TED UNIVERSITY

CMPE 491

Senior Design Project

"TEDU GuidAR"

Spatial Computing for Indoor Navigation

High Level Design Report

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1. Introduction

Indoor environments such as university campuses, museums, airports, hospitals, and large public buildings often pose navigation difficulties due to the lack of GPS reliability, complex layouts, and insufficient signage. To address this challenge, this project proposes an Augmented Reality (AR) Indoor Navigation System, named GuidAR, which leverages Simultaneous Localization and Mapping (SLAM) techniques to provide accurate, real-time indoor navigation support.

The system integrates the mobile device camera, Inertial Measurement Unit (IMU) sensors, and SLAM algorithms to construct a dynamic understanding of the surrounding environment. By overlaying virtual navigation cues such as arrows, labels, and directional indicators directly onto the real-world view, GuidAR aims to improve spatial awareness, reduce cognitive load, and deliver an intuitive and interactive navigation experience for users. The application is intended primarily for university environments, especially multi-floor campus buildings, but can be extended to other complex indoor spaces in the future.

1.1 Purpose of the System

The primary purpose of GuidAR is to provide a real-time, reliable, and user-friendly indoor navigation solution using augmented reality technologies. Unlike traditional 2D map-based navigation systems, GuidAR presents directions directly within the user's field of view, allowing them to follow a visual path aligned with physical surroundings.

The system seeks to:

- Enable precise localization and indoor positioning using SLAM-based tracking.
- Provide intuitive AR-based navigation with visual guidance elements.
- Support dynamic route recalculation if users deviate from the planned path.
- Assist users in locating classrooms, laboratories, offices, conference halls, and other important campus locations efficiently.
- Demonstrate the applicability of AR and spatial computing in real-world indoor navigation scenarios.

1.2 Design Goals

The design goals of the system are aligned with usability, performance, scalability, and reliability expectations of modern AR-based indoor navigation solutions. The main design goals include:

- **Real-Time Accurate Localization:**
  Achieve stable and continuous user tracking through SLAM and IMU fusion to ensure accurate positioning and smooth navigation.
- **Intuitive User Experience:**
  Provide a clean and minimal AR interface where essential information such as arrows, direction labels, turn indicators, and floor transition cues are clearly visible and easy to interpret.
- **Dynamic and Adaptive Navigation:**
  Continuously update navigation routes based on user movement and environmental changes, ensuring seamless correction when users deviate from the intended route.
- **Multi-Floor Navigation Capability:**
  Support vertical navigation, enabling guidance through elevators and staircases inside campus buildings.
- **High Performance and Stability:**
  Maintain smooth AR rendering and minimal latency to prevent motion discomfort and ensure a responsive experience.
- **Privacy and Security Awareness:**
  Ensure that visual data remains locally processed to protect user privacy and comply with ethical and professional standards.
- **Modular and Extensible Architecture:**
  Design the system so that additional buildings, maps, and AR features can be integrated easily in future work.

1.3 Definitions, Acronyms, and Abbreviations

- **AR (Augmented Reality):** Technology that overlays virtual objects and information onto the real environment through a device screen.
- **FPS (Frames Per Second)**: Frequency at which consecutive images are displayed on a screen.
- **GPS (Global Positioning System):** Satellite-based positioning technology, typically unreliable indoors.
- **IMU (Inertial Measurement Unit):** A sensor module consisting of accelerometers and gyroscopes used to measure motion and orientation.
- **SDK (Software Development Kit):** A collection of pre-built tools and libraries that allows developers to create applications for specific platforms.
- **SLAM (Simultaneous Localization and Mapping):** Technique used to construct or update a map of an unknown environment while simultaneously tracking the device's position within it.
- **POI (Point of Interest):** A specific destination within the indoor environment, such as a classroom, office, laboratory, restroom, or conference hall.
- **UI (User Interface):** Visual and interactive elements through which a user interacts with the software.

1.4 Overview

This report presents the development of the GuidAR indoor navigation system and explains its design approach, functional capabilities, system architecture, and implementation details. The following sections outline the functional and non-functional requirements, system models, user scenarios, path planning strategies, SLAM integration, AR visualization components, and system evaluation results.

The remainder of the document provides a comprehensive explanation of the technical workflow, including user interaction flow, map handling, path generation, SLAM-based localization, user interface design, performance considerations, and future enhancements of the application.

2. Proposed Software Architecture

2.1 Overview

The system will have a modular and layered architecture that will support both AR headsets MetaQuest3 and Mobile devices. The architecture will expand into perception, navigation logic, and user interaction which are independent subsystems. Therefore, we will ensure scalability, maintainability, and platform flexibility.

2.2 Subsystem Decomposition

2.2.1 Perception and Tracking Subsystem

Slam module will interact with camera and IMU sensors to build a sparse point cloud of the environment.

2.2.2 Mapping and Localization Subsystem

A point cloud mapping of the environment will be generated by SLAM module and sensors of MetaQuest3. These points will be used to estimate the user's position and align virtual objects with real-world geometry.

2.2.3 Navigation and Path Planning Subsystem

Pathfinding algorithm will use A*, which will take user coordinates and target coordinate to calculate the shortest path. Additionally, error handling system will be implemented for different states such as, navigating, idling and error.

2.2.4 Visualization and Interaction Subsystem

Visualization subsystem will draw the virtual path as arrows and lines and POI labels on top of the camera feed. Such as conference halls, dean's office, or any other video plugins. Additionally, in mobile, we will have screen overlays as usual 2D buttons. On Meta Quest 3, we will have the Spatial UI floating buttons and panels.

2.2.5 User Interface

Since this application will be on both Meta Quest 3 and mobile, we will be applying a shared design language, although platform specific inputs will be different such as touch screen versus Meta Quest 3's controllers and hand gestures.

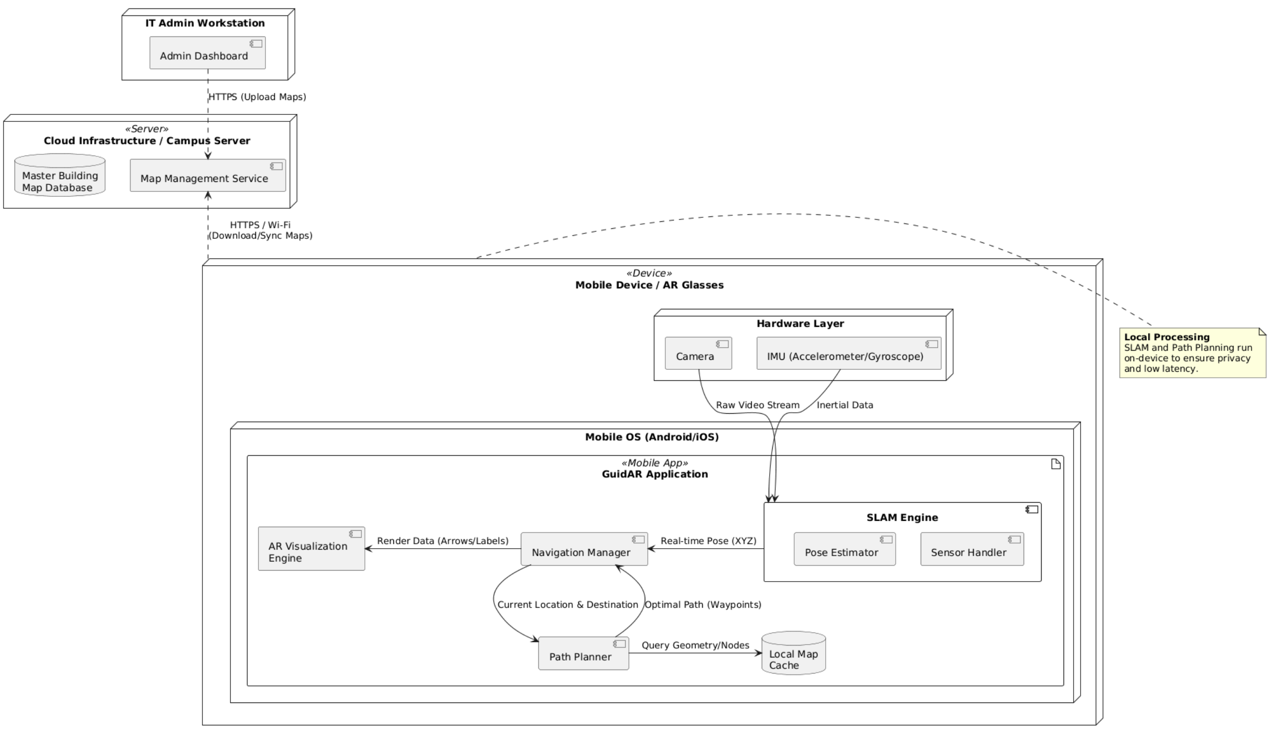
2.3 Hardware/Software Mapping

The GuidAR system is deployed on mobile devices and the Meta Quest 3 AR headset, utilizing each platform's sensing, processing, and display hardware to support real-time indoor navigation.

The Perception and Tracking Subsystem receives input from the device camera and IMU sensors, which is processed locally on the CPU/GPU to estimate the user's pose. The Mapping and Localization Subsystem and the Navigation and Path Planning Subsystem execute on the same processing hardware, accessing locally stored indoor map data to compute and update navigation paths in real time.

The Visualization and Interaction Subsystem is mapped to the GPU and display hardware, rendering AR navigation cues such as arrows, paths, and labels on the live camera view or directly within the headset's field of view. User interaction is handled through touch input on mobile devices and hand gestures or controller inputs on MetaQuest3. Core software components remain platform-independent, while hardware-specific interfaces handle sensing, rendering, and interaction.

2.3.1 Deployment Diagram



2.4 Persistent Data Management

The GuidAR system manages a limited set of persistent data required for indoor navigation and system configuration. This data is stored locally on the device to ensure low-latency access and offline operation.

Persistent data includes indoor map information, such as building layouts, floor connections, and predefined navigation nodes, as well as points of interest (POIs) including classrooms, offices, laboratories, and conference halls. Destination metadata such as room identifiers, floor numbers, and labels are also stored persistently to support search and navigation functionality.

This data is accessed by the Navigation and Path Planning Subsystem during route computation and by the Visualization Subsystem for labelling and guidance rendering. Runtime data generated by the SLAM process, including camera frames and temporary point clouds, is maintained in memory only and is not stored persistently. All persistent data is managed locally to preserve user privacy and reduce external dependencies.

2.5 Access Control and Security

The GuidAR system is designed primarily as a navigation assistance application and does not require user authentication or role-based access control for standard usage. All navigation functionality is available without login to ensure ease of access for students and visitors.

Access to device hardware components such as the camera and motion sensors is handled through platform-level permission mechanisms provided by the operating system. The application requests only the permissions required for core functionality. Persistent data such as indoor maps and points of interest is stored locally and accessed in a read-only manner during navigation to prevent accidental or malicious modification.

Optional administrative functionality, such as updating building maps or points of interest, can be restricted to authorized users or controlled through secure update mechanisms. Overall, the system prioritizes local processing, minimal data retention, and platform-enforced permissions to ensure user privacy and secure operation.

2.6 Global Software Control

The GuidAR system employs an event-driven and loop-based control flow to manage the transition between user interactions and real-time spatial processing. The control logic is divided into distinct phases that ensure the system remains responsive while maintaining a stable 60 FPS frame rate for AR rendering.

- **Initialization and State Management:** The system starts in an idle state until the user launches the application and selects a specific campus building. This triggers the Navigation Manager to initialize the SLAM module and load the corresponding building map from the database.
- **Synchronous Interaction Flow:** Searching for a destination and viewing a route preview follows a sequential request-response pattern where the UI Layer communicates with the Map & Data Layer to retrieve location coordinates.
- **Asynchronous Navigation Loop:** Once navigation begins, the system enters a high-frequency loop. In this phase, the SLAM System continuously provides camera and IMU updates to the Navigation Manager, which checks for path deviations.
- **Dynamic Interrupts:** If a user deviates from the calculated route, an interrupt is triggered to the Path Planner, which asynchronously recalculates a new optimal path without stopping the AR visualization.

2.7 Boundary Conditions

Boundary conditions define how GuidAR handles system startup, termination, and exceptional environmental constraints to ensure a robust user experience.

2.7.1 System Startup and Initialization

- **Environment Scanning:** Upon startup, the system requires a "warm-up" period of a few seconds where the user must scan the environment to allow SLAM to identify current coordinates.
- **Sensor Readiness:** The application must verify that the camera and IMU sensors are operational and have granted permissions before proceeding to the navigation interface.

2.7.2 System Termination

- **Destination Arrival:** The system identifies arrival when the user's coordinates match the destination's predefined proximity, triggering a confirmation message and ending the navigation loop.
- **Manual Exit:** Users can terminate the session at any time via the "X" button on the UI, which commands the Navigation Manager to stop sensor tracking and clear temporary path data.

2.7.3 Failure and Exceptional Conditions

- **Tracking Loss:** If SLAM tracking is lost due to rapid movement or obscured camera views, the system must prompt the user to re-scan the area to realign the path.
- **Environmental Constraints:** The system is designed to operate under "typical university lighting conditions"; however, extreme darkness or high-glare environments act as a boundary where SLAM accuracy may degrade.
- **Navigation Limits:** Handling vertical transitions (elevators and stairs) requires the system to detect floor changes and realign the 3D map to the new level.

2.7.4 Performance Constraints

Condition	**Constraint**
Latency	AR rendering must maintain minimal latency to prevent visual "jumps".
Frame Rate	A stable 60 FPS is required for responsive visualization
Data Privacy	No external transmission of camera data is allowed; all SLAM processing must remain local.

3. Subsystem services

3.1 SLAM and Sensor Subsystem

This subsystem serves as the foundation for spatial awareness by processing raw hardware data to understand the user's physical context.

- **Real-Time Localization:** Utilizes the device camera and Inertial Measurement Unit (IMU) sensors to track user movement and position continuously.
- **Environment Mapping:** Employs SLAM algorithms to generate a dynamic 3D understanding of the surrounding environment.
- **Sensor Data Fusion:** Integrates visual and inertial sensor data to maintain tracking stability even in complex indoor settings.

3.2 Navigation and Path Planning Subsystem

This core logic layer handles the intelligence behind finding the most efficient way to a destination.

- **Optimal Path Calculation:** Computes the best route to selected destinations such as classrooms, laboratories, or offices.
- **Dynamic Route Recalculation:** Automatically updates and recalculates the navigation path if the user deviates from the original route or if the environment changes.
- **Multi-Floor Navigation Support:** Manages vertical transitions, guiding users through stairs or elevators to reach destinations on different levels of a campus building.

3.3 Map and Data Management Subsystem

This subsystem manages the static and dynamic data required for university-wide navigation.

- **Destination Database:** Maintains a searchable directory of predefined locations, including instructor offices and conference halls.
- **Map Storage and Retrieval:** Loads specific campus building maps (e.g., D Block Ground Floor, K Block First Floor) upon application initialization.
- **System Maintenance:** Allows administrators to upload and update building maps to ensure the navigation data remains current.

3.4 AR Visualization and UI Subsystem

This subsystem is responsible for the user-facing elements, blending virtual information with the physical world.

- **AR Overlay Rendering:** Superimposes virtual directional arrows, labels, and floor transition indicators onto the real-world camera feed.
- **Interactive Interface:** Provides an intuitive UI for destination search, route previews, and real-time feedback during the walk.
- **Privacy-Centric Processing:** Ensures that camera data is processed locally on the device to protect user privacy.

4. Glossary

AR: Augmented-Reality

FPS: Frames per Second

GPS: Global Positioning System

IMU: Inertial Measurement Unit

SDK: Software Development Kit

SLAM: Simultaneous localization and mapping

POI: Point of interest

UI: User Interface

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