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Patient location tracking method for virtual escort systems in healthcare facilities

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ABSTRACT

This article proposes a hybrid patient location tracking method for virtual escort systems in healthcare facilities. To ensure the required positioning accuracy and seamless navigation, that are particularly important for individuals with limited mobility, the study introduces a hybrid method that integrates Quick Response code scanning, Bluetooth Low Energy beacons and Wi-Fi-based positioning technology. Each of these technologies fulfills a distinct role within the overall system architecture: Quick Response codes serve as discrete location markers, Bluetooth Low Energy beacons provide continuous proximity-based tracking, and Wi-Fi positioning enhances coverage in open indoor areas. A key aspect of this research is the integration of augmented reality technologies into the proposed hybrid positioning method. The overlay of real-time navigational cues within the user's field of vision via augmented reality-enabled devices, such as smartphones, enhances the intuitiveness and interactivity of the virtual escort system. This feature is particularly beneficial for individuals with disabilities, as it reduces cognitive load and improves spatial awareness in complex medical environments. The study presents a structural model of the augmented reality-based virtual escort system, comprising six modules: the Quick Response Code Scanning Module, Bluetoorh Low Energy Beacon Module, Wi-Fi Positioning Module, Optimal Route Search Module, Augmented Reality Module and Integration Module. The integration of these components leverages the advantages of each technology while compensating for their individual limitations. Furthermore, an interaction model for system components has been developed, outlining both external and internal information flows as well as the integration logic among the structural elements of the system. The paper also identifies promising directions for future research, including the development of methods, algorithms, and technologies for integrating advanced augmented reality functionalities, personalizing navigation routes using artificial intelligence algorithms, and enhancing the energy efficiency of the system.

Keywords: Virtual escort; augmented reality; healthcare facilities; tracking; navigation; indoor environment

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INTRODUCTION

Indoor navigation systems play a crucial role in ensuring mobility and accessibility, particularly for individuals with limited mobility, including the elderly, people with disabilities, and patients undergoing rehabilitation after surgery or injuries. Navigation in complex architectural environments, such as medical institutions, shopping malls, and airports, presents a significant challenge for this category of users, often causing disorientation, stressful situations, and delays. Traditional methods, such as printed maps or static navigation signs, do not always meet the needs of individuals with limited mobility, which may require step-by-step instructions, specially adapted routes, and real-time information updates. Addressing these challenges is crucial for ensuring that all individuals, regardless of their physical abilities, can navigate healthcare facilities effectively.

Navigation systems utilizing augmented reality (AR) technology demonstrate significant potential in addressing this issue. They enable the visualization of routes by overlaying digital cues on real-time images of the physical environment. These solutions improve user orientation in space, making the navigation process more intuitive and personalized. However, the effectiveness of AR technologies depends directly on the accuracy and reliability of the positioning subsystem. Standalone systems suffer from critical flaws: Quick Response (QR) codes lack continuous tracking; Bluetooth Low Energy (BLE) beacons degrade near metal/medical equipment; Wireless Fidelity (Wi-Fi) has meter-level drift. A hybrid fusion of these technologies mitigates these issues, while AR bridges the gap between digital coordinates and real-world navigation.

This study focuses on the problem of user location determination in augmented reality-based virtual escort system designed for individuals with limited mobility, emphasizing the application of such technologies in medical institutions. Healthcare environments with radio-frequency interference from magnetic resonance imaging (MRI) machines, multi-floor layouts, and wheelchair-accessible detours require a modular positioning system. Proposed hybrid method dynamically switches between QR (for landmarks), BLE (for corridors), and Wi-Fi (for open areas), while AR adapts routes to accessibility needs (e.g., avoiding stairs).

To improve positioning accuracy and ensure continuous indoor user tracking, a hybrid positioning method is proposed. This method is based on the combined use of QR codes for initial position initialization, BLE-beacons, and Wi-Fi positioning for subsequent movement tracking. QR codes provide efficient and accurate initial position determination, which is particularly important in medical institutions with well-defined entry points and key landmarks. BLE beacons and Wi-Fi positioning, in turn, enable higher accuracy and extended indoor coverage.

The proposed approach ensures an optimal combination of accuracy, scalability, and cost-effectiveness, which is critically important for deploying indoor navigation systems in healthcare facilities. The integration of this hybrid system with AR technologies enables the creation of real-time visual navigation cues, significantly improving user experience. For instance, a visitor to a medical facility can scan a QR code at the entrance to determine their location, after which the augmented reality module generates guidance in the form of arrows or digital signs overlaid on the smartphone camera image. As the user moves, the system dynamically updates navigation cues based on the current location, ensuring seamless navigation.

This article presents a comprehensive framework for a hybrid indoor positioning method that uniquely integrates QR code initialization, BLE beacon proximity tracking, and Wi-Fi fingerprinting to achieve robust, real-time navigation in healthcare environments. By fusing these technologies through an adaptive weighting mechanism, our method overcomes the limitations of standalone approaches while enabling precise AR visualization. Particular attention is paid to issues of ensuring high positioning accuracy, economic feasibility, scalability, and ease of use. Additionally, potential challenges related to signal interference, device compatibility, and data privacy are discussed.

1. ANALYSIS OF LITERARY DATA

In recent times, the issue of improving the quality of medical services has become increasingly urgent, further complicated by the current situation in Ukraine. As a result, there is a pressing need to find new scientific solutions for the application of modern information technologies, as well as advancements in science and engineering, to enhance these processes and improve medical information systems.

Studies [1, 2], [3, 4] focus on improving patient diagnostic processes. In [1], the experience of developing medical information technologies is analyzed, and a methodology for using fuzzy sets to implement an information expert system for medical diagnostics is proposed, particularly for assessing the degree of anatomical damage to the coronary arteries. Study [2] presents the development of a method for diagnosing skin diseases aimed at automating medical diagnostic decision-making and improving the efficiency of such decisions through telemedicine technologies and the intelligent processing of medical data. Studies [3, 4] introduce models, methods, and technologies for building an information system for remote patient diagnostics. Study [5] discusses the application of telemedicine technologies based on artificial intelligence.

The enhancement of medical data processing through intelligent approaches is examined in studies [6, 7], [8, 9]. The features of medical information system design, their components, and the specifics of developing application software are presented in studies [10, 11], [12]. Studies [13, 14], [15, 16], [17, 18], [19, 20], [21, 22], [23, 24], [25, 26] are dedicated to the analysis and development of new models, methods, and technologies for navigation systems, including those designed for indoor environments.

The article [13] is dedicated to the analysis of the accuracy of an indoor positioning system based on the Received Signal Strength Indicator (RSSI) of Bluetooth Low Energy technology. The research focuses on the development of an evacuation monitoring system using BLE transmitters on wristbands and receivers placed within a building. The authors analyze the impact of the environment on signal strength, determine optimal data processing methods, and evaluate the effectiveness of the approach through experimental measurements. The main advantages of the proposed system include low cost, ease of implementation, and potential applications in Industry 4.0.

In study [14], the indoor positioning process was based on heuristic optimization methods and was carried out by creating weighted visibility matrices of access points based on WiFi signal strength values. The proposed method utilizes Particle Swarm Optimization (PSO) and Genetic

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Algorithm (GA) approaches to determine the mobile user's location using a joint fitness function derived from the weighted visibility matrices. The method was tested in a virtual scenario where position ranges were determined according to RSSI levels. Both heuristic optimization methods were compared based on different criteria, with positioning accuracy achieving a maximum deviation of 3 meters for the GA-based method and 1.5 meters for the PSO-based method.

Study [15] employed beacons and scanners supporting two Bluetooth specifications – BLE 5.0 and 4.2 – for experimental tests. The measurement methodology consisted of three stages: converting received signal strength indication values into distance, placing multiple beacons on a single plane, and measuring in different directions. To enhance positioning accuracy, the study utilized a signal propagation model, trilateration, a correction coefficient, and a Kalman filter for data processing. Experimental results showed that positioning accuracy could reach 10 cm when beacons and scanners were positioned on a single horizontal plane in a low-noise environment. However, accuracy decreased to approximately one meter in a three-dimensional configuration and complex environments. The analysis indicates that BLE wireless signal strength is susceptible to interference in industrial conditions, yet its use remains feasible under specific circumstances. Additionally, Bluetooth 5.0 specifications demonstrate promise for real-time location systems (RTLS) due to their higher signal stability and better performance in low-interference environments.

Article [17] explores the application of Internet of Things (IoT) technologies for indoor positioning, focusing on energy efficiency and localization accuracy. The authors analyze wireless technologies such as ZigBee, Bluetooth Low Energy, and Long Range (LoRa), which offer low power consumption and hold potential for indoor positioning in distributed sensor networks. The study compares these technologies based on localization accuracy and energy efficiency, particularly considering the use of Received Signal Strength Indicator values to track mobile sensor nodes in IoT networks.

In article [19], a method for developing an efficient indoor navigation system is proposed, aimed at determining the shortest path between two points using Dijkstra's algorithm. Indoor navigation poses challenges in providing personalized navigation information and optimal routing, which is critical in environments where GPS is unavailable. The study examines the application of this algorithm for shortest path determination within buildings, as well as the digitization of maps and user location tracking via an Android mobile application. Experimental results confirmed the effectiveness of the proposed system, demonstrating its ability to provide optimal solutions for indoor navigation.

Article [20] reviews technologies, applications, and future research directions in the field of machine learning for indoor positioning and navigation in smart cities. Specifically, it analyzes the role of RSSI and machine learning-based algorithms in localization and navigation systems within buildings, given that GPS usage in enclosed spaces is impractical. The review also covers the evolution of indoor positioning systems, which have become key components of location-based services, and evaluates the potential of machine learning algorithms in improving localization accuracy and efficiency in indoor environments.

Article [21] presents a review of machine learning-based indoor positioning approaches that utilize Wi-Fi signal strength fingerprints. The authors analyze the key stages of these methods, including data preprocessing, data enrichment, the use of machine learning models for location prediction, and post-processing of results. Special attention is given to data collection challenges and the analysis of open datasets, as the effectiveness of machine learning methods largely depends on input data quality. The review also highlights modern challenges in machine learning-based indoor localization and proposes potential solutions for future research in this field.

Authors in [22] have examined location determination methods and developed a mobile application for the Android operating system to determine device locations using Wi-Fi sensors. The application implementation employs the trilateration algorithm and a logarithmic distance loss model to estimate distances to access points using the PSS approach.

In [23], the research team developed a navigation system incorporating an RGB-D camera and a hybrid map for a virtual reality system. This approach eliminates the need for navigation markers. The camera observes the surrounding environment, generating a point cloud and a floor map. To enhance accuracy, error correction methods were proposed.

Study [24] analyzes user survey data regarding satisfaction with the GuideMe software application, which enables indoor navigation using augmented reality technologies. The application received positive feedback, with respondents expressing satisfaction with its use. The “Behavioral Intention to Use” parameter achieved a high average score, demonstrating the relevance of augmented reality-based software solutions for indoor navigation.

In [25], an analytical review of approaches and solutions for indoor navigation systems is presented, including an analysis of Building Information Modeling (BIM) using Industry Foundation Classes (IFC). Another approach to augmented reality-based navigation systems is explored in [26], where a combination of cameras and inertial sensors is used to track 3D point clouds representing locations within a pre-scanned 3D spatial model. The navigation route is computed using the A* algorithm.

Study [27] proposes a mobile indoor navigation system that uses augmented reality technologies to display information about objects of interest. User location is determined by detecting markers placed in the environment, which are tracked by mobile device motion sensors. The navigation routes are calculated using the A* algorithm, and a spatial model is generated as a plane overlaying a mapping scene that utilizes latitude and longitude as coordinates.

In [28], a navigation system designed for visually impaired individuals is developed. This system uses Bluetooth beacons placed in the environment as reference points and is designed to be compatible with standard smartphones. Testing confirmed the system's functionality and reliability.

Study [29] presents research on a method for reconstructing indoor navigation elements based on RGB-D sensor data. A graph convolutional network recognition method is proposed to establish long-term interactions between primitives for describing real-world physical relationships. An adaptive room segmentation method is developed by combining distance transformation with watershed segmentation to define cellular spaces. Additionally, a topological connection reconstruction method is introduced to achieve a network-based graphical representation of indoor environments.

Study [30] provides an analytical review of the advantages and disadvantages of modern indoor navigation systems. The study includes an overview of commercial smart devices for route navigation through complex and large-scale buildings. Experimental results demonstrated that real-time access to navigation information improved accuracy and boosted user confidence, particularly among visually impaired individuals, compared to reliance on memory-based navigation.

The analysis of models, methods, and technologies for enhancing medical information systems has yielded the following insights: key research directions include the intelligent processing of medical data, decision support systems, and advancements in remote patient diagnostics, particularly through IoT devices and telemedicine. The review of navigation system models, methods, and tools highlights that scientific research focuses on issues such as labeling, semantics, optimal route determination, information display, and device localization. However, these studies do not address the adaptability of navigation routes to the needs of individuals with limited mobility, especially those with musculoskeletal impairments.

Therefore, the development of models, methods, and technologies for virtual escort systems in healthcare facilities that consider the needs of individuals with limited mobility remains highly relevant. A crucial element of such systems is patient location determination within medical facilities to minimize errors in optimal route planning. Consequently, the development of a patient location determination method for virtual escort software tailored to individuals with limited mobility is an urgent research priority.

2. THE PURPOSE AND OBJECTIVES OF THE RESEARCH

This study addresses the issue of user location determination in augmented reality systems designed for the needs of individuals with limited mobility, with a particular focus on the application of such technologies in healthcare facilities. The unique characteristics of hospital and clinic interiors, including multi-level structures, narrow corridors, and numerous obstacles, impose high demands on the accuracy and reliability of navigation solutions. Therefore, the development of a patient location determination method for virtual escort software aimed at assisting individuals with limited mobility in healthcare institutions remains a relevant and pressing challenge.

The objective of this publication is to develop hybrid patient location tracking method for augmented reality-based virtual escort systems in healthcare facilities.

The key tasks of this publication is to develop hybrid indoor positioning method for augmented reality-based virtual escort systems in healthcare facilities integrating QR code scanning, Bluetooth Low Energy beacons, and Wi-Fi localization, combined with augmented reality visualization, to enable accurate, continuous, and user-centric navigation for individuals with limited mobility.

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To achieve the primary tasks, it is essential to conduct a comprehensive analysis of contemporary approaches and solutions aimed at enhancing medical information systems and indoor navigation systems. This should be followed by the development of a structural model for a virtual escort system within healthcare institutions, incorporating the proposed hybrid indoor positioning method, as well as the design of an interaction model that reflects the relationships among system components in the context of the hybrid positioning approach.

3. RESEARCH METHODS

The research methodology employed in this study is centered around the development and evaluation of a hybrid indoor positioning system designed to enhance navigation for individuals with limited mobility in healthcare facilities. The approach combines theoretical analysis, mathematical modeling, and practical implementation to address the challenges of indoor navigation in complex environments. The research methods are structured to ensure the system's accuracy, scalability, and usability, while also considering cost-effectiveness and integration with existing infrastructure.

The study begins with a thorough analysis of existing literature on indoor positioning technologies, including Bluetooth Low Energy, Wi-Fi, QR codes, and augmented reality. This literature review serves as the foundation for identifying the strengths and limitations of current methods, which informs the design of the proposed hybrid solution. By synthesizing insights from various studies, the research establishes a clear rationale for combining multiple technologies to achieve a more robust and reliable navigation system.

The core of the research methodology involves the development of a hybrid positioning system that integrates QR codes, BLE beacons, and Wi-Fi-based localization. QR codes are used for initial position initialization, providing centimeter-level accuracy at key points within the facility, such as entrances and landmarks. This approach ensures that the system starts with a precise location reference, which is critical for accurate navigation. BLE beacons are employed for continuous tracking, offering medium-accuracy positioning through trilateration based on received signal strength. Wi-Fi positioning complements BLE by providing broader coverage, especially in areas where BLE signals may be weak or obstructed. The combination of these technologies ensures continuous and reliable tracking across different zones within the facility. The graph-based approach allows for efficient modeling of indoor spaces, facilitating accurate navigation.

Mathematical modeling plays a crucial role in the system's design. The indoor environment is represented as a directed graph, where nodes correspond to specific locations (e.g., room entrances, corridor intersections) and edges represent possible movement routes between these points. Each edge is assigned a weight based on factors such as distance, accessibility, and the presence of obstacles. Dijkstra's algorithm is used to calculate the shortest path between the user's initial position and the destination, ensuring optimal route selection. This graph-based model allows for efficient route optimization and dynamic updates as the user moves through the facility.

Sensor fusion techniques are employed to enhance positioning accuracy by combining data from multiple sources. The system uses trilateration to estimate the user's coordinates based on signals from BLE beacons and Wi-Fi access points. A path loss model is applied to convert RSSI values into distance estimates, which are then used to determine the user's position relative to the nearest node in the graph. Combining trilateration for BLE and Wi-Fi signals enhances the accuracy of indoor positioning systems. This hybrid approach compensates for the limitations of individual technologies, ensuring stable and accurate positioning even in complex environments.

The integration of augmented reality technology is another key aspect of the research methodology. The system generates real-time visual navigation cues, such as directional arrows and virtual signs, which are overlaid onto the user's smartphone camera feed. These AR overlays are dynamically updated based on the user's current location, providing intuitive and interactive guidance. The system continuously evaluates the device's position and orientation using inertial sensors and visual-inertial odometry (VIO) to ensure accurate alignment of AR objects with the physical environment.

The research also addresses technical and organizational challenges associated with the implementation of the hybrid system. Signal interference, device compatibility, data privacy, and user accessibility are analyzed, with potential solutions proposed to mitigate these issues. The study emphasizes the importance of optimizing beacon placement, ensuring cross-platform compatibility, and implementing robust data security measures to protect user information. Additionally, the system is designed with scalability in mind, allowing for gradual deployment and adaptation to different architectural layouts.

In summary, the research methods employed in this study are comprehensive and multidisciplinary, combining theoretical analysis, mathematical modeling, and practical implementation to develop a hybrid indoor positioning system that addresses the unique challenges of navigation in healthcare facilities. The integration of QR codes, BLE beacons, Wi-Fi positioning, and AR technology ensures a robust, scalable, and user-friendly solution that enhances mobility and accessibility for individuals with limited mobility.

4. RESEARCH RESULTS

The development of the proposed navigation system for individuals with limited mobility using augmented reality technology is based on a hybrid positioning method that combines QR-code scanning, BLE beacons, and Wi-Fi-based location determination. The integration of these technologies with AR tools ensures an intuitive and dynamic provision of real-time navigation instructions. To model user movement and optimize routing, the system employs a two-dimensional graph representation of the indoor space. This section discusses the mathematical foundations of system design, the architecture of its components, and their interaction within a comprehensive navigation solution.

To determine the user's coordinates (x, y), the trilateration method is used, which relies on distance data from at least three beacons. The obtained coordinates are mapped to the nearest vertex of the graph, allowing for efficient route adaptation based on the user's real-time location.

Wi-Fi-based positioning is employed as a supplementary method to BLE beacons, enabling user localization in areas where the BLE signal is either weak or unavailable. The system analyzes the received signal strength indicator from multiple Wi-Fi access points to estimate the user's coordinates. Similar to BLE-based positioning, the patient's location (x_i^k, y_i^k) is determined using trilateration methods and mapped to the nearest vertex in the graph-based environmental model. To enhance positioning accuracy and reliability, a hybrid algorithm is utilized, combining data from BLE beacons and Wi-Fi access points. In areas with dense BLE coverage, the system prioritizes BLE-based positioning due to its higher accuracy. However, in zones with sparse BLE coverage, Wi-Fi-based positioning is applied to ensure continuous user location tracking.

The developed user location determination method is implemented using Node.js with the Express framework in a virtual escort system with a client-server architecture. The client is a mobile application designed for smartphones, while the server can be either local (within a medical facility) or remote.

The indoor environment of the facility is proposed to be represented as a directed graph (1):

$$G = (V, E), \tag{1}$$

where V is the set of vertices (nodes), each corresponding to a specific location within the building, such as a room entrance, corridor intersection, or landmark; E is the set of edges, each connecting two vertices and representing a possible movement route between corresponding points.

Each edge $e \in E$ is assigned a weight $\omega(e)$, defining the "cost" of traversing the given path. The value of this function may depend on various parameters, including the distance between vertices, accessibility level (e.g., presence of stairs or elevators), existence of obstacles, or crowd density. The graph model is used to calculate the optimal route between the user's initial position and the destination using shortest path search algorithms, specifically Dijkstra's algorithm.

Let the user start from node v_i^α determined by scanning a QR code, and reach the final node v_δ^α.

The optimal route is represented as a sequence of connected vertices:

$$\gamma = \{v_1^\alpha, v_2^\alpha, v_3^\alpha, \dots, v_\delta^\alpha\}. \tag{2}$$

The total cost of traversing the route is calculated as the sum of the weights of the edges belonging to γ:

$$Total\ Cost = \sum_{e \in \gamma} \omega(e). \tag{3}$$

The obtained route is transformed into a sequence of AR-based navigation cues, such as directional arrows or virtual signs, facilitating user orientation within the space.

To ensure accurate initialization of the user's location within the navigation system, QR codes are deployed at designated points within the facility, including entrances to rooms and key landmarks. Each QR code contains encoded information about its coordinates (x, y) within the two-dimensional graph-based representation of the environment.

The process of determining the initial position of the k-th user proceeds as follows: after scanning a QR code, the system decodes its content and establishes the current node $v_i^{\alpha k}$ in the graph based on the obtained coordinates:

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$$v_i^{\alpha k} = (x_i^k, y_i^k). \quad (4)$$

This approach ensures that navigation starts from a precisely defined location, minimizing errors in subsequent positioning and routing processes.

For continuous location determination within the facility, BLE beacons are placed at key points, each corresponding to a specific vertex of the graph. Position determination is performed by analyzing the received signal strength from the nearest beacons. The signal propagation model for BLE-based positioning was utilized to estimate distances.

The distance d between the user and the beacon is estimated using the path loss model:

$$RSSI = RSSI_0 - 10\eta \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma, \quad (5)$$

where $RSSI_0$ is the signal strength at the reference distance d_0; η is the path loss exponent depending on environmental characteristics; d is the distance between the user and the beacon; X_σ is a random variable modeling signal fluctuations caused by surrounding obstacles.

The obtained RSSI values are converted using the logarithmic distance path loss model:

$$d = 10^{\frac{A-RSSI}{10n}}, \quad (6)$$

where d is estimated distance (in meters); A is reference RSSI at 1 meter (calibrated per Wi-Fi acess point or BLE-beacon); n is path-loss exponent (environment-dependent, e.g., 2 for free space, 4 for dense indoor).

The following is a method for converting RSSI values using the Node.JS programming language:

```
_calculateDistance(rssi, txPower, pathLossExponent)
{
    const distance = Math.pow(10, (txPower - rssi) / (10 * pathLossExponent));

    //Apply non-linear correction for short distances
    if (distance < 1) {
      return distance * 0.8; // Empirical correction factor
    }
    return distance;
  }
```

Next, the trilateration with least squares method is applied.

Given N access points or BLE beacons with known coordinates (x_i, y_i) and calculated distances d_i to the user, the distance equation for $i = 1,2,\dots,N$ is as follows:

$$(x - x_i)^2 + (y - y_i)^2 = d_i^2. \quad (7)$$

This forms a nonlinear system of equations. To solve it, the system is linearized into a matrix form $CX = B$, where:

$$C = \begin{bmatrix} 2(x_N - x_1) & 2(y_N - y_1) \\ 2(x_N - x_2) & 2(y_N - y_2) \\ \dots & \dots \\ 2(x_N - x_{N-1}) & 2(y_N - y_{N-1}) \end{bmatrix},$$

$$X = \begin{bmatrix} x \\ y \end{bmatrix},$$

$$B = \begin{bmatrix} x_1^2 - x_N^2 + y_1^2 - y_N^2 + d_N^2 - d_1^2 \\ \dots \\ x_{N-1}^2 - x_N^2 + y_{N-1}^2 - y_N^2 + d_N^2 - d_{N-1}^2 \end{bmatrix}.$$

Since RSSI measurements are noisy, it is essential to assign weights ω_i to each equation based on signal reliability. To apply these weights, the weight matrix W is defined as:

$$W = diag(\omega_1, \omega_2, \dots, \omega_{N-1}). \quad (8)$$

After applying the weight matrix W to the system $CX = B$ and transposing matrix C for dimensional consistency and proper transformation into a normal equation form, the weighted least squares equation is expressed as:

$$X = (C^T W C)^{-1} C^T W B, \quad (9)$$

where C is the design matrix constructed from BLE-beacon or Wi-Fi acess points coordinates; W is the weight matrix (diagonal matrix of signal confidence weights); B is the observation vector which is derived from distances; X is the unknown position vector (x, y).

The following is a software implementation of the least squares trilateration method.

```
_leastSquaresPosition(anchors) {
   // Construct matrices for Cx = b
   const C = [];
   const b = [];

   for (let i = 0; i < anchors.length - 1; i++) {
     const xi = anchors[i].x;
     const yi = anchors[i].y;
     const ri = anchors[i].distance;
     const xn = anchors[i+1].x;
     const yn = anchors[i+1].y;
     const rn = anchors[i+1].distance;

     C.push([2*(xi - xn), 2*(yi - yn)]);
     b.push(
       Math.pow(xi, 2) - Math.pow(xn, 2) +
       Math.pow(yi, 2) - Math.pow(yn, 2) +
       Math.pow(rn, 2) - Math.pow(ri, 2)
     );
   }
```

```
  // Solve using Moore-Penrose pseudoinverse
  const C_matrix = math.matrix(C);
  const b_vector = math.matrix(b);
  const C_transpose = math.transpose(C_matrix);
  const pseudoInverse = math.multiply(
    math.inv(math.multiply(C_transpose, C_matrix)),
    C_transpose
  );

  const solution = math.multiply(pseudoInverse,
b_vector);
  const x = solution._data[0];
  const y = solution._data[1];

  // Calculate residual error
  const residuals = anchors.map(anchor => {
    const dx = x - anchor.x;
    const dy = y - anchor.y;
    return Math.abs(Math.sqrt(dx*dx + dy*dy) -
anchor.distance;
  });

  const rmse = Math.sqrt(mean(residuals.map(r =>
r*r)));

  return {
    x,
    y,
    z: anchors[0].z,
    accuracy: rmse,
    method: 'least_squares'
  };
}
```

The hybrid positioning system is integrated with a navigation interface utilizing augmented reality technology. After initializing the user's initial position v_i^α by scanning a QR code, the system determines the optimal route γ to the destination v_δ^α based on the two-dimensional graph model of the environment.

Subsequent navigation is carried out through the AR interface, which overlays visual cues (directional arrows, virtual signs, etc.) onto the mobile device's camera feed. Visual instructions are updated in real time, adapting to user movement. If the user deviates from the calculated route, the system recalculates the optimal path and updates AR navigation accordingly. This approach ensures accurate and timely navigation instructions, enhancing the overall user experience.

The architecture of the proposed virtual guidance system in healthcare facilities consists of the following key modules (Fig. 1).

1) QR Code Scanning Module – responsible for initializing the user's initial position v_i^α in the two-dimensional graph representation of the environment.

2) BLE Beacon Module – provides medium-accuracy positioning using trilateration based on received signal strength analysis.

3) Wi-Fi Positioning Module – extends coverage by employing RSSI-based location determination methods from Wi-Fi access points.

4) Optimal Route Search Module – performs shortest path calculations γ in the graph model using a modified Dijkstra’s algorithm and a production-based decision model.

5) Augmented Reality Module – generates real-time visual cues, adapting them according to the user's current location and calculated route.

6) Integration Module – combines information from BLE beacons and Wi-Fi access points, enhancing positioning accuracy and reliability under varying radio environment conditions.

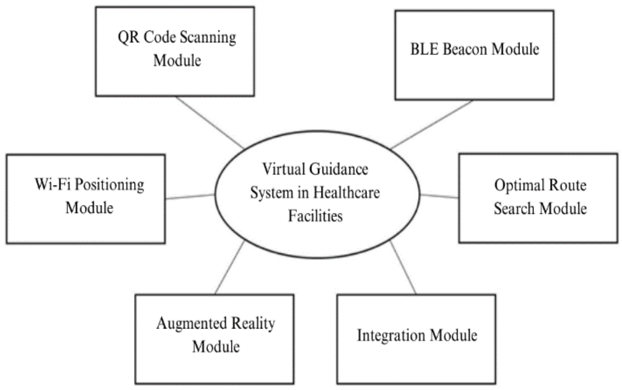

Fig. 1. **The structure of the virtual guidance system in healthcare facilities**
Source: **compiled by the authors**

The proposed hybrid positioning system for indoor navigation using augmented reality technology is based on a two-dimensional graph representation of the environment, allowing for effective space modeling and route optimization. The integration of various positioning methods, including QR code scanning, BLE beacons, and Wi-Fi-based location determination, ensures high accuracy, reliability, and accessibility of the system for users with limited mobility.

The model of system component interaction is presented in Fig. 2.

The application of mathematical optimization methods, particularly shortest path algorithms, facilitates the construction of the most efficient and accessible routes. The proposed architecture serves as a promising foundation for further advancements in indoor navigation technologies and the implementation of innovative solutions in pathfinding using augmented reality.

The integration of a hybrid positioning system with AR-based navigation tools is a key component of the developed solution, ensuring intuitive and dynamic real-time navigation management for users with reduced mobility. By combining the advantages of the hybrid positioning system with AR navigation capabilities, the system provides a seamless, adaptive, and comfortable indoor orientation experience.

The generation of navigation prompts in the augmented reality system is performed by projecting the calculated route (1) onto the visual representation of the real world perceived by the user. This process consists of several key stages. In the first stage, the route is projected, where the path γ is represented as a sequence of coordinates $\{(x_0^k, y_0^k), (x_1^k, y_1^k), \ldots, (x_i^k, y_i^k)\}$ in a two-dimensional graph space. The obtained coordinates are transformed into the augmented reality coordinate system using a transformation matrix T, which accounts for the device's orientation and its position relative to the graph.

The coordinates of each route point (x_k, y_k) are transformed into device coordinates (x_k', y_k') using a matrix:

$$\begin{bmatrix} x_k' \\ y_k' \\ 1 \end{bmatrix} = T \begin{bmatrix} x_k \\ y_k \\ 1 \end{bmatrix}, \quad (10)$$

where the coordinates are represented in homogeneous coordinates to account for translation and rotation. The transformed coordinates (x_k', y_k') are used to place virtual navigational cues, such as arrows or markers, in the user's field of view. As the user moves, the matrix T and, accordingly, the coordinates of the virtual objects are updated in real time, ensuring an accurate representation of the route according to the current position and orientation of the device.

In the second stage, the route is visualized as AR overlays, including navigational elements such as directional arrows or virtual road signs. The position of each overlay element is determined by its corresponding coordinates in the AR system, ensuring the correct display of movement direction. Dynamic route updates occur in real time as the user changes their position. With each device movement, the user's coordinates (x_i^k, y_i^k) are updated, and the system recalculates the current remaining route (1). All AR overlays are accordingly adjusted, ensuring accurate and up-to-date navigation prompts.

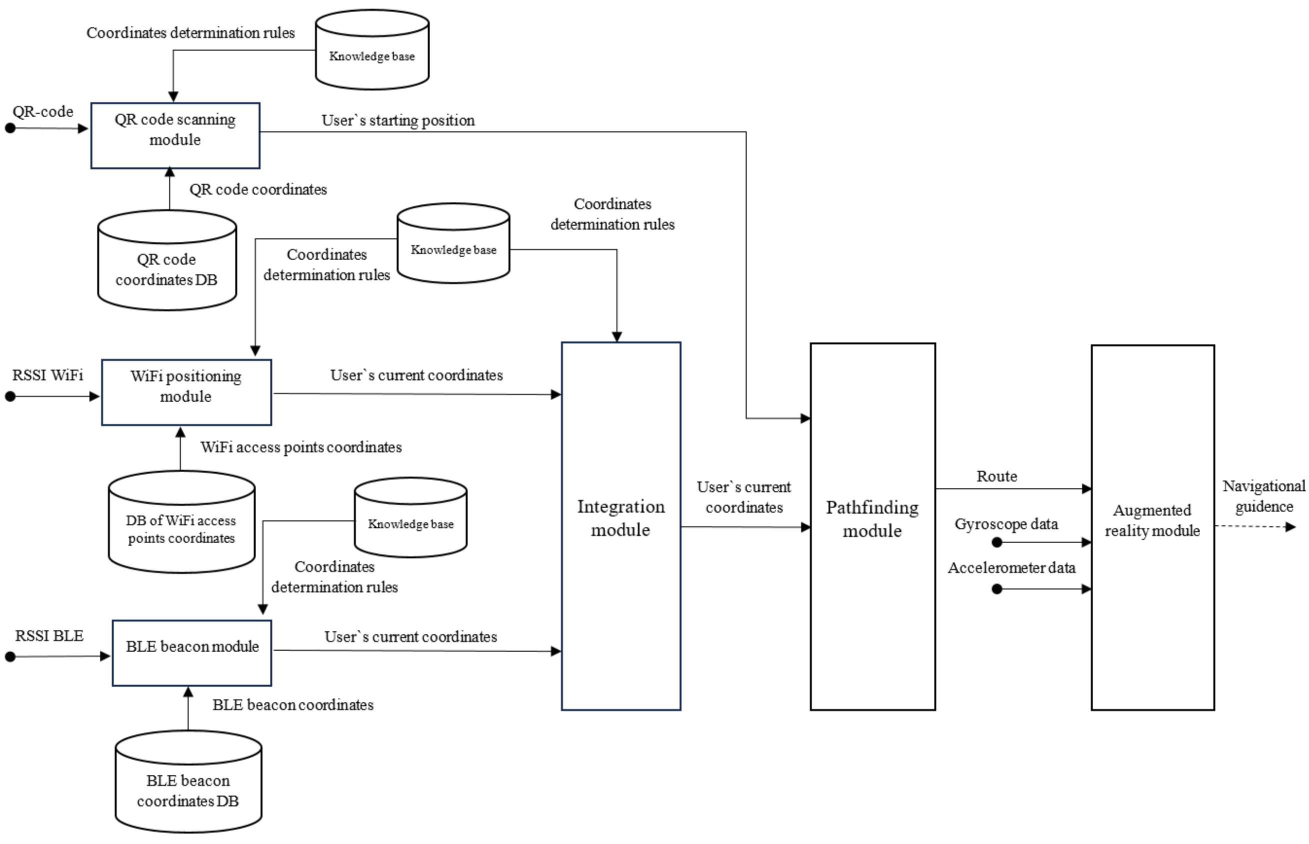

Fig. 2. **Model of system component interaction**
Source: **compiled by the authors**

To precisely align augmented AR objects with the real environment, the system continuously evaluates the device's position and orientation using inertial and visual data. Accelerometers and gyroscopes are employed to track movement and rotation, while the smartphone camera's video stream is utilized for visual-inertial odometry (VIO), enhancing positional accuracy.

The device's position is described by a transformation matrix T, which establishes the corres-pondence between the device's local coordinate system and the global graph coordinate system. As the user moves, this matrix is updated in real time, ensuring proper alignment of AR overlays with the physical environment.

To guarantee the most efficient and accessible navigation path, the system employs real-time route optimization algorithms. In the event of a deviation from the planned route γ, an optimal path γ' is recalculated based on the updated position v_i. The optimization process involves recalculating the route by determining the shortest path from the current position v_i to the target node v_δ^α using Dijkstra's algorithm. The computed route γ' is projected into the augmented reality coordinate system and updated as corresponding AR overlays. Dynamic AR navigation updates ensure that all changes in the route are immediately reflected in the visual prompts, providing continuous and adaptive navigation management, thus enhancing the accuracy and usability of the system for users with reduced mobility.

Consider a scenario in which a mobility-impaired patient navigates a hospital facility to reach the radiology department. The navigation process begins with the initialization of the patient's starting position. This is achieved by scanning a QR code located at the main entrance, allowing the system to register the initial coordinate v_i^α on the two-dimensional building graph. The optimal route γ is then calculated between the starting point v_i^α and the target location v_δ^α, corresponding to the radiology department. Dijkstra's algorithm is used to compute the shortest path, ensuring efficient route selection while considering spatial constraints and accessibility.

The subsequent stage involves the use of augmented reality to visualize navigation prompts. The AR mobile application overlays interactive navigation elements, such as directional arrows or virtual indicators, onto the smartphone camera's live image, guiding the user through the calculated route. As the patient moves, their current position v_i is continuously updated based on data received from BLE beacons and Wi-Fi access points. This enables the system to dynamically adjust the positioning of AR overlays, tailoring navigation prompts to the user's real-time location changes. Upon reaching the destination, the system confirms the arrival and may provide additional information, such as further instructions or the location of necessary medical personnel.

The integration of a hybrid positioning system with augmented reality navigation technologies enables the development of an efficient indoor navigation solution tailored for users with reduced mobility. A two-dimensional graph-based spatial representation is employed to model the navigation environment, while mathematical optimization methods, particularly shortest-path search algorithms, ensure route calculation accuracy.

The combination of BLE, Wi-Fi, and augmented reality technologies enhances the navigation experience, allowing users to receive clear visual prompts in real time. Dynamic route updates in case of deviations from the initial plan ensure that users always have access to up-to-date navigation information, increasing the system's reliability and convenience.

The further advancement of positioning and augmented reality technologies opens new prospects for developing even more accurate and accessible navigation solutions capable of improving user mobility in complex architectural environments.

One of the key advantages of the hybrid system is the use of QR codes to initialize the user's starting position. This technology ensures centimeter-level accuracy in determining the initial location, which is critical for the precision of subsequent navigation. In the context of medical facilities, a patient scanning a QR code at the hospital entrance receives a highly accurate location determination, significantly improving further navigation. Moreover, the use of QR codes reduces the need for complex initial calibration or reliance on wireless signals, minimizing potential errors and enhancing user convenience.

The hybrid approach is designed to optimize costs while maintaining high performance. QR codes offer a cost-effective solution, requiring only printed or digital markers at key points within a facility. BLE beacons are relatively inexpensive and have long-lasting autonomous operation, reducing the need for frequent maintenance. Utilizing existing

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Wi-Fi infrastructure for positioning further decreases financial expenditures, as it eliminates the necessity for installing costly new equipment. By gradually deploying system components based on institutional needs, the hybrid approach proves to be an efficient solution even for medical facilities with limited budgets.

The combination of three technologies ensures high scalability and adaptability to various architectural environments. QR codes can be easily relocated or added to new locations, BLE beacons provide precise tracking in high-traffic areas, and Wi-Fi covers large spaces, ensuring continuous navigation. This approach allows the system to be integrated into both small clinics and large hospital complexes, offering a flexible configuration tailored to user needs. The integration of multiple technologies enhances system reliability by compensating for the limitations of each component. Specifically:

− QR codes provide high accuracy but are limited to specific scanning points.

− BLE beacons are effective in controlled zones but are sensitive to physical obstructions.

− Wi-Fi-based positioning offers extensive coverage but has lower accuracy.

By combining these methods, the system ensures stable and continuous positioning, even in complex environments, such as when the surroundings change or when one of the technologies loses signal. This approach offers a balance between cost and accuracy, making it suitable for healthcare settings. The hybrid system is designed with user-friendliness in mind, making it accessible to a wide range of users. The use of QR codes for initial positioning requires no specialized skills, while navigation through augmented reality provides intuitive visual guidance.

The integration with AR technology enables the system to dynamically adjust routes in response to environmental changes. For instance, if obstacles appear in corridors or if the layout changes, routes can be automatically recalculated, significantly improving navigation efficiency. The hybrid system enhances inclusive navigation by offering adaptive routes for users with special needs. For example, the system can consider the availability of ramps and elevators while avoiding stairs, making navigation more accessible for individuals with limited mobility.

One of the major advantages of the hybrid approach is its ability to leverage existing infrastructure, such as Wi-Fi networks and smartphone cameras. This simplifies system implementation and reduces financial and organizational costs, making it accessible to a wide range of institutions. The system is designed with future technological advancements in mind, allowing for the integration of new positioning methods, such as ultra-wideband (UWB) technology or enhanced 3D mapping algorithms. This ensures long-term efficiency and upgradeability of the system.

A hybrid positioning system for navigation using augmented reality offers significant advantages; however, its implementation and operation are accompanied by various technical and organizational challenges. Ensuring the efficiency, reliability, and user-friendliness of such a system requires a comprehensive approach to addressing potential issues. The main challenges include signal interference, device compatibility, data privacy, user accessibility, and system maintenance, integration with existing infrastructure, user adaptation, environmental changes, cost considerations, and ethical concerns.

One of the key technical challenges is signal interference and the impact of environmental factors. In medical facilities, complex layouts, dense walls, and other physical obstacles can degrade positioning accuracy, particularly for BLE beacons and Wi-Fi-based localization. To ensure stable operation, it is necessary to optimally place beacons, conduct regular system calibration, and combine multiple technologies to enhance signal reliability. Another critical aspect is device compatibility and performance. The system must function correctly across a wide range of mobile devices, considering different hardware configurations and augmented reality platforms, such as ARKit for iOS and ARCore for Android. This necessitates the development of cross-platform solutions, performance optimization, and extensive testing on various devices to ensure stable operation.

Data privacy and security are crucial concerns, as the system may collect information about users' locations. To enhance security, data processing should be performed locally on the device, collected data should be anonymized, and a transparent data usage policy should be implemented, allowing users to control access to their personal information. Ensuring accessibility and inclusivity is also essential, particularly for individuals with mobility impairments. The system should incorporate voice prompts and adaptive display settings. Conducting user testing with individuals with special needs can help identify and eliminate accessibility barriers.

System maintenance and scalability require careful planning. A modular design is recommended, allowing for the gradual implementation of new features, along with automated calibration algorithms to reduce maintenance costs. The system's expansion should be carried out in phases, gradually increasing coverage based on the facility's needs. Integrating the system with existing platforms, such as hospital information systems, may present challenges. The use of open APIs and adherence to industry standards can facilitate the integration process. Collaboration with facility administrators can help minimize disruptions during deployment.

User adaptation to the new system is a critical factor in successful implementation. Providing educational materials, step-by-step instructions, and initial support can help users quickly become familiar with the system. Incorporating feedback mechanisms will enable continuous system improvement based on user experiences. Dynamic changes in the indoor environment, such as layout modifications, furniture relocation, or equipment placement, can impact positioning accuracy. To adapt to such changes, dynamic mapping methods, such as Simultaneous Localization and Mapping (SLAM), should be employed, and the system's database should be regularly updated.

Financial and resource constraints are also significant factors. The implementation of the system requires a cost-benefit analysis, securing additional funding, and utilizing open-source software solutions to reduce development and licensing costs. Additionally, ethical considerations regarding the use of augmented reality and positioning technologies must be taken into account. The principles of privacy, inclusivity, and transparency should form the foundation of the system's design. Engaging stakeholders in the decision-making process can help ensure compliance with ethical standards and enhance user trust.

CONCLUSIONS AND PROSPECTS OF FURTHER RESEARCH

As a result of the conducted research, a hybrid patient location tracking method for augmented reality-based virtual escort systems in healthcare facilities was proposed. This method is implemented through the integration of QR code technology, Bluetooth Low Energy beacons and Wi-Fi localization. The integration enables the system to combine the strengths of each individual technology while mitigating their respective limitations. By incorporating QR codes, BLE beacons, and Wi-Fi localization, the system overcomes the inherent constraints of standalone positioning approaches. QR codes offer centimeter-level accuracy at critical initialization points, such as entrances and landmarks, providing a dependable reference for navigation. BLE beacons support continuous medium-accuracy tracking within corridors and confined indoor spaces, whereas Wi-Fi localization extends positioning coverage in open areas where BLE signal strength may degrade. This multi-technology approach ensures seamless positioning across heterogeneous indoor environments, effectively addressing challenges such as signal interference caused by medical equipment or structural barriers.

The integration of augmented reality further enhances user experience by overlaying intuitive visual cues-such as directional arrows or virtual signage-onto the smartphone camera feed. This real-time guidance significantly reduces cognitive load and enhances spatial awareness, which is particularly beneficial in complex healthcare settings where traditional navigational tools, such as static maps, often prove insufficient.

An analysis of contemporary approaches and solutions aimed at improving medical information systems has identified several key research directions. In particular, a considerable portion of current studies focuses on the intelligent processing of medical information. The evaluation of models, methods, and technologies in this domain reveals major areas of interest, including decision support systems, remote diagnostics – especially through the use of Internet of Things (IoT) devices and telemedicine – as well as the semantic interpretation, route optimization, information visualization, and device localization in indoor navigation systems.

A structural model for a virtual escort system within healthcare institutions was developed, incorporating six distinct modules: the QR Code Scanning Module, BLE Beacon Module, Wi-Fi Positioning Module, Optimal Route Search Module, Augmented Reality Module, and Integration Module. In addition, an interaction model was designed to represent both external and internal information flows, as well as the interconnections among the structural components of the proposed system.

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The proposed hybrid positioning method presents several technical and ethical challenges that must be addressed. These include minimizing signal interference, ensuring compatibility with a wide range of devices, safeguarding user data privacy, and adhering to the principles of inclusive design. To meet these objectives, it is necessary to implement optimized beacon placement, ensure cross-platform support, employ on-device data processing technologies, and follow the guidelines of universal design.

Promising directions for future research include the development of methods, algorithms, and technologies for integrating advanced augmented reality functionalities, personalizing navigation routes using artificial intelligence algorithms, and improving the system's energy efficiency. Moreover, extending the application scope of the proposed method and system to other environments, such as airports, university campuses, and smart city infrastructure, will enhance their versatility and social impact. Collaboration with healthcare institutions and rehabilitation specialists may also open additional opportunities for applying the system in patient monitoring and telemedicine domains.

Thus, the proposed hybrid indoor positioning method based on augmented reality represents a promising solution that combines technological innovation, cost-effectiveness, and ease of use. The further advancement of this method and system—particularly in terms of algorithmic optimization, enhanced security, and inclusive design—will contribute to improving the quality of life for individuals with limited mobility by providing a higher level of independence and accessibility in public spaces, which is of critical relevance to contemporary society.

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Метод відстеження місцеперебування пацієнта у системах віртуального супроводу в медичних закладах

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АНОТАЦІЯ

В статті запропоновано гібридний метод відстеження місцеперебування пацієнта у системах віртуального супроводу в медичних закладах. Для забезпечення необхідної точності внутрішнього позиціонування та безперешкодної навігації, що особливо важливо для осіб із обмеженою мобільністю, запропоновано гібридний метод, який поєднує сканування кодів швидкого доступу, використання маячків Bluetooth Low Energy та технологію позиціонування за допомогою Wi-Fi. Кожна з цих технологій відіграє унікальну роль у загальній системі: коди швидкого доступу слугують дискретними маркерами місцеположення, маячки Bluetooth Low Energy забезпечують безперервне відстеження на основі відстані, а позиціонування з Wi-Fi покращує покриття у відкритому просторі. Ключовим аспектом дослідження є інтеграція в запропонований гібридний метод позиціонування технологій доповненої реальності. Накладання навігаційних підказок у реальному часі на поле зору користувача за допомогою пристроїв із підтримкою доповненої реальності, таких як смартфони, дозволяє зробити систему віртуального супроводу більш інтуїтивною та інтерактивною. Ця особливість є цінною для осіб з інвалідністю, оскільки знижує когнітивне навантаження та підвищує просторову обізнаність у складних медичних середовищах. У дослідженні запропоновано структурну схему системи віртуального супроводу на основі доповненої реальності, що включає модуль сканування кодів швидкого доступу, модуль маячків Bluetooth Low Energy, модуль Wi-Fi позиціnування, модуль пошуку оптимального маршруту, модуль доповненої реальності та модуль інтеграції. Інтеграція визначених модулів дозволяє використати переваги кожного з них та зменшити їх недоліки. Розроблено модель взаємодії компонентів системи, де визначено зовнішні та внутрішні інформаційні потоки та інтеграційну взаємодію визначених структурних елементів системи. Визначено перспективні напрямки майбутніх досліджень, зокрема методи, алгоритми та технології інтеграції передових функцій доповненої реальності, персоналізація маршрутів на основі алгоритмів штучного інтелекту та підвищення енергоефективності системи.

Ключові слова: віртуальний супровід; доповнена реальність; медичні заклади; відстеження; навігація; внутрішнє середовище

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