Improving Indoor Localization Accuracy with BLE Fingerprinting and SLAM

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Abstract

Indoor localization is essential for robotics, asset tracking, and smart environments. This study develops a BLE fingerprinting system using ESP32-C6 anchors and a SLAM-enabled robotic platform. The robot mapped the lab while collecting BLE signals to create a fingerprint dataset, later used for heatmap generation and location estimation. Challenges include signal fluctuations, antenna orientation, and motion-induced errors. Despite these, the system proves BLE-based localization is feasible, scalable, and efficient for indoor positioning.

Introduction

Why Indoor Localization?

- GPS signals are unreliable indoors.
- Essential for navigation, asset tracking, and location-based services such older people indoor monitoring [1].

Why Bluetooth Low Energy (BLE)?

- Low power consumption.
- Cost-effective and widely available in consumer devices.
- Compatible with existing infrastructure (smartphones, IoT devices).

How BLE-Based Localization Works?

- Received Signal Strength Indicator (RSSI): Estimates distance based on signal attenuation.
- Fingerprinting: Pre-maps signal strengths in an environment for positioning.
- Proximity-Based Methods: Uses the nearest BLE beacon to determine location.
- Trilateration: Calculates position based on signal strength from multiple beacons.
- Angle of Arrival (AoA) & Time of Flight (ToF): Uses advanced hardware to measure the direction and time delay of signals. [2]

Pros & Cons of BLE Fingerprinting?

Pros:

- Higher Accuracy.
- Less Affected by Obstacles.
- Does Not Require Specialized Hardware.

Cons:

- Time-Consuming Setup.
- Sensitive to Environmental Changes.
- Deployment Complexity.

References

[1] H. Nguyen *et al.*, "Human-centered explainable psychiatric disorder diagnosis system using wearable ecg monitors," in *(PAKDD 2025)*.

[2] Hayward *et al.*, "A survey of indoor location technologies, techniques and applications in industry," *Internet of Things*, vol. 20, p. 100608, 2022.

[3] Azghadi *et al.*, "An adaptive indoor localization approach using wifi rssi fingerprinting with slam-enabled robotic platform and deep neural networks," in *2024 34th International Conference on Collaborative Advances in Software and COmputiNg (CASCON)*, pp. 1–10, IEEE, 2024.

Method

Figure 1 provides an abstract overview of the steps and components of our work that have been implemented.

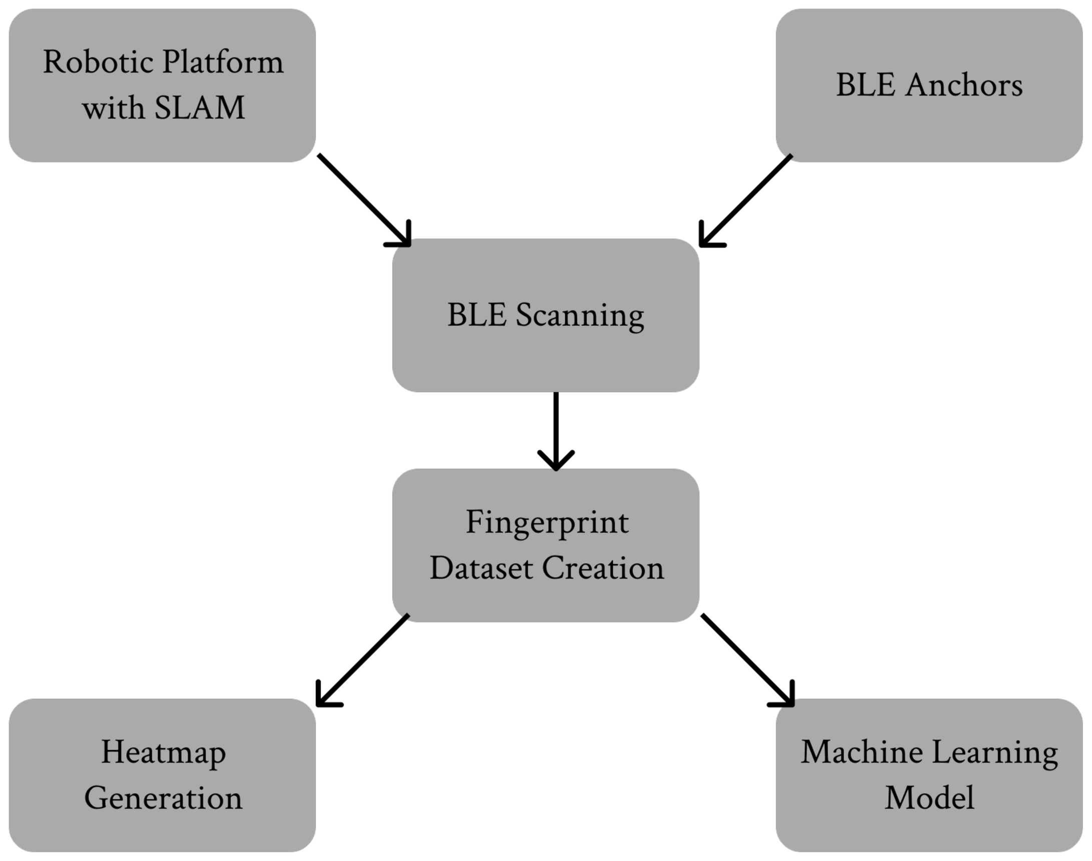


Figure 1. BLE Fingerprinting Localization system Overview

We designed the system architecture based on our previous experiment in paper [3], which utilizes a Wi-Fi module for indoor localization.

Mapping the Environment with SLAM

- The robotic platform autonomously navigated the lab while running a SLAM algorithm.
- The SLAM system generated a 2D spatial map of the environment, continuously tracking the robot's exact location.

Collecting BLE Fingerprints

- As the robot moved, it simultaneously performed BLE scans, detecting signals from the ESP32-C6 anchors.
- Each scan was synchronized with the robot's current position, associating signal strength (RSSI) with precise spatial coordinates with the help of Dynamic Time Warping (DTW).
- This process resulted in a dense fingerprinting dataset containing BLE signal measurements mapped to known locations.

Data Processing & Heatmap Generation

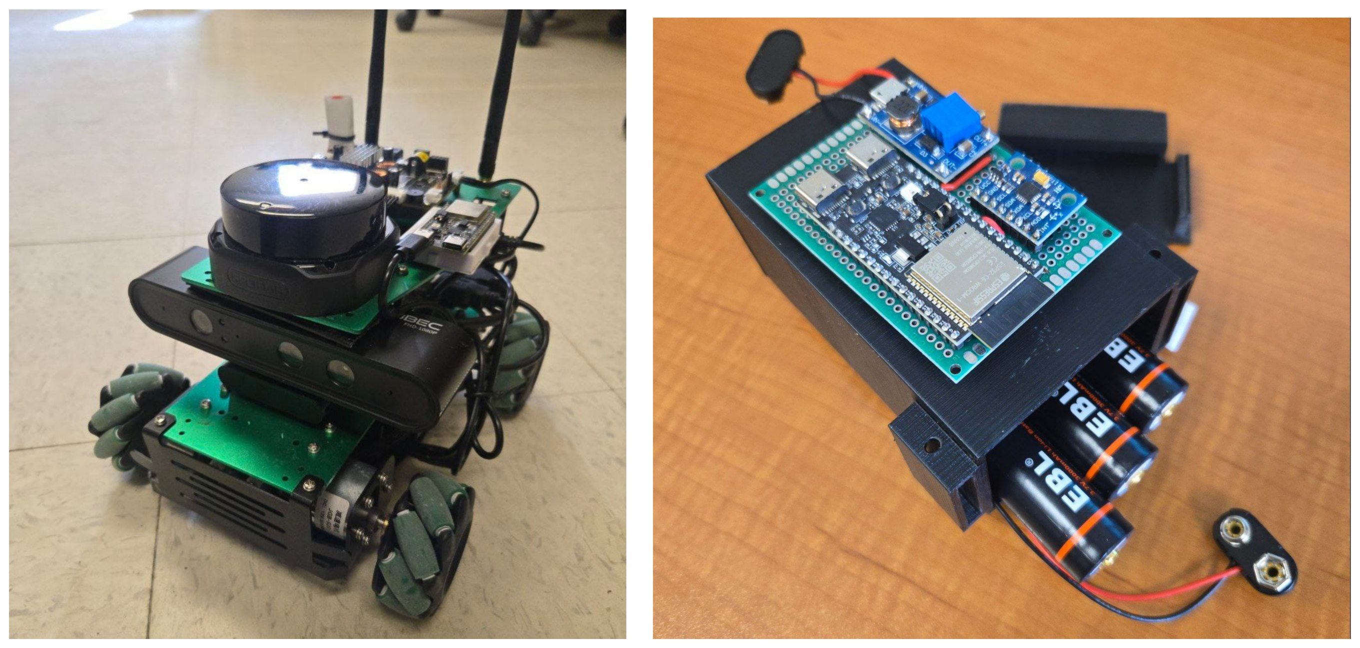
- The collected data was used to plot heatmaps of RSSI values for each anchor.
- These heatmaps visually represented the signal distribution across the lab space, highlighting variations in BLE coverage.

Machine Learning-Based Localization

- The fingerprint dataset was used to train a predictive model capable of estimating a device's location based on real-time BLE scans.
- The model learned spatial signal patterns and was validated to ensure accurate positioning within the lab environment.

Result and Evaluation

We trained a neural network with collected data and achieved a localization error of 0.6 meters. Compared to the traditional methods of collecting BLE samples, our approach can collect more data in a shorter time, resulting in a more accurate localization. In Figure 2 we provided our robotic platform and anchor prototype images. Also, Figure 3 demonstrates the signal strength heatmap of one anchor in our lab and the location icon shows the anchor location on the spatial map.



(a) Robotic Platform (b) BLE Anchor

Figure 2. Our anchor and robotic platform developed to build BLE localization system

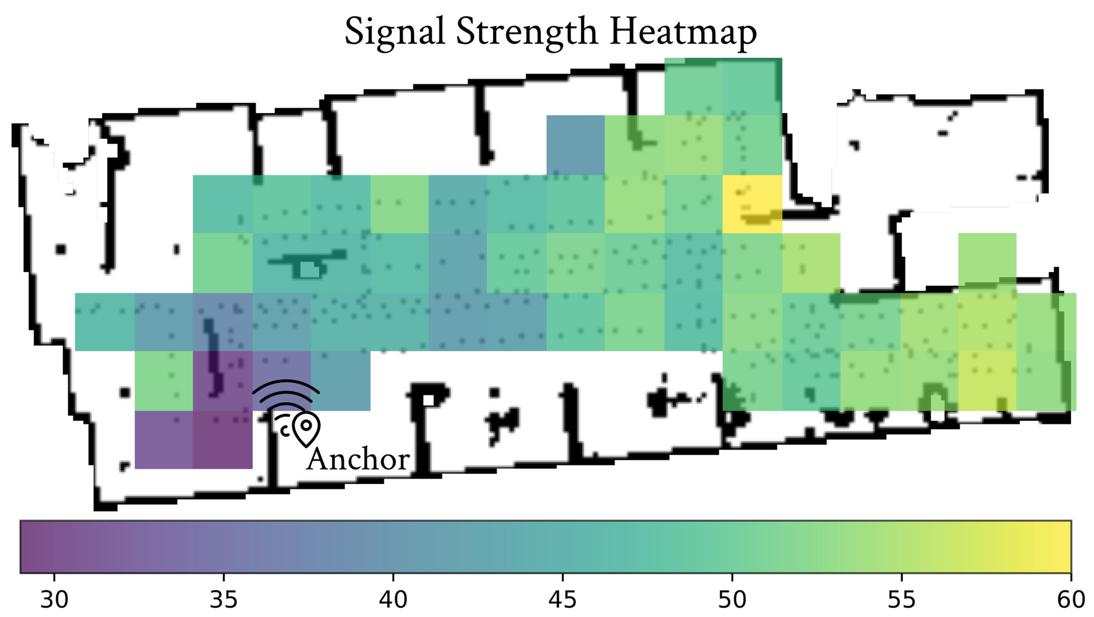


Figure 3. Overlapping the signal strength from one anchor with the sample collection location on the 2d generated map with lidar and SLAM

Conclusion and Future works

This research focuses on improving indoor localization accuracy using fingerprinting-based methods with BLE. So far, we have successfully developed and tested a basic fingerprinting data collection system. To improve the accuracy and robustness of the indoor localization system, future work will focus on the following key areas:

- Multi-Receiver Device Integration for Noise Reduction
- Incorporating ESP32 Antenna Pattern into Localization Calculation
- Reducing Data Collection Errors Due to Robot Speed and ESP32 Scanning Delay

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