DESIGN AND EVALUATION OF AN INDOOR POSITIONING SYSTEM FOR HOSTAGE RESCUE MISSIONS

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ABSTRACT

Indoor positioning has become an important research direction with applications in various fields such as military, healthcare, and industrial systems. Among these, designing and implementing indoor positioning systems for specialized surveillance missions - such as hostage rescue - represents a promising yet underexplored area. This paper provides an overview of current indoor positioning technologies and techniques, and proposes a system based on Ultra-Wideband (UWB) technology. The system is developed and tested in a simulated hostage rescue training scenario, where the soldier is modeled and tracked in a 3D virtual environment. This setup enables commanders to visually monitor real-time movements and assess tactical compliance during the training process. Experimental results demonstrate that the system achieves high positioning accuracy and shows strong potential for practical application in complex indoor military operations.

Keywords: *Indoor positioning, Internet of Things, 3D Graphic, urban warfare, training process.*

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1. INTRODUCTION

Over the past decade, the world has witnessed numerous crises, including the Russia-Ukraine war, the earthquake disaster in Türkiye and the Israel-Hamas conflict. These events have highlighted the increasing relevance of urban warfare as a critical and complex form of modern combat. Urban warfare involves military operations conducted in densely populated areas, particularly in high-rise building zones with numerous physical obstacles. Such operations demand well-trained soldiers capable of operating effectively in confined environments.

Typical urban missions include combat in multi-story structures, counter-terrorism efforts, hostage rescue, and disaster response operations (e.g., earthquakes, fires, and floods). These scenarios share common characteristics: limited maneuvering space, time-sensitive decision-making, and the need for rapid, coordinated actions. As a result, military personnel must undergo multi-level training-from basic to advanced scenarios-to build operational readiness. Effective monitoring and evaluation of training exercises are essential and increasingly rely on the application of modern technologies.

Emerging technologies such as the Internet of Things (IoT) and 3D graphics have become integral to the Fourth Industrial Revolution and are widely adopted in military training environments. These technologies enhance the ability to track and visualize soldier movements, thereby improving the quality of training and reducing potential losses in real-world combat situations. Among these, positioning technology plays a pivotal role by providing real-time location data of soldiers within training environments, both outdoors and indoors. This positional information serves as input for visualization systems that render soldier movements on 2D or 3D maps, enabling commanders to monitor progress and assess individual performance against tactical objectives.

In this paper, we propose an indoor positioning and monitoring system that utilizes IoT technology for data acquisition and 3D graphics for real-time visualization. The system determines and displays soldier positions within an indoor training environment, while also mapping their movement trajectories. This enables commanders to analyse behavioral responses, tactical compliance, and situational handling capabilities.

The remainder of this paper is structured as follows:

- Introduction;
- Related research and our contributions;
- Framework designing;
- Experimental results;
- Conclusion.

2. PREVIOUS RELATED WORK AND OUR CONTRIBUTIONS

A wide range of positioning technologies have been developed to locate people, objects, or mobile devices, each offering advantages suited to specific application scenarios. Among them, the Global Positioning System (GPS) is the most widely used for outdoor positioning due to its high accuracy and global coverage. However, GPS signals are significantly attenuated or blocked in indoor environments, rendering it ineffective for indoor applications [1].

To address this limitation, Indoor Positioning Systems (IPS) have been introduced as real-time tracking solutions capable of determining the location of people or objects within enclosed environments [2]. Unlike GPS, IPS operates within buildings and other indoor spaces where satellite signals are unavailable or unreliable. These systems rely on a variety of technologies, algorithms, and signal processing techniques to estimate position accurately.

Several technologies have been employed in the development of IPS, each with different characteristics in terms of range, accuracy, cost, and complexity. The most common include: RFID [3, 4], WIFI [5, 6], UWB [7-11], Ultrasonic [12, 13], Zigbee [14, 15], Infrared [16,17], Bluetooth [18, 19]. The selection of a specific technology depends on the requirements of the application, including spatial resolution, infrastructure constraints, and real-time performance.

Indoor motion tracking applications require high positioning accuracy, and in recent years, UWB short-range wireless technology has gained significant attention due to its high precision, compact hardware design, and reliable performance in complex indoor environments. UWB has become a preferred choice for industrial applications where accurate and real-time tracking is essential. Indoor Positioning Systems (IPS) based on UWB have been widely adopted in various domains, including item tracking in logistics and manufacturing, providing mobility assistance for the elderly and disabled, supporting indoor navigation for visually impaired individuals in public facilities, monitoring human movement in crowded areas, and enhancing overall security and safety measures. Based on the comparisons presented in Table 1, this study proposes the development of an indoor positioning system using UWB technology, due to its high positioning accuracy and low power consumption.

Table 1. Comparison of indoor positioning technologies

Positioning technology	Accuracy	Energy consumption	Advantages	Disadvantages
RFID	Dm-m	low	High positioning accuracy, Small size, wearable tag and low cost	Small positioning range, noise
WIFI	m	high	large scale and Low cost	Multiple access points are needed to improve accuracy
UWB	cm-dm	low	High positioning accuracy	High cost
Ultrasonic	cm	low	Very high positioning accuracy	Restricted by obstacles and High cost
Zigbee	m	low	Low Energy consumption	Affected by multipath effects
Infrared	m	low	Low cost, high positioning accuracy	Short range, High cost
Bluetooth	m	low	Small device size	Small range

Several indoor positioning systems have been proposed by researchers worldwide for applications in fields such as military and industrial sectors:

Rantakokko et al. [20] proposed a training monitoring system that integrates RF, UWB, and GPS technologies to support high-accuracy positioning. Their work provides a comprehensive survey of technologies and system architectures for tracking soldiers and first responders, with a particular focus on indoor positioning solutions where GPS signals are unreliable or unavailable.

The Zen TacSim® [21] system is designed to support the training of military and security forces engaged in counter-terrorism and urban combat operations, particularly those involving physical intervention in built-up areas or buildings. It captures and transmits all movements and actions occurring within indoor environments in near real-time to the Exercise Control Centre (ExCon), providing both 2D/3D visualizations and live video footage. The system offers a realistic tactical training environment, enabling continuous monitoring and comprehensive recording of all events for real-time assessment and post-exercise analysis through After-Action Review (AAR).

Poucet [22] developed a multi-technology indoor positioning system tailored for military and firefighting operations. These prototypes were independently tested by the French National Defense through full-scale trials, which replicated typical military operational scenarios.

Sewio's Real-Time Location System [23] enhances organizational safety by improving the protection of team members, reducing the time required for mustering and rescue operations, and increasing overall security. Additionally, the system streamlines the reconciliation of location-based work hours, contributing to more efficient operational management.

Indoor positioning systems have found widespread application in numerous fields, especially in military contexts. Consequently, the development of such systems for specialized surveillance tasks is of considerable importance.

3. FRAMEWORK DESIGNING

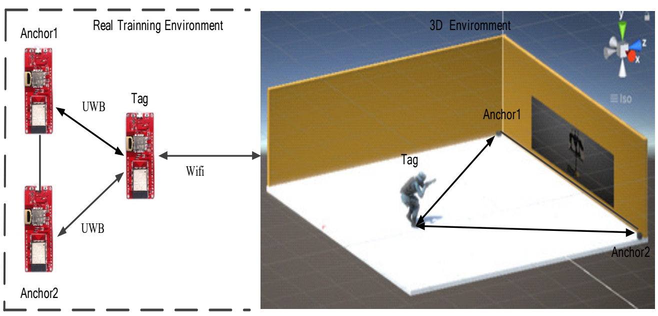

Figure 1. Indoor positioning system for hostage rescue missions

The design framework (as illustrated in Figure 1) includes: IoT devices and 3D environment (Computer).

IoT devices include:

- 02 sensors mounted on the wall (Anchor 1 and Anchor 2);

- 01 wearable sensor attached to the soldier (Tag);

The virtual environment is developed using the Unity3D game engine. Within this 3D environment, the soldier's position is continuously updated in real time via the User Datagram Protocol (UDP).

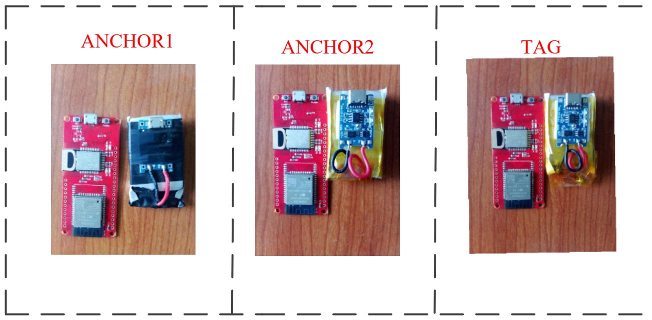

Figure 2. IoT devices include Anchor1, Anchor2 and Tag

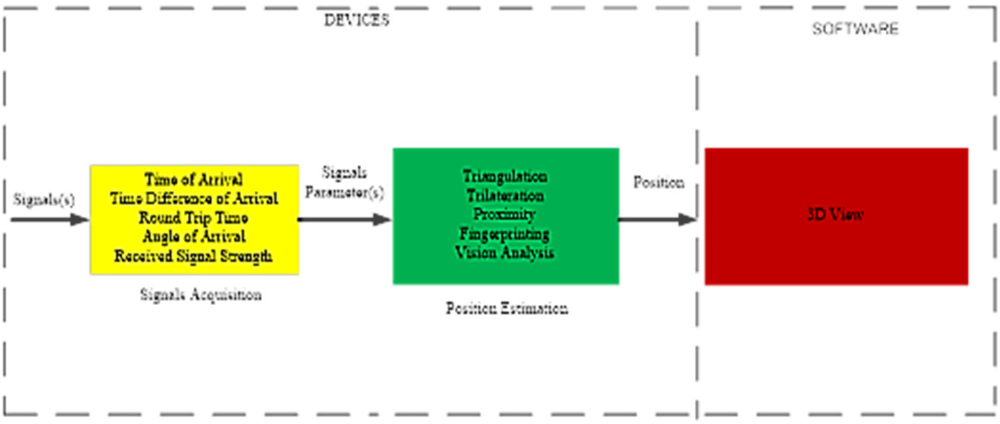

Figure 3. Signals acquisition and positioning process

In this research, the ESP32 UWB Ultra-Wideband module developed by Makerfabs is utilized, offering a positioning error of less than 10 cm, as stated by the manufacturer [24, 25]. The module integrates the BU01 unit, which is based on the DW1000 chip, and is interfaced with an ESP32 Wi-Fi module equipped with I/O expansion. The device operates similarly to a continuous scanning radar, establishing precise communication with a reference device (referred to as an anchor) to determine its own position with high accuracy.

Signals acquisition and positioning process (Figure 3) include three steps:

Step1: Signals acquisition.

Some popular signals acquisition techniques: Time of Arrival (Time of Flight), Time Difference of Arrival, Round Trip Time, Angle of Arrival, Received Signal Strength [1]. Time-of-arrival (TOA) or time-of-flight (TOF) is a signal acquisition technique that measures the time it takes for a signal to travel from the transmitter node to the receiver or target node.

Specifically, the formulas used to calculate the ToF and the corresponding distance d are:

$$ToF = (T_{round} - T_{reply})/2 \quad (1)$$

$$d = ToF.v \quad (2)$$

Where, v is the propagation velocity.

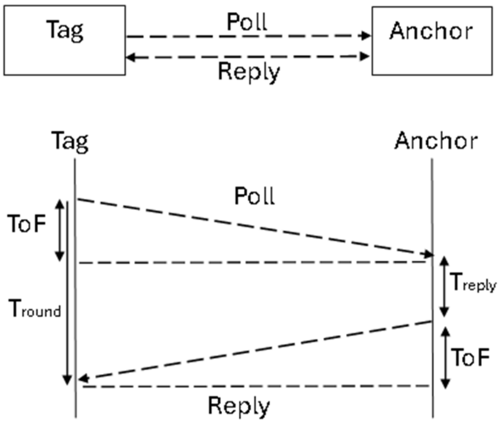

Figure 4. Calculation time of flight process

Step 2: Position Estimation.

The common Estimation Techniques: Triangulation, Trilateration, Proximity, Fingerprinting, Vision Analysis [1]. This study employs the triangulation method to calculate the position (Figure 5).

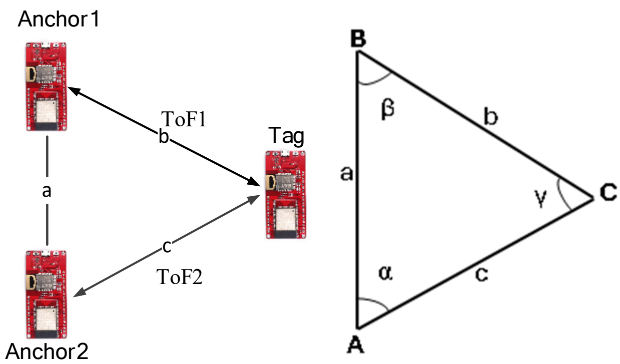

Figure 5. Positioning Estimation

After calculating the flight time from Tag to Anchor1 (ToF1) and Anchor2 (ToF2), it is easy to calculate the distance Tag-Anchor 1 (b), Tag-Anchor 2 (c), because the distance Anchor1-Anchor2 (a) is known. If we set the Anchor1 point as the corner with coordinates A(0,0), then Tag will have coordinate C(ccosα, c sinα), as calculated by Equation (3).

$$\cos\alpha = (a^2 + c^2 - b^2)/2ac \quad (3)$$

Step 3: 3D display.

Data is sent from Tag to computer via Wifi, then information about coordinate location C is synchronized and displayed on 3D map, as shown in Figure 6.

4. EXPERIMENT RESULTS

To evaluate the effectiveness of the proposed indoor positioning system in the context of tactical training, an experiment was conducted in a controlled indoor environment simulating a realistic hostage rescue scenario. As illustrated in Figure 6, the system setup included two fixed anchors (Anchor 1 and Anchor 2) mounted on opposite walls and a wearable Tag device attached to the lower leg of a soldier. A central computer system was responsible for acquiring real-time positioning data and synchronizing the soldier's location with an avatar in a 3D virtual training environment developed using Unity3D.

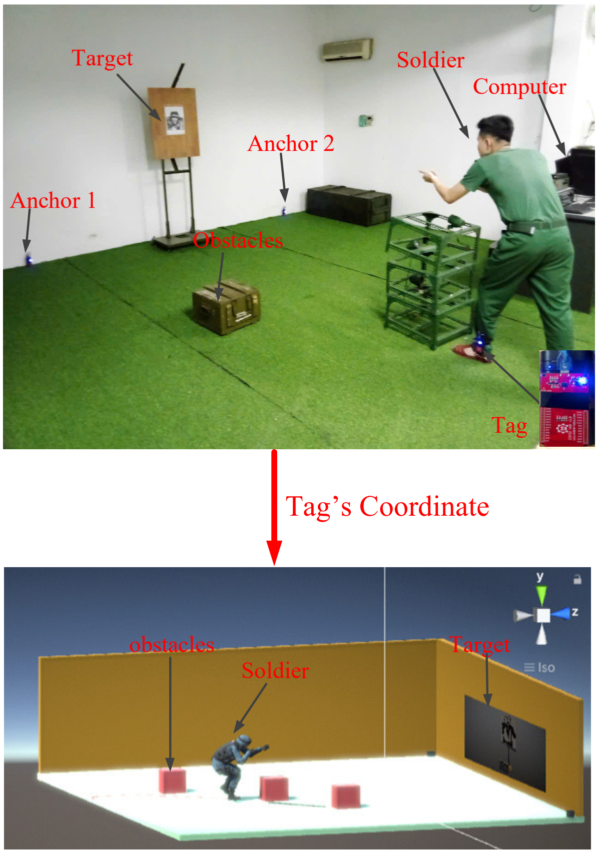

Figure 6. Soldier positioning results

In the simulated scenario, the soldier was tasked with infiltrating a multi-room indoor space to locate and neutralize a designated target while avoiding virtual threats such as surveillance cameras and simulated hostiles. The training environment was designed with multiple obstacles-including walls, furniture, and blind corners-to emulate the complexity of confined, low-visibility urban combat conditions. The soldier was instructed to follow a predefined tactical path while maintaining stealth, low visibility, and speed constraints, thereby increasing the cognitive and operational challenge.

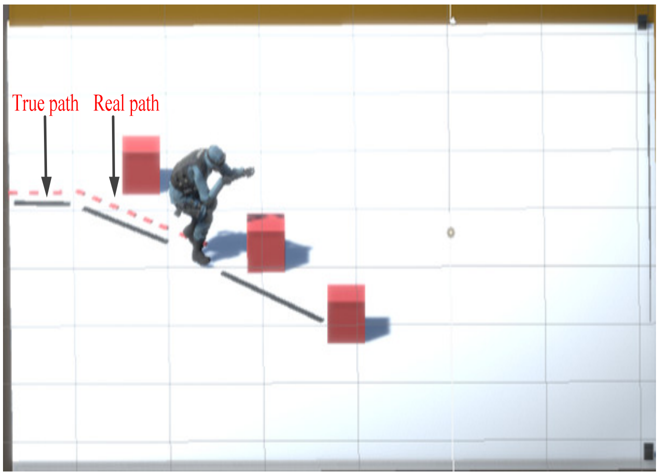

Figure 7. Path monitoring

The ESP32 UWB module was used to determine the soldier's location via Time of Flight (ToF) measurements between the Tag and the Anchors. With a reported accuracy of less than 10cm, the module provided precise spatial data, which were then processed using triangulation algorithms to estimate the soldier's 2D position. These coordinates were transmitted to the computer system via Wi-Fi and rendered in the 3D virtual environment. As shown in Figure 7, the system was able to record and visualize both the planned trajectory (True Path) and the actual path followed by the soldier (Real Path). The actual path closely matched the designated trajectory, with only minor deviations observed near corners or during navigation through narrow spaces. These discrepancies can be attributed to real-time maneuvering decisions and slight delays during directional changes.

Quantitative analysis of the experimental data revealed that the average localization error remained within the 8 - 10cm range, in line with the manufacturer's specification. The system also exhibited low latency, with update intervals of less than 200 milliseconds, enabling stable real-time tracking. From a tactical evaluation standpoint, the recorded movement data offered useful insights into the soldier's behavioral response, including compliance with planned routes, interactions with obstacles, and decision-making at critical junctions. Notably, the soldier adhered to 92% of the predefined route, demonstrating a high level of tactical discipline. Hesitations and brief deviations recorded at intersections further allowed instructors to assess situational awareness and cognitive response under operational constraints.

The ability to synchronize real-world movements with a 3D simulation in real time brings considerable advantages to training evaluation. It enables instructors to monitor movement efficiency and tactical behavior with visual clarity, replay specific segments for after-action review, and quantify mission outcomes using objective metrics such as route adherence, completion time, and deviation frequency. This functionality significantly enhances the pedagogical value of the training environment, making it more immersive, measurable, and actionable.

In summary, the experimental results confirm that the proposed UWB-based indoor positioning system delivers high accuracy and reliable real-time synchronization in complex indoor conditions. The system not only meets technical requirements for tracking precision and responsiveness but also supports comprehensive assessment of tactical performance. These findings highlight its potential for deployment in urban combat simulations, particularly in scenarios involving hostage rescue, where spatial awareness and precise movement coordination are critical to mission success.

5. CONCLUSION

This paper presents the design and evaluation of an indoor positioning system for special applications using IoT and 3D graphics technologies. The system aims to support military training activities that take place in complex indoor environments, particularly in hostage rescue scenarios. The main contributions of this work include:

- Modelling soldiers in a 3D environment;

- Accurately locating soldiers in an indoor environment and synchronizing their 3D models within a simulated environment;

- Building a 3D graphics environment of the training area, obstacles, targets;

- Drawing the movement trajectory, comparing it with the desired trajectory.

Future development will focus on extending the system to support multi-object tracking in indoor environments. This includes managing group-based training scenarios that involve dynamic and complex tactical arrangements, requiring accurate coordination and real-time monitoring of multiple personnel.

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