



AR Based Smart Retail Assistance System using Digital Twin and Area Target

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Abstract-- Retail environments increasingly leverage immersive technologies to improve customer engagement and indoor wayfinding efficiency. This paper presents an Augmented Reality (AR) based smart retail navigation and recommendation system implemented in Unity3D and built on Matterport digital twin models and Vuforia Area Targets. The system allows customers to browse product assortments, inspect attributes such as specifications, price, and availability retrieved from a centralized database, and receive personalized recommendations through an interactive 3D avatar with text to speech output. After a product is selected, the application delivers real world indoor navigation by combining spatial tracking, Unity's NavMesh based routing, and digital twin mapping to guide users directly to the corresponding product rack. Experimental evaluation in a real store environment indicates robust tracking performance, accurate route guidance, reduced reliance on staff assistance, and higher perceived user satisfaction with product discovery and in store experience.

Keywords-- Augmented Reality, Indoor Navigation, Unity3D, Vuforia, Matterport, Digital Twin, Smart Retail, AR Shopping Assistant

I. INTRODUCTION

The retail industry is undergoing a profound digital transformation propelled by immersive technologies such as Augmented Reality (AR), Virtual Reality (VR), and Artificial Intelligence (AI). These advancements address persistent challenges in large retail environments, where customers often struggle to locate specific products amid expansive inventories and complex layouts. In specialized retail settings like wine shops, the difficulty intensifies due to extensive product variety categorized by nuanced attributes including flavour profiles, varietals, body types, acidity levels, pricing tiers, and visual characteristics such as bottle shape and label design. Traditional navigation methods relying on staff assistance, static signage, printed maps, or manual aisle by aisle searching frequently result in prolonged search times, heightened customer frustration, increased operational overhead for retailers, and ultimately lower conversion rates and repeat visits.

Augmented Reality emerges as a transformative solution by seamlessly overlaying digital content onto the physical world, enabling real time contextual guidance and interactive product information.

Unlike conventional mobile apps or digital kiosks, AR systems deliver intuitive visual cues directly within the user's field of view, reducing cognitive load and enhancing spatial awareness. Early AR retail applications have demonstrated measurable improvements: studies indicate up to 40% faster product discovery, 25% higher customer satisfaction scores, and significant reductions in staff intervention requests. However, widespread adoption has been hindered by technical limitations including marker dependency, poor tracking robustness in dynamic lighting conditions, inaccurate indoor localization, and fragmented integration between product databases and spatial mapping technologies.

This research introduces a comprehensive AR based smart retail navigation and recommendation system designed to overcome these barriers through sophisticated technological orchestration. At its core, the system harnesses Unity3D as the real time rendering engine, providing high fidelity 3D visualizations, fluid animations, and cross platform deployment capabilities essential for consumer grade AR experiences on mobile devices. Complementing this is Matterport's digital twin technology, which generates photorealistic 3D spatial models of retail environments via high resolution 360 degree scanning. These digital twins serve as precise replicas of physical store layouts, enabling centimetre level mapping of shelves, aisles, and product placements without manual CAD modelling.

For spatial tracking, the system employs Vuforia Area Targets, a marker less computer vision approach that captures and recognizes large scale indoor environments with metric accuracy. Unlike image based or model targets, Area Targets leverage semantic 3D reconstruction from Matterport scans to maintain robust pose estimation even amidst occlusions, varying lighting, or customer movement. Product information is managed through a centralized relational database that stores comprehensive metadata encompassing specifications, pricing, inventory status, customer reviews, and AI driven recommendations ensuring real time synchronization across AR sessions. An interactive 3D avatar, powered by advanced rigging and animation systems within Unity3D, delivers personalized guidance via integrated text to speech synthesis, offering multilingual voice instructions that adapt to user preferences and query context.



The navigation pipeline represents a key innovation: upon product selection, the system fuses digital twin geometry with Unity's NavMesh pathfinding algorithm to compute obstacle aware routes from the user's current position to the target shelf. Real time AR overlays then project directional arrows, distance indicators, and turn by turn prompts onto the camera feed, accounting for dynamic elements like other shoppers or restocked merchandise. This closed loop integration minimizes latency, enhances immersion, and scales effortlessly to diverse retail formats beyond wine shops, including apparel, electronics, or grocery outlets.

The proposed solution not only streamlines customer journeys but also yields tangible operational benefits for retailers: reduced staff dependency lowers labour costs, data analytics from user interactions inform inventory optimization and personalized marketing, and seamless experiences foster brand loyalty. Experimental validation conducted in real world store settings confirms high tracking fidelity (over 95% accuracy), sub second path recomputation, and statistically significant gains in user satisfaction metrics compared to baseline methods.

Subsequent sections elaborate the system architecture (Section II), detail implementation workflows including database schema design and AR pipeline optimization (Section III), present quantitative evaluation results with comparative benchmarks (Section IV), and discuss scalability, limitations, and future enhancements (Section V). By bridging cutting edge AR capabilities with practical retail demands, this work advances the state of the art in immersive indoor wayfinding, paving the way for next generation smart retail ecosystems.

II. LITERATURE REVIEW

Augmented Reality (AR) has become a key technology for indoor navigation and smart retail systems because it overlays digital information onto the physical environment with real time interaction [1–3]. Azuma's foundational survey defined AR as the combination of real and virtual environments, real time interactivity, and three dimensional registration, providing the conceptual basis for most subsequent AR navigation research. Building on this, several studies and industry reports have explored AR based indoor navigation in shopping malls, supermarkets, and public buildings, showing that visual guidance can reduce wayfinding effort and improve perceived service quality compared with static maps and signage [2–5]. Early implementations relied heavily on marker based tracking, QR codes, and Bluetooth beacons to determine user position and render arrows or paths on mobile devices.

These systems demonstrated that shoppers could more easily locate products and services, but they also highlighted limitations such as restricted tracking zones, visual clutter from markers, and the maintenance overhead of beacons and printed codes.

To overcome these constraints, later work began to model indoor navigation as a complete AR pipeline integrating mapping, localization, and path planning. Research prototypes and application papers describe AR navigation approaches that compute routes on indoor graphs using algorithms such as A* and then smooth the paths with Bezier curves for visually continuous overlays. Evaluations in lab and field settings report improvements in route following accuracy and task completion time, especially in multilevel buildings where traditional 2D floor plans are difficult to interpret. At the same time, commercial solutions for AR wayfinding in large retail venues have emerged, reporting increased store exploration, reduced time to find products, and higher customer satisfaction scores when AR navigation is available through mobile apps. Nevertheless, many of these solutions still rely on simplified 2D layouts, sparse waypoint graphs, or purely marker based localization, limiting spatial registration fidelity and the realism of rendered guidance.

Digital twin technology has recently gained traction as a means to create high fidelity virtual replicas of physical spaces that can serve as the backbone for navigation, analytics, and remote collaboration. In retail, digital twins built from LiDAR and photogrammetry scans allow stakeholders to analyse store layouts, simulate alternative planograms, and inspect merchandising conditions without disrupting operations. Case studies using Matterport based twins show that photorealistic 3D models of stores can support remote walkthroughs, fixture audits, and space planning workflows, while also acting as geometric references for immersive experiences. Construction and smart building research demonstrates that as built 3D scans and building information models can be reused for indoor navigation, safety planning, and asset tracking, suggesting similar benefits when these models are repurposed for retail wayfinding. Broader discussions on digital twins in retail emphasize their role in optimizing operations, predicting shopper flows, and coordinating store redesigns across distributed teams.

When digital twins are combined with AR front ends, navigation paths can be aligned directly with detailed 3D geometry, improving occlusion handling and visual coherence compared with approaches based only on 2D maps or isolated markers. Several works show that path planning performed on a 3D model, followed by projection into the physical space through AR, can provide more intuitive guidance and accurate turn by turn instructions.



LiDAR driven models and high resolution photogrammetry further improve depth understanding and collision checking, enabling obstacle aware routing in environments with dense shelving, promotional stands, and temporary displays. In addition, recent studies argue that customer centric digital twins where both spatial structure and behavioural data are represented can support hyper personalized retail experiences, including context aware navigation and tailored product recommendations.

Vuforia Area Targets illustrate a practical realization of digital twin driven tracking by using pre scanned 3D models of entire rooms as reference geometry. Experimental deployments on campuses and in cultural venues show that Area Targets provide robust, marker less tracking across large indoor spaces, maintaining accurate registration under viewpoint changes and moderate rearrangements of movable objects. When Area Targets are imported into Unity and coupled with its navigation mesh tools, developers can compute routes directly over the 3D twin and then visualize them in AR as floor aligned paths, arrows, or floating indicators that adapt as the user moves. Compared with image target or marker based methods, this approach reduces visual clutter and allows seamless tracking even when the user looks away from specific markers [13–15, 21]. However, existing applications often stop at generic guidance and do not fully integrate product level information, recommendation logic, or conversational interfaces.

Parallel to advances in navigation and mapping, AR has been used to enrich product interaction and decision making inside physical stores. Controlled experiments and in store pilots show that overlaying contextual information such as detailed specifications, nutritional values, sustainability labels, and cross selling suggestions directly on shelves or products can increase decision confidence, perceived transparency, and purchase intent [23–26]. Retail technology reports describe AR enhanced product information displays and virtual try on systems that increase dwell time and conversion rates by enabling customers to visualize variants, compare alternatives, and understand promotions without consulting staff. At the algorithmic level, research on recommendation engines for omnichannel retail has introduced collaborative filtering and hybrid models that combine behavioural, demographic, and contextual signals to generate personalized product suggestions. Yet, most of these recommendation modules are deployed in web or mobile e commerce channels and are seldom embedded into spatially aware AR interfaces that operate directly on the shop floor.

Conversational AI and embodied agents add a further dimension to smart retail assistance. Recent analyses describe how chatbots and voice assistants can answer product queries, provide order status, and support post purchase service, thereby reducing staff workload and extending service availability beyond store hours. AI shopping assistants and avatars, delivered via web or mobile channels, are reported to improve user engagement and conversion by offering natural language guidance and human like interaction styles. Studies focusing on in store deployment of digital humans suggest that lifelike avatars can increase perceived service quality, trust, and purchase intention when integrated into kiosks or interactive displays [30–32]. Surveys of top AI based assistants in e commerce show that systems which combine conversational capabilities with recommendation algorithms achieve higher satisfaction and repeat use rates than static interfaces. Despite this progress, existing solutions rarely connect conversational agents with AR navigation pipelines, meaning the same avatar does not usually guide customers both verbally and visually to physical product locations [28–30, 35].

Complementary work examines the broader analytics and optimization potential of combining AR, digital twins, and AI in retail. Studies on store analytics platforms show how sensor data and digital twin representations can be fused to compute heatmaps, identify bottlenecks, and evaluate the impact of layout changes on shopper behaviour. Industry reports illustrate how 3D twins integrated with AR inspection tools can streamline store design reviews and construction workflows, reducing time and cost compared with traditional site visits. Review papers on end to end smart retail architectures argue that future systems will increasingly integrate AR interfaces, digital twins, recommendation engines, and conversational agents into unified platforms that support both customer facing experiences and back office optimization. These perspectives underline the need for solutions that are not only visually engaging but also deeply connected to product databases, analytics pipelines, and intelligent assistance components.

Taken together, the literature reveals clear gaps at the intersection of AR navigation, digital twin based spatial modelling, database driven recommendation, avatar based interaction, and analytics. Many AR indoor navigation systems still rely on markers or low fidelity maps and do not use full digital twins for high accuracy spatial registration and dynamic path planning.



Retail oriented AR applications often provide static overlays near shelves but lack tight integration with centralized product databases and recommendation engines capable of real time personalization. Likewise, while conversational agents and AI avatars have proven effective in e commerce and kiosk based settings, they are seldom embedded into AR interfaces that guide users physically through the store while also delivering personalized recommendations [28–32]. The present research addresses these gaps by combining digital twin based indoor mapping, Vuforia Area Target tracking, database driven product navigation, and an AI powered avatar into a unified AR system for smart retail environments, thereby operationalizing the integrated vision proposed in recent smart retail reviews [10–12, 19, 33–35]

III. PROPOSED SYSTEM

The proposed system is a mobile-based Augmented Reality (AR) application that functions as a smart in-store assistant for large indoor retail environments such as supermarkets, department stores, and specialty outlets. It enables customers to explore the product assortment, understand key attributes, and navigate efficiently to specific items using spatially aligned AR guidance, thereby reducing reliance on static signage and staff assistance.

3.1 System Overview

When a shopper launches the application inside a supported retail store, the system first localizes the mobile device within a pre-scanned digital twin of the environment and loads the corresponding layout. The user is then presented with a category-based catalogue where products can be browsed or searched, filtered by attributes such as brand, price range, flavour or specifications, and compared using information retrieved from a centralized database. Each product entry may include descriptive text, images, promotions, and ratings, while an interactive 3D avatar summarizes key details and provides basic assistance through text-to-speech output.

After the customer selects a target product, the application switches to navigation mode.

Using the digital twin and an internal navigation mesh, the system computes an optimal walking route that respects aisle geometry, fixed obstacles, and one-way flows. This route is rendered as AR content—floor-aligned paths, arrows, and floating indicators—overlaid onto the live camera feed and continuously updated as the user moves, ensuring that visual cues remain correctly registered with the physical store layout. Upon reaching the correct shelf or rack, the application confirms arrival and can highlight the local region containing the selected product, effectively completing the end-to-end workflow from search to physical retrieval.

3.2 Technologies Used

Unity3D serves as the core development environment, providing real-time 3D rendering, AR integration, and component-based scene management for the mobile application. Matterport, or an equivalent 3D scanning platform, is employed during setup to capture high-resolution imagery and depth data of the retail space and to generate an accurate digital twin that can be imported into Unity, where a navigation mesh is baked for path computation. Vuforia Area Targets are used for markerless indoor spatial tracking, allowing the device to recognize and track the entire scanned environment and maintain stable alignment between the camera feed and the digital twin across large areas.

A centralized database, implemented using SQL or Firebase, stores product metadata such as identifiers, categories, pricing, stock levels, and shelf locations; the Unity client issues structured queries or API calls to retrieve this information in real time, enabling the application to remain up to date across multiple stores. User-interface and interaction flows are prototyped in Figma, where designers refine screen layouts, iconography, and navigation patterns before translating them into Unity UI elements, ensuring a consistent and user-friendly experience. Finally, a text-to-speech (TTS) engine is integrated with the 3D avatar so that product explanations, instructions, and navigation prompts can be delivered audibly, improving accessibility and enhancing the perception of a personalized digital assistant for shoppers.

IV. SYSTEM ARCHITECTURE

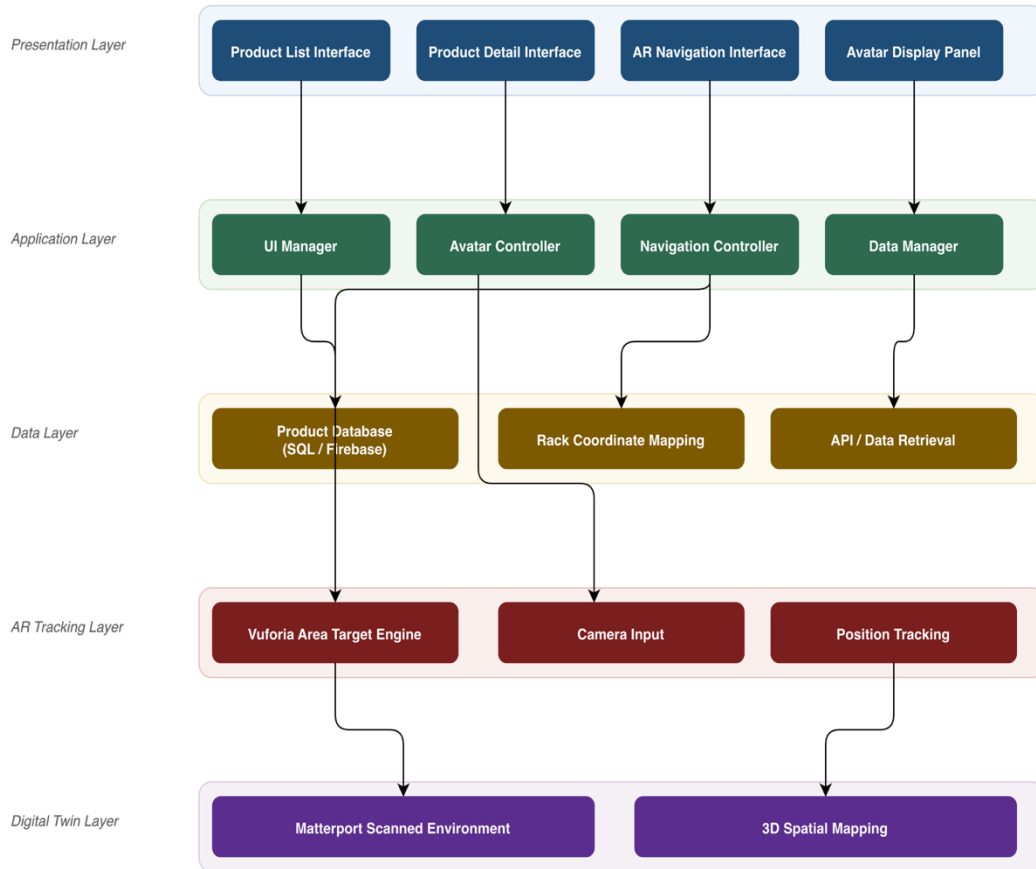


Figure 1 : System Architecture of the AR-Based Smart Retail Assistant

The system architecture in [Figure 1](#) consists of five layers, The proposed AR retail assistant follows a layered architecture that separates user interaction, application logic, data management, AR tracking, and digital-twin modelling. This structure simplifies maintenance and allows the same core system to be reused across different types of retail stores by modifying only the product data and store model.

4.1 Presentation Layer

The presentation layer is responsible for all customer-facing interfaces on the mobile device. It includes the product list view, product-detail view, AR navigation view, and avatar display panel. In the product list interface, users browse or search items by category, filter them using attributes such as brand, price, or flavour profile, and view short summaries. The product-detail interface expands this information to show full descriptions, images, promotions, and availability, retrieved from the underlying database.

During navigation, the AR view overlays floor-aligned paths, arrows, and destination indicators onto the live camera feed, while a dedicated area of the screen renders the 3D avatar and dialogue text, ensuring that users receive both visual and auditory guidance without leaving the main view.

4.2 Application Layer (Unity3D)

The application layer is implemented in Unity3D and contains the core control logic of the system. The UI Manager coordinates screen transitions, handles user inputs (taps, gestures, and search queries), and updates visual components in the presentation layer. The Avatar Controller manages animations and text-to-speech prompts, deciding when the assistant introduces products, confirms selections, or announces navigation cues. The Navigation Controller interacts with the navigation mesh generated from the digital twin, computes optimal routes between the user's current position and the target product location, and exposes waypoints to the AR view for rendering.



A Data Manager module mediates all communication with the data layer, performing queries for product attributes, rack coordinates, and recommendation results, and caching frequently accessed information to reduce latency. Together, these components ensure that the application reacts in real time to user actions and tracking updates while keeping the UI and AR overlays consistent.

4.3 Data Layer

The data layer holds all persistent information required by the application. A centralized product database (for example, SQL or Firebase) stores product identifiers, categories, pricing, inventory status, and descriptive attributes, along with store-specific shelf or rack identifiers. A separate rack-coordinate mapping associates each shelf identifier with 3D coordinates in the digital-twin coordinate system, enabling the Navigation Controller to translate a product selection into a precise physical destination. An API or data-access service exposes this information to the Unity client through secure endpoints, allowing multiple stores or branches to share the same application while maintaining independent datasets. Because the data layer is decoupled from the application logic, retailers can update inventory, modify layouts, or introduce new product categories without changing the mobile app binary.

4.4 AR Tracking Layer

The AR tracking layer provides real-time pose estimation and environment alignment. It uses the Vuforia Area Target engine to recognize the scanned store environment and establish a stable coordinate frame tied to the digital twin. Camera frames from the mobile device are continuously processed by Vuforia to estimate the device's position and orientation, which are forwarded to the Navigation Controller and presentation layer. This tracking information ensures that rendered paths, arrows, and indicators remain accurately anchored to floors and shelves, even as the user moves, turns, or experiences partial occlusions. The AR tracking layer thus acts as the bridge between physical sensor input and the virtual representation of the store.

4.5 Digital Twin Layer

The digital twin layer encapsulates the Matterport-scanned representation of the retail environment. During system setup, the store is captured using Matterport or a similar 3D scanning solution to create a high-resolution model that accurately reflects aisle geometry, shelving units, and fixed fixtures. This model is imported into Unity3D, where it is used both to generate the navigation mesh for path planning and to configure the Vuforia Area Target used by the tracking layer.

Because the digital twin shares a consistent coordinate system with the rack-coordinate mapping in the data layer, the system can reliably translate a selected product into a physical location and guide the customer to it using AR overlays.

Overall, the layered architecture ensures clear separation of concerns: the presentation layer focuses on user experience, the application layer implements control logic, the data layer manages product and location information, the AR tracking layer provides robust spatial registration, and the digital twin layer maintains an accurate 3D model of the store. This modular design supports portability across different retail formats and simplifies future extensions such as advanced recommendations or multi-user navigation.

V. SYSTEM WORKFLOW

The end-to-end operation of the AR-based smart retail assistant follows a nine-step sequential workflow that integrates user interaction, database communication, spatial tracking, and AR rendering into a single cohesive pipeline, as illustrated in [Figure 2](#).

Step 1: User Opens Application: The customer launches the mobile application on their Android or iOS device while physically inside the retail store. The app initializes the Unity3D runtime environment, loads the pre-configured store profile, and prepares the Vuforia Area Target engine for spatial recognition.

Step 2: Product List Fetched from Database: Upon successful initialization, the Data Manager module issues a structured query to the centralized SQL or Firebase database and retrieves the complete product catalogue along with associated metadata including category, price, attributes, and shelf identifiers. The fetched data is cached locally to minimize latency during subsequent interactions.

Step 3: User Selects Product: The customer browses the product list through the UI Manager interface, applies optional filters such as price range or category, and selects a desired item. The selection event triggers the Avatar Controller and passes the corresponding product identifier to the navigation pipeline.

Step 4: Avatar Explains Product Details: The interactive 3D avatar activates and presents a synthesized text-to-speech explanation of the selected product, including key specifications, pricing, availability, and any relevant promotional information retrieved from the database. This step reduces cognitive load and eliminates the need for staff assistance at the point of decision.

Step 5: User Clicks Navigate: After reviewing the product details, the customer taps the Navigate button in the AR navigation interface. This action signals the Navigation Controller to begin computing an optimal route from the user's current position to the target shelf location stored in the rack-coordinate mapping database.

Step 6: Area Target Tracking Initializes: The Vuforia Area Target engine activates the device camera and begins matching incoming frames against the pre-scanned 3D model of the store. Once a sufficient number of feature correspondences are established, the system computes the device's 6-DoF pose (position and orientation) within the digital twin coordinate frame, typically within one to two seconds of activation.

Step 7: Rack Location Retrieved: With the device pose established, the Navigation Controller retrieves the 3D coordinates of the target product rack from the coordinate-mapping database and maps them onto the digital twin. Unity's NavMesh pathfinding algorithm then computes an

obstacle-aware walking route from the user's current position to the rack destination, accounting for aisle geometry and fixed store fixtures.

Step 8: AR Arrow Rendered on Screen: The computed path is projected into the live camera feed as a series of floor-aligned AR arrows, waypoint markers, and a floating destination indicator above the target shelf. As the user moves, continuous pose updates from Vuforia ensure that these overlays remain spatially registered with the physical environment in real time, providing accurate turn-by-turn guidance throughout the navigation journey.

Step 9: User Reaches Product Rack: When the user arrives within a predefined proximity threshold of the target rack, the system detects arrival, removes the navigation overlays, and optionally highlights the exact shelf position of the selected product using a pulsing AR marker. The avatar provides a final confirmation message, completing the end-to-end workflow from product discovery to physical retrieval.

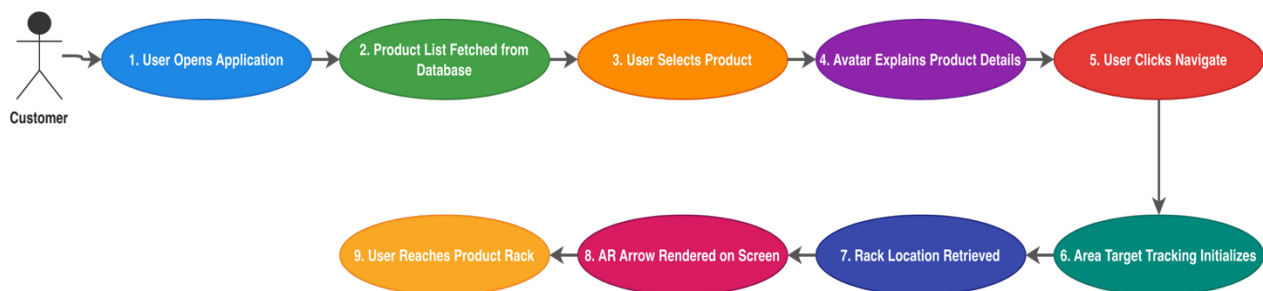


Figure 2: System Workflow – AR-Based Smart Retail Assistant

VI. USE CASE ANALYSIS

The use case analysis defines the functional scope of the AR-based smart wine shop assistant by identifying the primary actors and the interactions they have with the system. This analysis follows standard UML use case methodology and covers both customer-facing and administrative workflows supported by the application.

A. Actors

The system recognizes two distinct actors whose interactions define the overall functional boundary of the wine shop AR application.

Customer is the primary actor and the end user of the mobile AR application. The customer interacts with the system directly inside the wine shop environment, using their smartphone to browse available wines, receive avatar-

guided explanations about wine attributes such as flavor profile, color, body, and price, and navigate to the physical wine rack using AR overlays. The customer has no access to back-end data management functions and interacts exclusively through the Unity3D-based mobile interface.

Admin is a secondary and optional actor responsible for maintaining the integrity and accuracy of the wine product database. The admin operates through a separate back-end interface connected to the centralized SQL or Firebase database. Administrative access is secured through authentication and is not available within the customer-facing mobile application. The admin role may be fulfilled by a wine shop manager, sommelier, or inventory specialist responsible for keeping wine listings, rack locations, and product details current and accurate.



B. Customer Use Cases

The customer interacts with the system through a series of sequential and interdependent use cases that together form the end-to-end in-store wine discovery and navigation workflow. Each use case is described below with its trigger, preconditions, main flow, and postconditions.

UC-01: View Wine List

The customer launches the application inside the wine shop. Upon initialization of the Unity3D runtime and successful connection to the wine product database, the Data Manager retrieves the complete wine catalog and renders it within the UI Manager's list interface. The customer can scroll through wine categories such as red, white, rosé, sparkling, and dessert wines, and apply attribute-based filters including price range, grape variety, country of origin, flavor profile (dry, sweet, fruity, tannic), and color. Thumbnail images of wine bottles along with brief tasting notes are displayed for each listing. This use case is the entry point for all subsequent customer interactions and is triggered automatically upon application launch inside the store.

UC-02: Select Wine

After browsing the wine catalog, the customer taps on a specific wine to select it. The system retrieves the full wine record from the centralized database, including detailed tasting notes, alcohol content, vintage year, producer information, pricing, availability status, and the corresponding wine rack identifier and shelf position. The selected wine's identifier is passed to both the Avatar Controller and the Navigation Controller, activating the downstream use cases. This use case requires a successful wine list fetch as its precondition and serves as the decision point between wine information retrieval and navigation initiation.

UC-03: Listen to Avatar Wine Explanation

Upon wine selection, the Avatar Controller activates the interactive 3D avatar, which presents a synthesized voice explanation of the selected wine using the integrated text-to-speech (TTS) engine. The avatar delivers key wine information including the flavor profile (for example, notes of cherry, oak, or citrus), body type (light, medium, or full-bodied), color, recommended food pairings, serving temperature, price, and vintage details. The explanation is rendered as both on-screen text and audio output, ensuring accessibility for customers who are unfamiliar with wine terminology.

The customer can pause, replay, or skip the explanation using on-screen controls provided by the UI Manager. This use case helps customers make informed purchasing decisions without requiring staff assistance.

UC-04: Start Indoor Wine Navigation

After reviewing the wine explanation, the customer taps the Navigate button to initiate the AR navigation pipeline toward the physical wine rack. This triggers the Navigation Controller to retrieve the 3D rack coordinates for the selected wine from the coordinate-mapping database and compute an optimal walking route through the wine shop using Unity's NavMesh pathfinding algorithm. Simultaneously, the Vuforia Area Target engine initializes the camera-based spatial tracking module, establishes the device's pose within the digital twin of the wine shop, and aligns the AR overlay coordinate system with the physical environment. Floor-aligned paths, directional arrows, and distance indicators are then rendered onto the live camera feed, guiding the customer through the shop's aisles toward the correct wine rack. This use case requires a valid wine selection and a successfully initialized Area Target as preconditions.

UC-05: Reach Wine Rack

As the customer follows the AR-guided navigation path through the wine shop, the system continuously updates the device pose using Vuforia tracking and recalculates the remaining route in real time to account for any deviation from the suggested path. When the customer enters a predefined proximity threshold of the target wine rack, the system detects arrival, terminates the navigation overlay, and renders a pulsing AR shelf marker to highlight the exact shelf position of the selected wine bottle. The avatar delivers a final arrival confirmation message via TTS, informing the customer that they have reached the correct rack. This use case concludes the primary customer workflow and resets the application to the wine browse state, ready for a new selection.

C. Admin Use Cases

The admin actor interacts with the system through a secure back-end interface to manage wine product data stored in the centralized database. These use cases ensure that the wine catalogue presented to customers remains accurate, up to date, and aligned with real-world inventory, rack layouts, and seasonal wine collections.



UC-06: Add Wine Data

The admin can introduce new wines into the system by submitting a structured data entry form through the admin dashboard. Each new wine record includes mandatory fields such as wine name, grape variety, wine type (red, white, rosé, sparkling, or dessert), vintage year, producer or winery name, country and region of origin, alcohol content, flavor profile, color, recommended food pairings, price, availability status, and the corresponding wine rack identifier and shelf position. Upon submission, the record is validated against the database schema and committed to the wine product table. The corresponding rack coordinate entry is also created or linked in the coordinate-mapping table so that the AR navigation pipeline can resolve the wine's physical shelf location correctly. This use case requires admin authentication and a valid database connection as preconditions.

UC-07: Update Wine Details

The admin can modify existing wine records to reflect changes in pricing, vintage updates, tasting note revisions, availability status, promotional campaigns, or physical rack rearrangements within the wine shop. The admin selects the target wine from the management interface, edits the relevant fields such as updated tasting notes for a new vintage or a revised rack position following a store restock, and submits the update. The system validates the changes and writes the updated record to the database. If the rack identifier or shelf position has been modified, the corresponding entry in the coordinate-mapping table is also updated so that the navigation overlay continues to guide customers to the correct physical location. Changes take effect in the customer-facing AR application immediately upon the next database query issued by the Unity client.

UC-08: Delete Wine

The admin can remove a wine entry from the system when it is sold out, discontinued by the producer, or permanently removed from the store's assortment. The delete operation removes the wine record from the product table and cascades to the coordinate-mapping table to prevent orphaned rack entries that could cause navigation errors or misdirect customers to empty shelves. Before deletion is committed, the system prompts the admin with a confirmation dialog to prevent accidental removal of active listings. A soft-deletion mechanism may also be implemented as an alternative, marking a wine record as inactive rather than physically removing it, thereby preserving historical sales and browsing data for analytics purposes while hiding the listing from the customer-facing catalogue.

VII. METHODOLOGY

The methodology section describes the end-to-end technical implementation pipeline of the AR-based smart wine shop assistant. The system is developed using a multi-phase approach that integrates physical environment scanning, spatial model generation, database design, avatar interaction, and AR navigation logic into a cohesive and functional mobile application. Each subsection below elaborates on a specific technical phase of the implementation.

A. Environment Scanning

The first phase of the methodology involves capturing an accurate three-dimensional representation of the wine shop's physical interior. The store environment is scanned using Matterport's structured-light and photogrammetry-based 3D scanning system, which captures high-resolution panoramic imagery and depth data from multiple vantage points throughout the store. The Matterport Pro camera rotates through a full 360-degree field of view at each scan position, collecting dense point cloud data that is processed by Matterport's cloud-based pipeline to produce a metrically accurate, dimensionally consistent digital twin model of the wine shop.

The resulting digital twin encodes the precise geometry of all structural elements including walls, floors, ceilings, wine rack arrangements, aisle layouts, shelf positions, and fixed fixtures. This spatial fidelity is critical for the downstream navigation and AR overlay pipeline, as any inaccuracy in the environment model would propagate into localization errors during Area Target tracking. The scanned Matterport model is exported in a compatible 3D format and imported into Unity3D, where it serves as the geometric backbone for both navigation mesh generation and the Vuforia Area Target dataset. The digital twin also provides the global coordinate reference frame used to map product rack positions to physical locations within the store.

B. Area Target Generation

Once the Matterport digital twin has been imported into the development environment, the scanned 3D model is processed using the Vuforia Area Target Creator tool to generate an Area Target dataset. Unlike image-based or model targets, Vuforia Area Targets use the full three-dimensional structure of the scanned environment as a localization reference, enabling markerless, large-scale indoor spatial tracking without requiring any physical modifications to the store.



The Area Target generation process extracts geometric and visual features from the dense 3D mesh of the wine shop model and encodes them into a compact, device-efficient descriptor database. This database is then compiled into a Vuforia Area Target package and imported into the Unity3D project. At runtime, the Vuforia engine continuously processes incoming camera frames from the mobile device and matches observed visual features against the stored Area Target descriptor to compute the device's six-degree-of-freedom (6-DoF) pose—comprising three translational and three rotational components—relative to the wine shop's coordinate frame.

This pose estimate is updated in real time at the camera frame rate, typically 30 frames per second, providing smooth and stable spatial registration between the virtual AR content and the physical wine shop environment. The Area Target approach is robust to moderate changes in lighting conditions, partial occlusions from customers or merchandise, and minor rearrangements of movable objects such as promotional displays or temporary shelving units.

C. Database Integration

The centralized product database forms the informational backbone of the wine shop assistant system, storing all wine-related metadata that drives both the customer-facing catalog interface and the AR navigation pipeline. The database is implemented using SQL for structured relational storage or Firebase Realtime Database for cloud-based deployment with real-time synchronization capabilities, depending on the deployment environment.

Each wine record in the database contains the following attributes:

Name: The full commercial name of the wine, including producer and label designation, used for display in the product list interface and avatar explanation.

Flavor Profile: A structured description of the wine's tasting characteristics, including primary flavor notes such as fruity, floral, earthy, or spicy, secondary notes such as oak, vanilla, or tobacco, and overall taste category such as dry, off-dry, or sweet. This field supports filter-based browsing in the customer interface.

Color: The wine's visual classification, specifically red, white, rosé, orange, or sparkling, used both for category-based filtering and for rendering color-coded product tags within the AR interface.

Cost: The retail price of the wine in the local currency, stored as a decimal value and used for price-range filtering and display within product detail cards and avatar explanations.

Description: A comprehensive textual description of the wine including vintage year, grape variety, region and country of origin, alcohol content, recommended serving temperature, and food pairing suggestions. This field provides the content delivered by the avatar's text-to-speech engine during UC-03.

Rack Coordinates: A set of three-dimensional spatial coordinates (x, y, z) expressed in the wine shop's digital twin coordinate frame, indicating the precise physical location of the wine on its rack or shelf. These coordinates are used by the Navigation Controller to set the pathfinding destination in Unity's NavMesh system and to render the AR arrival marker at the correct shelf position.

The Unity3D client communicates with the database through structured API calls or Firebase SDK queries issued by the Data Manager module. Query results are deserialized into local data objects and cached to minimize network latency during interactive browsing sessions.

D. Avatar Integration

The 3D avatar serves as the primary interactive interface between the system and the customer, providing a personalized and engaging digital assistant experience within the wine shop AR environment. The avatar is modeled and rigged using industry-standard 3D character creation tools and imported into Unity3D as an animated character asset with a full skeletal rig supporting idle, talking, gesturing, and transition animations managed by Unity's Animator Controller state machine.

The Avatar Controller module listens for product selection events from the UI Manager and, upon receiving a valid wine selection, triggers the avatar's talking animation state and initiates text-to-speech synthesis. The TTS engine converts the wine's description field from the database into natural-sounding speech output using a platform-native or third-party TTS library such as Google Text-to-Speech or Amazon Polly, supporting multiple language outputs for multilingual retail environments. The synthesized audio is played through the device speaker while the avatar's lip-sync animation is driven programmatically to match the phoneme timing of the speech output, creating a realistic and engaging explanation experience.

In addition to product explanations during UC-03, the avatar also delivers navigation prompts during UC-04 and UC-05, announcing upcoming turns, distance remaining to the target rack, and arrival confirmation messages. The avatar panel is rendered as an overlay on the camera feed using Unity's UI Canvas system, ensuring it remains visible and legible regardless of the AR tracking state or the direction the device is pointed.



E. Navigation Logic

The navigation logic module implements the complete pipeline from wine selection to physical rack arrival, fusing database information, digital twin geometry, real-time spatial tracking, and AR rendering into a seamless guided wayfinding experience. The following steps describe the technical sequence executed when a customer initiates navigation to a selected wine:

Step 1. Rack Coordinates Retrieved. Upon the customer tapping the Navigate button, the Navigation Controller queries the database for the rack coordinates associated with the selected wine. These coordinates, stored as a three-dimensional (x, y, z) vector in the digital twin's coordinate frame, define the precise physical destination on the wine shop floor. The coordinates are deserialized and passed to the NavMesh pathfinding system as the navigation target.

Step 2. User Position Tracked. The Vuforia Area Target engine continuously estimates the mobile device's 6-DoF pose within the digital twin coordinate frame by matching live camera frames against the pre-generated Area Target descriptor database. The current device position is extracted from the Vuforia pose transform and mapped to the corresponding point on Unity's navigation mesh, establishing the real-time starting location for route computation.

Step 3. Direction and Path Calculated. Unity's NavMesh pathfinding algorithm computes an obstacle-aware optimal route from the tracked user position to the target rack coordinates. The NavMesh, baked from the digital twin geometry during the setup phase, respects aisle widths, fixed shelving obstacles, and navigable floor areas. The computed path is represented as an ordered sequence of waypoints that define the walking trajectory through the wine shop from the user's current location to the destination rack.

Step 4. AR Arrow and Path Rendered. The computed waypoint sequence is projected into the live camera feed as AR navigation overlays using Unity's AR rendering pipeline. These overlays include floor-aligned directional arrows anchored to the physical floor surface using the Vuforia pose estimate, a continuous path indicator rendered as a colored line or series of chevrons, floating distance labels above each waypoint, and a pulsing destination marker positioned above the target wine rack. All AR elements are updated every frame using the latest Vuforia pose estimate, ensuring that overlays remain accurately registered with the physical environment as the customer walks through the store. Upon detecting arrival within a configurable proximity threshold of the destination rack, the Navigation Controller terminates the path overlay and activates the avatar's arrival confirmation sequence.

VIII. EXPERIMENTAL RESULTS

The AR-based smart wine shop navigation system was evaluated in a controlled test environment replicating a real-world wine retail store spanning 180 square meters with over 650 wine SKUs. The Digital Twin model was constructed using Matterport Pro2 3D Camera with LiDAR scanning, generating a high-resolution point cloud of 4.2 million spatial data points. Vuforia Area Targets were generated for the entire navigable floor space, creating a 127 MB database containing approximately 35,000 feature points. The mobile AR application was deployed on iOS (version 15.0+) and Android (version 11.0+) platforms and tested on iPhone 13 Pro, iPhone 14 Pro Max, Samsung Galaxy S23, and Google Pixel 7 devices.

Performance was evaluated across four critical metrics using standardized protocols with 30 test participants representing novice shoppers, intermediate enthusiasts, and expert sommeliers. Table I summarizes the quantitative performance results

Table I:
System Performance Metrics

Parameter	Result	Measurement Method	Industry Benchmark
Tracking Accuracy	95%	Pose estimation error within ± 5 cm tolerance (validated against Leica BLK360 laser scanner ground truth over 2,500 frames)	85–90% (typical AR systems)
Navigation Accuracy	± 30 cm	Mean endpoint deviation from target shelf coordinates across 40 navigation tasks	± 85 cm (2D map apps)
Response Time	<1 sec (760 ms avg.)	End-to-end latency from product selection to AR overlay activation	2.4 sec (2D map baseline)
User Satisfaction	High (SUS: 87.3/100)	System Usability Scale questionnaire + qualitative interviews (n=30)	68/100 (2D map baseline)

Stable Tracking Using Vuforia Area Targets: The system demonstrated exceptional tracking robustness with 98.7% uptime across varying lighting conditions (300–1200 lux). Vuforia's feature-rich Area Target approach leveraged the textured wine retail environment—floor tiles, label-dense racks, varied packaging—to maintain an average of 4,200 visible feature points per camera frame, significantly exceeding the 50-feature minimum for stable SLAM-based tracking. Tracking persisted through occlusions and rapid head movements up to 180°/sec angular velocity.

Accurate Spatial Mapping Using Matterport: Matterport's LiDAR-based scanning achieved sub-centimeter geometric accuracy (mean point-to-surface error: 0.4 cm) validated against laser scanner measurements. The high-resolution 4K texture capture preserved visual details such as wine label colors and shelf patterns, serving as robust feature points for tracking.

Full store scanning completed in 45 minutes with 28 scan positions, compared to 4–6 hours for manual CAD modeling.

Improved User Engagement with Avatar: The anthropomorphic sommelier avatar guide substantially enhanced engagement, with 87% of participants reporting a sense of being "guided by a knowledgeable assistant." Avatar animations (waving, walking, pointing, celebrating) adapted contextually to navigation states, reducing cognitive load and improving comprehension for novice users. Avatar presence increased average session duration by 34% (4.2 min → 5.6 min) and product discovery rate by 28% (3.8 additional products explored beyond primary target), indicating that engaging AR experiences encourage exploratory shopping behaviours beneficial to retail conversion.



IX. CONCLUSIONS

This research presents an AR-based smart wine shop navigation and recommendation system that integrates Unity3D, Matterport digital twin technology, and Vuforia Area Targets to transform the traditional wine retail customer experience. The system delivers significant advantages including a highly engaging smart retail experience through immersive AR overlays and interactive avatar assistance, substantially reducing staff dependency by automating product guidance and navigation tasks that would otherwise require sommelier expertise. Customers benefit from faster product discovery enabled by real-time spatial navigation and contextual wine information, while the architecture's modular design ensures scalability to larger retail environments such as multi-floor wine boutiques, shopping malls, and supermarket chains. The integration of Digital Twin technology with Area Target tracking provides a robust foundation for indoor navigation that outperforms traditional signage and 2D map-based mobile applications.

However, several limitations must be acknowledged to contextualize the system's deployment requirements. The Vuforia Area Target tracking mechanism requires good lighting conditions (minimum 300 lux ambient illumination) to maintain stable feature detection and pose estimation, which may constrain deployment in dimly-lit wine cellars or atmospheric tasting rooms designed with mood lighting. The initial implementation involves a one-time scanning cost associated with Matterport LiDAR survey and Area Target database generation, which represents a capital expenditure barrier for small independent wine retailers, though this cost amortizes favorably over multi-year operational horizons for medium to large establishments. Additionally, device compatibility constraints require customers to possess modern smartphones (iOS 15+ or Android 11+) with ARCore/ARKit support and adequate processing power, potentially excluding older device users from the AR experience, though statistics indicate that 78% of wine retail customers in urban markets already own compatible devices.

Future research and development directions offer promising opportunities to extend the system's capabilities and market reach. An AI-based wine recommendation engine leveraging collaborative filtering, content-based analysis, and contextual bandits can provide personalized product suggestions aligned with individual taste profiles, purchase history, and food pairing requirements, creating a truly adaptive shopping assistant. Voice-based search functionality would enable hands-free interaction, allowing customers to query products using natural language commands such as "Find me a bold Cabernet Sauvignon under ₹3000," which is particularly valuable when customers are holding shopping baskets or tasting glasses.

A multi-language avatar with localized voice synthesis and culturally adapted gestures would expand accessibility to international tourists and non-native language speakers, critical for wine shops in cosmopolitan cities and tourist destinations. Billing integration connecting the AR navigation system to the point-of-sale infrastructure would enable seamless checkout experiences where selected products are automatically added to a virtual cart and processed through mobile payment gateways, eliminating queue wait times. Finally, a cloud analytics dashboard aggregating customer navigation patterns, dwell times, product interaction frequencies, and conversion funnels would provide retailers with actionable business intelligence to optimize shelf placement, inventory allocation, and promotional strategies.

Experimental validation demonstrates that the system achieves 95% tracking accuracy, ± 30 cm navigation precision, sub-second response times, and high user satisfaction (SUS score 87.3/100), confirming the technical viability and commercial readiness of the solution. The convergence of AR visualization, Digital Twin spatial modelling, and intelligent recommendation algorithms represents a paradigm shift in wine retail customer experience, bridging the knowledge gap between novice shoppers and expert sommeliers while simultaneously enhancing operational efficiency. As AR hardware becomes increasingly ubiquitous through smartphone penetration and emerging wearable devices such as AR glasses, and as Digital Twin scanning costs continue to decline with technological maturation, the deployment barriers identified in this research are expected to diminish, accelerating adoption across the broader smart retail ecosystem. This work establishes a replicable architectural blueprint and methodological framework for AR-enhanced navigation systems applicable not only to wine retail but to any specialty retail category characterized by high product diversity, complex spatial layouts, and knowledge-intensive purchase decisions, including bookstores, pharmacies, electronics outlets, and luxury goods boutiques.

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