

Enhancing Signal-Based Positioning Systems with Augmented Reality in Controlled Environments

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Abstract— This paper presents an Augmented Reality (AR)-enhanced approach to improving the accuracy and efficiency of signal-based indoor positioning systems, particularly in controlled environments such as laboratories, cleanrooms, and data centers. Traditional positioning systems face challenges related to manual fingerprint database creation, accuracy, and environmental variability. The proposed system automates the database creation process using AR for real-time distance measurement and visual reference capture, significantly reducing manual effort and errors. In the positioning phase, the system combines signal strength data with AR-based distance validation and visual reference comparisons to improve location accuracy. The integration of AR enhances the system's ability to provide more reliable positioning results in environments where conditions, such as lighting and surface textures, are stable. This paper outlines the architecture and key components of the system while future work will focus on empirical validation and optimization of the system for real-world applications.

Keywords—Augmented Reality, Fingerprint, Signal, Positioning System, Database

I. INTRODUCTION

Indoor positioning systems have become essential for a wide range of applications, from navigation in large facilities to tracking equipment in complex environments [1]. However, while Global Navigation Satellite System (GNSS) are highly effective for outdoor positioning, their signals do not perform reliably indoors due to interference from walls and other obstacles. This has led to the development of alternative methods for indoor positioning, many of which rely on signal strength measurements from Wi-Fi access points, Bluetooth beacons, or Ultra-Wideband (UWB) systems [2]. Among these methods, fingerprinting—where a database of signal strength measurements at known locations is created—has gained popularity due to its relative simplicity and low infrastructure requirements.

Despite its widespread use, fingerprint-based indoor positioning systems have several inherent limitations [3]. The process of creating a fingerprint database is traditionally labor-intensive and prone to errors. Signal strength measurements must be manually collected at multiple reference points throughout the environment, with each point requiring precise distance measurements and signal

assignments. These measurements are subject to human error, and the data collection process is time-consuming, especially in large or complex environments. Additionally, traditional systems rely solely on signal strength, which can fluctuate due to environmental changes, leading to decreased accuracy over time.

To address these challenges, this paper introduces an Augmented Reality (AR)-enhanced indoor positioning system designed to automate the fingerprint database creation process and improve positioning accuracy. AR technology, which allows digital information to be overlaid on the physical environment, offers significant potential to streamline and enhance indoor positioning. By leveraging AR's ability to measure distances in real-time and capture visual references of the environment, our system significantly reduces the manual effort required to build a fingerprint database while increasing its efficiency and reliability. Moreover, AR is also used to improve the accuracy of positioning estimates during the location determination phase. By combining signal strength data with AR-based distance validation and visual reference matching, the system can more accurately estimate the user's location, especially in controlled environments where conditions such as lighting and surface textures are consistent. These controlled environments, such as laboratories, cleanrooms, and data centers, are ideal settings for the deployment of this system because they provide stable conditions that support the optimal performance of AR technology [4].

This paper outlines the design of the AR-enhanced positioning system, focusing on its architecture, the process of automating fingerprint database creation, and the improvements made to the positioning phase through AR integration. While specific algorithmic details are beyond the scope of this work, the paper provides a conceptual and technical overview that highlights the potential of AR to transform indoor positioning in environments that demand high precision. Additionally, we discuss the limitations of the system, including its dependency on stable environmental conditions and its relatively high battery consumption due to continuous AR processing. Future work will focus on empirical validation and real-world testing to further demonstrate the system's performance and address potential

challenges. The ultimate goal is to refine the system for broader deployment across various dynamic indoor.

II. BACKGROUND

This section provides an overview of signal-based positioning techniques, challenges in fingerprinting, and the integration of AR in positioning systems.

A. Signal-Based Positioning Systems

Fingerprinting, which relies on creating a database of signal strengths at various reference points, is one of the most widely used approaches for indoor positioning [5]. The positioning process involves matching real-time signal measurements with those stored in the fingerprint database to estimate a user's location. The primary advantage of this method is its ability to function using existing infrastructure (e.g., Wi-Fi or Bluetooth), making it relatively easy to deploy in many environments. However, fingerprinting presents several challenges as follows.

1) Labor-Intensive Database Creation: Creating a fingerprint database requires physically moving through the environment and measuring signal strengths at each reference point. This process is labor-intensive, prone to human error, and time-consuming, especially in large or complex environments.

2) Environmental Sensitivity: Signal strength can fluctuate due to changes in the environment (e.g., moving objects, interference from other devices), which can lead to inconsistencies between the recorded fingerprints and the real-time data, reducing the system's accuracy.

3) Device Dependency: Variability in hardware between different devices (e.g., different smartphones or laptops) can lead to discrepancies in signal strength measurements, further complicating fingerprint matching.

To address these challenges, various enhancements to the fingerprinting approach have been proposed. Some studies have explored the use of crowdsourcing to gather fingerprint data more efficiently [6], while others have investigated the application of machine learning algorithms to improve the robustness of fingerprint matching [7]. However, these methods still rely on the fundamental process of manual data collection, which remains a significant bottleneck.

B. AR in Positioning Systems

The integration of AR into indoor positioning systems is a relatively new area of research. AR provides the ability to overlay digital information onto the physical environment, offering new ways to enhance the positioning process. AR-based systems use visual data from cameras and sensors to track a user's movement and location within a space, often in combination with other methods such as signal-based positioning or PDR (Pedestrian Dead Reckoning) [8]. AR has primarily been explored in two areas within the context of positioning.

1) Visual Guidance: AR can provide real-time visual navigation aids, such as arrows or markers, to guide users through indoor environments [9]. While this improves the user experience, it does not directly address the limitations of fingerprint database creation or positioning accuracy.

2) Improving Accuracy: AR's ability to capture visual information in real-time has been used to augment traditional positioning methods [10]. For example, visual data can be used to validate or correct position estimates from signal strength measurements or PDR, leading to more accurate results.

Despite these advancements, AR has not been widely adopted for automating the fingerprint database creation process. The potential for AR to automate distance measurement, capture visual references, and improve the accuracy of signal-based positioning systems remains underexplored.

III. AR-BASED FINGERPRINT DATABASE CREATION

Creating an accurate fingerprint database is a key step in signal-based indoor positioning systems, as it forms the foundation for comparing real-time signal measurements to known reference points. To address the challenges of traditional methods, our system leverages AR technology to automate the fingerprint database creation process, resulting in faster, more accurate, and less labor-intensive data collection.

A. Automated Distance Measurement

The AR system continuously tracks the user's movement within the environment, calculating the distance between reference points in real time. This eliminates the need for manual tools and measurements, reducing potential errors and ensuring that each signal measurement is precisely mapped to its correct location. The AR camera captures spatial data, enabling seamless and accurate distance logging throughout the environment.

B. Signal Measurement Assignment

While tracking the user's location, the system automatically collects signal strength data from wireless sources such as Wi-Fi access points and Bluetooth beacons. These measurements are then assigned to the corresponding coordinates based on the real-time tracking from the AR system. This automation guarantees that signal strength data is consistently and accurately linked to the correct location, significantly improving database reliability.

C. Visual Reference Capture

In addition to signal strength and location data, the system captures visual references at each reference point. These images are stored in the fingerprint database alongside the signal strength data and coordinates. During the positioning phase, these visual references can be used to verify and refine location estimates by comparing the real-time camera view with the stored images, adding another layer of accuracy to the system.

IV. AR-BASED POSITIONING ENHANCEMENT

In the positioning phase, our system incorporates AR technology to enhance both accuracy and robustness by leveraging spatial and visual information in addition to signal strength data.

A. AR-Based Distance Calculation

During the positioning phase, the AR system continuously tracks the user's movement and calculates the distances between the user's current location and nearby reference points stored in the fingerprint database. This AR-based distance calculation is achieved using the device's camera and IMU (Inertial Measurement Unit) sensors, which provide real-time updates on the user's position relative to the environment. By comparing these real-time distances with the distances stored in the fingerprint database, the system can more accurately determine the user's proximity to specific reference points. This additional layer of distance validation helps to refine the location estimate, particularly in environments where signal strength alone may be ambiguous.

B. Visual Reference Verification

In addition to signal strength and distance calculations, the AR-enhanced system utilizes visual reference images captured during the fingerprint database creation phase. As the user moves through the environment, the system compares the current camera view with the stored reference images to verify the estimated location. The visual comparison is performed using image processing techniques such as feature matching or template matching. This verification step helps to ensure that the estimated location is not only consistent with the signal data but also matches the physical appearance of the environment. This is particularly useful in distinguishing between similar signal profiles in different areas, which might otherwise lead to incorrect location estimates.

C. Multi-Dimensional Fingerprint Matching

The system combines three key elements—signal strength similarity, AR-based distance validation, and visual reference matching—into a multi-dimensional fingerprint matching process that enhances positioning accuracy. Signal strength measurements are compared against the fingerprint database, while AR tracks the real-time distance between the user and nearby reference points, adding a layer of spatial validation. Simultaneously, the AR system uses visual reference images to verify the user's location by matching the current camera view with stored visual data. By integrating these three sources of information, the system ensures greater robustness and precision, as inconsistencies in signal strength are cross-checked against spatial distances and visual context, resulting in more reliable positioning even in challenging indoor environments.

V. IMPLEMENTATION

The AR-enhanced positioning system is built on an Android platform utilizing ARCore [11], Google's platform for building augmented reality experiences. ARCore enables

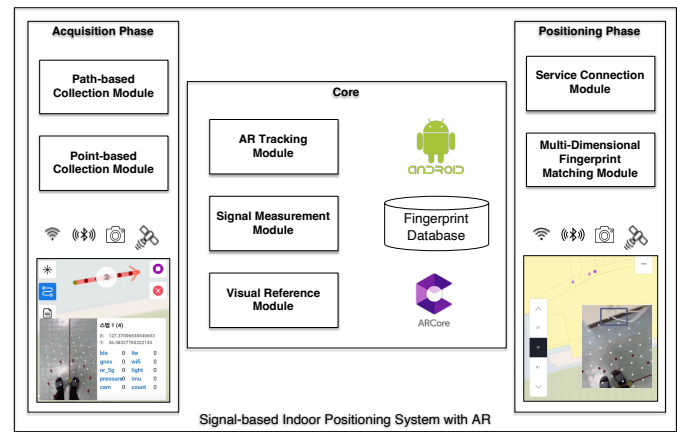


Figure 1. AR-enhanced Positioning System Architecture

key features such as motion tracking, environmental understanding, and light estimation, which are essential for accurate fingerprint database creation and positioning. The architecture of the system is designed to seamlessly integrate ARCore with signal strength measurements and visual reference data to provide real-time tracking, data collection, and positioning.

Figure 1 illustrates the architecture of the AR-enhanced positioning system, highlighting the major components involved in both the fingerprint database creation and the positioning phases. The AR Tracking Module, powered by ARCore, uses the device's camera and sensors to continuously track the user's movement and calculate distances in real time. This spatial data is essential for both the fingerprint database creation and positioning phases, as it allows the system to automatically measure distances between reference points and log user movement without manual input. In conjunction with the AR tracking, the Signal Measurement Module collects signal strength data from wireless sources such as Wi-Fi access points and Bluetooth beacons. The system automatically associates these signal measurements with the corresponding spatial data from the AR module. This ensures that signal data is consistently and accurately mapped to the correct location, eliminating errors introduced by manual data collection. The Visual Reference Module enhances the system's positioning accuracy by capturing visual references during the database creation phase. These images are stored in the fingerprint database alongside signal strength data and spatial coordinates. During the positioning phase, the system uses ARCore to compare the real-time camera view with the stored visual references, further refining the location estimate by providing visual verification.

The system supports two data collection approaches for the creation of the fingerprint database: path-based collection and point-based collection. In the path-based collection approach, the user defines a start and end point along a predefined path. ARCore calculates intermediate points based on a preset distance, and the system prompts the user to capture signal measurements and visual references at each point. This structured approach ensures thorough coverage in environments with predictable layouts, such as corridors or

large open spaces. For environments with less predictable layouts, the point-based collection approach offers greater flexibility by allowing users to move freely within the environment. The ARCore system continuously tracks the user's position and automatically collects signal strength and visual data at regular intervals, making it suitable for dynamic spaces without predefined paths. The collected data, including signal strength measurements, ARCore-calculated distances, and visual references, is stored in a centralized fingerprint database. This database is critical during the positioning phase, where real-time data is compared with stored fingerprints to provide highly accurate location estimates. The integration of ARCore into both the database creation and positioning phases ensures that the system can maintain high accuracy, even in environments where signal strength is variable.

VI. CONCLUSIONS

This paper presented an AR-enhanced indoor positioning system that improves the accuracy and efficiency of signal-based positioning by automating the fingerprint database creation process. The integration of real-time distance validation and visual reference matching during the positioning phase provides enhanced precision, especially in controlled environments like laboratories and cleanrooms. While the system shows promising improvements, it has limitations, such as dependency on stable environmental conditions and battery consumption from continuous AR tracking. Future work will focus on empirical validation in real-world scenarios and optimizing the system for broader application, including dynamic environments and improved energy efficiency.

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