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A REVIEW OF CURRENT TREND IN INDOOR PEDESTRIAN NAVIGATION

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Abstract— Indoor pedestrian navigation systems have become indispensable in modern times, facilitating efficient navigation through complex indoor environments such as malls and airports. Traditional GPS technology falls short in these settings due to signal blockage and reflections, leading to the emergence of indoor positioning systems (IPS). Leveraging technologies like Bluetooth beacons, Wi-Fi triangulation, and ultra-wideband signals, IPS provides precise real-time navigation within buildings. Augmented reality (AR) and virtual reality (VR) further enhance the indoor navigation experience, offering visual cues and pre-navigation simulations. Despite challenges such as precise mapping and signal interference, the adoption of indoor navigation technologies has increased, driven by the demand for better user experiences. This abstract explores the methods, technologies, and challenges associated with indoor pedestrian navigation, providing insights into current trends and future developments.

I. Introduction

Systems for positioning and navigation are among the most vital instruments that are utilized by all people in the modern world. Pedestrians often must orient themselves in new towns or places. Pedestrian navigation is particularly handy when pedestrians need guidance to reach their destination in these kinds of situations. Not only that, but pedestrian navigation has become an important topic for theoretical and practical research in several fields, including mapping, geographic information science, global and indoor location, spatial behaviour, psychology, sociology, and neuroscience. To put it simply, pedestrian navigation is the process of directing pedestrians between designated origins and destinations. The main target of pedestrian navigation is to deliver relevant assistance whenever and wherever it is needed, uniquely customized to the pedestrians or user's specific information needs and presented in their preferred formats.

GPS technology has long been used for outdoor navigation in urban contexts, but as we spend more time indoors, navigating through confined spaces like malls, airports, and office buildings becomes more difficult. This is because, in indoor navigation system, GPS cannot work properly as the materials of walls in building will block or reflect GPS signals, preventing them from entering the space making satellite signals cannot be effectively received, and the weak signal within the room makes it hard to determine one's location [1]. Thus, there is a need for an accurate indoor navigation system for better pedestrian navigation.

A combination of cutting-edge technologies, creative mapping techniques, and user-centered design has led to a notable advancement in indoor pedestrian navigation. Indoor positioning systems (IPS) are the backbone of real-time navigation apps because they precisely locate people within buildings using a variety of technologies, including Bluetooth beacons, Wi-Fi triangulation, UWB (Ultra-Wideband) signals, and magnetic positioning [2-3]. For instance, pedestrians or app users can improve their navigation experience by using augmented reality (AR) and virtual reality (VR) aspects in these apps. AR provides visual hints, while VR provides pre-navigation simulations. In fact, some companies have realized the benefits of these systems and have implemented them to enhance visitor experiences at airports, shopping centres, warehouses, and museums. Even with these advancements, issues including precise mapping, interference from signals, data security, and affordability still exist [1, 4]. The current trends influencing indoor pedestrian navigation are examined in depth in this article. This article explores the methods used in indoor navigation systems alongside their techniques and challenges.

Over the past ten years, there has been a noticeable increase in the adoption and utilization of several cutting-edge technologies for indoor navigation, including Bluetooth beacons, Wi-Fi triangulation, ultra-wideband (UWB), and magnetic positioning and many more. This trend has especially picked up steam from the middle of 2010s onward. Since then, there has been an especially quick uptake of these technologies due to several causes, including the growing popularity of location-based services, the growing cost of hardware, and the need for better user experiences in intricate interior spaces [5]. In the next years, we may anticipate even more cutting-edge and seamless indoor navigation systems as these technologies continue to develop and converge. The methods or technology that are now widely applied will be described in this section along with their usage or contributions in indoor pedestrian navigation field.

II. Methodology Review

A. Bluetooth Beacons

Around 2013 or so, Bluetooth beacons gained popularity as businesses started using them for indoor navigation and proximity marketing. But this method only allows for basic position and area estimation because Bluetooth signals are susceptible to interference from the outside world [6]. Bluetooth beacons are tiny, wireless gadgets that send signals via Bluetooth Low Energy (BLE) technology [7]. Nearby smartphones, tablets, and other compatible devices take up these signals. Beacons are frequently positioned in real places, such shops, airports, or museums, to launch location-based applications or send relevant material to users' devices. They function by transmitting distinct identifiers that applications running on compatible devices can identify, enabling location-aware interactions, proximity-based notifications, and personalized experiences [8].

Indoor pedestrian navigation with Bluetooth support is a potential solution to pedestrian navigation in small spaces, but it has several limitations. Placing Bluetooth beacons in strategic locations across indoor spaces makes it easier for smartphones or other Bluetooth-enabled devices to locate users. The key to this system's power is its real-time guidance capability, which it provides via specialized mobile applications. It does this by utilizing the signals these beacons broadcast to predict users' whereabouts [9].

However, several variables affect how effective Bluetooth-based navigation systems are. The quantity and placement of beacons can interfere with accurate location determination, making precise navigation difficult in some situations.

Furthermore, these systems' dependability may be impacted by signal interference from other wireless devices or physical impediments, which could occasionally result in inaccurate placement [10].

Despite these obstacles, Bluetooth-enabled indoor navigation systems have proven to be adaptable in a few industries. For example, by guiding customers to preferred stores or products, they expedite shopping experiences in the retail industry. These approaches can be used to help passengers locate gates or facilities at transportation hubs like airports and improve event attendees' experiences at events by helping them navigate big venues more effectively.

Although Bluetooth technology provides a practical way for pedestrians to navigate indoor spaces, these systems' dependability and precision can be affected by external circumstances. When further developed and improved, it has the potential to greatly enhance indoor navigation experiences, even in the face of occasional restrictions given its broad use in a variety of situations.

Table 1 describes a few examples of research papers/articles that make use of Bluetooth beacons in indoor navigations. The focus, technologies used, and their strengths and weakness are also described briefly.

These papers present various Bluetooth-based indoor pedestrian navigation strategies, each with benefits and drawbacks of their own. The optimal option is determined by the requirements and surroundings. For complex public buildings, [3] offers a thorough answer. But, if accuracy is the primary concern, [11] would be preferable. Meanwhile, for cost-effective and low-power applications, [12] offers a simpler option, but paper [11] or [13] might be better for higher accuracy or specific use cases.

B. Ultra-Wideband (UWB)

Over the past few years, indoor positioning systems have increased their use of ultra-wideband (UWB) technology.

From 2018 to 2020, major breakthroughs in standards and hardware have emerged, paving the way for UWB adoption across a wide range of industries. UWB technology may interfere with GPS and aircraft navigation radio equipment, as well as existing systems that operate in the ultra-wide spectrum, even though it offers many other benefits, such as high accuracy positioning, low power consumption, license-free operation, high level of multipath resolution, large bandwidth, and high data rate communication. UWB systems have become one of the most popular indoor positioning technologies compared to other technologies, and they are now utilized in a far wider range of applications [5].

Since UWB popularity has grown over the years, a lot of research discuss the usage of UWB in indoor navigation alongside its benefits and drawbacks. Table 2 shows six research publications, each with a different approach, addressing the application of UWB technology for indoor pedestrian navigation.

Based on the papers mentioned above, the application of UWB for precision and resilience will be hybrid systems that combine UWB with other technologies such as INS or PDR. Meanwhile UWB-based SLAM made deployment easier by allowing for on-the-fly mapping. Other than that, one of the review papers also offered insightful information on UWB's potential for clever logistics. The optimal option ultimately depends on specific needs, such as high accuracy in challenging situations, ease of setup, or knowledge of UWB in logistics. Though there is still work to be done to solve issues like cost and NLoS, UWB provides a lot of potential for safe and dependable indoor navigation.

C. Inertial Navigation

Utilizing inertial navigation, indoor pedestrian navigation tracks changes in orientation and movement by utilizing sensors such as gyroscopes and accelerometers built into the device itself. Although there are certain benefits to this approach, there are also some underlying drawbacks. Systems that use inertial navigation continually measure changes in direction and velocity to track a user's movements. They are especially helpful in places where GPS signals are not available, including interiors where satellite signals cannot get through. But these systems have built-in flaws, such as drift, which causes errors to compound over time and result in inaccurate position estimation [11] [20]. Furthermore, to keep accuracy, inertial navigation needs to be calibrated and corrected frequently.

Despite these difficulties, inertial navigation offers certain benefits. It functions without the need for external infrastructure and provides continuous tracking even in situations when GPS is not available. When used in conjunction with Wi-Fi or Bluetooth-based systems, inertial navigation can improve accuracy and be a useful addition to existing indoor positioning techniques [21-22]. Inertial navigation is used for indoor pedestrian navigation in a variety of settings, such as storage facilities, industrial facilities, and visually impaired people. It also helps with location-based applications.

Simply put, to sum up, in situations where GPS is unavailable, inertial navigation is an invaluable aid for indoor pedestrian navigation. Although it provides continuous tracking capabilities, more developments and integration with complementing positioning technologies are required and being investigated/researched now to increase overall accuracy and dependability due to its drift susceptibility and frequent calibration requirements.

Table 3 illustrates the relatively recent developments in inertial navigation that have benefited pedestrian indoor navigation for various reasons. The reviewed research publications experimented using few types of IMU and they all bring different focus and benefaction.

In short, significant progress in indoor pedestrian navigation with IMUs is demonstrated in all six publications. The optimal method will vary depending on certain requirements and preferences, including the kind of movement (walking, running, etc.), the form factor of the device, and the required accuracy. It may be possible to increase accuracy and robustness even further with additional study in sensor fusion algorithms, lower limb model integration, and adaptive error correction techniques.

D. Map Matching and Dead Reckoning

Using map matching and dead reckoning techniques, indoor pedestrian navigation offers a systematic way to estimate user positions in confined spaces. This technique continuously updates and approximates a user's location as they travel around an indoor area by fusing sensor data with previously created maps [29].

Map matching is the process of matching known reference points on a map with sensor data, such as gyroscope and accelerometer readings. This is enhanced by dead reckoning, which continuously determines a user's position based on movement, direction, and recognized landmarks or reference points. Using these methods, an interactive model of a user's path across the mapped indoor environment is produced. Although dead reckoning and map matching allow for continuous tracking, they are prone to compounding mistakes [30]. Over time, cumulative disparities in predicted positions can result from minor errors in sensor readings or deviating from the intended course; this phenomenon is referred to as "drift." The precision of the estimated position may be impacted by this drift, particularly in intricate interior spaces with lots of twists and turns.

Nevertheless, several indoor navigation applications have shown benefit from these techniques, such as helping customers navigate intricate building layouts, leading them across expansive facilities like malls, and supporting location-based services in manufacturing or warehouse environments.

Among the map matching and dead reckoning-based indoor navigation technologies that are popularly used and investigated now are as in Table 4. Table 4 reviews and explains the methods used in each paper along with their strengths and weaknesses.

The technological difference between the method used in publications papers:

- Sensor Fusion vs. Single Sensor:
  [31] and [32] employ sensor fusion to improve accuracy, but [33] and [34] depend on single sensors due to their affordability and ease of use.
- Algorithm Complexity:
  [33] and [34] concentrate on low-complexity algorithms for real-time performance, whereas [31] and [32] use sophisticated filtering and estimating approaches.
- Integration of Smartphones:
  For user comfort and accessibility, papers [32] and [34] make use of smartphones.

These interior navigation techniques vary mostly in how they aim for accessibility, complexity, and accuracy. With their sophisticated map matching and sensor fusion algorithms, [23] and [32] are the most precise, but their complex methods require more computer power and more hardware, such as radio systems and foot-mounted sensors. However, [33] and [34] promote efficiency and simplicity by using widely available cell phones and low-complexity algorithms, which makes them ideal in situations where resources are limited. But at the expense of a slightly reduced accuracy.

To summarize, indoor navigation and continuous tracking are made possible via map matching and dead reckoning algorithms. These techniques are useful for assisting users in navigating confined environments, even if they are prone to cumulative errors, particularly in complicated spaces. They have the potential to be further improved by improving sensor technology and map databases.

E. Magnetic Positioning

Although magnetic location is not as widely used as other technologies, it has been researched and developed over the past 10 years, with various stages of application and research focused mostly on its applicability for interior navigation scenarios. Due to strong magnetic field interference and abnormalities brought on by the building's metal structure, numerous studies have discovered recently that accurate interior positioning based on magnetic fingerprints will become achievable. The validity of an indoor magnetic field-based locating method is examined by researchers considering the layout of the building, the kinds of smartphones, where they are placed, whether there is furniture there, and whether there are any metallic objects that are personal [35].

When compared to Wi-Fi fingerprints, this method which is magnetic field fingerprint-based positioning offers numerous benefits which are; magnetic fields are ubiquitous and don't require additional specialized infrastructure for deployment, the distribution of the magnetic field remains relatively constant over a period of several months and the density of people in an area has minimal impact on the magnetic field [35]. Evidently, there has been a rise in the use of ambient magnetic-based indoor locating techniques for pedestrians with smartphones. Besides, as GPS and other related technologies is said to be expensive as the implementation and maintenance process can be quite costly, magnetic provides a less expensive, dependable, and effective method of indoor navigation [36].

There are a few articles that delve into and explore the use of magnetic fields in indoor navigation technology. [37] implemented the combination of magnetic matching and dead reckoning, supported by innovative mismatch detecting methods. This led to the result’s accuracy obtained in this paper is high (45.9%-67.9% error reduction, as mentioned in the paper). Meanwhile, [38] concentrates on simulating pedestrian movement and uses a better particle filter together with sophisticated step detection to increase resilience and accuracy. Its main objective is to improve pedestrian movement modelling. This research improves accuracy and resilience by utilizing an enhanced particle filter and sophisticated step detection, demonstrating its ability to handle a variety of conditions. Other than that, [39] offers device independent performance and makes use of a fingerprint database of magnetic patterns, requiring no initial position. This approach provides independence from devices and ease of usage. No matter the smartphone is being used, its fingerprint database of magnetic patterns achieves an impressive 2-3 m error rate for 50% of users, eliminating the necessity for initial position determination.

Meanwhile [40] addresses the mitigation of gyroscope errors by creating a new quasi-static magnetic field detecting technique that provides better heading error suppression. Its exclusive focus is on solving gyroscope error, which is a recurring problem in interior navigation. Its unique quasi-static magnetic field sensing technique efficiently reduces heading errors, making it a useful instrument in circumstances where gyroscope accuracy is at risk. [35] demonstrates its effectiveness in many settings with remarkable accuracy from 0.64m to 2.34m RMS. The synergistic combination of dead reckoning, Kalman filtering methods, and magnetic field sequences is credited with this achievement. In the meantime, [41] employs a modified particle filter with magnetic fingerprint maps for efficient accuracy improvement. The utilization of a modified particle filter in conjunction with magnetic fingerprint maps results in a significant improvement, with an error range of 0.6-0.8m within a designated testing area.

The most ideal approach depends on the specific priorities or needs for the indoor navigation technology and the environment. By understanding the strengths and limitations of each method, magnetic fields can be deployed righteously in this indoor navigation field. In contrast, it can be concluded that the methods used in [35] and [37] led to the highest accuracy, and methods used in paper, [39] and [41] are more flexible and user-friendly.

F. Augmented Reality (AR) Integration

The integration of Augmented Reality (AR) in navigation apps is an important advancement in indoor navigation, as it completely transforms the way users interact and perceive their environment in confined places. AR overlay-enabled navigation apps use the camera and sensors on a smartphone or other device to seamlessly overlay digital data onto the screen representation of the actual environment. This combination produces an augmented view that improves the user's understanding of their surroundings by superimposing useful visual signals and directions in real-time over the actual location [44-45].

These augmented reality overlays provide users with clear direction when navigating indoor areas. For example, directional indicators or augmented reality markers may overlay the real world and show up on screens as users hold up their devices, directing them to their destination [44]. To make navigation simpler and more user-friendly, these markers which may be arrows, lines, or icons which could be superimposed onto walls, floors, or other points of reference within the indoor environment.

Additionally, dynamic and interactive elements are made possible by AR integration in navigation apps. Users that are interested in particular areas of interest within the indoor space may receive multimedia content or additional contextual information [44]. For instance, pointing the device at an exhibit in a museum may prompt further information or launch a virtual tour guide that overlays historical details about the display, improving the user's experience.

Because these AR overlays are real-time, users may get instant and useful information, which greatly enhances their experience navigating intricate indoor spaces. AR integration improves spatial awareness and facilitates better self-orientation by superimposing digital information onto the real environment. This makes indoor navigation simpler and more effective. Due to the recent emergence of AR, a lot of research publications that investigate various AR-powered navigation techniques as well as examine their advantages and possible uses have been published. Table 5 reviews and explains the methods used in each paper along with their advantages and limitations.

This collection of studies explores a wide range of indoor navigation options, including generic guidance systems and customized apps for use in libraries and by people with visual impairments. While machine learning, sensor fusion, and visual recognition fuel these many approaches, user experience and accuracy remain vary, with each solution showing its own set of constraints. Future studies may focus on improving accuracy, accessibility, and user involvement, which would improve the ability to navigate indoor environments inclusively and easily.

Table 1: Review of papers that uses Bluetooth technology in indoor navigations

Paper	Focus	Technologies	Strength	Weakness
[3]	Public and commercial facilities with multiple levels and connections (airports, museums, e tc.)	• Bluetooth beacons for indoor cell positioning • Pedestrian dead reckoning with smartphone sensors (camera, GPS, WiFi, Bluetooth, air pressure, inertial) • Geographic-topological building model for navigation and user orientation • Voice commands for destination selection • Multi-level routing algorithms considering stairs, elevators, and walking areas	Comprehensive solution covering various aspects of indoor navigation in complex environments	May require complex infrastructure setup and potentially higher power consumption with sensor usage
[11]	Improved accuracy and robustness compared to single technologies	• Data-driven inertial navigation with deep neural network for pedestrian motion modeling • Bluetooth Low Energy (BLE) for localization • Particle filter for data fusion	Significantly reduces positioning error compared to BLE alone, less affected by smartphone usage. Combines strengths of inertial navigation and BLE for better accuracy and drift control	Requires computational power for deep learning model, potentially higher battery consumption
[12]	Cost-effective and low-power indoor positioning	• BLE transmitters as reference points • Received signal strength indicator (RSSI) for distance estimation	A simple and efficient approach reduces installation density compared to other beacon-based methods.	Lower accuracy compared to other papers, may not be suitable for complex
		• Simple proportional correction for improving RSSI accuracy	Potentially lower cost and implementation effort	environments
[13]	Specific application for car search in parking garages	• BLE beacons for positioning assistance • Mobile app with "turn-by-turn" navigation and heading correction • Local coordinate system for parking space and beacon identification	Practical application with user-friendly navigation in a specific context	Limited scope compared to other papers, not a general-purpose indoor navigation solution

Table 2: Reviews and comparisons of UWB-based indoor navigation papers

Paper	Focus	Technologies	Strength	Weakness
[14]	Hybrid system with INS: Combines UWB with an inertial navigation system (INS) for improved accuracy in dynamic environments like construction sites	Hybrid INS/UWB: Combines UWB with an inertial navigation system (INS) for accuracy in dynamic environments like construction sites	Utilize hybrid approaches to mitigate limitations of both UWB and other technologies like INS or PDR (Pedestrian Dead Reckoning), leading to better accuracy and robustness	Increased complexity compared to standalone UWB systems due to additional sensor fusion and processing requirements
[15]	Simultaneous localization and mapping (SLAM): Uses UWB with a gyroscope for SLAM without needing pre-mapped anchor positions	Simultaneous Localization and Mapping: Uses UWB and a gyroscope for SLAM without needing pre-mapped anchor positions	Enables SLAM without prior anchor knowledge, potentially reducing setup complexity	Accuracy might be lower than other hybrid approaches due to relying solely on UWB and a gyroscope
[16]	Review of UWB for smart logistics: Provides an overview of recent UWB advancements for precise positioning in indoor logistics applications	Precision Positioning for Smart Logistics: Reviews recent UWB advancements for precise positioning in indoor logistics	Provides a comprehensive review of UWB technology and its suitability for smart logistics applications	Review nature lacks specific research findings
[17]	Robust PDR/UWB integration: Combines UWB with pedestrian dead reckoning (PDR) for harsh environments, addressing NLoS issues and PDR drift	PDR/UWB: Integrates UWB with PDR to address non-light-of-sight (NLoS) issues and PDR drift in harsh environments	Utilize hybrid approaches to mitigate limitations of both UWB and other technologies like INS or PDR, leading to better accuracy and robustness	Increased complexity compared to standalone UWB systems due to additional sensor fusion and processing requirements
[18]	Improved PDR/UWB integration: Enhances accuracy through gait detection, step length estimation, and dynamic noise adjustment in the NLoS condition	Improved PDR/UWB: Enhances hybrid accuracy through gait detection, step length estimation, and NLoS noise adjustment		
[19]	UWB/INS integration for robust environments: Combines UWB with INS using particle filtering and zero-speed update to improve accuracy and reliability in NLoS and complex environments	UWB/INS Integrated Pedestrian Positioning: Focuses on UWB/INS integration with particle filtering and zero-speed update for NLoS robustness and improved accuracy in complex environments	Focuses on NLoS robustness through a specific UWB/INS integration method, potentially improving performance in challenging environments	Potential computational overhead due to particle filtering

Table 3: Reviews of IMU-based indoor navigation papers

<table>
<tr><th>Paper</th><th>Type of IMU</th><th>Sensor fusion and algorithms</th><th>Focus and contributions</th><th>Accuracy and performance</th></tr>
<tr><td>[23]</td><td rowspan="3">Use foot-mounted IMUs, which offer more accurate motion data but can be cumbersome to wear</td><td rowspan="4">Primarily use Extended Kalman Filters (EKFs) for sensor fusion and state estimation</td><td rowspan="2">Focus on improving accuracy by utilizing different modes for different gait phases (stance and swing)</td><td>Report average position errors between 1.5m and 2.3%</td></tr>
<tr><td>[24]</td><td>Doesn't explicitly mention accuracy but claims improved heading drift reduction</td></tr>
<tr><td>[25]</td><td>Emphasizes trajectory reconstruction for both indoor and outdoor environments, including floor walking and stair climbing.</td><td>Doesn't provide quantitative accuracy results but demonstrates successful trajectory reconstruction.</td></tr>
<tr><td>[26]</td><td>Uses IMUs embedded in smart glasses, which are more convenient but can have lower accuracy due to their placement</td><td>Demonstrates feasibility of using embedded IMUs in smart glasses for indoor navigation with acceptable accuracy.</td><td rowspan="2">Report average position errors between 1.5m and 2.3%</td></tr>
<tr><td>[27]</td><td>Use foot-mounted IMUs, which offer more accurate motion data but can be cumbersome to wear</td><td>Employs a novel threshold-less turn detection method along with a Kalman filter for heading correction</td><td>Introduces a Pelvic rotation-ZUPT Turn Detector (PZTD) heading correction method to overcome heading drift without relying on external references</td></tr>
<tr><td>[28]</td><td>Uses multiple IMUs on different body parts, which adds complexity but can improve accuracy during vigorous movements</td><td>Proposes an adaptive zero-bias estimation algorithm and a lower limb model constraint for improved accuracy and stability</td><td>Develops a multi-node system with lower limb model constraints to handle vigorous movements like running and jumping</td><td>Achieves sub-0.3% average distance error for walking, running, and hybrid motion</td></tr>
</table>

Table 4: Reviews of indoor navigation papers that utilizes map matching and dead reckoning technologies

Paper	Map matching	Dead reckoning	Strength	Weakness
[31]	Utilizes optimized wall crossing detection and room grouping algorithm for real-time performance with large maps	Improved PDR model estimates turn rate bias to address error growth, further enhanced by Received Signal Strength (RSS) measurements for initialization and faster convergence	Highly accurate (0.75m error 90% of the time), works with large maps, real-time performance	Complex implementation, requires foot-mounted sensors
[32]	Particle filter map matching integrated with PDR and short-range radio frequency systems for long-term drift correction	Traditional PDR using smartphone inertial measurement units (IMU)	Drift-free, accurate and reliable long-term tracking, works on smartphones	Complex, computationally expensive, requires additional infrastructure
[33]	Uses likely and unlikely path algorithms to correct PDR errors like orientation and displacement drift	Single foot-mounted inertial sensor with zero velocity updates and Madgwick filter for step length and orientation.	Low-complexity, online correction, significant endpoint accuracy improvement (up to 60%)	Performance varies depending on scenario, can decrease accuracy in some cases.
[34]	Basic map matching with a known indoor map to reduce PDR error over time	Smartphone IMU for PDR	Simple, user-friendly, works with smartphones in casual postures	Less accurate than other approaches, requires pre-existing map

Table 5: Reviews of papers that uses AR technology in indoor navigation field

Paper	Focus	Technology	Advantages	Limitations
[46]	Interactive indoor navigation	Interactive indoor navigation	Context-sensitive, interactive experience	Experiment limited to Sunway University campus
[47]	Indoor map visualization	Bluetooth, sensor fusion, particle filter	Dynamic map overlays, improved spatial awareness	Average positioning error of 1.47 m
[48]	Device comparison for indoor navigation	Smartphones, Google Glass	Wearable perceived as more accurate, faster navigation	No significant difference in performance between devices, worse route memory with digital aids
[49]	Library navigation using AR markers	Vuforia, Unity3D, IBM Watson	Improved user experience, direction and information access	Limited to pre-defined markers, requires app installation
[50]	AR-assisted navigation for visually impaired	Smartphones, ARKit, convolutional neural networks (CNNs)	Accessible, virtual path guidance, object recognition	Requires pre-recorded virtual paths
[51]	Improving AR navigation accuracy	Smartphones, ARKit, Kalman filter (KF)	Increased accuracy through data fusion (GPS, AR, Bluetooth)	Requires pre-recorded virtual paths
[52]	AR-based en-route assistance	Geomagnetic positioning, space coordinates transformation	Infrastructure-free, no GPS reliance	Limited to directional arrows, single-floor buildings

III. Conclusion

The ever-evolving landscape of indoor spaces necessitates a corresponding advancement in the tools that guide us within them. Indoor pedestrian navigation technologies have risen to this challenge, each presenting a unique solution to the intricate puzzle of efficient movement. Through this review, we have delved into the strengths and limitations of Bluetooth beacons, UWB, inertial navigation, map-matching, magnetic positioning, and augmented reality, unveiling a tapestry of possibilities woven from their diverse capabilities. Technologies for indoor navigation are developing quickly, with many competing to become the "ultimate guide." Bluetooth beacons are the most economical option; UWB is the most accurate; and inertial navigation is the most independent. However, no one technique is infallible. Their strengths will be smoothly blended in the future through synergy. Consider a system that uses inertial navigation as a backup, switches to UWB for precise tasks, and uses beacons for initial location. User-friendliness is ensured via magnetic placement and map-matching, which refines the journey. Interactive experiences add the finishing touches to augmented reality paintings. Analyzing different approaches to indoor pedestrian navigation highlights their unique benefits and drawbacks. Every method has applications in various indoor contexts. However, they face similar difficulties, such as enhancing accuracy and managing external influences. These techniques will probably be combined in the future to create more dependable systems by merging their advantages into an integrated approach. Technological developments could lead to more reliable indoor navigation in a variety of enclosed situations.

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