transitions, available localization estimates would be combined using a proposed context-aware fusion strategy [1], with foot-mounted IMU step-counting intended to provide a supplementary dead-reckoning estimate that bridges brief dropouts. This logic is a design proposal only; its feasibility and performance have not yet been demonstrated.

Figure 2. Indoor–Outdoor Mode-Switching and Sensor Fusion Flow

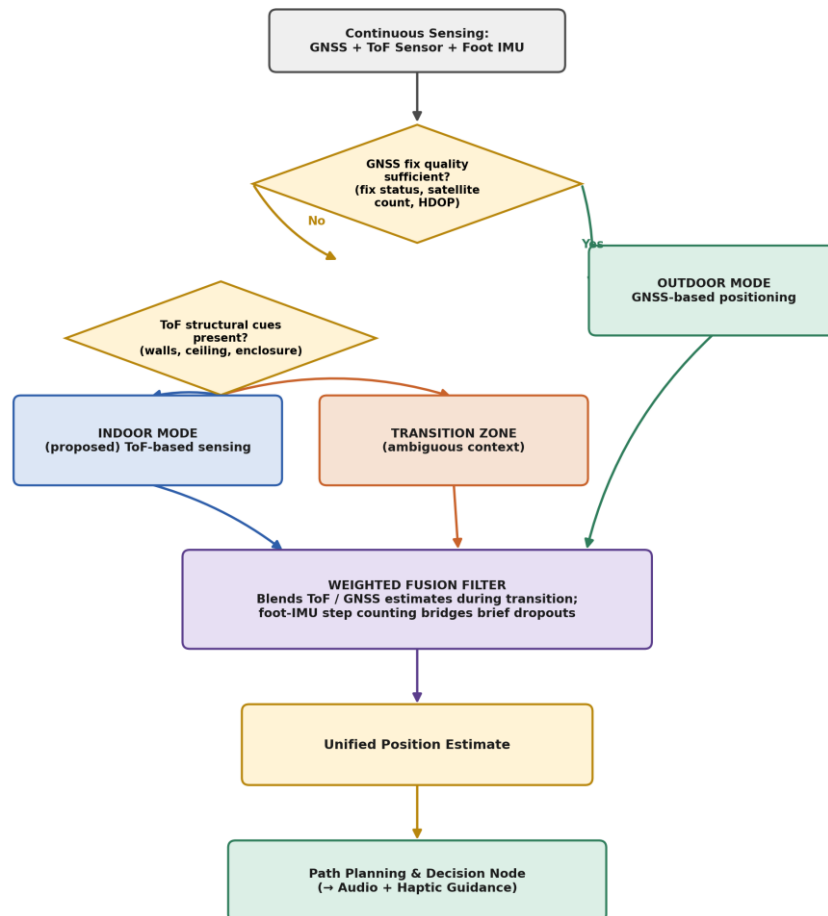


Fig 3 – Proposed indoor–outdoor mode-switching and sensor fusion concept (not yet implemented or validated)

5. Proposed Evaluation Framework

This section proposes what would be measured following future prototype fabrication, structured as a Prototype → Experiment → Raw Data → Analysis → Result pipeline for each test. These are proposed experiments for future validation, not experiments already conducted; no results exist yet, and each expected output is explicitly marked.

5.1 Experiment 1 — Indoor Localization Accuracy

Proposed procedure: mark fixed waypoints along an indoor test route using measuring tape; walk the route wearing the prototype; log the system's estimated position at each waypoint alongside the true (tape-measured) position.

- Raw data to collect: estimated (x, y) vs. ground-truth (x, y) at each of N waypoints
- Analysis: per-waypoint position error (Euclidean distance); mean and standard deviation across the route
- Output: Table — Waypoint | Estimated Position | Ground Truth | Error (cm)

Expected output: Mean localization error will be calculated after future prototype validation.

5.2 Experiment 2 — Outdoor GNSS Accuracy

Proposed procedure: repeat position logging at surveyed outdoor reference points, under both open-sky and near-building conditions.

- Raw data to collect: GNSS reading vs. surveyed reference coordinates, per condition
- Analysis: mean error (m) separately for open-sky and near-building conditions
- Output: Table — Condition | Mean Error (m) | Max Error (m)

Expected output: Mean outdoor GNSS error under open-sky and near-building conditions will be calculated after future prototype validation.

5.3 Experiment 3 — Indoor–Outdoor Mode-Switch Reliability

Proposed procedure: walk through at least 10 indoor↔outdoor transitions (e.g., building doorways); log the mode detected by the system and the time taken to stabilize after each transition.

- Raw data to collect: transition number, correct/incorrect mode detected, switch latency (ms)
- Analysis: success rate (%), mean switch latency
- Output: Table + bar graph of latency per transition

Expected output: Mode-switch success rate and mean latency will be calculated after future prototype validation.

5.4 Experiment 4 — Obstacle Detection Performance

Proposed procedure: place known obstacles at set distances/positions; walk toward them; log whether each was detected, the alert latency, and any false positives.

- Raw data to collect: obstacle ID, distance, detected (Y/N), alert latency (ms), false positives
- Analysis: precision, recall, mean detection latency
- Output: Table — Obstacle | Distance | Detected | Latency (ms)

Expected output: Precision / recall / mean detection latency will be calculated after future prototype validation.

5.5 Experiment 5 — Haptic/Audio Response Time

Proposed procedure: trigger a test alert; measure elapsed time from sensor event to audio/haptic output using a logged timestamp difference.

- Raw data to collect: trigger timestamp, output timestamp, per trial ($N \geq 20$ trials)
- Analysis: mean and standard deviation of response time

Expected output: Mean audio/haptic response time will be calculated after future prototype validation.

5.6 Experiment 6 — Battery/Power Runtime

Proposed procedure: run the system continuously from full charge until shutdown; log elapsed time.

Expected output: Continuous runtime on full charge will be calculated after future prototype validation.

5.7 Experiment 7 (Optional) — Usability Trial

Proposed procedure: Future usability evaluation could involve adult volunteers in a controlled simulated-navigation study or, subject to institutional ethics approval and appropriate participant safeguards, visually impaired participants.

- Raw data to collect: task completion time, number of collisions, subjective confidence rating (1–5 scale)
- Analysis: mean comparison between prototype and baseline

Expected output: Task completion time / collision count / confidence rating will be calculated after future prototype validation.

6. Discussion: Contribution and Limitations

The individual sensing modalities used in this system — ToF-based obstacle detection, GNSS outdoor positioning, IMU-based footwear sensing, ROS 2-based coordination, and AI-based scene understanding — are each well established in prior work [1]–[8]. The intended contribution of this project is the proposed architectural combination of indoor ToF-based localization, with SLAM considered as a potential future implementation, and GNSS-based outdoor positioning within a ROS 2 pipeline, coupled with a footwear sensing and haptic unit.

As no prototype has been built at the time of writing, this discussion is necessarily conditional and describes expected rather than demonstrated behavior. Once the proposed experiments in Section 5 are completed on a future prototype, this section would be revised to discuss actual measured performance, comparison against the related systems in Table 1, and any deviations between expected and observed behavior. Anticipated limitations of the proposed design include the computational and power budget of running ToF-based sensing (and, if implemented, SLAM) on a wearable compute platform, the added weight and complexity of a two-device hardware system, and the dependency of the proposed indoor-outdoor classifier on reliable transition-zone behavior, none of which have yet been tested.

7. Conclusion

This paper presented a proposed design for a wearable assistive navigation system for visually impaired individuals that would combine indoor ToF-based sensing with GNSS-based outdoor positioning across a coordinated smart-glasses and smart-shoe hardware pair, coordinated through a ROS 2 architecture. Candidate hardware components have been identified (Table 1) and a proposed evaluation framework has been specified (Section 5). As no physical prototype has been fabricated, this paper reports no performance results; all quantitative claims are marked and remain to be established through future prototype construction and testing. Future work is the immediate next step: fabricate the prototype, execute the proposed experiments in Section 5, and revise Sections 5–6 and the Abstract with actual measured results before this work could be presented as a validated system.

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