

A Unified AR Navigation Framework for Indoor and Outdoor Environments Using Point Clouds and GPS

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ABSTRACT

Indoor navigation remains a critical challenge for existing GPS based systems, particularly within large campuses, warehouses, retail complexes, and industrial facilities. This study introduces a fully integrated navigation framework that seamlessly unifies outdoor GPS based routing with indoor digital-twin navigation using point cloud data. The proposed system, developed in Unity, supports real time localization, augmented reality (AR) based guidance, and hotspot driven pathfinding in complex indoor environments.

Outdoor navigation is powered by GPS and Mapbox APIs for route computation, while indoor navigation employs Matterport generated digital twins combined with point cloud based spatial mapping to achieve high precision localization and mapping. The system autonomously detects transition boundaries between outdoor and indoor zones, dynamically switching navigation modes to maintain continuity.

A real-world deployment in beverage warehouse and retail scenarios demonstrates significant improvements in navigation accuracy, product accessibility, and overall user experience. The proposed approach offers a scalable and adaptable framework suitable for smart campuses, industrial facilities, retail spaces, and constrained environments such as defence installations.

Keywords: Indoor navigation, Outdoor navigation, Digital twin, Point cloud, Unity 3D, AR navigation, GPS routing, Smart retail, Matterport camera

INTRODUCTION

Navigation technologies have transformed how people move through outdoor environments. Applications such as GPS based mapping systems and digital navigation platforms enable users to travel efficiently across cities, highways, and large geographic regions. However, these systems rely heavily on satellite-based positioning, which often becomes unreliable or unavailable inside buildings. As a result, navigating complex indoor environments such as shopping malls, airports, hospitals, warehouses, and corporate campuses remains a significant challenge. Users frequently struggle to locate specific stores, departments, meeting rooms, or service areas once they enter large facilities where GPS signals are weak or completely obstructed.

Traditional indoor navigation approaches attempt to address this problem using technologies such as Wi-Fi triangulation, Bluetooth beacons, or QR code-based positioning. While these solutions can provide approximate location awareness, they often lack spatial precision and fail to deliver an intuitive navigation experience. Moreover, many of these systems operate independently of outdoor navigation platforms, forcing users to switch between different applications when transitioning from outdoor to indoor environments. This fragmentation reduces usability and limits the effectiveness of navigation systems in real world scenarios where seamless transitions between environments are essential.

Recent advancements in 3D spatial computing technologies offer promising solutions to these limitations. Technologies such as 3D scanning, digital twins, point cloud modelling, and augmented reality (AR) enable the

creation of highly accurate virtual representations of physical environments. Point cloud data generated from LiDAR scanners, photogrammetry, or depth cameras can capture detailed spatial structures of indoor environments, allowing precise mapping of corridors, shelves, entry points, and objects. When integrated with digital twin platforms, these models can replicate real world environments in a virtual space, enabling more accurate localization and spatial interaction within buildings.

Augmented reality further enhances indoor navigation by overlaying visual guidance directly onto the user's physical environment through mobile devices or AR enabled headsets. Instead of relying solely on traditional map interfaces, users can follow visual navigation cues such as arrows, markers, and contextual information superimposed onto real world surroundings. This significantly improves usability, especially in complex indoor environments where traditional maps may be difficult to interpret. Additionally, AR enabled systems can provide contextual information such as product descriptions, location-based analytics, and points of interest, thereby transforming navigation systems into interactive spatial information platforms.

This paper presents a real world implemented navigation system that integrates outdoor and indoor navigation using a unified architecture. The system combines GPS based outdoor navigation powered by Mapbox, indoor navigation using point cloud based digital twins, and augmented reality guidance implemented within a Unity based visualization platform. By seamlessly transitioning between outdoor GPS navigation and indoor spatial localization, the proposed system provides users with continuous navigation assistance from the point of origin to the exact indoor destination. Furthermore, the platform enables contextual interaction with the environment, allowing users to retrieve location specific information such as product details, facility information, and spatial analytics.

The proposed approach demonstrates how integrating spatial computing technologies with modern navigation frameworks can significantly improve navigation accuracy and user experience across mixed environments. By combining outdoor geospatial mapping with indoor digital twin models and AR visualization, the system establishes a unified navigation paradigm capable of supporting applications across retail environments, smart campuses, logistics warehouses, and public infrastructure.

LITERATURE REVIEW

Navigation technologies have evolved rapidly with the integration of geospatial systems, mobile computing, and spatial computing technologies. Traditional navigation systems primarily focused on outdoor environments using satellite-based positioning methods, while recent research has explored indoor localization technologies, digital twin environments, and augmented reality visualization to address the challenges of navigating complex indoor spaces. Existing literature in this domain can be broadly categorized into three areas: GPS-based outdoor navigation, indoor positioning technologies, and digital twin-based spatial navigation enhanced with augmented reality.

GPS-Based Outdoor Navigation

Outdoor navigation systems largely depend on the Global Positioning System (GPS) combined with digital mapping platforms and geospatial information systems. Modern navigation services such as [Mapbox\(2025\)](#) and other geospatial platforms enable accurate route planning, location tracking, and real-time navigation across large geographic regions. Geographic Information Systems (GIS) play a critical role in these systems by enabling spatial data analysis, route optimization, and geographic visualization ([Goodchild, 2020](#)).

Recent studies have explored improvements in outdoor navigation accuracy through the integration of mobile sensors, edge computing architectures, and next-generation wireless communication technologies such as 5G networks ([Wang et al., 2021](#); [Li et al., 2022](#)). These hybrid positioning frameworks combine GPS with inertial sensors and network-based positioning techniques to enhance reliability in urban environments ([Chen et al., 2023](#); [Xu et al., 2024](#)). Artificial intelligence methods have also been incorporated into navigation systems to support predictive routing, traffic-aware path planning, and intelligent navigation assistance ([Zhang et al., 2022](#); [Ahmed et al., 2023](#)).

Despite these improvements, GPS-based navigation systems face significant challenges in indoor environments. Satellite signals often experience attenuation and multipath interference when entering buildings, leading to unreliable positioning ([Zafari et al., 2022](#); [Liu et al., 2023](#)). Consequently, GPS-based navigation alone cannot provide accurate guidance within complex indoor environments such as shopping malls, hospitals, airports, or corporate campuses.

Indoor Navigation Technologies

To overcome the limitations of GPS in indoor environments, researchers have developed several indoor positioning approaches. Early indoor navigation systems relied on wireless signal-based localization techniques, including Wi-Fi fingerprinting, Bluetooth Low Energy (BLE) beacons, and Radio Frequency Identification (RFID) systems ([Yassin et al., 2020](#); [Brena et al., 2021](#)). These techniques estimate user positions based on signal strength measurements from nearby transmitters.

While such approaches provide basic indoor localization capabilities, they often require significant infrastructure deployment and frequent calibration ([Alarifi et al., 2021](#)). Wireless signals can also fluctuate due to environmental changes, obstacles, and interference, which may reduce positioning accuracy ([Khan et al., 2022](#); [Nguyen et al., 2023](#)).

More recent studies have explored vision-based localization approaches, particularly Simultaneous Localization and Mapping (SLAM). SLAM techniques enable systems to construct spatial maps while simultaneously tracking user movement using camera sensors ([Cadena et al., 2020](#); [Mur-Artal & Tardós, 2021](#)). These methods allow dynamic mapping of indoor environments without requiring extensive infrastructure, although their performance may be affected by lighting conditions or visual ambiguities.

Hybrid indoor positioning systems combining multiple sensor modalities have also been proposed to improve localization performance. These systems integrate Wi-Fi signals, inertial sensors, and visual data to achieve higher positioning accuracy in complex indoor environments ([Singh et al., 2022](#); [Gupta et al., 2023](#)). However, many existing indoor positioning solutions focus primarily on localization accuracy and provide limited support for intuitive navigation visualization.

Digital Twin and Point Cloud Navigation

Recent advancements in 3D spatial mapping technologies have introduced digital twin environments and point cloud datasets as promising solutions for indoor navigation. Digital twins create virtual representations of real-world environments that enable spatial analysis, monitoring, and navigation within highly accurate 3D models ([Batty, 2021](#); [Tao et al., 2021](#)). These models are typically generated using LiDAR scanning or photogrammetry, producing dense point cloud datasets that capture the geometric structure of indoor spaces ([Zhao et al., 2022](#); [Luo et al., 2022](#)).

Point cloud-based navigation systems enable detailed spatial modeling of buildings, including corridors, walls, and objects, which improves navigation accuracy within indoor environments ([Chen et al., 2024](#)). Digital twin platforms such as Matterport allow interactive exploration of indoor spaces and support hotspot-based navigation within virtual building models ([Matterport, 2024](#)). These technologies are increasingly used in smart buildings, facility management systems, and intelligent retail environments ([Jones et al., 2023](#); [Das et al., 2024](#)).

In parallel, Augmented Reality (AR) technologies have emerged as an effective method for improving user interaction with navigation systems. AR navigation overlays digital navigation cues directly onto the physical environment, allowing users to follow visual instructions such as arrows, markers, and path indicators ([Azuma, 2023](#)). Studies have shown that AR-based navigation significantly improves spatial understanding and reduces cognitive load compared to traditional map-based interfaces ([Billinghurst et al., 2022](#); [Speicher et al., 2021](#); [Brown et al., 2021](#)).

Development platforms such as Unity and AR Foundation provide powerful tools for implementing real-time AR navigation systems, including spatial mapping, object tracking, and visualization capabilities ([Unity](#)

[Technologies, 2025](#)). These platforms enable developers to build immersive navigation experiences for mobile devices and AR-enabled hardware.

Despite the rapid development of indoor navigation technologies, most existing solutions operate independently within either indoor or outdoor environments. This separation results in fragmented user experiences when transitioning between outdoor and indoor spaces. Recent research emphasizes the need for integrated frameworks capable of combining GPS-based outdoor navigation with digital twin-based indoor navigation and AR visualization ([Park et al., 2022](#); [Kim et al., 2023](#); [Kumar et al., 2024](#)).

The system proposed in this research addresses this gap by integrating GPS navigation, point cloud-based digital twins, and augmented reality guidance within a unified Unity-based platform. This integrated approach enables seamless navigation across indoor and outdoor environments while providing enhanced spatial visualization and contextual information.

Proposed System Overview

The proposed system introduces a unified navigation framework that seamlessly integrates outdoor GPS based navigation with indoor navigation powered by digital twin environments and point cloud models. Traditional navigation systems typically operate independently in either outdoor or indoor environments, creating discontinuity when users move from streets or parking areas into large buildings such as shopping malls, airports, hospitals, or corporate campuses. The proposed system addresses this limitation by combining multiple technologies including GPS positioning, point cloud spatial mapping, augmented reality visualization, and digital twin modelling to create a continuous navigation experience across both indoor and outdoor environments.

The architecture of the system leverages GPS based navigation for outdoor environments and automatically transitions to indoor spatial navigation when users enter a mapped building. Outdoor navigation is handled using geospatial routing services that provide location tracking, route generation, and map visualization. Using GPS signals and mapping APIs, the system calculates optimal routes from the user's starting location to the destination building entrance. Once the user approaches the indoor boundary of the mapped environment, the system detects the transition from outdoor space to indoor space and automatically switches from GPS based navigation to indoor localization.

A key component of the proposed system is the use of digital twin technology combined with point cloud data to represent indoor environments. Indoor spaces such as malls or warehouses are scanned using LiDAR sensors or 3D scanning technologies to generate detailed point cloud datasets that capture the geometry of corridors, rooms, walls, and objects within the building. These point cloud datasets are then converted into a digital twin representation that mirrors the real-world environment in a virtual 3D space. The digital twin model serves as the foundation for indoor navigation by providing accurate spatial information about the layout of the environment. Within the system, these models are integrated into a Unity based visualization platform, enabling interactive rendering and real-time navigation within the digital environment.

The system also incorporates an automatic indoor outdoor detection mechanism that determines whether the user is currently in an outdoor or indoor environment. This detection is based on factors such as GPS signal availability, predefined geofencing boundaries around buildings, and spatial triggers defined within the digital twin environment. When the user crosses the defined building boundary, the navigation engine automatically switches from GPS based routing to indoor navigation mode. This automated transition ensures that users do not need to manually change navigation modes, thereby improving usability and maintaining continuity throughout the navigation process.

For indoor navigation, the system uses a point cloud-based localization approach combined with hotspot-based navigation nodes. Key locations within the digital twin environment are defined as navigation hotspots, which may represent important locations such as store entrances, corridors, elevators, escalators, product aisles, or service counters. These hotspots act as navigation nodes that allow the system to compute optimal indoor paths

between locations. When a user selects a destination within the indoor environment, the navigation engine calculates a route through the network of hotspots and guides the user step by step toward the target location.

To enhance user interaction and improve navigation clarity, the system integrates Augmented Reality (AR) based directional guidance. AR technology overlays visual navigation cues directly onto the user’s physical environment through a mobile device interface. Instead of interpreting traditional 2D maps, users can follow visual indicators such as arrows, path markers, and directional guides superimposed onto their real-world surroundings. This approach simplifies navigation within complex indoor environments where interpreting maps or floor layouts may be challenging.

Another important feature of the proposed system is the ability to provide contextual information and product visualization within indoor spaces. When users navigate within retail environments such as shopping malls or stores, the system can display product information, promotional content, or store details associated with specific locations. For example, when a user approaches a product aisle or store hotspot, the system can display relevant product descriptions, availability information, or promotional offers. This feature transforms the navigation platform into a spatial information system that not only guides users but also enhances their interaction with the environment.

The Unity based visualization platform plays a critical role in integrating these functionalities into a unified system. Unity enables real-time rendering of digital twin environments, integration of AR capabilities, and interactive visualization of navigation paths and spatial information. By combining geospatial navigation services, point cloud models, AR visualization, and hotspot-based routing within a single platform, the proposed system provides a comprehensive navigation solution capable of supporting a wide range of real-world applications.

Overall, the proposed system demonstrates how integrating GPS navigation, point cloud based digital twins, and augmented reality technologies can overcome the limitations of traditional navigation systems. By enabling seamless transitions between outdoor and indoor environments and providing intuitive visual guidance, the system significantly improves navigation accuracy and user experience. The framework can be applied in various environments including shopping malls, airports, corporate campuses, warehouses, hospitals, and smart buildings, where precise indoor–outdoor navigation is essential for efficient movement and spatial awareness.

System Architecture

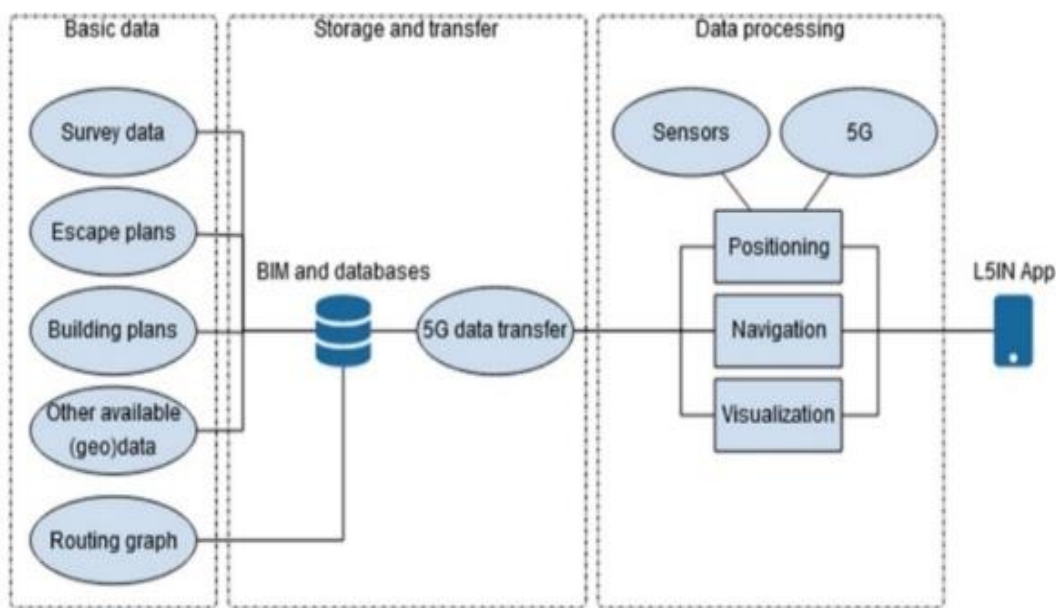


Figure 1: Solution Architecture Diagram for indoor navigation

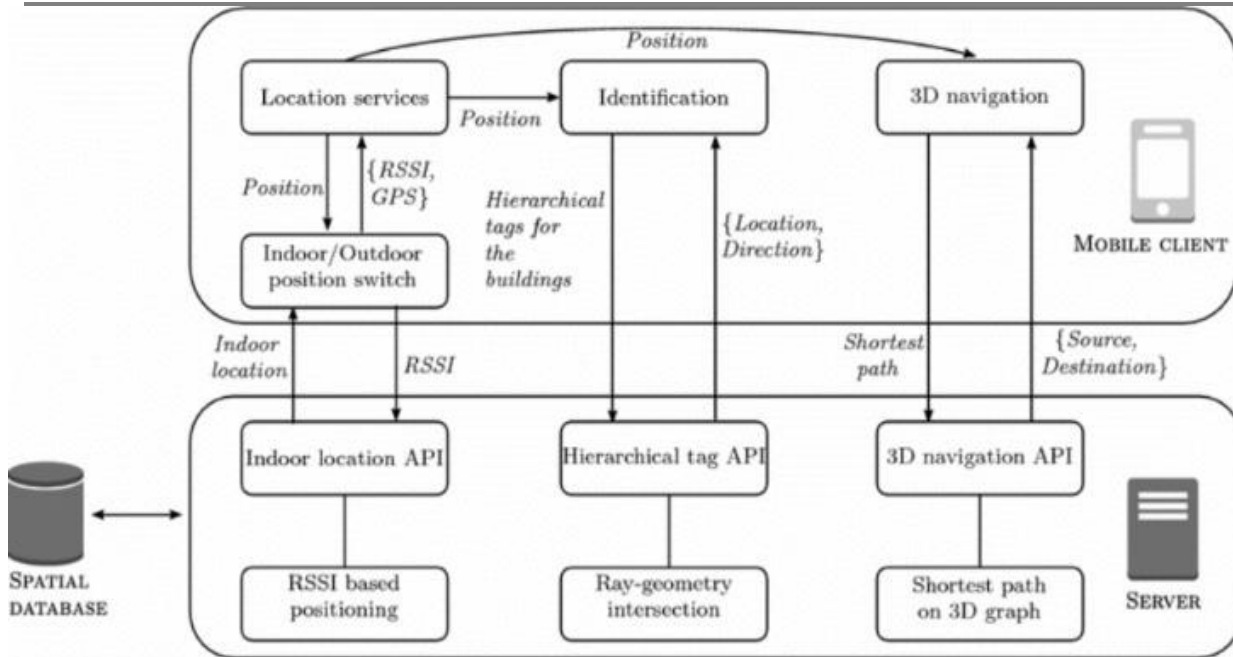


Figure 2: Solution Architecture Diagram for outdoor navigation

The architecture illustrated in [figure 1](#), [figure 2](#) above highlights how basic spatial data, positioning systems, processing engines, and mobile applications interact to enable navigation services. Spatial datasets such as building plans, routing graphs, and geospatial data are stored in databases and transferred through network services. Positioning data obtained from GPS, sensors, and wireless signals is processed by navigation engines that compute routes and deliver visualization instructions to the mobile client. In the proposed system, this architecture is extended by incorporating digital twin environments, point cloud datasets, and augmented reality rendering within a Unity-based mobile application.

Mobile Application (Unity 3D)

The mobile application layer serves as the primary interface through which users interact with the navigation system. The application is developed using the Unity 3D engine, which provides capabilities for real time 3D rendering, augmented reality integration, and cross platform mobile deployment. Unity is particularly well suited for this application because it supports advanced graphics, spatial interaction, and AR frameworks that are required for visual navigation systems. The mobile application is designed to support both Android and iOS platforms, allowing the navigation system to reach a wide range of users. Through Unity's cross platform development capabilities, a single codebase can be deployed across multiple mobile operating systems while maintaining consistent functionality and performance.

One of the core functionalities of the mobile application is AR based camera navigation. Using the device camera and motion sensors, the system overlays navigation instructions directly onto the user's real-world environment. These instructions include directional arrows, path indicators, and location markers that guide users toward their destination. Augmented reality visualization enhances spatial understanding by allowing users to follow navigation cues within the physical environment rather than interpreting traditional map-based interfaces. The mobile interface also provides a destination selection interface, enabling users to search for or select their target location. This interface may include options such as store names, product categories, building departments, or predefined points of interest. Once a destination is selected, the navigation engine calculates the optimal path and displays navigation instructions through the AR interface.

In addition, the mobile application handles automatic indoor–outdoor environment detection. By analysing GPS signal availability and predefined building boundaries, the system determines whether the user is currently in an outdoor or indoor environment. This detection mechanism triggers the appropriate navigation module, ensuring seamless transitions between outdoor and indoor navigation.

Outdoor Navigation Module

The outdoor navigation module is responsible for guiding users from their initial location to the entrance of a building or indoor environment. This module relies on GPS based positioning and geospatial routing technologies to determine the user's location and calculate optimal navigation paths. The system uses GPS location tracking to obtain the user's real time geographic coordinates. These coordinates are processed through mapping services to identify the user's position relative to roads, pathways, and buildings. GPS provides accurate positioning in open outdoor environments and is therefore suitable for large scale navigation across campuses, parking areas, or city streets.

To perform route generation and map visualization, the system integrates the Mapbox routing engine. Mapbox provides navigation APIs capable of calculating optimal routes between locations while considering road networks, walking paths, and geographic constraints. The routing engine generates navigation instructions that guide the user from their starting location to the designated building entrance.

For specialized environments such as corporate campuses, industrial facilities, or private properties, the system supports custom route creation. In such environments, traditional public mapping systems may not include internal pathways or restricted access roads. Custom route definitions allow administrators to define navigation paths specific to the campus layout, enabling accurate routing within private spaces. To enhance the navigation experience, the outdoor navigation module also integrates augmented reality directional arrows. These arrows are displayed through the mobile device camera, guiding users toward the correct direction in real time. AR based navigation cues help users interpret route instructions more intuitively than conventional map-based navigation.

Indoor Navigation Module

The indoor navigation module provides precise navigation within buildings where GPS signals are unavailable or unreliable. This module is built upon digital twin environments and point cloud spatial models that accurately represent the geometry and layout of indoor spaces. Indoor environments are first scanned using 3D scanning technologies such as LiDAR or photogrammetry, producing dense point cloud datasets that capture the spatial structure of the building. These point clouds include detailed representations of walls, corridors, rooms, and interior objects. The point cloud data is then processed to generate a digital twin model of the indoor environment.

The system integrates Matterport digital twin environments to provide realistic 3D representations of indoor spaces. Matterport scanning technology captures high-resolution spatial data that can be used to construct interactive indoor environments. These digital twins enable navigation systems to understand building layouts and compute navigation paths.

Within the digital twin environment, the system defines navigation hotspots that represent important locations such as entrances, elevators, hallways, store sections, or product aisles. These hotspots function as navigation nodes within a spatial graph. When a user selects an indoor destination, the navigation engine computes the shortest path between the current location and the destination using the hotspot network.

Once the navigation path is generated, the system performs indoor path rendering within the Unity application. The path is displayed as visual indicators or AR guidance cues that direct the user through the building. Because the navigation path is derived from the digital twin model, it reflects the actual spatial layout of the building, ensuring accurate navigation guidance.

Cloud & Data Layer

The cloud and data layer serves as the backend infrastructure that manages spatial data, navigation information, and system analytics. This layer is responsible for storing and processing the data required for navigation services. One of the primary components of this layer is the location database, which stores spatial information

related to buildings, navigation nodes, routing graphs, and geographic coordinates. This database supports both outdoor geospatial data and indoor spatial data, enabling unified navigation across environments.

In addition to spatial data, the cloud layer also manages product metadata and contextual information. For example, in retail environments the system can store product descriptions, store information, promotional content, or inventory data associated with specific locations. When users approach these locations, the mobile application retrieves the relevant data and displays it through the interface. The cloud layer also supports analytics and usage tracking. By monitoring navigation interactions, the system can collect insights related to user movement patterns, popular routes, frequently visited areas, and dwell times within specific locations. These analytics can provide valuable insights for businesses, enabling them to optimize store layouts, improve facility management, and enhance user experience.

Furthermore, the cloud infrastructure enables data synchronization between indoor spatial models and mobile devices. Updates to building layouts, navigation nodes, or product metadata can be deployed through cloud services, ensuring that the mobile application always operates with the most current spatial data.

METHODOLOGY

The methodology of the proposed system focuses on enabling seamless navigation across outdoor and indoor environments by integrating GPS based positioning, digital twin spatial models, and augmented reality visualization. The navigation workflow is divided into four major stages: user localization, outdoor navigation, indoor detection and switching, and indoor navigation using point cloud data. These stages collectively ensure that users can move from their starting location to an indoor destination without interruption while receiving intuitive navigation guidance.

User Localization

The navigation process begins when the user launches the mobile application on their smartphone. Upon opening the application, the system initializes the device sensors and retrieves the user's current geographic coordinates using the Global Positioning System (GPS). GPS provides accurate positioning in outdoor environments and allows the application to determine the user's location relative to surrounding streets, buildings, and navigation points. The retrieved coordinates are then used to centre the navigation interface and display nearby points of interest on the map interface.

Once the user's location has been identified, the system queries the backend database to retrieve nearby destinations and available navigation points. These destinations may include building entrances, stores within a shopping mall, service counters, or product locations depending on the application context. The mobile interface presents these options through an intuitive user interface where the user can either search for a destination or select one from a list of predefined locations.

After the user selects a desired destination, the navigation engine begins preparing the routing instructions required to guide the user toward that location. At this stage, the system determines whether the destination is located outdoors or within an indoor environment. This classification allows the navigation system to activate the appropriate navigation module and ensures that the user receives the most accurate guidance depending on the environment.

Outdoor Navigation

If the selected destination is located outdoors or if the user needs to travel to a building entrance before entering an indoor environment, the system activates the outdoor navigation module. In this stage, the application uses the Mapbox routing engine to compute the optimal route between the user's current location and the destination point. The routing algorithm analyses available pathways, road networks, and walkable routes to generate the most efficient path.

Once the route has been generated, the navigation instructions are transmitted to the mobile application and displayed to the user. The system continuously updates the user's position using GPS signals and compares the real-time location with the calculated route. This enables the system to provide dynamic navigation guidance and recalculate routes if the user deviates from the suggested path.

To improve navigation usability, the system integrates Augmented Reality (AR) directional guidance during outdoor navigation. Instead of relying solely on traditional map visualization, the application uses the mobile device camera to overlay directional arrows and navigation cues directly onto the real-world environment. These visual cues guide users toward the correct direction and improve spatial awareness, particularly in large campuses or complex outdoor areas where map interpretation may be difficult.

Indoor Detection and Navigation Switching

A critical aspect of the proposed methodology is the automatic detection of indoor environments and the seamless transition from outdoor navigation to indoor navigation. As the user approaches the destination building or enters a predefined navigation zone, the system monitors the user's position and detects proximity to the building boundary. This detection can be achieved using a combination of geofencing techniques, signal strength monitoring, and predefined spatial triggers associated with indoor environments.

When the user crosses the defined boundary of the building, the system identifies that the user has entered an indoor navigation zone. At this point, the GPS signal quality typically decreases due to the structural interference of the building. The system therefore automatically disables GPS-based navigation and activates the indoor navigation module. This automatic switching mechanism ensures that the user does not experience interruptions in navigation guidance.

Following the environment transition, the system loads the digital twin model of the building, which contains detailed spatial information about the interior structure. The digital twin includes floor layouts, corridors, navigation nodes, and points of interest within the building. By loading this digital twin environment, the system prepares the necessary spatial data required for indoor navigation.

Indoor Navigation Using Point Cloud



Figure 1: 3D view of Matterport scanned model object

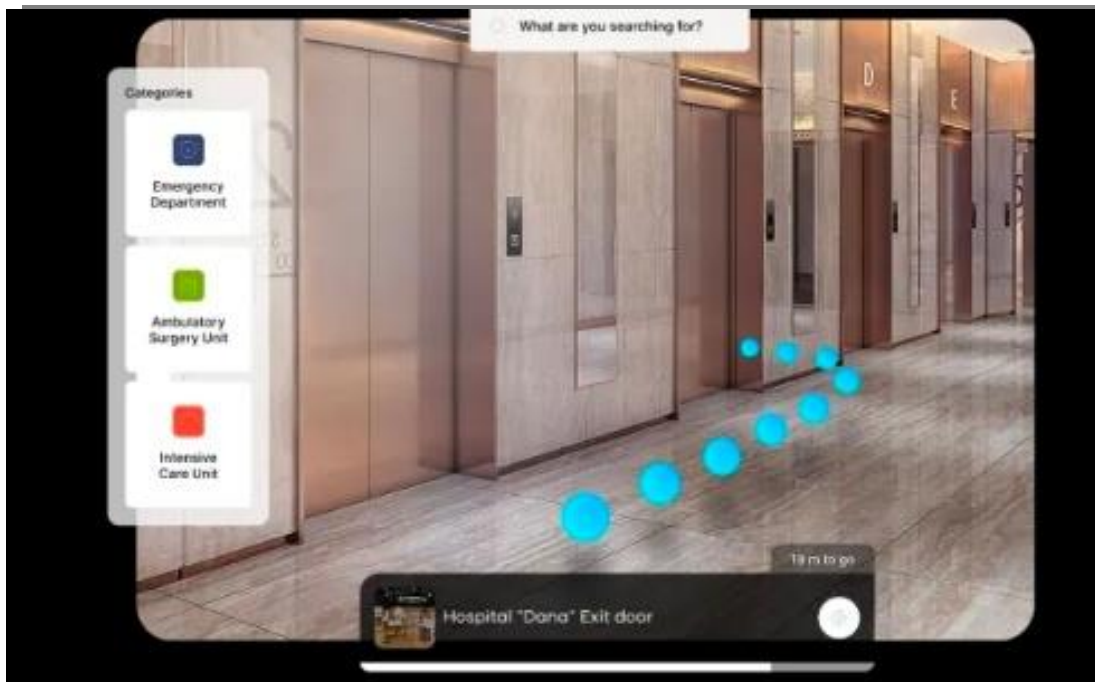


Figure 2: Indoor navigation view

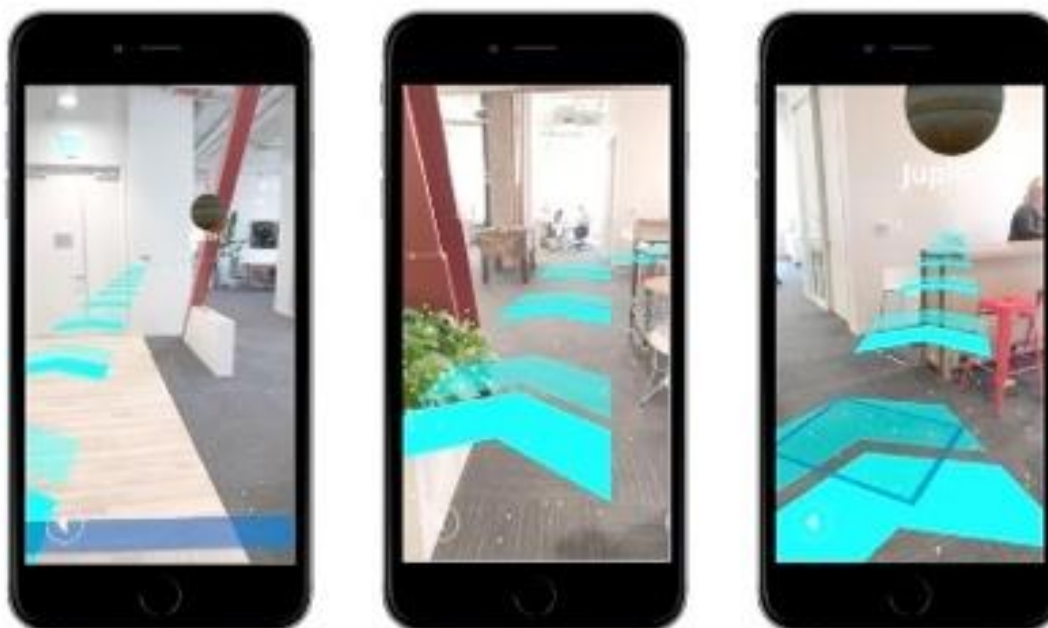


Figure 3: Mobile view for indoor navigation

Once the indoor environment is loaded, the navigation system uses **point cloud-based spatial data** refer [Figure 1](#) to guide the user to the destination within the building. The digital twin environment is generated from point cloud datasets obtained through LiDAR scanning or photogrammetry techniques. These point clouds capture the geometric structure of the indoor space and allow the system to accurately reconstruct the building layout in a virtual environment.

Within the digital twin environment, the system defines **navigation hotspots** that represent important locations such as corridors, store entrances, product aisles, elevators, and service counters. These hotspots act as nodes within a navigation graph that allows the system to compute the shortest path between the user's current position and the selected indoor destination. The routing algorithm analyses the connectivity between these nodes to determine the optimal path through the building.

After computing the navigation path, the system renders the route within the Unity-based mobile application and provides **augmented reality navigation guidance inside the building**. Visual indicators such as directional arrows, path markers, and guidance lines are displayed through the mobile device camera, allowing users to follow navigation instructions directly within the physical environment. Additionally, when users approach specific locations such as product displays or service counters, the system can display **contextual information including product descriptions, promotional details, or location-specific content**.

This methodology ensures that users receive **continuous navigation guidance from outdoor locations to precise indoor destinations**, while also enhancing the navigation experience through AR visualization and contextual spatial information.

Navigation Scenarios

Several navigation scenarios are supported within the deployed environment, demonstrating the flexibility of the unified framework. In outdoor-to-outdoor scenarios such as moving from one building to another on a campus, the system relies solely on GPS and Mapbox-based routing, providing AR arrows for direction along outdoor paths. In outdoor-to-indoor scenarios, for example guiding a user from a parking area to a specific store rack, the system first uses GPS navigation until the building entrance and then automatically switches to indoor navigation, using the digital twin and hotspot paths to reach the target rack.

Indoor-to-indoor scenarios are handled entirely within the digital twin, allowing users to move between different store sections or racks using hotspot-based navigation paths, while AR guidance provides intuitive visual cues inside the building. Conversely, indoor-to-outdoor scenarios, such as guiding users from an indoor location back to parking, start with hotspot-based indoor routing to the building exit, followed by GPS and Mapbox navigation from the exit to the outdoor destination. Qualitative observations from these scenarios indicate improved wayfinding efficiency, reduced search time for products, and a more intuitive user experience compared with traditional static maps or text-based directions. Refer [Figure 2](#).

Deployment Environment

The system has been deployed in a beverage warehouse and retail storage environment to evaluate its performance under real operational conditions. In this scenario, indoor spaces such as storage racks, product aisles, and service counters are mapped as digital twins, and product locations are linked to navigation hotspots within the model, enabling product-level routing. Users can select specific products or categories, and the system guides them from outdoor parking areas or building entrances to the exact rack or shelf location using the unified navigation workflow. In addition to navigation, the deployment supports product information display at relevant hotspots and collects user movement analytics that can be used to analyse buying patterns and optimize layout. Refer [Figure 3](#).

Use Cases and Discussion

The unified indoor–outdoor navigation framework supports a variety of use cases across different domains. In smart retail and warehousing, the system enables product navigation, inventory locating, and smart shopping assistance by guiding users directly to product locations while providing contextual product information and promotional content at relevant hotspots. These capabilities can reduce time spent searching for items, support efficient picking operations, and enhance the overall shopping experience.

On large campuses such as universities, hospitals, and corporate sites, the system can guide visitors from outdoor parking areas or public transport stops to specific departments, classrooms, wards, or meeting rooms without requiring separate outdoor and indoor navigation applications. In industrial and factory environments, the framework can support navigation for maintenance staff, machine operators, and safety personnel by providing routes to machines, control rooms, or emergency exits, potentially improving response times and safety compliance.

In restricted or military areas and private campuses, the system can operate as an independent navigation solution using privately hosted maps and digital twins, offering secure mapping and offline routing within controlled networks without exposing sensitive spatial data to public mapping platforms. Across these use cases, the unified architecture and AR-based interface provide consistent interaction patterns and visual cues, simplifying adoption and reducing training requirements compared with managing separate tools for indoor and outdoor navigation.

Advantages, Challenges, and Future Work

Advantages

The proposed system offers several advantages over traditional navigation approaches that separate indoor and outdoor guidance. By integrating GPS-based outdoor navigation, point-cloud-based digital twins, and AR visualization into a single framework, the system provides seamless indoor–outdoor navigation without requiring users to change applications or modes manually. The use of digital twins and point clouds enables accurate product-level and location-level navigation indoors, which is particularly valuable in complex retail or warehouse environments where conventional GPS cannot operate.

Independence from standard online maps for indoor spaces allows the system to function in private or restricted environments while still leveraging public map data outdoors. The architecture is scalable and extensible due to its cloud-based data management and modular navigation components, and the integration of analytics enables real-time insights into user movement, popular routes, and dwell times that can inform facility design and operational decisions. AR-based guidance improves usability by presenting navigation instructions in a visually intuitive manner, reducing cognitive load compared with reading 2D maps.

Challenges and Limitations

Despite its benefits, the framework faces several challenges and limitations. Achieving high indoor localization accuracy remains a complex task, particularly in dynamic environments where layouts change or temporary obstacles are introduced, which may require periodic rescan and model updates. Handling large point-cloud datasets for extensive facilities can be computationally intensive and may demand efficient data compression, level-of-detail management, and optimized rendering strategies to maintain real-time performance on mobile devices.

The initial scanning and digital twin creation process requires effort and specialized equipment such as LiDAR scanners or high-quality cameras, which may introduce cost and logistical constraints for large-scale deployments. Real-time synchronization between cloud-hosted models and mobile devices is also essential to keep navigation data up to date, particularly when product locations, store layouts, or route configurations change frequently. Additionally, defining and maintaining custom routes in private campuses or industrial facilities requires coordination with site administrators and may need dedicated tools for editing navigation graphs.

Future Work

Future enhancements to the system could focus on making navigation more intelligent, personalized, and collaborative. AI-based route prediction could analyse historical movement patterns and real-time data to suggest optimal routes, anticipate congestion in aisles or corridors, and provide adaptive guidance for different user profiles or tasks. Voice assistant integration could allow hands-free navigation instructions, enabling users to focus on their surroundings while receiving spoken directions and contextual information.

In smart retail scenarios, recommendation engines could suggest products or offers based on user preferences, previous purchases, or real-time behaviour, combining navigation with personalized shopping assistance. Heatmap analytics generated from aggregated movement data could help retailers and facility managers optimize layouts, shelf placements, and signage. Integrating IoT sensors such as occupancy detectors, beacons, or environmental sensors may enhance real-time awareness and support features like dynamic re-routing around crowded or restricted areas. Multi-user navigation support could enable group coordination, asset tracking, or staff assignment, opening additional use cases in logistics, events, and emergency response.

CONCLUSION

This paper presented an integrated indoor–outdoor navigation system that combines GPS-based outdoor routing with digital-twin- and point-cloud-based indoor navigation in a single Unity 3D mobile application. The framework supports automatic switching between outdoor and indoor navigation modes, hotspot-based indoor routing, and AR-based visual guidance, thereby providing continuous navigation from outdoor origins to precise indoor destinations without requiring manual changes by the user.

A real-world deployment in a beverage warehouse and retail environment demonstrates improved navigation efficiency, enhanced product discovery, and a better user experience compared with traditional map-based or text-based directions. The architecture is scalable and suitable for applications in smart retail, industrial facilities, campuses, and smart-city infrastructure, and it can be extended with AI-driven route prediction, voice assistance, IoT integration, and multi-user support to further increase its effectiveness.

Declarations

6.1. Author Contributions

Both the authors contributed equally to conceptualizing, investigation, data simulation and writing the paper.

6.2. Institutional Review Board Statement

Not applicable.

6.3. Informed Consent Statement

Not applicable.

6.4. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

ACKNOWLEDGMENT

Not applicable.

Conflicts of Interest

The authors declare no conflicts of interest.

REFERENCES

1. Ahmed, S., Rahman, M., & Kim, D. (2023). Smart campus navigation using hybrid positioning technologies. *IEEE Access*, 11, 22145–22158.
2. Alarifi, A., Al-Salman, A., Alsaleh, M., et al. (2021). Ultra-wideband indoor positioning technologies: Analysis and recent advances. *IEEE Communications Surveys & Tutorials*, 23(2), 1049–1075.
3. Azuma, R. (2023). Location-based augmented reality navigation systems. *IEEE Computer Graphics and Applications*, 43(1), 45–54.
4. Batty, M. (2021). Digital twins. *Environment and Planning B: Urban Analytics and City Science*, 48(2), 1–6.
5. Billingham, M., Clark, A., & Lee, G. (2022). A survey of augmented reality technologies and applications. *Foundations and Trends in Human–Computer Interaction*, 15(2), 73–272.
6. Brena, R., Garcia-Vazquez, J., Galvan-Tejada, C., et al. (2021). Evolution of indoor positioning technologies. *ACM Computing Surveys*, 54(1), 1–33.
7. Brown, T., Wilson, A., & Patel, S. (2021). Mobile augmented reality navigation systems: Design and evaluation. *IEEE Virtual Reality Conference*, 312–320.

8. Cadena, C., Carlone, L., Carrillo, H., et al. (2020). Simultaneous localization and mapping: Current trends and future directions. *IEEE Transactions on Robotics*, 36(6), 1–19.
9. Chen, L., Zhang, Y., & Kumar, P. (2024). Indoor navigation using point cloud and digital twin technologies. *Sensors*, 24(3), 1502.
10. Chen, X., Li, Z., & Zhou, Y. (2023). AI-driven navigation systems for smart cities. *IEEE Access*, 11, 55321–55335.
11. Das, S., Roy, P., & Mukherjee, A. (2024). Digital twin architecture for smart building navigation systems. *IEEE Smart Cities Conference*, 1–8.
12. Goodchild, M. F. (2020). Geographic information systems and spatial analysis for navigation applications. *International Journal of Geographical Information Science*, 34(3), 1–10.
13. Gupta, R., Sharma, V., & Patel, D. (2023). Spatial computing frameworks for indoor navigation systems. *ACM Computing Surveys*, 55(6), 1–34.
14. Jones, D., Snider, C., Nassehi, A., et al. (2023). Characterizing digital twins in smart buildings. *Automation in Construction*, 145, 104567.
15. Khan, A., Hussain, S., & Lee, J. (2022). Machine learning techniques for indoor positioning systems. *Sensors*, 22(4), 1210.
16. Kim, J., Park, H., & Lee, S. (2023). Hybrid indoor-outdoor navigation framework for smart environments. *IEEE Internet of Things Journal*, 10(5), 4120–4132.
17. Kumar, R., Singh, A., & Verma, N. (2024). Augmented reality navigation for retail environments. *Computers & Graphics*, 113, 98–108.
18. Li, Y., Wang, X., & Sun, J. (2022). 5G-based positioning technologies for next-generation navigation systems. *IEEE Network*, 36(4), 120–126.
19. Liu, H., Darabi, H., Banerjee, P., & Liu, J. (2023). Survey of wireless indoor positioning techniques. *IEEE Systems Journal*, 17(2), 2018–2031.
20. Luo, H., Zhao, Y., & Li, Q. (2022). Point cloud-based indoor mapping techniques. *Remote Sensing*, 14(5), 1180.
21. Mapbox. (2025). Navigation SDK and Routing APIs Documentation. Mapbox Inc.
22. Matterport. (2024). Digital Twin Technology for Indoor Mapping. Matterport Inc.
23. Mur-Artal, R., & Tardós, J. (2021). ORB-SLAM systems for visual navigation. *IEEE Robotics and Automation Letters*, 6(4), 689–696.
24. Nguyen, T., Le, H., & Pham, D. (2023). Deep learning approaches for indoor localization. *IEEE Access*, 11, 77120–77135.
25. Park, S., Lee, H., & Choi, J. (2022). Seamless indoor-outdoor navigation using hybrid positioning. *Sensors*, 22(18), 7041.
26. Singh, P., Kumar, R., & Sharma, A. (2022). Sensor fusion-based hybrid navigation systems. *IEEE Sensors Journal*, 22(15), 14780–14790.
27. Speicher, M., Hall, B., & Nebeling, M. (2021). What is mixed reality? A taxonomy of immersive technologies. *IEEE ISMAR*, 272–283.
28. Tao, F., Zhang, M., & Liu, Y. (2021). Digital twin-driven smart manufacturing. *IEEE Transactions on Industrial Informatics*, 17(6), 1–10.
29. Wang, Z., Zhang, H., & Li, J. (2021). Edge computing for location-based navigation services. *IEEE Internet of Things Journal*, 8(9), 7223–7232.
30. Xu, Y., Zhou, H., & Chen, J. (2024). Multi-sensor fusion positioning systems for mobile navigation. *IEEE Sensors Journal*, 24(2), 1035–1046.
31. Yassin, A., Nasser, Y., Awad, M., et al. (2020). Recent advances in indoor localization technologies. *IEEE Communications Surveys & Tutorials*, 22(2), 1–30.
32. Zafari, F., Gkelias, A., & Leung, K. (2022). Indoor localization systems and technologies: A survey. *IEEE Communications Surveys & Tutorials*, 24(1), 1–30.
33. Zhang, Y., Wang, L., & Chen, Q. (2022). Artificial intelligence-based route optimization. *Transportation Research Part C*, 138, 103610.
34. Zhao, H., Li, J., & Sun, Y. (2022). LiDAR-based spatial mapping for indoor environments. *Remote Sensing Letters*, 13(7), 1–10.
35. Unity Technologies. (2025). AR Foundation and Spatial Mapping Documentation. Unity Technologies.