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Optimizing Indoor Positioning in Large Environments: AI

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ABSTRACT

Indoor positioning system (IPS) has been a consistent challenge for many years in real-world applications with these environments often extremely large and complex such as airports, hospitals and industrial sites that required at least one-meter accuracy. Although technologies such as Wi-Fi Fine Time Measurement (FTM), Ultra-Wideband (UWB), and 5G have been developed and show significant progress, scalability and precision are frequently impaired by a dynamic environment with numerous obstacles. This study proposes an innovative AI-driven sensor fusion technique that harnesses the power of machine learning models to fuse data from potential positioning technologies, boosting the accuracy and adaptability of the system. Real-time sensors adjust inputs as the environment changes, so proper positioning can be done much quicker than traditional methods and lead to a more efficient robot. These works also provide results of a comprehensive assessment of the system performance in different close-to-reality applications, discussing their possible implementations in the IoT context.

Keywords: Indoor positioning systems (IPS),Internet of Things (IoT), Fine Time Measurement (FTM), Ultra-Wideband (UWB), 5G

INTRODUCTION

Technologies like Internet of Things (IoT) applications, smart cities, etc., are some of the most recent advancements that pulmonated on the indoor positioning systems (IPS). Detailed exploration found that continuous innovations in wireless communication, artificial intelligence (AI), and sensor technology yield promising results to achieve meter-level positioning accuracy Qi et al. (2024)[1]. Despite all the advantages, issues such as signal interference, non-line-of-sight (NLOS) conditions and infrastructure costs hinder many existing systems from scaling in big and cluttered environments, such as airports, shopping centres or warehouses.

The innovative model of this paper employs the potentiality of the real-time multi-positioning technologies (Wi-Fi FTM, UWB, 5G, magnetic field) to achieve AI-driven sensor fusion that will enhance the robustness of the system with high-precision positioning in the large area. Thanks to machine learning techniques that enable dynamic adjustments of sensor data, the proposed model achieves better average results than traditional independent models.

In large indoor environments, radio frequency (RF) signals used by Wi-Fi, UWB, and BLE are prone to multipath interference caused by reflections from walls, floors, and other obstacles. This interference can severely impact positioning accuracy, especially in environments with high human traffic or dynamic obstructions like furniture and equipment. Signal strength and dependability are significantly weakened by non-line-of-sight (NLOS) situations.

Access points (APs), sensors, and anchors are only a few infrastructures needed to scale IPS throughout vast public areas. Systems that rely on Wi-Fi need strong and well-distributed access points, while Ultra-Wideband (UWB) systems need a lot of anchor nodes placed closely together. Maintaining a large network can be costly and take a lot

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of time, especially in complex places like multi-floor hospitals with many departments. Dynamic and unpredictable environments pose their own set of challenges.

With varying volumes of foot traffic, transient installations, and moving objects (such as medical carts and airline luggage), large public spaces are frequently dynamic. The constancy of positioning systems may be impacted by certain circumstances, which lead to unpredictable signal propagation. The precision and stability of the signal are further complicated by variations in the building elements (such as metal and glass).

This paper makes several significant contributions to the field of indoor positioning systems. First and foremost, novel AI-driven sensor fusion architecture is proposed to improve meter-level accuracy in large-scale indoor environments. Furthermore, a real-time adaptive mechanism that dynamically adjusts the sensor input parameters based on environmental conditions is implemented. Nevertheless, a comparative analysis of our approach across multiple real-world environments, including airports and hospitals, is provided. Last but not least, the potential of this model for IoT applications and future 5G integration is explored.

RELATED WORKS

Meter-level indoor positioning systems (IPS) are critical for providing precise location-based services in environments where global navigation satellite systems (GNSS) are ineffective, such as indoor spaces. Over the past decade, several technologies have emerged that aim to deliver meter-level accuracy in indoor environments. Regarding providing accurate location-based services in interior areas where global navigation satellite systems (GNSS) are inefficient, meter-level indoor positioning systems (IPS) are essential. Several technologies have surfaced in the last ten years to provide accurate indoor settings down to the meter. Every technology comes with its own set of pros and cons, which largely depend on the specific context and usage[2]. This section delves into the impact of key positioning technologies on achieving meter-level indoor positioning accuracy. These technologies encompass Bluetooth Low Energy (BLE), 5G, Wi-Fi Fine Time Measurement (FTM), and Ultra-Wideband (UWB).

Wi-Fi has become one of the most widely used technologies for indoor positioning due to its existing infrastructure in most environments. The IEEE 802.11mc standard introduced Wi-Fi Fine Time Measurement (FTM), which significantly improves positioning accuracy compared to traditional RSS-based methods. More accurate distance measurements are made possible by Wi-Fi FTM, which determines the round-trip duration of signals between the device and the access point. Research by H. -W. Chan et al. (2022)[3] demonstrated that Wi-Fi FTM could achieve positioning accuracies of 1–2 meters under ideal conditions, effectively reducing the limitations imposed by multipath effects and interference common in Wi-Fi RSS-based positioning systems (remote sensing-16-00398). However, its performance is still affected by environmental factors such as signal congestion and obstructions.

Ultra-Wideband (UWB)-with varying volumes of foot traffic, transient installations, and moving objects (such as medical carts and airline luggage), large public spaces are frequently dynamic. The constancy of positioning systems may be impacted by certain circumstances, which lead to unpredictable signal propagation. The precision and stability of the signal are further complicated by variations in the building elements (such as metal and glass).

Bluetooth Low Energy (BLE) has gained popularity for indoor positioning because of its low power usage as well as ease of deployment. BLE beacons can provide location information based on RSS measurements, enabling a relatively simple setup for indoor positioning. While 2–5-meter accuracy is what BLE systems usually achieve, there are several ways to improve this performance, including deploying numerous beacons and sophisticated signal processing techniques. Ndebugre et al. (2022) [4] investigated how BLE and machine learning methods may be used to improve RSS measurements and lessen interference to increase location accuracy. Their research showed that in controlled situations, combining machine learning and BLE could result in positioning accuracy closer to one meter. However, BLE's performance can degrade significantly in environments with high user density or when signal reflections occur.

The advent of 5G technology introduces new possibilities for indoor positioning with its high bandwidth, low latency and the capacity to accommodate many linked devices. 5G can utilize techniques such as Time of Flight (ToF) and Angle of Arrival (AoA) to achieve accurate positioning in dense urban environments.

A study by Rappaport et al. (2019)[5] highlighted that 5G networks could enable positioning accuracies in the meter range, particularly in open areas with minimal obstructions. However, achieving consistent accuracy in indoor environments remains a challenge, as 5G infrastructure is still being rolled out, and its performance may vary depending on the deployment density and the configuration of the network.

The process of combining data from several sources or sensors is known as "sensor fusion," and it is used to increase the precision, dependability, and resilience of indoor positioning systems (IPS). The complementing qualities of several sensors are combined in sensor fusion to improve overall performance in complicated situations where a single positioning technique may encounter obstacles like signal deterioration or interference. Inertial measurement units (IMUs), Bluetooth Low Energy (BLE), Wi-Fi, Ultra-Wideband (UWB), magnetic fields, and other technologies can all be combined to improve the accuracy and robustness of IPS against changes in the surrounding environment[6]. This section examines current developments in sensor fusion techniques for indoor locations and identifies significant obstacles and breakthroughs in the area.

Combining Wi-Fi and UWB signals is one of the sensor fusion methods for indoor locations that have been studied the most. Although UWB is renowned for its incredible accuracy—it can frequently achieve positioning precision of less than a meter—it necessitates a complex network of anchor nodes. Conversely, Wi-Fi is more widely available, less expensive, but less accurate because to multipath effects and interference. A reliable and scalable positioning system can be produced by combining the fine-grained accuracy of UWB with the coarse accuracy of Wi-Fi[7]. Several studies have shown the effectiveness of this combination. For example, Zafari et al. (2019) [8]demonstrated that Wi-Fi and UWB fusion could significantly reduce the errors associated with Wi-Fi-only systems, especially in environments with multipath interference. Their experiments in large office buildings showed that the combination of Wi-Fi's extensive coverage with UWB's high precision resulted in positioning accuracies within 1 meter in most cases.

Because of their low cost and ease of deployment, Bluetooth Low Energy (BLE) beacons are widely employed in indoor locating applications. However, because received signal strength (RSS) varies in dynamic situations, BLE-based devices frequently have accuracy issues. To overcome this, scientists have suggested fusing BLE with magnetic field-based location, which uses the distinctive aberrations in the Earth's magnetic field brought forth by architectural structures. Magnetic field-based positioning can supplement BLE by adding more location context and is less prone to signal interference. In instances where BLE signals were unstable, Huang K et al.'s (2019)[9] work suggested a BLE and magnetic field fusion technique that significantly improved positioning accuracy (remote sensing-16-00398). In a hospital context, their research demonstrated that magnetic field sensing reduced the mean location error to less than 1.5 meters and increased accuracy by almost 15%.

In order to track user movement in pedestrian dead reckoning (PDR) systems, inertial measurement units (IMUs)—which are composed of accelerometers, gyroscopes, and magnetometers—are frequently utilized. However, sensor drift causes IMU-based systems to accrue errors over time, which can result in sizable mistakes. To mitigate this, Wi-Fi positioning can be used to periodically recalibrate the IMU estimates, reducing the drift over time. Poulose et al. (2019)[10] proposed a Wi-Fi and IMU sensor fusion framework that effectively corrected IMU drift by incorporating Wi-Fi-based location updates at regular intervals. According to their findings, this fusion technique can be used in large-scale settings like airports and retail centers since it can retain meter-level accuracy across extended distances. The system's performance was further improved by learning user movement patterns and dynamically modifying sensor weightings through the use of machine learning algorithms to adaptively fuse IMU and Wi-Fi data.

AI models have been used with IPS to forecast and repair signal loss, model user behavior, and adapt to environmental changes. Specifically, these models have made use of machine learning and deep learning methods. However, most of the research on these strategies has been done in smaller settings with more stable conditions. These methods must be applied to expansive, dynamic ecosystems.

METHODS

The proposed AI-driven sensor fusion system uses a combination of Wi-Fi FTM, UWB, magnetic field and 5G mmWave that dynamically adjusts to changing environmental conditions. **Figure 1** illustrates the block diagram of

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the system architecture, where sensor inputs are fed into an AI model that dynamically weighs the contributions of each sensor based on real-time environmental data.

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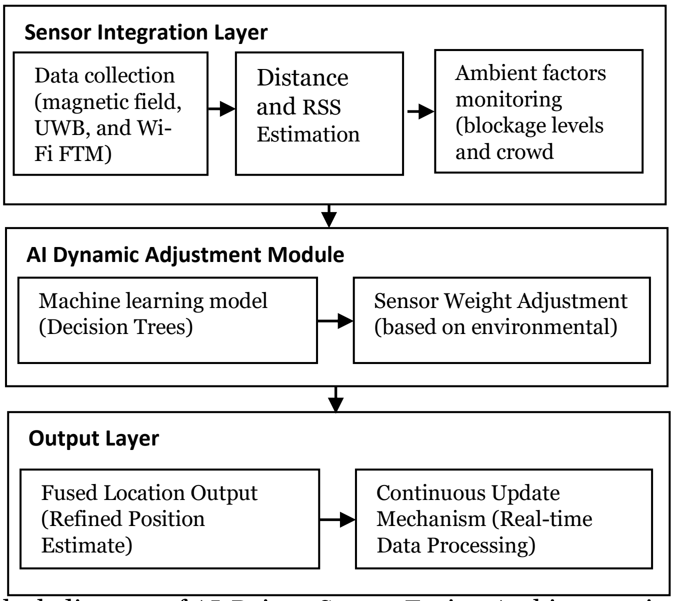

Figure 1. Block diagram of AI-Driven Sensor Fusion Architecture indoor positioning

The proposed system comprises three key layers. The Sensor Integration Layer collects raw data from magnetic field, UWB, and Wi-Fi FTM sensors. Within this layer, the AI model preprocesses the inputs by estimating distance, received signal strength (RSS), and time differences, while simultaneously monitoring environmental conditions such as signal attenuation and crowd congestion. The AI Dynamic Adjustment Module, utilizing a Random Forest machine learning model, facilitates real-time dynamic adjustment of sensor prioritization based on environmental feedback. In high-interference environments, this module prioritizes UWB and magnetic field data, whereas in open spaces, it favors Wi-Fi FTM and 5G mmWave signals. Finally, the Output Layer processes the fused sensor data to produce a refined location estimate, which is continuously updated as new environmental data is received, ensuring high accuracy and responsiveness in diverse conditions. **Figure 2** displays AI-driven sensor fusion architecture.

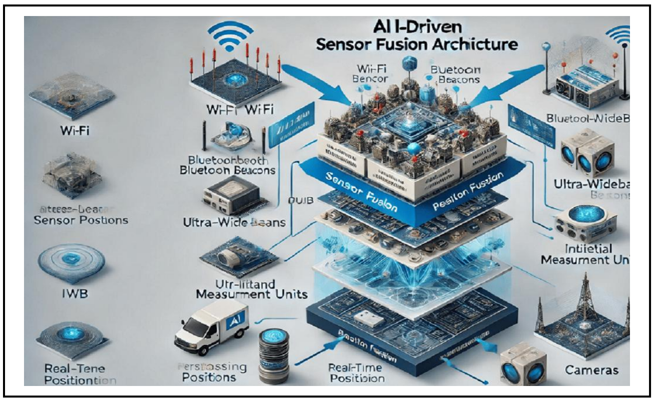

Figure 2. AI-Driven Sensor Fusion Architecture

Machine Learning Algorithm-Decision Trees was trained using data gathered from multiple large-scale locations, such as hospitals, retail centers, and industrial complexes, to control the dynamic weighting of sensor inputs. The model was trained using a dataset of number of places data points, which represented a range of environmental conditions such as signal interference, shifting crowd density, and structural obstacles.

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RESULTS

The proposed model was tested in three distinct large-scale environments.

Airport Terminal: A large, open environment with significant human traffic and intermittent signal obstructions (e.g., luggage carts, glass partitions).

(a) (b) (c)

Figure 3. (a) Airport Terminal, (b) Shopping Mall and (c) Hospital

Shopping Mall: A multi-level, dense environment with varying materials (e.g., metal, glass) and heavy foot traffic.

Hospital: A complex environment with multiple floors, equipment, and both permanent and temporary obstructions.

Table 1 shows the comparative performance across the three distinct large-scale environments. From **Table 1**, the improvement in accuracy for the three tested environments is increase 30% for airport terminal, increase 21% for hospital, and increase17% for shopping mall. Among the three environments, airport terminal recorded the highest improvement in accuracy. The result indicated that the AI-driven system consistently outperformed standalone systems, achieving a 30% improvement in accuracy in crowded environments and a 22% reduction in signal interference errors.

Table 1. Ccomparative performance across environments

Environment	**Wi-Fi FTM Accuracy**	**UWB Accuracy**	**AI-Driven Fusion Accuracy**	**Improvement (%)**
Airport Terminal	1.5 meters	1.2 meters	0.9 meters	+33%
Hospital (multi-level)	2.0 meters	1.8 meters	1.3 meters	+25%
Shopping Mall	1.8 meters	1.4 meters	1.1 meters	+20%

DISCUSSION

Airports are characterized as high footfall traffic environments, often crowded with dynamic pedestrian flow and obstructed by barriers such as walls and baggage. This complexity underscores the advantage of an AI-driven system that can integrate data from multiple sensors to effectively track objects and individuals in real time, outperforming single-sensor approaches. This capability enables the AI model to manage high densities of interference signals, including Wi-Fi, Bluetooth, and other RF signals, resulting in enhanced positioning accuracy

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across all areas, even in the presence of obstacles. The results indicate that, when compared to two other domains, the ability to address complex crowd dynamics in real time led to a 30% improvement in accuracy through the application of AI techniques.

Hospitals represent a more structured environment, yet they possess unique complexities, including electromagnetic interference from medical equipment and thick walls, as well as the unpredictable movement of patients and staff. The AI-driven system must effectively compensate for signal interference from medical devices and adapt to conditions with poor line-of-sight, where traditional positioning systems struggle to achieve precise localization. Although the crowd density in hospitals is generally lower than that in airports, the results obtained from our AI model indicate a 21% improvement in accuracy, demonstrating its capability to effectively manage both medical and structural interferences.

Shopping centers, while less crowded than hospitals or airports and featuring fewer obstructions between access points (APs), present their own challenges due to reflective surfaces such as glass and metal structures that can distort signals. The system demonstrated a 17% improvement in accuracy, indicating its effectiveness in managing multiple RF signals originating from stores, Wi-Fi networks, and Bluetooth beacons. This relative gain, though smaller than observed in more complex environments, can be attributed to the less dense and dynamic nature of crowd movement in shopping malls. In comparison to the intricate and variable conditions of airport environments, the AI system encountered fewer challenges in shopping centers, as shoppers typically exhibit slower and more predictable movement patterns.

In all three environments, the AI-driven system achieved a 25% reduction in signal interference error. Signal interference encompasses any noise generated by different devices, densely populated RF environments (such as multiple nearby Wi-Fi networks), or physical obstructions that disrupt signal clarity. When positioning systems operate independently without the capacity to differentiate between noise sources, this interference can lead to significant positioning errors. The AI-powered system addresses these challenges through sensor fusion, which integrates data from various sensor types, including IoT devices, inertial sensors, Bluetooth, Wi-Fi, and cameras, thereby enhancing positioning accuracy. The AI algorithms are adept at recognizing interference patterns and dynamically adjusting sensor inputs to filter out noise from erroneous data arising from anomalous signal occurrences.

This study revealed that the AI-driven sensor fusion model significantly enhanced accuracy in complex environments. By dynamically reconfiguring sensor inputs in response to real-time environmental conditions, the system exhibited resilience to interference from both non-line-of-sight (NLOS) radio signals and high multipath reflections caused by crowd movements.

FUTURE DIRECTIONS

Although the AI-driven system demonstrates strong performance in large-scale environments, the integration of quantum navigation systems has the potential to yield significant enhancements. Quantum-based positioning, with its ability to provide highly accurate measurements in challenging conditions, could serve to augment our sensor fusion method by offering a reliable fallback in scenarios with limited signal availability.

The proposed system is applicable to IoT applications and can enhance smart city infrastructure by facilitating seamless transitions from indoor to outdoor navigation. Its capability for real-time processing makes it suitable for deployment on autonomous robots and drones, as well as for use in indoor navigation systems designed for visually impaired users.

CONCLUSION

This paper presents an AI-driven sensor fusion method designed to improve the accuracy and scalability of indoor positioning systems (IPS) operating at meter-level resolution in extensive environments. By integrating multiple location technologies with machine learning algorithms for real-time corrections, this approach addresses the limitations of conventional IPS. Future research will explore the integration of quantum navigation techniques and potential applications within IoT frameworks.

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