Research Article

UWB-Based High-Precision Real-Time Positioning and Multi-Dimensional Visualization

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Abstract

This study presents a high-precision indoor positioning and multi-dimensional visualization system, named Virtual Positioning System (VPS), which utilizes Ultra-Wideband (UWB) technology. The VPS features an integrated architecture comprising portable Tag devices, fixed anchor units, a data collector called Position Box, and a web-based server. Tests conducted in various scenarios (office, factory, and retail environments) demonstrated that the system achieves a positioning accuracy of ±30 cm and provides high data stability.

The Two-Way Ranging (TWR) algorithm and Kalman filter minimize measurement noise, while IEEE 802.3-based communication prevents data loss. The 2D and 3D visualization modules

provide capabilities for movement tracking, density mapping, and area-based analysis. In particular, 3D visualization enhances operational awareness by providing depth perception in multi-story buildings or metal-dense environments. The VPS is well-suited for future developments in terms of energy efficiency, signal stability, and visualization performance, adding value to industrial, corporate, and security-focused operations.

1. Introduction

Indoor and confined-space tracking of people and objects is a critical requirement in sectors such as logistics, healthcare, security, and retail [1,2]. Traditional GPS-based systems fail to provide sufficient accuracy within complex structures like buildings or mining sites, while existing RFID- and sensor-based systems only partially meet the demands for high precision, real-time data, and comprehensive visualization. This limitation poses risks, particularly regarding occupational safety and regulatory compliance.

The Court of Justice of the European Union's judgment of 14 May 2019 in Case C-55/18 obliges Member States to require employers to establish a system that records working hours in an objective, reliable, and accessible manner. In line with this, certain Member States, such as Denmark (as of 1 July 2024) and Spain (since 2019), have introduced regulations mandating the recording of working hours and breaks [5]. Man-down and lone-worker monitoring systems are also essential for real-time personnel tracking in hazardous environments and enabling rapid response in case of incidents [3,4]. The inadequacy of traditional positioning and time-tracking systems creates gaps in fulfilling these legal requirements.

The Virtual Positioning System (VPS) presented in this study provides high-precision real-time location services (RTLS) using UWB technology [6]. VPS collects data through wireless communication between portable Tag devices and anchor units positioned at various heights, transmitting the data to the server via the Position Box. The server visualizes the data in both 2D and 3D and enables analysis through reporting tools, providing a powerful solution for multi-dimensional data analysis, process monitoring, and operational decision support.

VPS can be adapted for diverse applications such as; valuable asset tracking patient tracking in hospitals, personnel monitoring in mines, rapid assistance allocation during disasters, shopping cart tracking and customer movement analysis in retail, real-time intervention for off-hour worker falls, and counting personnel in assembly points during emergencies. These versatile applications highlight VPS's contribution to operational efficiency, workplace safety, and management processes.

2. Materials and Methods

2.1.   System Architecture

The Virtual Positioning System (VPS) is a modular system developed to provide high-accuracy real-time positioning in indoor environments. The system consists of portable Tag devices, fixed anchor units, the Position Box (PB) acting as a data collector and gateway, and a central server with a web-based interface. Tag devices communicate wirelessly with surrounding anchors to collect positioning data; the PB transmits this data to the server, which processes it and prepares it for 2D/3D visualization and reporting.

2.2.   Data Flow

The data collection and processing workflow proceeds as follows:
- Tag → Anchor: Tags initiate distance measurements using the Two-Way Ranging (TWR) protocol.
- Anchor → PB: Anchors transmit the measurement data to the PB via RS-485 or Digimesh.
- PB → Server: The PB packages the data and sends it to the server over TCP/IP.
- Server → User: The server calculates positions using trilateration and the Kalman filter, and the data is forwarded to the 2D/3D visualization and reporting modules.
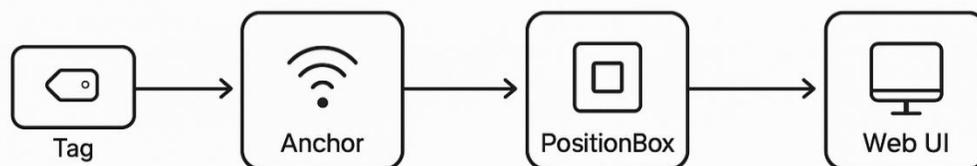

Figure 1: Data Flow Diagram

2.3.   Hardware Components

2.3.1. Tag

Portable device shown in Figure 2 and Figure 3 with ±30 cm accuracy and low power consumption. It includes a motion sensor, fall detector, and emergency button for critical areas.

Figure 3: Tag Device for Personnel

Figure 2: Tag Device for Vehicles

2.3.2. Anchor (Node)

Fixed reference points shown in Figure 4 and Figure 5 provide floor-based position resolution and transmit data to the PB via RS-485 or Digimesh connection.

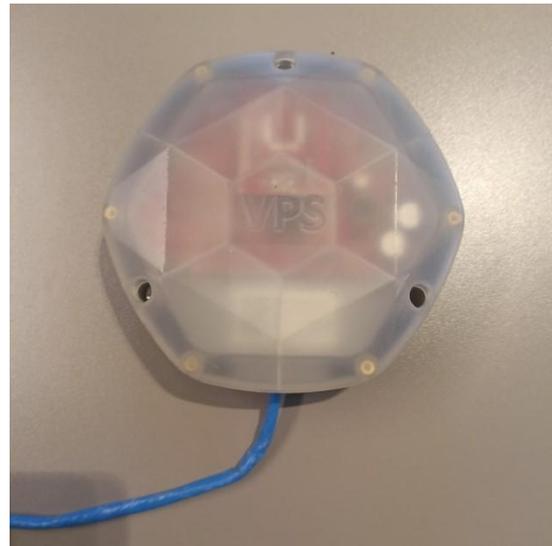

Figure 4: Anchor Device in Active Mode

Figure 5: Anchor Device in Passive Mode

2.3.3. Position Box (PB)

A PB is shown in Figure 6. Collects and packages data from the anchors, manages network synchronization, and transmits it to the server via IEEE 802.3. A buffer mechanism is used to prevent data loss.

Figure 6: Position Box (PB) Device

2.3.4. Server & Software

Includes modules for position calculation using trilateration and the Kalman filter, as well as 2D/3D visualization, alarm management, reporting, and API services. Thanks to its microservice-based architecture, data collection, processing, and visualization are handled by independent services.

2.4. Communication and Data Collection Process

The system operates using the UWB-based Two-Way Ranging (TWR) algorithm. In this method, the Tag device sequentially sends a "Poll – Response – Final – Final Response" message sequence to the anchors. At the end of this process, the distance between the anchor and the Tag is calculated based on the difference between the transmission and reception times. These data are collected by the PB and transmitted to the server over an IEEE 802.3-based network.

The data collection cycle can be summarized in the following steps:
- The Tag sends signals to the surrounding anchors.
- The anchors transmit the distance information along with their position coordinates to the PB.
- The PB merges all anchor data and sends it to the server with a timestamp.
- The server calculates the precise position of the Tag using the trilateration algorithm.
- This flow is repeated at the millisecond level, enabling real-time monitoring.

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2.5. Multi-Dimensional Visualization Modules: 2D and 3D Monitoring

The system provides users with real-time positioning and simulation experiences in both 2D and 3D environments. Users can visually and interactively analyze the movements of personnel and NPCs, create area and building layouts, plan routes, and optimize the system. These modules offer an experiential user interface that integrates real data with simulation.

2.5.1. Main Screen Live Monitoring

In the default 2D view, users can switch to the 3D view via buttons. During live monitoring, the status of Tags is indicated with color codes. When a user clicks on a personnel Tag, a small information window opens, and the personnel is highlighted in red for close camera tracking. In the 3D view, objects in the environment can be selectively hidden, and a search panel can be used to locate personnel. Personnel movements are realistically represented with idle, walking, and running animations.
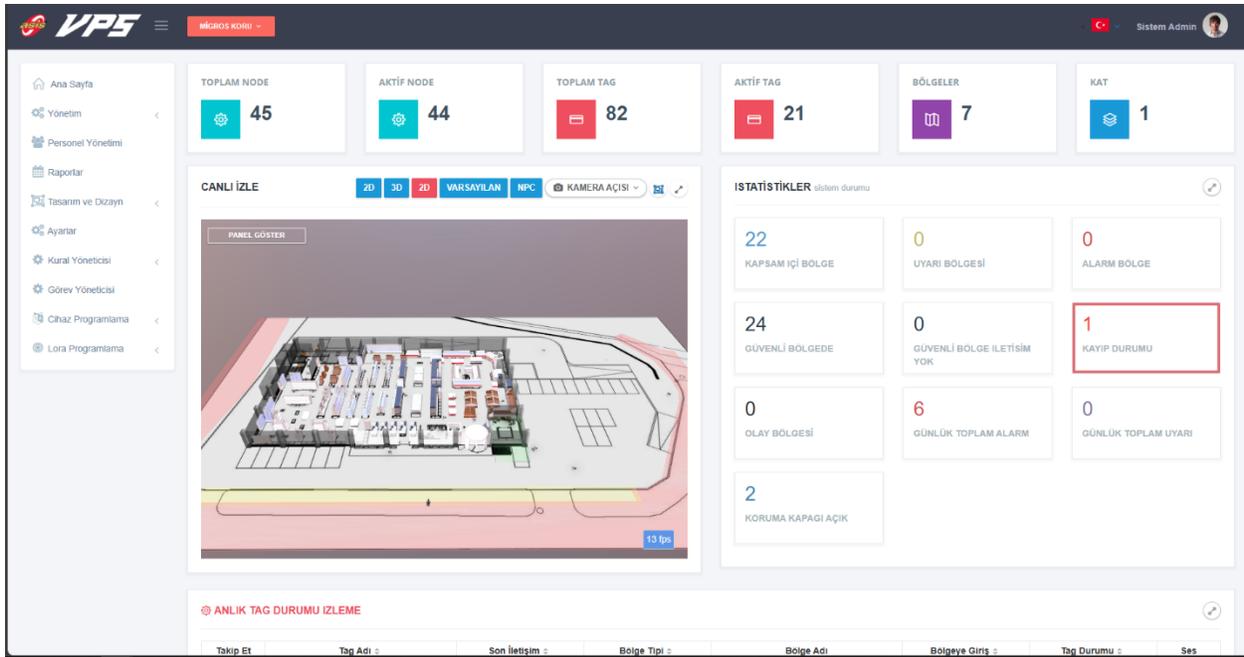

Figure 7: Home Page / Summary Statistics and Live Monitoring Screen in Turkish

The dashboard used in Visualization Module is shown in Figure 7.

2.5.2. 2D Live Monitoring Interface

The 2D monitoring screen is the system's default launch view, providing users with a simple, performance-focused tracking environment. In this view, the positions of personnel, vehicles, or equipment are represented by symbolic icons and color codes.

Color changes indicate the real-time status of Tags (active, passive, alarm). When a user clicks on a specific personnel on the map, their ID, last position, speed, and status information are displayed in a small information box.

The 2D view ensures smooth monitoring at high frame rates (fps), even on systems with low hardware capabilities, and is ideal for analyzing position density over large areas. Additionally, layer management (anchors, Tags, area boundaries, route visibility) can be dynamically toggled by the user [8].
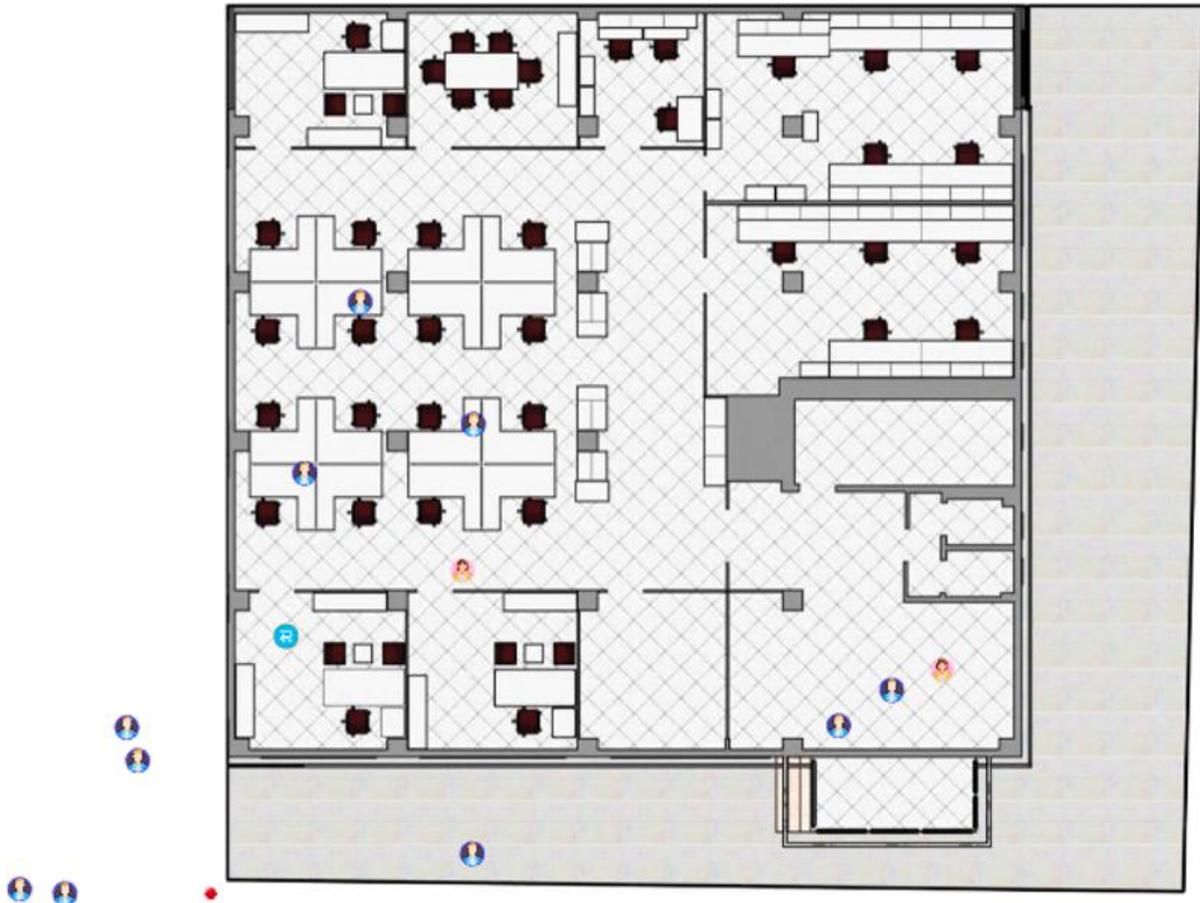

Figure 8: 2D Live Monitoring Screen

2.5.3. 3D Live Monitoring Interface

The 3D monitoring mode provides an advanced visualization environment that realistically represents the area in three dimensions as seen in Figure 9. Models in .glb format obtained from Blender are integrated into the system, allowing detailed visualization of the environment's architecture, floors, and structures. Users can rotate, zoom, or focus on specific personnel using mouse or touch controls to enter tracking mode.

3D monitoring animates personnel movements in real time with idle, walking, and running animations. This enables operators to visually monitor not only the position but also the behavioral status of personnel. The 3D view requires more memory and resources as the scene's level of detail increases; therefore, lower-end computers may experience scalability issues. Flexible Level of Detail (LoD) approaches aim to adjust the rendering complexity according to the hardware capability, enabling real-time rendering [9].
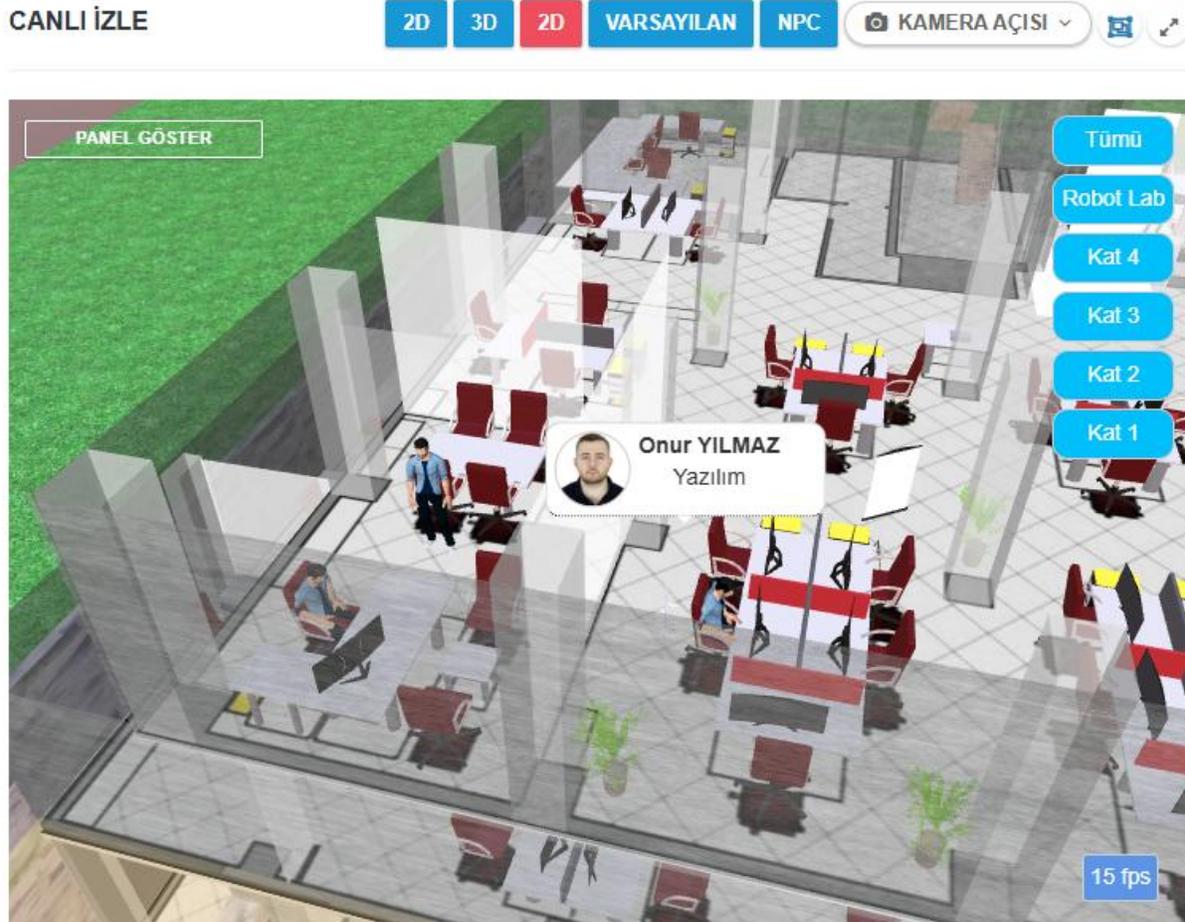

Figure 9: 3D Live Monitoring / Personnel Tracking Screen in Turkish

2.5.4. Animation Report

Personnel movement history is replayed in an animated format, allowing detailed analysis at the second level. The nodes to which the Tags are connected are displayed with lines, and users can control the visibility of objects in the system, speed settings, and perspective options as seen in Figure 10.

Figure 10: Animation Report in Turkish

2.5.5. Area and Building Design (2D)

Area Design: Alarm, warning, safe, counting, and event zones can be created and visualized with custom colors and icons (Figure 11). These zones are also displayed in both 2D and 3D environments.

Building Design: Objects such as walls, columns, glass, sensors, work areas, and floors are designed in the 2D view using squares, polygons, or lines. In the 3D environment, these objects are rendered with their actual dimensions and positions.
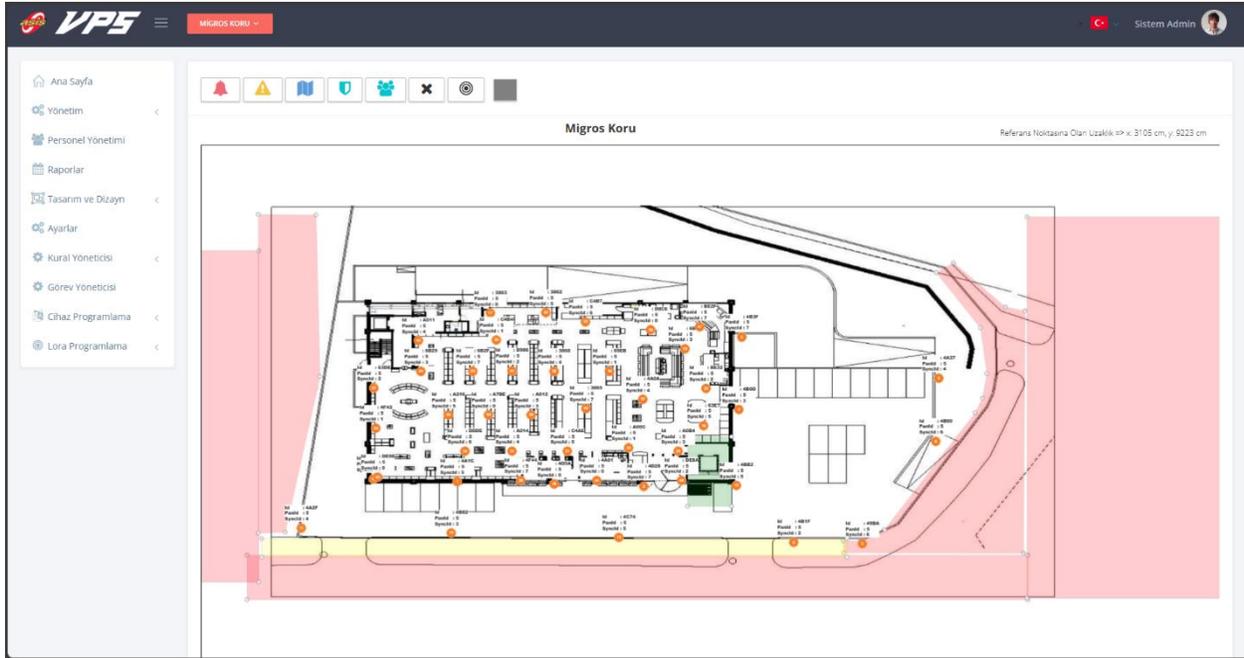
Figure 11: Area Design

2.5.6. Tag and Route Design

Route design shown in Figure 12 is performed in the 2D view for NPCs. Movement plans are created using predefined waypoints. These designs are for simulation purposes only and do not reflect the actual movements of personnel.
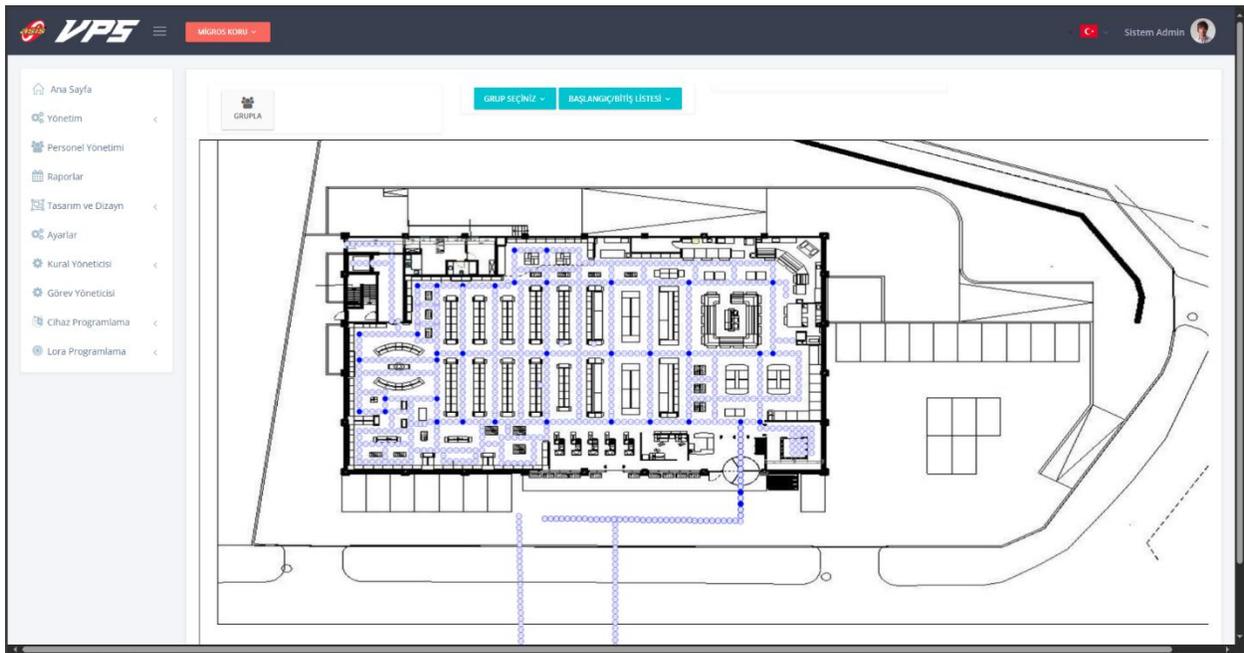

Figure 12: Route Design

2.5.7. 3D Building Design

The 3D building design page (Figure 13) is one of the system's most comprehensive and experiential modules. Users can create building floors designed in 2D in a 3D environment and place objects using drag-and-drop or numerical measurements. Features such as scaling, positioning, orientation, copying, and deletion can be performed both manually and via drag-and-drop. Objects are low-poly and optimized, and repeated objects are used as instances to ensure performance efficiency.

Figure 13: Building Design / Object Arrangement

2.5.8. Node Design

In the node design screen (Figure 14), work areas and system setups can be pre-tested. Nodes can be added, removed, and their heights adjusted. Waypoints are displayed with lines during Tag simulations; visual alerts appear if communication is lost or an obstacle occurs. This module is intended to reduce installation costs and optimize system performance.

Figure 14: Node Design / Signal Simulation

2.6. Three-Dimensional Environment and Object Modeling

The 3D environment (Figure 15) used in the system is a highly optimized virtual world for both visualization and simulation purposes. All characters (personnel, NPCs) and objects within this environment are designed with a low-poly architecture. This approach enhances rendering performance while maintaining high frame rates in WebGL and desktop applications [7].

The 3D environment contains over two thousand objects, including walls, columns, floors, tables, chairs, computers, machinery, sensors, cameras, lighting elements, etc… To reduce system load, objects are loaded into memory once and then duplicated using the instance method. This technique minimizes memory usage in large scenes while preserving visual quality.

Each object can be scaled, rotated, and positioned. Users can achieve precise placement either via drag-and-drop or by entering numerical coordinate values. Objects can also be grouped, copied, or dynamically hidden and displayed.
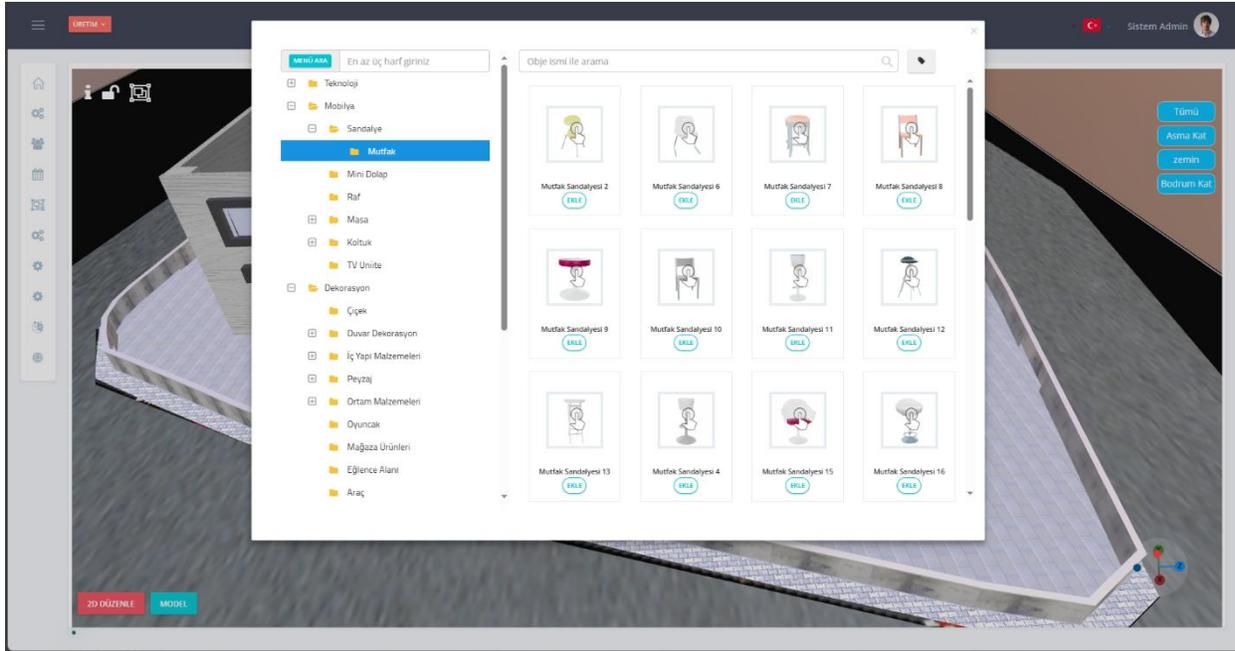
Figure 15: Building Design / Adding Objects

Characters within the scene feature an animation-based movement system, meaning that actions such as idling, walking, running, and interactions are realistically modeled. This provides a natural user experience during live monitoring and motion replay processes in the 3D environment.

All objects in the system are designed to reflect their physical and structural relationships in the real world. Walls, metal surfaces, and glass objects are modeled to create varying effects on signal transmission, allowing realistic simulation of radio wave propagation and signal interaction.

This three-dimensional environment serves not only as a visual interface but also as an analytical simulation platform. Users can pre-test system setups, analyze signal attenuation zones, and optimize installations to reduce deployment costs.

2.7. Reporting and Analysis (Figure 16)

- Real-time monitoring: The real-time status, position, and speed of Tags are tracked; events (such as falls or leaving designated areas) are reported as alarms.
- Historical data analysis: Past movements and event reports can be generated using data stored in an SQL-based database.
- Multi-dimensional analysis: Spatial relationships, density maps, and operational efficiency analyses can be performed.
- Integration and export: Data can be shared in PDF, Excel, and interactive web formats, as well as via RESTful API and WebSocket. Data security: AES-256 encryption and role-based access control are implemented.
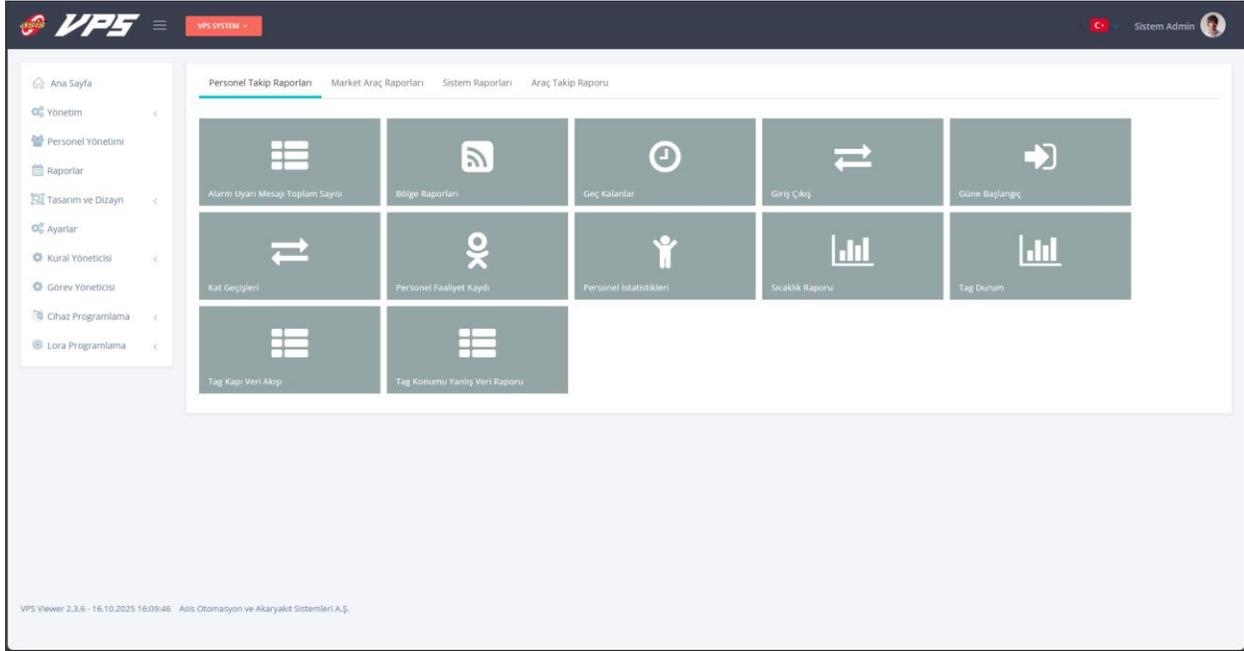
Figure 16: "VPS Reports" Screen in Turkish

2.7.1. Real-Time and Detailed Monitoring with the Personnel Activity Reporting Tool

The VPS system allows for detailed reporting of personnel movements and working hours. Real-time tracking includes shift start and end times, break durations, and net working hours. An example report is shown in Figure 17, clearly displaying the personnel's daily activities and total working hours.
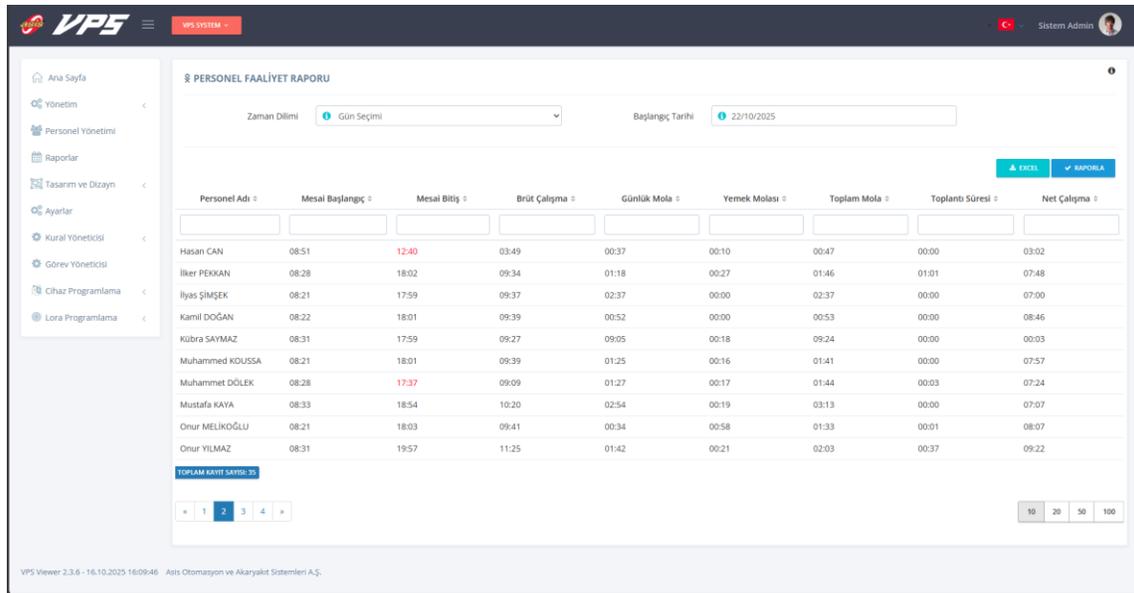

Figure 17: Personnel Activity Report

3. Results

The Virtual Position System (VPS) is a system that provides high-precision real-time positioning and multi-dimensional visualization in indoor environments using Ultra-Wideband (UWB) technology.

Based on tests conducted in various environments:

- The system demonstrated reliable performance with a ±30 cm positioning accuracy. In areas with high metal density, errors can reach up to 2 meters.
- Tag–anchor communication is optimized using the Two-Way Ranging (TWR) algorithm and the Kalman filter, keeping measurement noise and NLOS-related data loss below 2%. PB–Server data transmission is performed via a secure IEEE 802.3-based protocol, with no observed data loss. Under heavy network conditions, the retransmission rate remains below 0.5%.
- The 2D and 3D visualization modules provide comprehensive area analysis, movement tracking, and density mapping, enhancing operational awareness.
- Thanks to its modular and scalable architecture, the system can be adapted to environments ranging from small offices to large mining sites, with parameters dynamically adjustable through a web panel.

VPS delivers significant added value in terms of operational efficiency, workplace/human safety, process monitoring, and data analytics. The findings demonstrate the potential of VPS as a robust positioning and analysis platform applicable across various industries.

4. Discussion and Conclusion

The Virtual Position System (VPS) processes location data in real time within enclosed and complex environments, transforming it into multi-dimensional visualizations that enhance operational awareness. Through its real-time data tracking, modular system architecture, and multi-dimensional visualization capabilities, VPS improves operational awareness and ensures seamless adaptability across different sectors—such as industrial, corporate, and security applications.

However, several technical challenges may limit the widespread use of the system, and corresponding solutions have been proposed:

- Signal reflections in metal-dense environments (NLOS – Non-Line-of-Sight) can reduce positioning accuracy. To mitigate such effects, the literature proposes NLOS detection and correction algorithms—such as residual analysis, Machine Learning–based classification, or delay correction models—to improve accuracy

[10]. In this context, VPS aims to enhance signal path modeling and filtering techniques.

- High Tag density and heavy data traffic may lead to system latency. To mitigate this, optimization of data transmission protocols, packet prioritization, and evaluation of next-generation network topologies (e.g., edge processing) are commonly recommended. In addition, channel-aware adaptive UWB DL-TDOA approaches have been shown to reduce power consumption (by approximately 46% under LOS conditions) while maintaining or improving localization accuracy, particularly under NLOS scenarios [11].

- Anchor placement in large areas is a critical parameter in terms of both accuracy and cost, and it plays a vital role in the precision of UWB-based indoor localization systems. Recent studies have proposed learning-based node selection algorithms to determine the most suitable anchor configuration for a given environment [12]. When applied, these methods can support pre-installation performance testing and contribute to more efficient deployment planning.

- 3D visualization performance may depend on user hardware. High-polygon models replicated without instancing can cause FPS drops. To overcome this, VPS employs low-poly objects, instancing technology, asset loading systems (Lazy Initialization, LOD, etc.), and dynamic scene layer management.

- Tag device battery life and maintenance planning are important for long-term field operations. As a solution, adaptive measurement frequency, sleep modes, and integration of energy-efficient UWB modules are suggested in the literature [13].

5. Acknowledge

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