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Research Article/ Review Article/ Perspective Article (Remove where relevant)

Development of an Indoor localization and positioning system in non-GPS environment using standalone smart phones and its implementation in construction site photo management application.

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Abstract

This research paper presents a novel indoor localization and positioning system designed for GPS-denied environments, specifically construction sites. It addresses the challenge of self-positioning on construction sites, where GPS signals are unavailable, such as in tunnels, buildings, and underground areas. We developed a high-precision self-positioning algorithm using a smartphone's camera and sensors to track location without external signals. The system combines a camera-based algorithm that tracks image pixel movement with augmented reality (AR) and smartphone sensors (accelerometer, gyroscope, magnetometer, and barometer). Unlike existing technologies like beacons, Wi-Fi, UWB, markers, and SLAM, which often lack accuracy, our system achieves centimeter-level precision for indoor positioning. The system is integrated into a construction site photo management app that automatically tags photos with accurate location data, including latitude, longitude, and the camera's orientation (roll, yaw, and pitch). The app places a pin on a map showing the camera's direction, ensuring precise geotagging. This system enhances construction site productivity by providing reliable documentation, essential for tracking and managing site progress. Geotagged images and metadata can be used for site inspections, progress monitoring, and decision-making. The research demonstrates the effectiveness of combining smartphone-based camera algorithms, AR, and sensor fusion to solve indoor positioning challenges in construction environments. This system has been tested in several construction sites and confirmed the accuracy of centimeter (cm) precision. The system's high precision and real-time capabilities offer a groundbreaking solution to the limitations of current indoor positioning technologies used in the construction sites.

Keywords: augmented reality; indoor localization; indoor positioning; map creator; site photo management, smartphone.

Highlights

- High precision Indoor Positioning without GPS
- Capture image with required localization information
- Enhanced construction site documentation and management

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1 Introduction

Construction sites often contain areas where GPS signals are weak or unavailable, such as basements, enclosed structures, and underground levels (Groves, 2013). This limitation poses significant challenges for achieving accurate localization, navigation, and digital documentation using traditional GPS-based systems. Although various indoor localization technologies have been developed, such as Bluetooth beacons (Zhang, 2017), Wi-Fi triangulation (He, 2016), ultra-wideband (UWB) (Zhang, 2021) (Coppens, 2022), and simultaneous localization and mapping (SLAM) (Zou, 2022), these methods typically require additional hardware, stable network connectivity, or pre-installed visual markers. Such prerequisites are often difficult to meet on construction sites, which are highly dynamic, frequently reconfigured, and typically lack consistent infrastructure. Consequently, many existing indoor localization solutions are impractical for real-world deployment in active construction environments.

At the same time, large volumes of photographs are captured daily at construction sites for documentation and communication. However, these images often lack contextual metadata, such as precise location, orientation, and viewing direction, which limits their usefulness are of no use after the completion of specific tasks with the photos.

To address these challenges, we developed a smartphone-based indoor localization and navigation system that relies solely on the built-in camera and sensors of standard smartphones (Lamsal, 2024). This approach eliminates the need for external infrastructure and enables rapid, flexible deployment in real-world construction environments. In addition to enabling self-localization, the system can automatically tag site photos with accurate location and orientation data, transforming everyday images into structured, actionable information. These enriched photos can then support tasks such as inspection, progress monitoring, and communication among construction site workers.

Building on this system, we developed a site photo management application aimed at streamlining task instruction workflows, particularly communication between site managers and foremen. In current practice, site managers often patrol the site, identify issues, and provide instructions using photos taken on-site. However, this process typically involves manually indicating photo locations on printed site maps and physically guiding workers to specific spots, an approach that is time-consuming, labour-intensive, and commonly referred to in the industry as “patrol.” Reducing the burden of this repetitive task is considered essential for advancing work style reform in the construction industry.

To solve this problem, our proposed system integrates the smartphone-based indoor localization and navigation system with a photo management application. It enables users to capture site images that are automatically tagged with spatial metadata and pinned directly onto a digital site map upon capture. This capability supports the digital transformation of construction site management and promotes safer, more efficient workflows. The system has been tested across multiple construction sites and has demonstrated its potential to enhance productivity and operational efficiency.

2 Indoor Localization and Navigation System

We developed a novel smartphone-based system for indoor localization and navigation. The proposed system leverages the built-in sensors and cameras of the Huawei P30 Pro smartphone (Notebook

Check, 2019), integrating them with an image recognition-based algorithm to achieve accurate and reliable indoor localization without relying on GPS or external devices.

The system utilizes multiple sensing capabilities of the smartphone to estimate the user's location and movement. Specifically, the camera is used to estimate motion by tracking changes in image feature points (Yin, 2022), while distance data is captured using the Time-of-Flight (ToF) sensor (Zafari, 2017). Additionally, the inertial measurement unit (IMU) captures device movement (Francek, 2023), and initial positioning is obtained through AR Core (Lamsal, 2019). By combining these data sources, the system can calculate self-location in real-time.

A significant challenge in developing this system was designing an algorithm to accurately estimate movement from image feature point changes and integrating all functionalities into a single mobile application (Albahar, 2022). The resulting system operates as a standalone indoor localization and navigation solution, requiring only a smartphone, with no dependence on external infrastructure. The image showing the flow of our indoor localization and navigation system is shown in Figure 1.

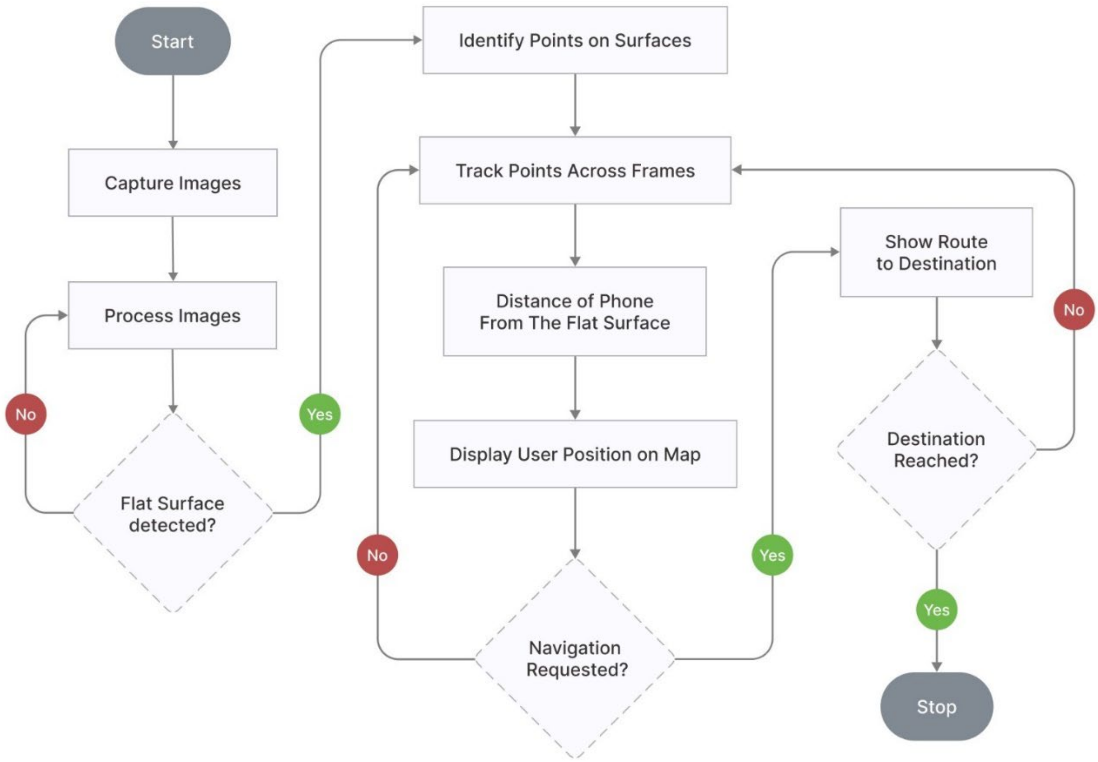

Figure1: Flow of the Indoor localization and navigation system.

2.1 Special Features of our indoor localization and navigation system

The proposed system includes a smartphone application that displays the user's real-time position on a 2D map and provides a navigation path to a specified indoor destination. It consists of three main components: a PC-based map creation tool (Map Creator), a smartphone with the navigation app installed, and a cloud server for data synchronization. Figure 1 illustrates the configuration of this system. The key features of the proposed system are as follows:

① High Accuracy Localization Without GPS: The system estimates the user's position using only the smartphone's camera, achieving high accuracy even in GPS-denied environments such as indoor construction sites (Khraisat, 2011). This eliminates the need for additional external devices or sensors, reducing cost and setup workload.

② Simplified Mapping Without Lidar or SLAM: Unlike conventional SLAM (Zhang, 2015) or VSLAM (Tseng, 2022) methods that require Lidar scan data (Gonzalez, 2022), our system sets walking routes using a simple plan-view image file. This significantly reduces the time and labour required to scan and create maps in frequently changing construction environments.

③ Marker less Reference Point Identification: Fiducial AR markers are not required for reference point registration. Instead, images of the surrounding landscape at key positions can serve as visual markers. While fiducial AR markers may still be used, they are not essential, thus minimizing preparation effort and enhancing system adaptability in dynamic construction settings.

④ Automatic Recording and Data Utilization: Images captured during navigation are enriched with metadata, including timestamp, coordinates, and camera orientation (Kim, 2021). This enables the automated placement of pins on a plan view for inspection purposes and facilitates various documentation and monitoring tasks during and after construction. The recorded images provide not only visual evidence but also valuable indoor context information.

3 Structure of On-site Photo management application

This research presents a photo management application designed for indoor environments where GPS is not available. The core feature of the system is its ability to estimate the user's movement and direction in real time using only a smartphone. It analyses the movement of image feature points in photos taken by the user and combines this with data from built-in sensors (e.g., accelerometer and gyroscope).

Typically, such processing requires a high-performance PC, but we optimized the algorithm to run efficiently on a smartphone. This improvement enables high-accuracy self-localization, reliable distance estimation, and reduced power consumption. When a user takes a photo, the app automatically places a pin at the photo location on a floor plan. It also adds precise latitude and longitude information to the image. The system is made up of three main components as shown in figure 2 and described as follows.

- Map Creator: Generates floor plans, marker data, and marker positions.
- Administrator App: Uses the generated map data to set up and manage each worksite.
- Photo Machine App: Based on our indoor localization and navigation system, The app. is Installed on smartphones, it allows users to capture and upload photos in real time on-site with the co-ordinate information. All photos and related metadata are saved to a cloud server for centralized management.

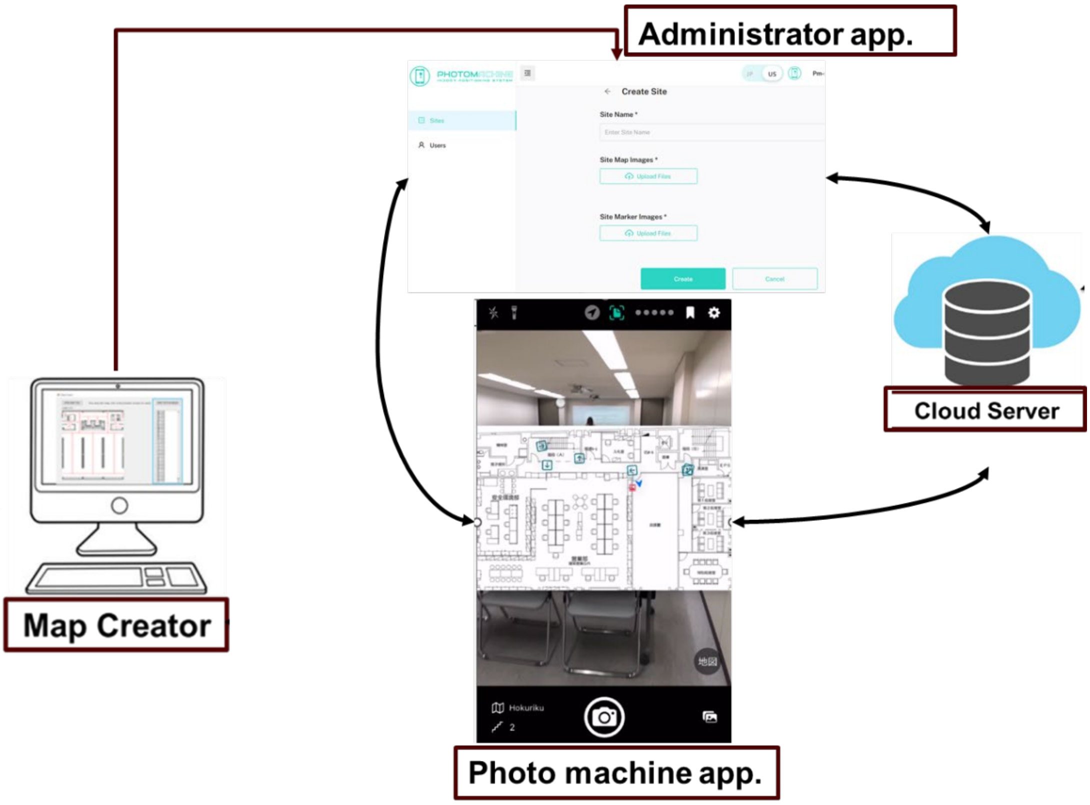

Figure 2: System configuration of On-site Photo management application

3.1 Map Creator

The Map Creator is a PC application that transforms standard 2D construction drawings into interactive digital maps with geographic reference. Users register the physical scale, select reference markers, latitude and longitude coordinates for a known reference point inside a 2D map. The system computes relative marker positions across the map and automatically determines latitude and longitude of the marker point based on the scale and orientation of the map. This system reflects a new approach of creating a site map without patrolling the site with expensive lidars and cameras. The operation screen of the Map Creator system is shown in Figure 3.

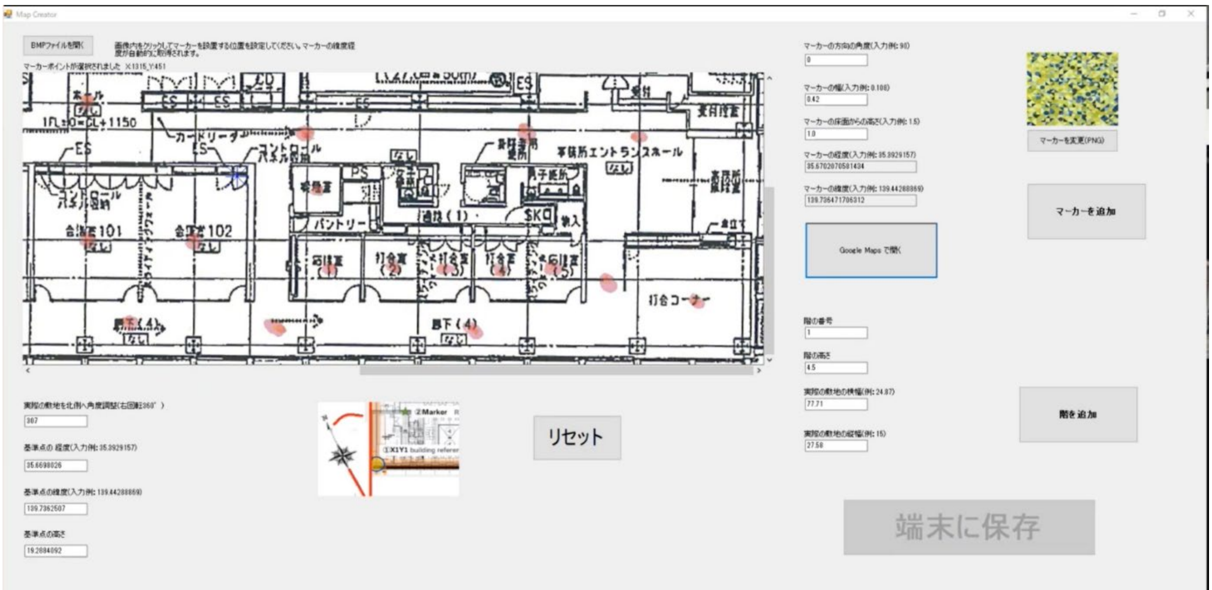

Figure.3: Operation Screen of Map Creator

The features of Map creator are explained as follows.

I. Bitmap Map Import and Scaling: Users can import floor plans in bitmap format and scale them by registering known distances and setting base coordinates. Key features such as corridors and entryways can be annotated to aid navigation.

II. Orientation and Geolocation Assignment: By setting a north reference and assigning geographical coordinates to known markers, the application calculates the latitude and longitude of all map features. This allows photos taken later to be precisely geotagged.

III. Visual Verification with Google Earth: To ensure accuracy, the system exports calculated coordinates to Google Earth. This visual verification process provides a straightforward way for users to confirm the alignment and scale of the generated map.

IV. Export and Compatibility: The output includes the bitmap map, spatial metadata, and marker positions in a format directly loadable by the mobile application, ensuring smooth data integration.

3.2 Administrator application

The Administrator application functions as the core system for managing site data and facilitating the integration of spatial information with photographic documentation. Its primary role is to register and organize site-specific data generated by the Map Creator, enabling seamless downstream use by the Photo Machine application.

Upon receiving the spatial data outputs from the Map Creator, specifically the site map file, map point file, map info file, and marker images, the Administrator Application allows users to upload and register these files under a newly defined site profile.

Once registration is completed, the Administrator Application automatically establishes a new operational site within the platform. This site serves as a structured environment where the Photo Machine application can access spatial references, overlay captured images onto the map, and manage photo metadata according to specific geospatial markers. The accurate linkage between spatial data and field images is critical for maintaining location fidelity and ensuring efficient visual documentation workflows. The operational screen of the administrator application is shown in figure 4.

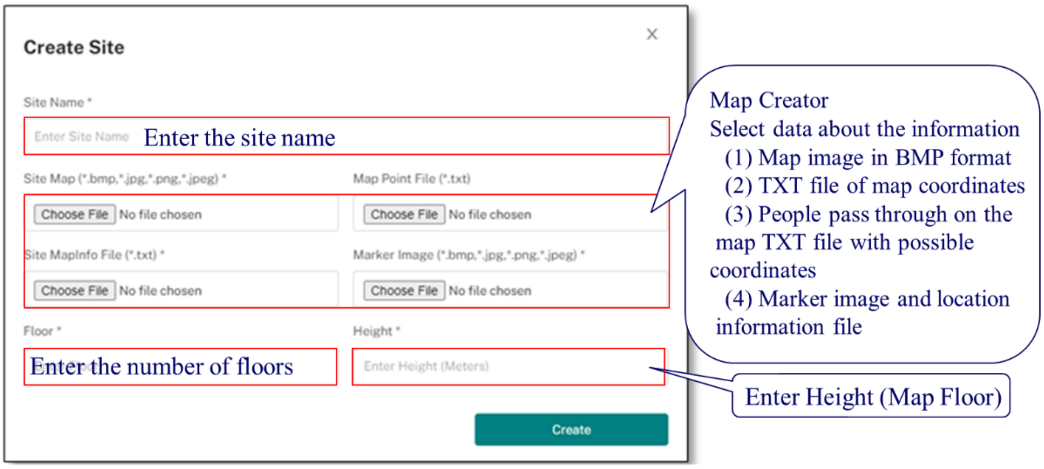

Figure 4: Operational screen of the administrator application.

3.3 Photo Machine application

The Photo Machine mobile application enables users to capture images during site patrols and automatically associate them with the estimated indoor self-localization data at the time of capture. This functionality ensures that every photo taken in the field is contextually linked to its spatial location within the construction site.

The flow of the Photo machine application is shown in figure 5. Upon launching the application, the user is presented with an interactive map of the construction environment, which has been generated and exported from the Map Creator tool. This map is displayed directly on the smartphone screen, and the user's position is continuously updated in real time as they move throughout the site. The system maintains a live visualization of the user's location relative to the map, enhancing situational awareness and navigation accuracy.

When a photo is captured, the application records the estimated location of the smartphone and places a virtual pin on the map corresponding to that position. In addition to the image itself, the system automatically embeds a comprehensive set of metadata including the timestamp, standard EXIF image data, geographic coordinates (latitude and longitude), local map coordinates (x, y), camera orientation (yaw, pitch, roll), and device posture. The operational screen of the Photo machine application is shown in Figure 6. This rich set of contextual information ensures that each image can serve not only as visual documentation but also as an accurate spatial data point within the broader construction management workflow.

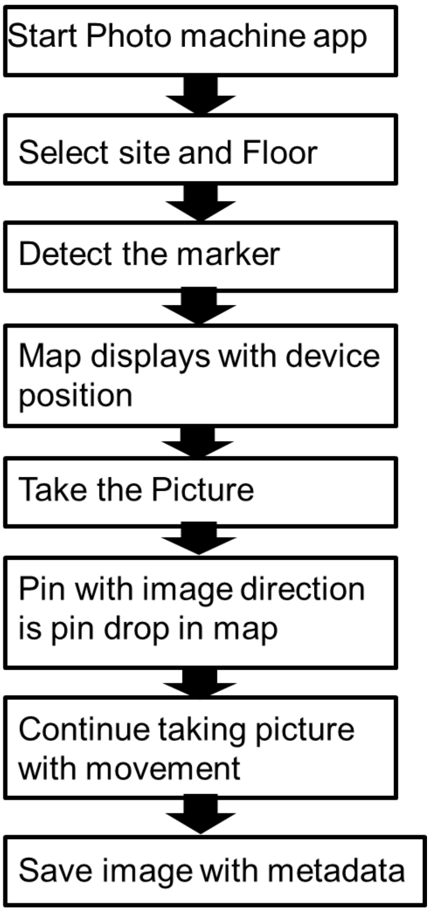

Figure 5: Flow of the Photo machine app

Figure 6: Operational screen of Photo machine app.

4 Experimentation

To verify the accuracy and practical performance of our proposed smartphone-based indoor localization system, we conducted a field experiment within a modern office building measuring approximately 80 meters in length and 30 meters in width. The objective was to simulate realistic usage scenarios such as photo documentation and spatial tagging in a GPS-denied environment.

During the experiment, a test user walked throughout the building while capturing images at various checkpoints using the Photo Machine application installed on a Huawei P30 Pro smartphone. Each image capture triggered the internal localization system to compute the user's position based on feature point tracking from the camera, inertial measurements, ToF (Time of Flight) sensor readings, and AR-based initialization.

At the time of each photo capture, a corresponding pin was automatically placed on the map view within the app. To benchmark the localization accuracy, we simultaneously recorded the GPS coordinates obtained from the smartphone's GPS module. These GPS points and the system-generated points were both exported and visualized using Google Earth.

Our observations were as follows:

- **Proposed System Accuracy:** The photo pins aligned perfectly with the intended interior positions on the digital map, with average localization error recorded below **1 cm**. Figure 7 visually demonstrates the accuracy of our proposed indoor localization system during real-world testing. It overlays two separate experimental walkthroughs (Test 1 and Test 2) inside a commercial office building. In Figure 7, The upper maps in each verification show the planned movement path and the corresponding photo capture points (numbered 1–7). The lower maps display the actual positions where the photos were automatically pinned by the application using the proposed localization algorithm. As shown, all pins are accurately aligned with the expected indoor positions, demonstrating the centimeter-level accuracy of the system. The center and right images show how the captured image metadata, including time and location, are reflected in both the mobile app UI and PC management interface.

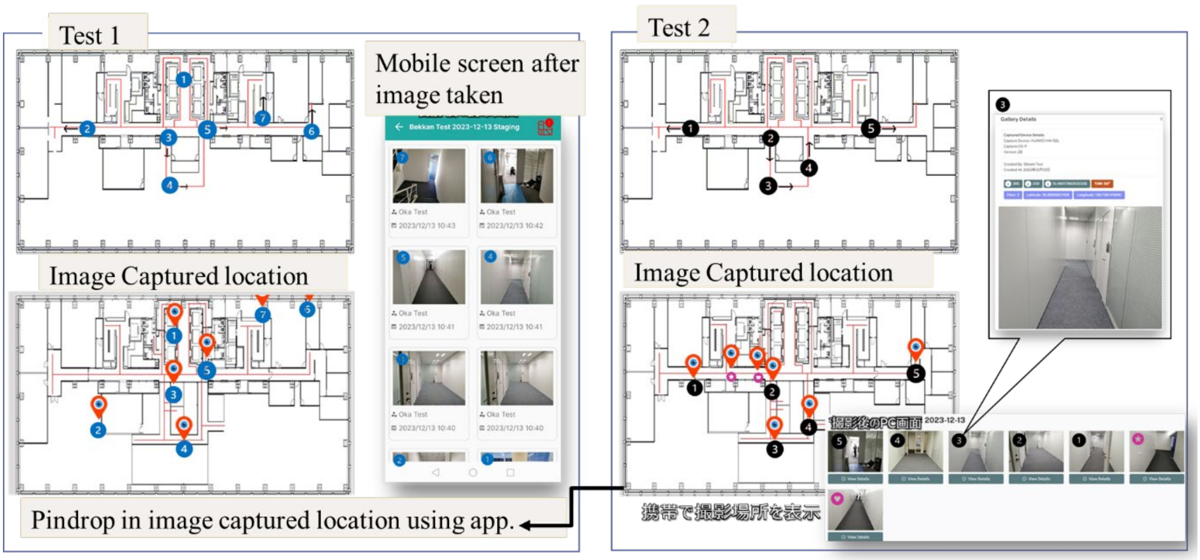

Figure 7: Image showing the accuracy of our proposed system.

- **GPS Accuracy:** The GPS data points showed large errors, often placing the user more than 5 meters away from their actual position. In some cases, the GPS even located the user outside the building. Figure 8 shows the results of the experiment comparing GPS with our proposed system. Blue arrows represent the photo locations estimated by our system. Pink arrows represent the locations estimated using GPS. As seen in the figure, the pink arrows are often outside the building layout, while the blue arrows stay correctly inside the map. This clearly shows that our system provides much more accurate positioning than GPS in indoor environments. This visual evidence confirms that the system successfully localizes and visualizes each image capture point in real time without external infrastructure. Pins generated by the system perfectly align with the expected positions on the site layout, reinforcing the system's precision.

Figure 8: Image comparing accuracy with GPS and our Proposed system.

5 Discussion and Conclusions

The experimental results confirm that our smartphone-based indoor localization system significantly outperforms conventional GPS in indoor environments. Achieving centimetre accuracy using only onboard sensors and camera of the smart phone data represents a major advancement in the domain of infrastructure free indoor positioning.

One of the key advantages of our system is that it operates entirely as a standalone solution without requiring external beacons, AR markers, Lidar scans, or pre-installed network infrastructure. This makes it highly suitable for deployment in construction sites and similar dynamic environments where GPS is unreliable, and setup conditions vary frequently.

In addition, the integration of the localization system with the Photo Machine application provides a powerful tool for visual documentation and inspection workflows. The ability to embed spatial metadata directly into construction site images along with automated map pinning can substantially reduce the time and effort required for communication, tracking, and reporting tasks.

While the current results are promising, further experiments in larger and more complex construction sites are planned to assess scalability and long-term stability. We are also exploring real-time map updates and multi-user synchronization features for future versions of the system.

In conclusion, our proposed system represents a practical, scalable, and accurate solution for indoor localization and documentation in GPS-denied environments. Its deployment on construction sites is expected to improve productivity, communication, and decision-making processes across all phases of project delivery.

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