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WIRELESS SENSOR NETWORK BASED LOCALIZATION FOR ENHANCED DEVICE TRACKING IN HEALTHCARE ENVIRONMENTS

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ABSTRACT

The growing demand for accurate, real-time indoor positioning in healthcare environments has led to the exploration of alternative localization technologies beyond traditional GPS. Hospitals face the challenge of tracking mobile diagnostic equipment and coordinating personnel under tight operational constraints. This paper presents a practical implementation of an indoor positioning system (IPS) within an outpatient medical facility in Hungary, designed to track the movement of a shared mobile ultrasound device. Three technologies were investigated: Wi-Fi (using RSSI fingerprinting), Bluetooth Low Energy (BLE) beacons, and Ultra-Wideband (UWB) with ToF-based trilateration. All solutions were implemented using ESP32 microcontrollers, supported by custom Arduino code and MATLAB for data analysis. Results show significant differences in accuracy and reliability, with UWB proving superior for precision-demanding medical use cases.

Keywords: Indoor Localisation, Wireless Sensors Network, UWB, ESP32

1. INTRODUCTION

The demand for positioning and localization is nearly as old as humanity itself. Even ancient scholars engaged with the challenge, and as humans began traveling greater distances, it became increasingly important to be aware of one's exact location [1], [2]. Today, at any given moment, the need may arise to determine one's precise whereabouts, and the direction required to reach a designated destination in a timely manner. On land, this is often aided by natural landmarks and terrain features; when these are recognizable, position estimation becomes possible with a certain degree of accuracy [3]. Localization, however, provides a more precise result than simple positioning. Not only can coordinates be determined, but the exact physical location on the Earth's surface corresponding to those coordinates can also be identified. Naturally, this requires high-quality maps, which enable further information extraction based on the determined coordinates and also support route planning for navigation purposes. This need for accurate localization has become critical not only in everyday travel and orientation but also in transportation and various industrial activities. Nowadays, the ability to determine one's own position using a mobile phone is taken for granted by most individuals. Real-time tracking of public transportation while waiting at a stop or following the route of a delivery is already a standard feature in many people's lives.

Modern society has become inconceivable without the use of the Global Positioning System (GPS); however, this method is mostly applicable to outdoor tracking [4][5]. Primarily driven by industrial demands, several indoor localization systems have been developed, enabling not only the tracking of vehicles moving across large distances but also the monitoring of mobile objects within facilities and buildings.

Currently, a variety of such systems are available, differing in reliability, accuracy, operating technology, cost, maintenance requirements, and other critical attributes. These differences fundamentally determine which applications a particular system is suited for. For this reason, it is not yet evident which technologies are best suited to which intralogistics applications, nor which system attributes require further development [7].

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This publication seeks to provide a brief overview of outdoor and indoor localization methods. Indoor positioning methods and technologies will then be collected and analyzed. Based on defined criteria, a suitable indoor localization system for a specific domain—healthcare institutions—will be identified. The aim was also to design and implement a simplified version of this system. Drawing from experiences during the COVID-19 pandemic, it has become clear that technological development within healthcare systems has played a pivotal role worldwide in recent years. Across Europe—including in Hungary—a shortage of adequately trained healthcare personnel has been observed. Supporting the efficiency of healthcare professionals through technological advancements is a critical need. These systems not only assist and monitor the work of medical staff but also contribute to improved patient recovery outcomes.

The aim of this publication was the implementation of a model for an effective indoor localization system in a hospital diagnostic unit within an outpatient healthcare facility. Determining the exact location of equipment, tools, and even personnel—and using this data for locating, mobilizing, and organizing them—can save time for healthcare staff during daily operations, especially under high workloads such as during a pandemic or in the case of unforeseen accidents. The specific task undertaken was the effective tracking of a mobile diagnostic device. The ultrasound machine in question is used across multiple examination rooms, and it is often not located at its scheduled station. This leads to unnecessary delays in daily operations, causes workflow disruptions, and results in conflicts. A technical solution was thus sought to eliminate these inefficiencies.:

2. MATERIALS AND METHODS

In a healthcare institution, localization systems are required to be highly accurate, reliable, and resistant to interference, as buildings often contain thick walls, and in the case of radiology departments, even lead shielding or other attenuating materials that reduce the effectiveness of radio frequency-based technologies. At the same time, Wi-Fi networks are typically operational within such buildings, which can be taken into consideration when selecting the appropriate technology. The selection of the applied method was primarily determined by the specific performance requirements. A system had to be developed that was capable of indicating the position of a specific device—the MINDRAY M6 mobile ultrasound machine—within the building. The principal requirement for the positioning system was to signal when the mobile diagnostic device was moved beyond a 3-meter radius from its designated location. During clinical use, the device is often transported to a patient's bedside or to a different examination room within the department. However, following its use, it should be returned to its original position so that the next user can easily locate it. In daily practice, this protocol is frequently not followed, creating a need for a positioning solution that can provide alerts when the equipment is removed from its intended station. The device selected for testing had to be small, inexpensive, and, if possible, readily available. Among the available modules, the ESP32 module was chosen for this purpose.

2.1. The ESP32 board

The choice of the ESP32 module for a simple indoor Wi-Fi-based localization system offers several advantages that can enhance the project's efficiency and reliability. The ESP32-WROOM-32D chip features a dual-core processor, enabling parallel multitasking. This capability is particularly beneficial in localization systems, which often require real-time, rapid data processing, such as continuous measurement and evaluation of Wi-Fi signals and sensor data [6][8].

The ESP32 module includes built-in Wi-Fi and Bluetooth functionalities, facilitating wireless communication. This is advantageous for potential future integration with devices that also utilize Wi-Fi or Bluetooth. Additionally, ESP32 modules are relatively inexpensive, making them ideal for prototyping and experimentation without significant financial investment. They are widely available, easy to procure, and supported by extensive documentation. The ESP32 can operate in energy-saving modes, which is a

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significant benefit for systems requiring long operational periods, such as those powered by power banks or batteries. Furthermore, the ESP32 supports open-source libraries and is compatible with development environments like the Arduino IDE, allowing for rapid and straightforward development. A variety of compatible modules and sensors are also available, facilitating easy system expansion during experimentation. Overall, the ESP32-WROOM module was deemed an ideal choice for a simple indoor Wi-Fi-based localization system, combining high performance, wireless connectivity, cost-effectiveness, and development flexibility. The modules were sourced from a reputable supplier.

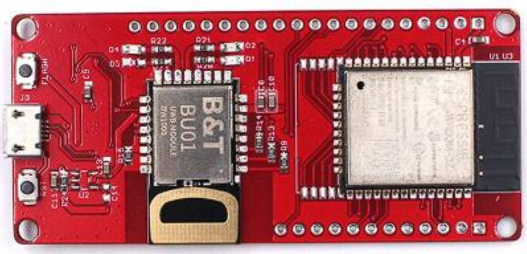

Figure 1. The ESP 32-WROVER module

Due to the application of Ultra-Wideband (UWB) localization methods in the research, the ESP32-WROVER module was also utilized. This development board enabled the implementation of a UWB-based localization system, as it offers a more stable module with enhanced RAM capacity, supporting high performance and wireless connectivity while remaining cost-effective.

2.2. The Software

For programming the ESP32 modules, I utilized the Arduino Integrated Development Environment (IDE) [10] version 1.8.19. This environment is known for its user-friendly interface, which simplifies programming tasks. Its straightforward library management system allows for the easy installation of various libraries available for different modules. The Arduino IDE is renowned for its simplicity and accessibility, making it suitable for beginners. It requires minimal configuration, enabling quick testing of basic code. Numerous libraries are available for the Arduino platform, facilitating the use of various ESP32 functionalities such as Wi-Fi, Bluetooth, sensors, motors, and other devices. Specialized libraries for the ESP32 can also be easily integrated into the Arduino IDE. Primarily designed for rapid prototyping, the Arduino platform allows for swift development and testing of ideas without necessitating deep hardware knowledge. Basic functionalities like Wi-Fi connectivity and Bluetooth communication can be achieved with concise code. The Arduino IDE supports a wide range of microcontrollers, including the ESP32. While the IDE already provides compatibility with the ESP32, it can also be easily integrated with familiar tools if needed. The ESP32 is a powerful microcontroller capable of Wi-Fi and Bluetooth communication, featuring multiple processor cores and supporting a broad array of peripherals (such as GPIO, ADC, DAC, SPI, and I2C). Programming the ESP32 within the Arduino IDE facilitates the utilization of these features without the need for complex code. The Arduino IDE is free and open source, allowing anyone to access and customize the development environment. It is also well-suited for designing graphical user interfaces. In my measurements, data received via the serial port was visualized using MATLAB.

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3. RESULTS AND DISCUSSION

The ESP32-WROOM-32D module's integrated Wi-Fi capabilities can be effectively utilized for indoor localization by leveraging existing wireless infrastructure. This approach primarily relies on the Received Signal Strength Indicator (RSSI) to estimate positions within a building. The methodology involves creating a comprehensive database, or "fingerprint," that maps RSSI values to specific locations. During operation, real-time RSSI measurements are compared against this database to determine the most probable current position. While this fingerprinting technique offers a cost-effective solution, it is susceptible to environmental changes. Alterations in the physical layout, such as the movement of large objects or changes in furniture placement, can significantly impact signal propagation, leading to decreased localization accuracy. Consequently, the fingerprint database requires regular updates to maintain reliability, especially in dynamic environments where the interior configuration frequently changes.
Despite these challenges, Wi-Fi-based localization remains advantageous in scenarios where low implementation costs are prioritized over high precision. The widespread availability of Wi-Fi networks within buildings facilitates the deployment of such systems without the need for additional infrastructure. However, the effectiveness of this method diminishes in outdoor settings due to the limited coverage and variability of Wi-Fi signals beyond enclosed spaces.

Indoor localization encompasses various technologies, each with distinct characteristics [11][12]:

- RFID (Radio-Frequency Identification): Utilizes tags and readers to determine object positions, commonly employed for asset tracking.
- BLE (Bluetooth Low Energy) Beacons: Employs low-power transmitters to monitor movement, particularly useful for tracking individuals.
- UWB (Ultra-Wideband): Offers high-precision localization but entails higher costs.
- LiDAR (Light Detection and Ranging): Uses laser pulses to map environments and ascertain positions.
- VPS (Visual Positioning System): Determines location based on visual reference points captured through camera images.
- IMU (Inertial Measurement Unit): Combines accelerometers and gyroscopes to track movement, often serving as a supplementary technology.

Each of these technologies presents trade-offs concerning accuracy, cost, and complexity. The selection of an appropriate system depends on specific application requirements and environmental conditions.

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Figure 2. Sensor module location on the ultrasound device

The BLE beacon technology can be used to track patient movements during preparation for imaging examinations, ensuring that no one is left behind or gets lost within the departments. More expensive UWB systems can be applied to track movements around CT or MR machines, particularly in areas where strict regulations govern who and when can be present in the space—this also enhances radiation safety. LIDAR and VPS technologies can assist in the precise positioning and calibration of imaging equipment, which is especially beneficial for high-precision procedures, such as interventional radiology. IMU technology can be integrated into portable imaging devices, enabling the system to detect if the device is tilted or moved, and even automatically recalibrate itself—this can be useful, for example, in mobile X-ray or C-arm X-ray systems.

The tested, simple Wi-Fi-based localization system operates in indoor environments and determines the position of devices based on the strength of Wi-Fi signals, specifically the RSSI values. Using the ESP32 microcontrollers that I have acquired, data is sent via the UDP protocol, allowing for fast and timed communication between devices. The system employs a fingerprinting method, utilizing a pre-recorded signal map, against which the current signal strengths are compared to compute the location. This very inexpensive and simple system proved effective for indicating when a device was moved; however, it was not precise in indicating distance. Its advantage lies in the fact that it did not require new infrastructure, as it relied on the existing Wi-Fi network in the building. However, the system was sensitive to environmental changes and noise, which negatively affected its accuracy (Fig 3.).

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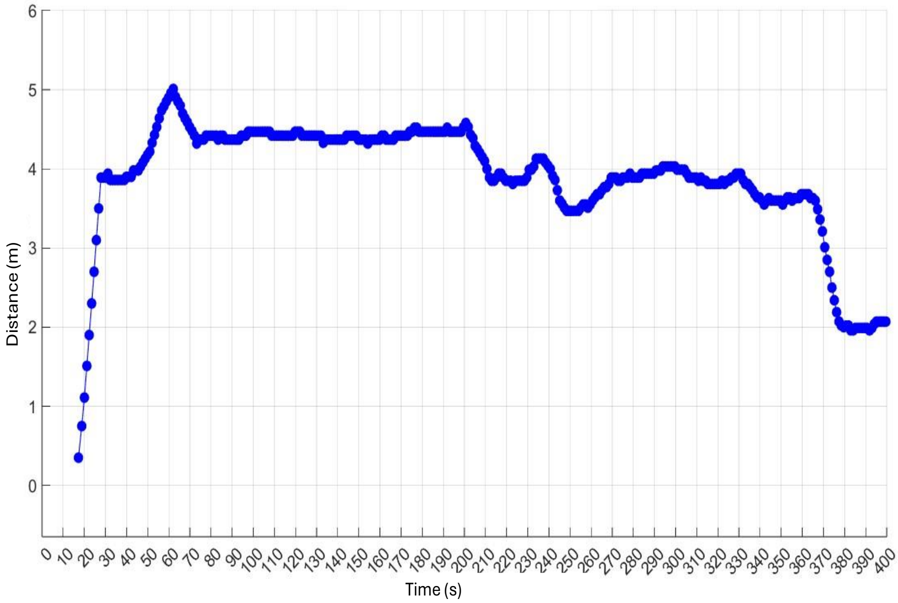

Figure 3. Result of the localisation system based on the WIFI

The built-in Bluetooth capabilities of the ESP32 module were also tested, allowing the device to operate wirelessly. Although Bluetooth-based distance measurement is a simple and convenient solution, significant accuracy issues were encountered in indoor environments. The RSSI value was strongly influenced by environmental factors such as walls, doors, human movement, and electromagnetic interference, often resulting in inaccurate measurements. However, determining the distance between devices could still be useful if the objective was simply to ensure that the devices remained within a designated area, such as a room. This method is most suitable when the aim is to detect the movement of devices, which could be combined with auditory or visual signals to provide a warning if the device exits the designated area.

For the UWB localization system, three ESP32-Wrover modules were used. The system relies on extremely short, nanosecond pulses for precise and energy-efficient distance measurement. UWB technology operates in a wide frequency range (above 500 MHz) and is highly resistant to indoor multipath propagation effects, making it suitable for accurate positioning even in reflective environments. The system measures the distance between a tag (transmitter) and reference points (anchors), typically using Time of Flight (ToF), Time of Arrival (ToA), and Time Difference of Arrival (TDoA) timing methods. These time-based techniques allow for position determination with centimeter-level accuracy.

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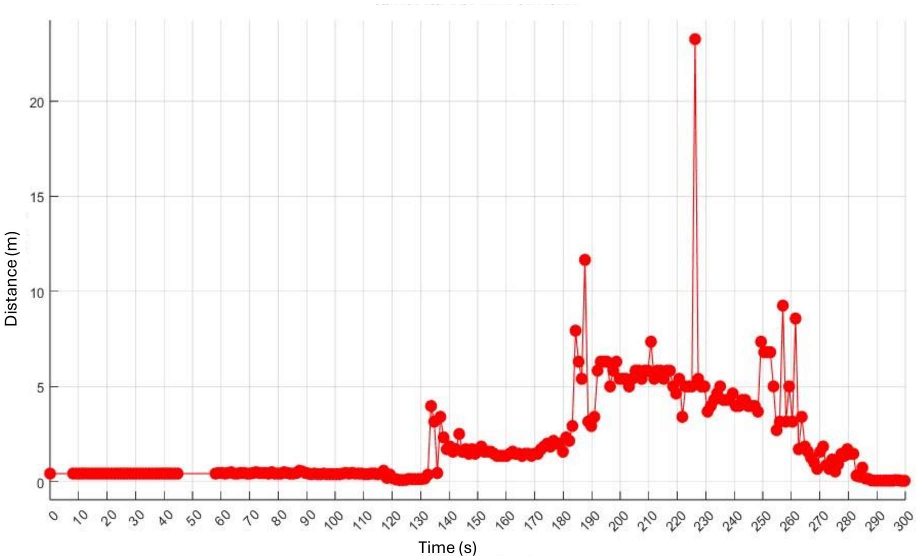

Figure 4. Result of the localisation system based on the Bluetooth technology

Devices using the ESP32-Wrover module and the Decawave DW1000 chip automatically initiate ranging when in proximity to each other, providing real-time, precise localization over short distances. This method was found to be the most effective. It was also confirmed that the module did not significantly affect the operation of the imaging device, even in Doppler mode.

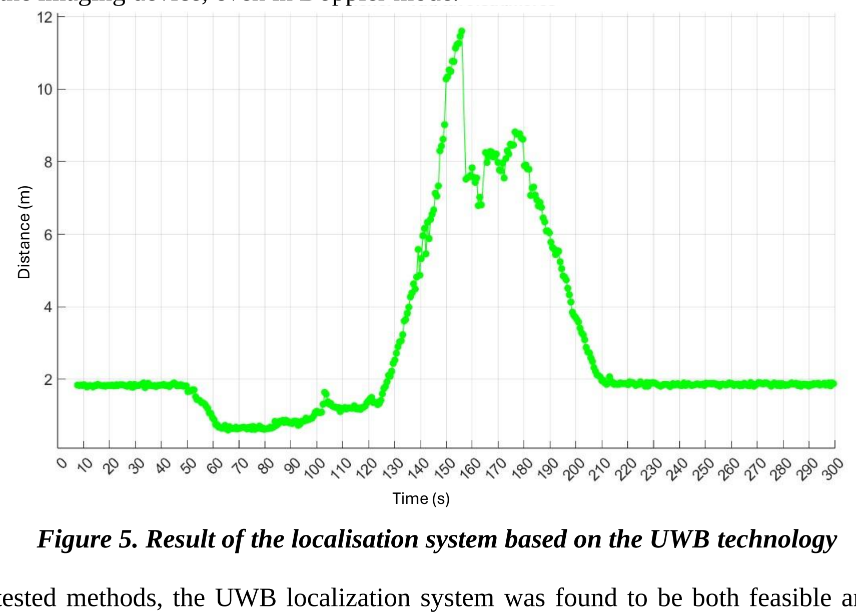

Figure 5. Result of the localisation system based on the UWB technology

Among the tested methods, the UWB localization system was found to be both feasible and sufficiently accurate for the intended task. With the installation of three reference points per floor, the positions of the

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designated devices could be accurately indicated with 3D visualization, allowing for the efficient tracking of the entire diagnostic equipment inventory with minimal investment.

4. CONCLUSIONS

The evaluation of various localization technologies has demonstrated that UWB-based systems offer the most effective and accurate solution for tracking the movement and positioning of devices in indoor environments, such as medical imaging equipment. While Bluetooth-based distance measurement proved to be a simple and convenient method, its accuracy was significantly impacted by environmental factors, limiting its effectiveness for precise location tracking. In contrast, the UWB system, utilizing ESP32-Wrover modules and the Decawave DW1000 chip, showed robust performance, providing centimeter-level accuracy even in reflective environments. The ability to measure the distance between tags and reference points through Time of Flight (ToF), Time of Arrival (ToA), and Time Difference of Arrival (TDoA) methods proved to be highly reliable for real-time localization. Furthermore, the integration of additional reference points for 3D visualization can enable the precise tracking of the entire diagnostic equipment inventory with minimal infrastructure costs. This makes UWB a suitable solution for environments where high accuracy and reliability are critical, such as in medical imaging facilities, where the correct positioning of equipment is essential for patient safety and procedural success. The findings suggest that UWB localization systems offer a practical, scalable, and cost-effective method for improving equipment management and ensuring operational efficiency in healthcare settings.

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