DEVELOPING A PEDESTRIAN NAVIGATION SYSTEM BY DESIGNING THE HARDWARE AND SOFTWARE FOR MEMS-BASED WEARABLE SENSORS (MEMSENSE) ROKETSAN

PROJECT TEAM

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Abstract. Conventional navigation systems depend on GPS signals, which are unreliable or unavailable in environments such as underground mines, indoor facilities, and disaster zones, leaving personnel at risk of disorientation, delays, and life-threatening errors. To address this, we developed a compact, low-cost, wearable navigation system that operates independently of GPS by leveraging two custom-designed SoC PCB boards —one mounted on the chest and one on the foot— each integrating a six-axis IMU, barometer, magnetometer, temperature sensor, and ESP32-S3 microcontroller. We collect angular velocity, acceleration, and temperature data and fuse them via Direction Cosine Matrices, Zero Velocity Updates, and a Kalman filter to derive accurate position, velocity, and altitude in the navigation frame. The processed navigation data are visualized in real time through a mobile-accessible web server application, demonstrating reliable tracking and orientation performance in GPS-denied scenarios.

PROJECT DESCRIPTION

The project delivers a compact, dual-sensor wearable navigation system that enables the agent to localize themselves in mines, tunnels and other GNSS-denied areas where disorientation can prolong rescue efforts and put lives at risk . The company did not specify neither any limitations nor specifications for this project, so that every objective, specification and limitation is decided by our group. Hence, shortly, this project aims to create a wearable navigation system that solely utilizes inertial navigation sensors rather than using GPS systems.

The motivation behind the project idea is to enable real-time location verification through a modern interface in GPS-denied environments, particularly multi-level mines where dense rock blocks satellite signals. Our affordable, lightweight wearable system supports agents with limited mobility or injuries, ensuring continuous tracking in the rare but critical events of entrapment or disorientation. the causalities due to the mine accidents are not just a national problem but a global concern. Concerning a research conducted in China, even though coal mine deaths have decreased from the peak value of 5938 causalities occurred in 2005, to 178 causalities observed in 2021, corresponding to a decrease of 97%, working in such harsh environments still inhibit danger [4]. The existing alternatives and their properties can be summarized as follows. Even though it is easier to implement, smartphone dead reckoning drifts quickly, FFT-based gait detectors fail during erratic motion although function in ordered actions; and military-grade PNT packs exceed $10000 and are too bulky for widespread deployment [5, 2, 3].

Through combining direct ZUPT triggering, browser-based visualisation and a fully solid-state, vibration-immune electronics stack, this design offers a rugged, GNSS-independent localisation aid that is affordable for civilian rescue teams yet readily hardened for military deployment, positioning the company at the forefront of compact personnel-tracking technology. Concering our own design specifications, the design couples a chest-mounted and a foot-mounted PCB, where each built around an ESP32 microcontroller and a 6-axis ASM330LHBG1 IMU, and integrates a piezoelectric force sensing resistor beneath the insole to mark zero-velocity instants directly. With Direction Cosine Matrix and Kalman filter fusion, the system maintains horizontal drift below 20% over 400–500m indoor paths and runs for 5–6h on a 500mAh Li-Po battery that recharges wirelessly in 1.5h. The complete kit fits within 55.9mm$\times$27.9mm chest board and foot board, with a combined mass$<$64g, and stays under the $2911 R&D limit while satisfying 0–60°C, 16-g shock and 2.53W power constraints.

The Big Picture of the project can be summarized as follows. The foot-sensor data travel to the chest module through low-power ESP-NOW [1] protocol. The chest unit fuses both IMU streams, verifies altitude with a BMP390 barometer, and hosts a password-protected WiFi4 web page that any phone or laptop can open to display a colour coded trace, live heading cursor and elevation bar. The overall power and data flow is indicated Fig.1.

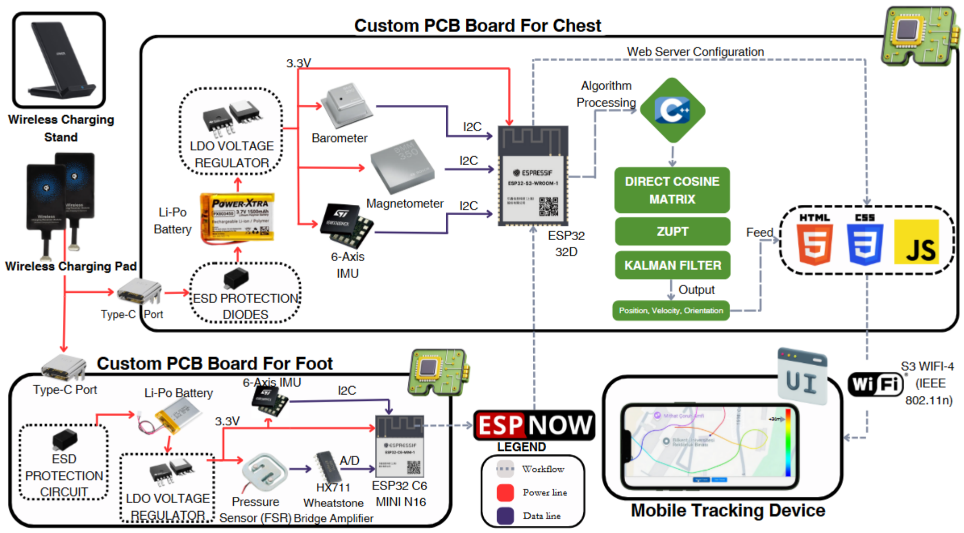


FIGURE 1. Big Picture of the Project

MILESTONES

The milestones of this project can be explained as follows.

Milestone-1: First Committee Meeting: The first milestone includes the selection of sensors and microcontroller, to achieve accurate navigation performance, efficient power consumption, and cost-effectiveness. Additionally, a web-based user interface was developed to visualize real-time navigation data—displaying both current position of the agent and historical tracks on a mobile device. Finally, the mathematical models for processing inertial sensor signals were established so that the theoretical foundation for the algorithm implementation is developed.

Milestone-2: Second Committee Meeting: Regarding the second milestone, a working prototype was assembled on a breadboard and successfully tested to transmit sensor data to the web server. This was followed by full hardware and software integration, achieving minimal-delay position updates on the navigation webpage. The PCB design was finalized to guarantee hardware stability, and additional sensor testing was performed to fine-tune the parameters of the mathematical models.

Milestone-3: Third Committee Meeting: Concerning the third milestone, the assembly and testing of the professionally manufactured PCBs and their onboard sensors was the primary objective. A wearable component was designed to ensure both accurate positioning and user comfort. In parallel, the algorithms were optimized by updating its parameters based on the real sensor data collected from the assembled PCBs.

Milestone-4: Fourth Committee Meeting: The final milestone involved comprehensive debugging of hardware, firmware, and user interface to deliver a fully integrated system capable of displaying live, accurate location on a mobile web page, followed by a formal presentation at the project fair demonstrating end-to-end real-time navigation.

DESIGN DESCRIPTION

Solution Strategy. The proposed inertial pedestrian navigation system was designed to enable accurate localization in GPS-denied environments, such as mines or complex indoor facilities, for search and rescue operations. The project strategy integrates three core components:

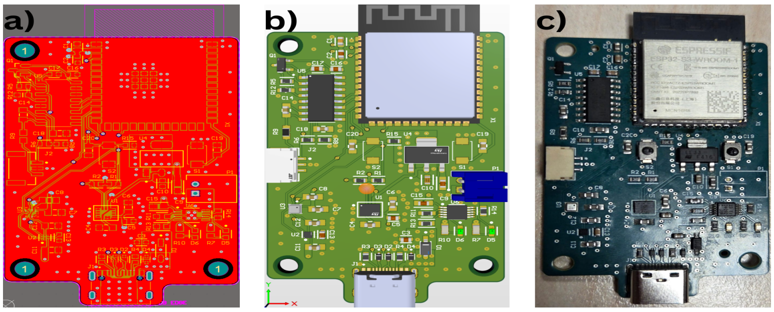
(1) A dual-IMU configuration (chest and foot-mounted) and signal processing for enhanced motion tracking.
(2) Custom-designed wearable PCBs optimized for power, size, and accuracy.
(3) A real-time web interface providing live tracking via wireless communication with any mobile device.

Finalized Simulation and Experimental Methods.

Movement Detection and Signal Processing. The signal processing pipeline utilizes three key techniques: Direction Cosine Matrix (DCM), Zero Velocity Update (ZUPT), and Kalman Filter (KF).
-**DCM**: Converts sensor data from body frame (BF) to navigation frame (NF), enabling orientation estimation.
-**ZUPT**: Detects foot-ground contact using a Force Sensing Resistor (FSR) for drift correction.
-**Kalman Filter**: Fuses data from accelerometers and gyroscopes with bias estimation to minimize cumulative errors.

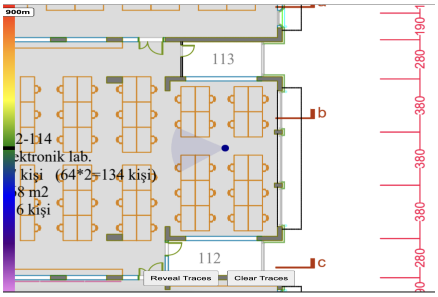
PCB Design Overview. The hardware features two PCBs, designed to reduce costs and optimize space. Each includes an ESP32-S3-WROOM-1U, ISM330-DHCXTR IMU, BMP390 barometer, HX711 load sensor amplifier, Type-C port for programming and charging, BMM350 magnetometer, and BQ24092 LiPo charging circuit. The foot-mounted PCB uses the load sensor and HX711 for ZUPT, detecting foot stillness—crucial for bias correction and error reduction. Wireless charging is supported via a pad connected to the Type-C port. Both PCBs use 4-layer Altium Designer layouts focused on minimizing noise and ensuring power stability. Fabricated and mounted PCB images are shown in Fig. 2a. RGB LEDs and a buzzer assist in bias estimation and temperature-based recalibration, notifying the user when completed. Enclosures were 3D-printed using SOLIDWORKS as shown in Fig.2b.

Real-Time Web Interface. The chest-mounted ESP32-S3 module hosts a secure web interface built using HTML/CSS/JavaScript. For this feature, the user does not need a WiFi access, the ESP32 is run in access-point mode and the user can directly connect to ESP32's WiFi. The key features of the web server can be indicated as real-time tracking of user location and orientation, historical path visualization with a color gradient, and altitude estimation using BMP390 barometric sensor. The ESP-NOW protocol for foot-to-chest transmission and Wi-Fi for web interface access handles communication. The user interface of the web server can be seen in Fig. 2c.



(A) a) 2D footprint of the designed PCB on Altium b) 3D view of the design c) Mounted PCB after fabrication.

(B) 3D printed cases for the PCBs for mechanical safety of the PCBs.



(C) User interface of the web server designed for inertial navigation at EEE building.

FIGURE 2. Sample Figures for the Project

Tools and Equipment. Table 1 presents the main tools and equipment used in the development of this project.

TABLE 1. Tools and equipment used in the project.

Tool/Equipment	**Purpose**
MATLAB	Algorithm development and simulation
Altium Designer	PCB schematic and layout
PlatformIO (VSCode)	Embedded C++ development
ESP32-S3	Microcontroller units
6-axis IMU (ISM330DHCXTR)	Motion tracking
50kg Force Sensing Resistor (FSR)	ZUPT implementation
HX711	Load sensor amplifier
BMP390 Barometer	Altitude verification
BMM50 Magnetometer	Initial orientation detection
LESD5D5	ESD protection
LDL1117S33R	3.3V Low-dropout voltage regulation
LiPo Battery (1500mAh)	Wearable power supply

RESULTS AND PERFORMANCE EVALUATION

1. Simulation and Experimental Results

We designed multiple real-world scenarios to evaluate the performance of our inertial navigation system. Below is a summary of the test setups:

- **Straight Path Walking:** A 30-meter walk forward and backward along a hallway. Total distance is 60 meters, net displacement is zero.
- **Corner Turns:** A path including two 90-degree turns resulting in a net displacement in the *y*-direction only.
- **Stair Navigation:** Ascending one floor and returning, to test vertical displacement and barometer response.

TABLE 2. Ground truth vs. measured values for various motion scenarios with absolute and relative error.

Scenario	**Axis**	**Ground Truth (m)**	**Measured (m)**	**Error (m)**	**Error (%)**
30m Straight Walking	X	30.0	32.11	2.11	7.03
	Y	0.0	1.10	1.10	-
Forward & Backward Walk	X	0.0	0.0017	0.0017	-
	Y	0.0	8.01	8.01	-
Turning Two Corners	X	0.0	0.005	0.005	-
	Y	7.2	8.55	1.35	18.75
Walking Up the Stairs	Z	3.6	3.42	0.18	5.00
Stairs Up and Down	Z	0.0	0.09	0.09	-

The system was able to maintain an error rate within the acceptable bounds. Especially in linear and vertical displacements, the results were highly consistent, confirming the viability of our ZUPT and Kalman filtering methods.

2. Performance Evaluation

Our performance evaluation can be explained as follows.

- The 3D printed enclosures were successfully worn during testing (Fig. 2b). The hardware was stable and did not interfere with motion.

- Bias estimation was integrated into the Kalman filter. This was shown to reduce drift over time when stationary, meeting expectations.

- Wireless charging worked successfully with LiPo batteries, verified via current measurements.

- Battery life tests were conducted using 1500mAh and 2800mAh LiPo batteries that exceeded 6 hours of full-time usage.

- Estimation runtime stayed below 30ms per step, under the 100ms threshold.

- A sampling rate of 100Hz was maintained in simulations and hardware, demonstrating stable estimation and low error.

- The web server UI was successfully accessed via mobile, showing real-time tracking with a color-coded scale bar on a lab map (Fig. 2c).

- ESP32 modules communicated wirelessly over ESP-NOW.

- Temperature differences were alerted through RGB LEDs and a buzzer to stop the user for recalibration.

- Our implementation of ZUPT and state-augmented Kalman filtering for drift correction aligns with best practices discussed in prior work, validating our modeling and filter design choices.

CONCLUSIONS AND FUTURE DIRECTIONS

The study presented a fully wearable, pedestrian navigation system that combines a chest mounted and a foot mounted PCB. The direct zero velocity triggers and a Kalman based fusion framework, reducing indoor drift to below 20% over 400-500m. The ESP NOW and Wi-Fi 4 interface streams real time position, heading and altitude to any browser. Thus, these results satisfy every requirement and place the prototype ahead of available products.

Before the semester ends the team will initially solder both PCBs, migrate the bias adaptive Kalman filter from MATLAB to on device C++, and complete a 400m validation demonstrating $<20\%$ drift.

In future iterations of the system, using vision-based technologies such as LIDAR or monocular/stereo cameras presents a compelling opportunity to enhance navigation performance, particularly in environments with irregular terrain or complex geometries. These sensing modalities could be used to implement visual odometry, offering improved robustness and drift correction over extended distances. Beyond the mining use case, the project shows significant potential for adaptation to other GPS-denied scenarios, such as military operations and firefighting in enclosed structures. Hence, the project can evolve into a versatile tool for real-time positioning across a wide range of high-stakes environments.

REFERENCES

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BEHIND THE SCENES