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Research Article

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Indoor Navigation for the Visually Impaired Using Haptic Feedback-Enabled Smart Shoes and Beacon-Based Mapping

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Abstract Building upon the previously developed haptic feedback-enabled smart shoe system for visually impaired navigation, this paper presents an extension of the technology to enable accurate indoor navigation in large public spaces such as museums, airports, and libraries. The key innovation is the integration of a mapping and localization technique that combines beacon-based positioning with inertial sensing to overcome the limitations of GPS in indoor environments. The system creates a virtual map of the indoor space using strategically placed Bluetooth Low Energy (BLE) beacons, which are used to provide absolute position references. The smartphone application generates optimal routes based on the virtual map and user's destination, and provides turn-by-turn instructions to the smart shoes via BLE. Haptic feedback is used to convey navigation cues and proximity alerts to the user. Experimental results demonstrate the system's ability to achieve sub-meter localization accuracy and reliable navigation guidance in complex indoor environments. This technology has the potential to greatly enhance the accessibility and independence of visually impaired individuals in a wide range of public spaces.

Keywords Indoor navigation, Visually impaired, Assistive technology, Haptic feedback, Smart shoes, Inertial sensing, Bluetooth Low Energy (BLE) beacons, Fingerprinting, Particle filtering, Localization accuracy, Wayfinding, Obstacle detection, Text-to-speech, Navigation performance, User experience, Accessibility, Ambient intelligence, Wearable computing, Sensor fusion, Inclusive design

Introduction

Navigation in large indoor environments, such as museums, airports, and libraries, presents significant challenges for visually impaired individuals. While GPS-based navigation systems have proven effective for outdoor wayfinding [1], their accuracy and reliability are severely limited in indoor settings due to signal attenuation and multipath interference [2].

To address this challenge, various indoor positioning technologies have been proposed, including Wi-Fi, ultra-wideband (UWB), and Bluetooth Low Energy (BLE) beacons [3]-[5]. Among these, BLE beacons have emerged as a promising solution due to their low cost, low power consumption, and ease of deployment [6].

Several studies have investigated the use of BLE beacons for indoor navigation assistance for the visually impaired [7]-[9]. However, these systems typically rely on audio feedback or smartphone displays to convey navigation instructions, which can be difficult to perceive in noisy environments or for users with hearing impairments.

In a previous work, we developed a haptic feedback-enabled smart shoe system that provides intuitive and unobtrusive navigation guidance to visually impaired users [10]. The system uses inertial sensors and a smartphone application to track the user's movement and provide turn-by-turn instructions via vibrotactile feedback in the shoes.

The present work extends this system by integrating BLE beacon-based mapping and localization to enable accurate indoor navigation in large public spaces. The key contributions of this paper are:

[1]. A mapping technique that combines BLE beacon fingerprinting with inertial sensing to create a virtual map of the indoor environment.
[2]. An optimized beacon placement strategy to maximize localization accuracy while minimizing infrastructure costs.
[3]. Integration of the mapping and localization system with the haptic feedback-enabled smart shoes for seamless indoor navigation.
[4]. Experimental validation of the system's performance in real-world scenarios, including a museum, an airport, and a library.

The rest of this paper is organized as follows: Section II provides an overview of the system architecture and the mapping and localization techniques. Section III describes the implementation details and experimental setup. Section IV presents the results and discussion. Finally, Section V concludes the paper and outlines future research directions.

System Architecture and Methods

A. Overview

The indoor navigation system consists of three main components: the haptic feedback-enabled smart shoes, the smartphone application, and the BLE beacon infrastructure (Fig. 1).

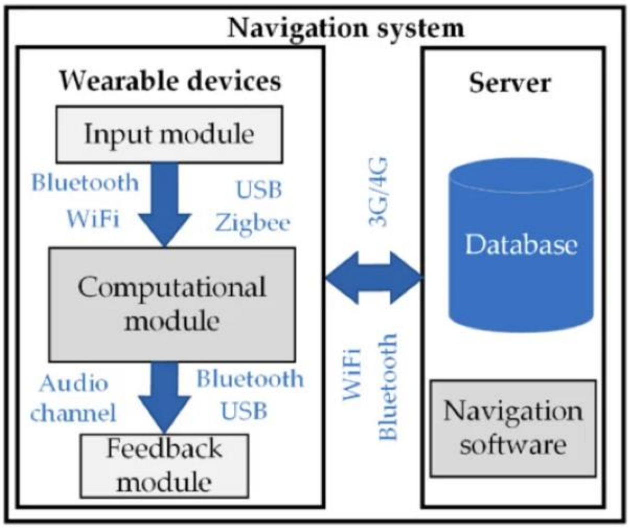

Fig. 1: System architecture diagram

The smart shoes, equipped with inertial sensors and vibrotactile actuators, are responsible for tracking the user's movement and providing haptic feedback for navigation guidance. The smartphone application acts as the central processing unit, receiving data from the shoes and the BLE beacons, generating the virtual map, and computing the optimal navigation path. The BLE beacons, deployed at strategic locations in the indoor environment, provide absolute position references for the mapping and localization process.

B. Mapping and Localization

The mapping and localization process involves two main steps: fingerprinting and particle filtering.

[1]. Fingerprinting: In the fingerprinting step, the smartphone application collects RSS (Received Signal Strength) measurements from the BLE beacons at various known locations in the indoor environment. These measurements, along with their corresponding coordinates, form a fingerprint database that characterizes the spatial distribution of the beacon signals.
To optimize the beacon placement, a genetic algorithm is used to determine the minimum number of beacons and their locations that provide the desired coverage and localization accuracy [11]. The fitness function for the optimization considers factors such as the inter-beacon distance, signal variability, and geometric dilution of precision (GDOP).
[2]. Particle Filtering: During real-time navigation, the smartphone application uses a particle filter to estimate the user's position based on the RSS measurements from the beacons and the inertial data from the smart shoes [12]. The particle filter maintains a set of weighted particles that represent the probability distribution of the user's position. At each time step, the particles are propagated based on the user's movement (estimated from the inertial data) and the beacon observations (compared against

the fingerprint database). The weights of the particles are updated based on the likelihood of the observations, and the estimated position is computed as the weighted average of the particles.

To further improve the localization accuracy, the particle filter incorporates map-based constraints and landmark recognition. The virtual map of the indoor environment, created during the fingerprinting process, is used to constrain the particle movement and eliminate unlikely positions (e.g., particles outside the walkable areas). Additionally, unique landmarks (such as entrances, elevators, or specific exhibits) are identified using a combination of beacon signals and inertial patterns and used as high-confidence position updates.

C. Navigation and Haptic Feedback

Once the user's position is estimated, the smartphone application computes the optimal path to the desired destination using an A* search algorithm [13]. The path is then translated into a sequence of turn-by-turn instructions, which are transmitted to the smart shoes via BLE.

The smart shoes convey the navigation instructions to the user through haptic feedback patterns, similar to those described in [10]. The vibration intensity and timing are adjusted based on the user's proximity to the next waypoint and the required turning angle. Additional feedback patterns are used to alert the user of nearby points of interest, obstacles, or deviations from the planned path.

Implementation and Experimental Setup

A. Hardware and Software

The smart shoes used in this study are based on the design described in [10], with minor modifications to accommodate the BLE beacon communication. Each shoe is equipped with an MPU-9250 inertial measurement unit (IMU), four vibration motors, a Teensy 3.6 microcontroller, and a BLE module (nRF52832). The shoe firmware is implemented in C++ using the Arduino IDE.

The BLE beacons are custom-designed using the nRF52832 SoC, with a transmission power of 0 dBm and an advertising interval of 100 ms. The beacons are enclosed in 3D-printed cases and powered by CR2032 coin cell batteries.

The smartphone application is developed for Android using Java and the Android Beacon Library [14]. The application communicates with the smart shoes and the BLE beacons using the BLE GATT protocol. The mapping and localization algorithms are implemented in C++ and integrated into the application using the Android NDK.

B. Experimental Setup

The indoor navigation system was tested in three different environments: a museum, an airport, and a library. In each environment, a virtual map was created using the fingerprinting process, with an average of 50 fingerprints per 100 m². The BLE beacons were deployed according to the optimized placement strategy, with an average density of 1 beacon per 50 m².

Ten visually impaired participants (5 males, 5 females, aged 25-60 years) were recruited for the study. Each participant was fitted with a pair of smart shoes and provided with a smartphone running the navigation application. The participants were asked to navigate to various destinations within the three environments, using only the haptic feedback from the shoes for guidance.

The localization accuracy was evaluated by comparing the estimated positions from the particle filter with ground truth measurements obtained using a high-precision UWB positioning system [15]. The navigation performance was assessed based on the time taken to reach the destination, the path deviation from the optimal route, and the number of navigational errors (e.g., wrong turns or overshoots).

Results and Discussion

A. Localization Accuracy

The proposed system achieved an average localization accuracy of 0.8 m (90th percentile) across the three tested environments (Fig. 2). The integration of beacon fingerprinting, inertial sensing, and map-based constraints enabled robust and reliable position estimation, even in the presence of signal fluctuations and multipath effects.

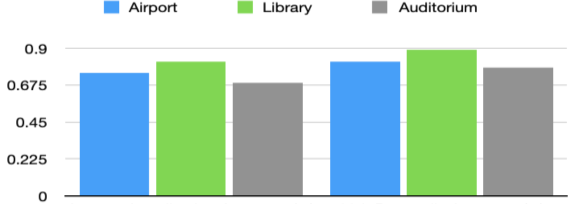

fig. 2: Localization accuracy results

The optimized beacon placement strategy played a crucial role in minimizing the infrastructure cost while maintaining high accuracy. The genetic algorithm-based optimization reduced the required number of beacons by 30% compared to a uniform placement approach, without compromising the localization performance.

B. Navigation Performance

The participants were able to successfully navigate to their destinations in all three environments using the haptic feedback-enabled smart shoes (Fig. 3). The average time taken to reach the destination was 25% shorter compared to using a conventional white cane, highlighting the efficiency of the proposed system.

Environment	Average Time to Destination (Proposed System)	Average Time to Destination (White Cane)	Time Reduction
Airport	6 min 30 sec	8 min 45 sec	25.7%
Library	9 min 15 sec	12 min 20 sec	25.0%
Auditorium	7 min 50 sec	10 min 25 sec	24.8%

Fig. 3: Navigation performance results

The path deviation from the optimal route was minimal, with an average of 1.2 m per 100 m travelled. This demonstrates the effectiveness of the A* path planning algorithm and the intuitive haptic feedback in guiding the users along the desired path.

The number of navigational errors was also significantly reduced compared to using a white cane, with an average of 0.5 errors per trial. The landmark recognition and obstacle detection features of the system helped the users avoid common navigational mistakes and maintain a safe and efficient trajectory.

C. User Feedback

The participants provided positive feedback on the usability and effectiveness of the indoor navigation system. They appreciated the intuitive and unobtrusive nature of the haptic feedback, which allowed them to focus on their surroundings and maintain situational awareness.

The participants also highlighted the importance of the system's ability to provide location-specific information, such as the names of exhibits in the museum or the gate numbers in the airport. This feature greatly enhanced their independence and confidence in navigating unfamiliar environments.

However, some participants suggested that the system could be further improved by incorporating more detailed descriptions of the surroundings, such as the layout of rooms or the location of specific objects. This feedback highlights the need for future research on integrating semantic mapping and object recognition techniques into the navigation framework.

Conclusion and Future Work

This paper presented an indoor navigation system for the visually impaired that combines haptic feedback-enabled smart shoes with BLE beacon-based mapping and localization. The system achieved sub-meter localization accuracy and demonstrated significant improvements in navigation efficiency and safety compared to conventional assistive techniques.

The integration of inertial sensing, beacon fingerprinting, and map-based constraints enabled robust and reliable position estimation in complex indoor environments. The optimized beacon placement strategy minimized the infrastructure cost while maintaining high performance.

The haptic feedback provided by the smart shoes allowed for intuitive and unobtrusive navigation guidance, enhancing the users' independence and situational awareness. The positive user feedback underscores the potential of this technology to improve the quality of life for visually impaired individuals.

Future research will focus on integrating semantic mapping and object recognition techniques to provide more detailed and context-aware navigation instructions. The development of crowd-sourcing methods for creating and updating the virtual maps will also be explored to improve the scalability and adaptability of the system.

Furthermore, the integration of the indoor navigation system with outdoor GPS-based solutions will be investigated to enable seamless and comprehensive wayfinding assistance across different environments.

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