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ENHANCING CONSTRUCTION SAFETY MANAGEMENT THROUGH UWB-IMU FUSION, BIM, AND GAME ENGINE TECHNOLOGIES

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Abstract. *This study proposes an integrated framework that combines ultra-wideband (UWB) and inertial measurement unit (IMU) sensor fusion with Building Information Modeling (BIM) and real-time 3D visualization using the Unity game engine to enhance construction site safety monitoring. The system addresses major risks such as falls, collisions, and entrapments through dynamic tracking, immersive visualization and automated hazard analysis. UWB positional accuracy is improved through IMU integration and Kalman filtering, enabling stable localization even in complex indoor environments. The Revit-based BIM model is imported into Unity for real-time hazard simulation, utilizing physics-based collision detection with Axis-Aligned Bounding Boxes (AABB). The resulting digital twin environment shifts safety management from reactive to predictive, contributing to more innovative, safer, and sustainable construction practices.*

1 INTRODUCTION

The construction industry remains one of the most hazardous occupational sectors globally, characterized by dynamic workflows, elevated workspaces, frequent interaction with heavy machinery, and exposure to harmful substances [1]. Despite continuous improvements in personal protective equipment and safety protocols, high incidences of fatal accidents—particularly falls, struck-by-object incidents, and caught-in/between events—persist across construction sites [2]. These categories remain the leading causes of occupational fatalities, as identified by the Occupational Safety and Health Administration (OSHA).

Construction site safety monitoring has traditionally relied on Real-Time Location System (RTLS) with fixed surveillance cameras. While providing broad coverage, these systems are constrained by the cognitive fatigue experienced by safety personnel monitoring multiple camera feeds, blind spots, poor visibility, resolution loss over distance, and the absence of automated hazard detection, leading to delayed and incomplete risk recognition [3]. Consequently, recent studies recommend integrating location sensors to enable 3D positioning and enhance camera-based construction site surveillance [4]. Furthermore, various radio-based sensors such as Radio Frequency Identification (RFID), Wi-Fi Fine Time Measurement (FTM), Bluetooth Low Energy (BLE), and particularly Ultra-Wideband (UWB), have shown increasing promise for their ability to deliver real-time tracking. These technologies can either be integrated with camera systems or deployed as stand-alone localization solutions [5]. Among these, UWB stands out for its centimeter-level positional accuracy and robustness against electromagnetic interference, making it highly suitable for complex indoor environments [6, 7, 8]. Despite its advantages, UWB performance is notably diminished in non-line-of-sight (NLOS) conditions due to multipath interference caused by obstacles such as reinforced concrete and mobile machinery typical in construction environments [9,10,11]. Nevertheless, ongoing research continues to focus on enhancing localization accuracy and ensuring motion continuity in obstructed, or signal-degraded environments [12,13].

In parallel, Building Information Modeling or Management (BIM) has evolved beyond its traditional role as a design and planning tool into a potential platform for integrating safety data and real-time monitoring [14,15,16,17]. However, recent research indicates few applications of BIM for construction safety management due to barriers which includes lack of knowledge, cost of implementation, and lack of standardization frameworks or guidelines [18,19].

This paper addresses the gap in integrating UWB-IMU-based tracking with spatial BIM data within real-time simulation environments. It proposes a comprehensive framework that fuses sensor data, BIM, and Unity-based game engine simulation to enable proactive hazard identification and mitigation on dynamic construction sites. Some construction risk scenarios, such as collision, were recreated in a controlled laboratory setting, where the system demonstrated the ability to perform automated hazard detection by leveraging optimized localization outputs. This study underscores the potential of sensor-integrated digital twins to enhance construction safety management through continuous monitoring, spatial awareness, and timely risk notification.

2 METHODOLOGY

This study integrates three core technological components: sensor fusion, a Building Information Modeling (BIM) platform, and a game engine to develop a robust and scalable system for real-time simulation and safety analysis on construction sites.

2.1 Sensor Fusion and Data Processing Architecture: UWB and IMU

The Ultra-Wideband (UWB) localization system employed in this study is based on the DW3000 development module, which integrates a DW3000 UWB transceiver with an onboard ESP32 microcontroller, as illustrated in Figure 1. This module operates within the 6.5 GHz to 8.0 GHz range [20], aligning with the high-band segment of the IEEE 802.15.4z standard for UWB communications [21]. By utilizing a broader spectrum, UWB offers improved spatial resolution and robustness in localization. Prior studies have demonstrated that UWB can achieve a positional accuracy of approximately 30–50 cm within a 30 m range [22, 23, 24].

The DW3000 chip is responsible for managing the transmission and reception of Ultra-Wideband (UWB) signals while executing precision ranging through Time of Flight (ToF) and Two-Way Ranging (TWR) protocols [25]. The ESP32 microcontroller acts as the control unit, coordinating the ranging sequence, processing timestamps, and wirelessly transmitting the calculated distance data to a host computer. This self-contained communication system eliminates reliance on external Wi-Fi infrastructure, thereby enhancing reliability in construction site environments. As illustrated in Figure 2, the Time-of-Flight (ToF) is measured between an Initiator (Tag) and a Responder (Anchor). The initiator sends a poll message and waits for a response. The ToF is calculated using the formula ToF = (T_loop − T_reply) / 2.

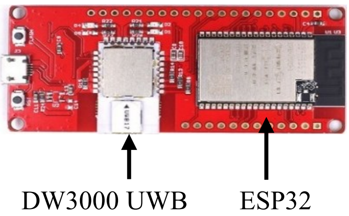

Figure 1: DW3000 UWB ESP32 module

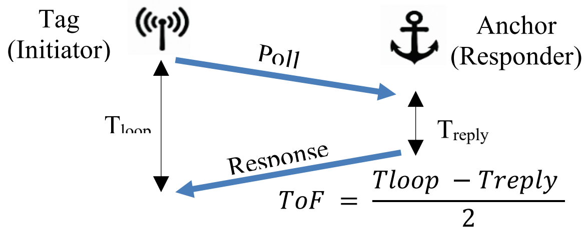

Figure 2: Two-Way Ranging (TWR)

As presented in Figure 3, this study presents a 3D localization system using Ultra-Wideband (UWB) technology with a four-anchor, one-tag configuration in a laboratory setting that simulates construction site conditions. The anchors form a fixed spatial reference frame, while the mobile tag—worn by a proxy worker—is programmed through Arduino IDE to initiate Two-Way Ranging (TWR) sessions. Round-trip times are converted into distance values and transmitted via ESP32 Wi-Fi to a host PC.

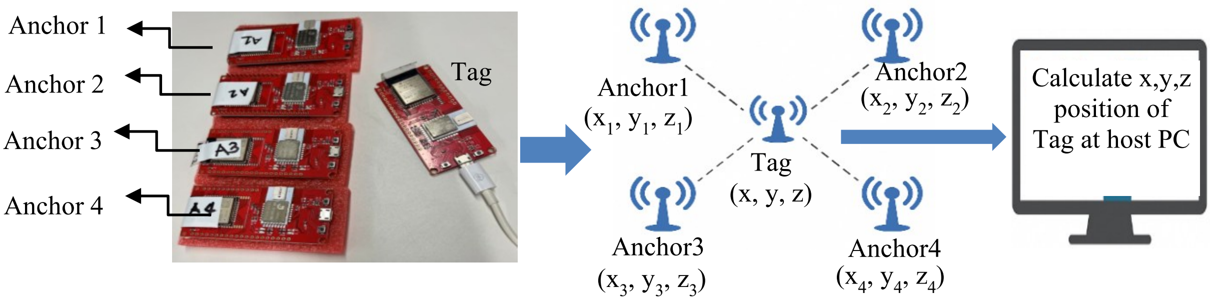

Figure 3: Ultra-Wideband-Based 3D Localization with Four Anchors and One Tag

These distance measurements serve as inputs for trilateration, which estimates the tag's real-time three-dimensional position (x, y, z) using the known coordinates of four anchors and the Euclidean distance equations [26]:

$$(x-x_1)^2+(y-y_1)^2+(z-z_1)^2=d_1^2 \quad (1)$$

$$(x-x_2)^2+(y-y_2)^2+(z-z_2)^2=d_2^2 \quad (2)$$

$$(x-x_3)^2+(y-y_3)^2+(z-z_3)^2=d_3^2 \quad (3)$$

$$(x-x_4)^2+(y-y_4)^2+(z-z_4)^2=d_4^2 \quad (4)$$

Although UWB offers high accuracy and low latency, its performance deteriorates under non-line-of-sight (NLOS) conditions due to obstructions such as concrete structures (Figure 4), steel reinforcements, or heavy equipment. To enhance reliability, the system incorporates an Inertial Measurement Unit (IMU) that captures high-frequency inertial data (linear acceleration and angular velocity) to estimate motion during UWB signal loss. The IMU is connected to an Arduino MKR WAN 1310, which transmits the data via LoRa, a low-power, long-range wireless protocol. As illustrated in Figure 5, LoRa operates in lower frequency bands (968MHz in Japan setting) and employs longer wavelengths than Wi-Fi (usually operates at 2.4GHz). These physical properties enable LoRa signals to experience less attenuation, penetrate dense materials such as concrete more effectively, and diffract around physical obstructions. Consequently, LoRa offers greater signal robustness and reliability in obstructed construction environments, making it a suitable choice for transmitting IMU data in this study.

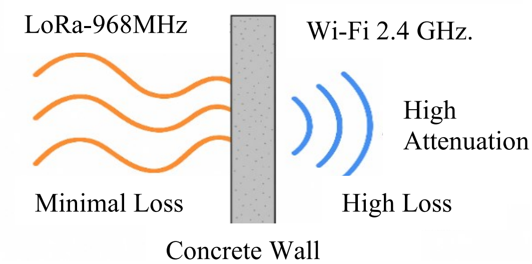

Figure 4: Performance of LoRa and Wi-Fi in signal transition in concrete

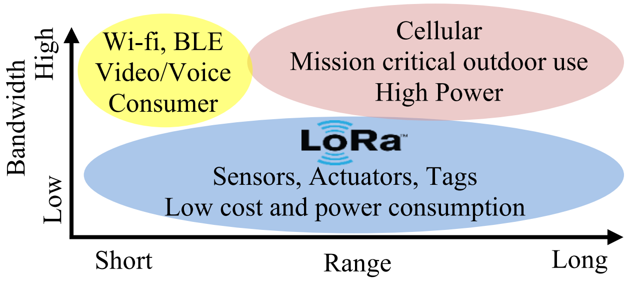

Figure 5: Comparison of Wireless Communication Technologies Based on Bandwidth and Range [27][28]

Figure 6 illustrates the setup where a second MKR WAN 1310 unit, configured as a receiver, is placed near the central processing system. It decodes incoming LoRa packets and transmits the parsed IMU data to a host computer via a USB serial connection for further processing and real-time visualization. Simultaneously, the ESP32 chip on the tag operates in Access Point (AP) mode, establishes a Transmission Control Protocol (TCP) server on a port, and transmits UWB distance measurements to a connected TCP client—Unity in this research which is running on the host PC.

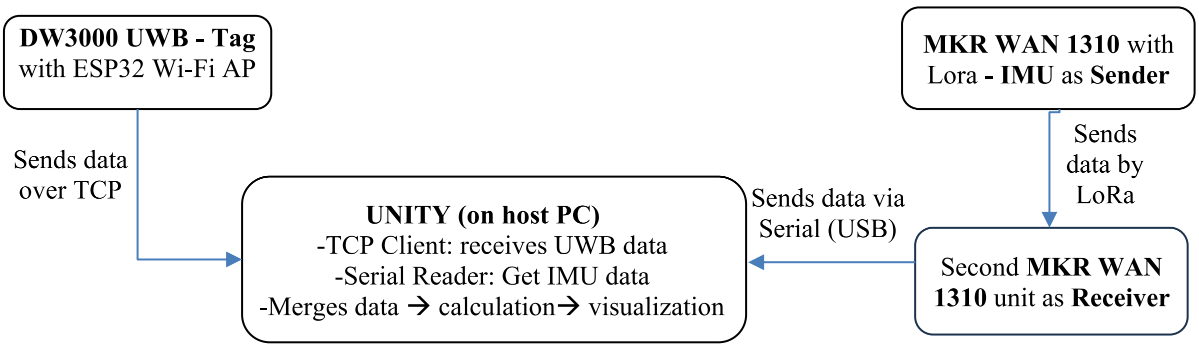

Figure 6: Integrated UWB-IMU Communication Workflow for Real-Time Visualization

This dual-protocol communication architecture—using Wi-Fi for UWB and LoRa for IMU—strategically balances bandwidth, power consumption, and robustness. Wi-Fi enables fast, low-latency transmission of high-precision distance data essential for trilateration, while LoRa ensures reliable delivery of motion data from wearable sensors even in obstructed environments.

2.2 BIM Model Development and Integration

Building Information Modeling/Management (BIM) is a critical component of the proposed framework as it provides the spatial and temporal foundation for real-time site monitoring and hazard detection. The BIM model displays the geometric and material characteristics of the construction environment and integrates scheduling information to support dynamic risk assessment throughout the project lifecycle. This section outlines the methodology for BIM model development, and preparation for real-time integration with sensor data.

Using Autodesk Revit, a conceptualized 3D BIM model of a laboratory room representing an indoor construction site setting was generated. For the validation experiment, the model incorporates simple modelling of walls and equipment, which are modeled as boxes to represent the bounding area. This comprehensive modeling serves as spatial reference for embedding the sensor data. The 3D model is exported as Autodesk Filmbox Interchange file format or .FBX, and then imported to Unity to implement real-time localization and hazard detection.

2.3 Game Engine Integration for Real-Time Localization and Hazard Detection

The Unity game engine is the central platform for real-time visualization and processing, integrating sensor data from two sources: the MKR WAN 1310 with an IMU module and the ESP32 with a DW3000 UWB module. Both microcontrollers are programmed in the Arduino IDE to execute their respective sensing and communication tasks. Sequentially, a custom program was developed in Unity, using Visual Studio as the integrated development environment, to sequentially receive inertial data via serial communication and UWB-derived distance data through the ESP32 Access Point Wi-Fi. The system first performs trilateration to estimate the tag's three-dimensional position (x, y, z) based on UWB distance inputs. Subsequently, it performs Extended Kalman Filter (EKF) to fuse the UWB and IMU data, thereby improving localization accuracy and robust tracking under dynamic and obstructed conditions typical of construction sites. This system architecture is illustrated in Figure 7.

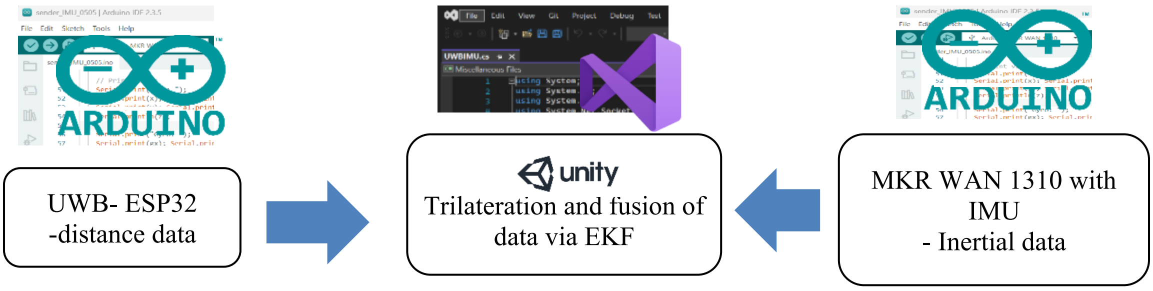

Figure 7: Sensor Data Fusion System Architecture for Real-Time Localization in Unity

This study implements real-time hazard detection and spatial risk analysis within the Unity environment. Axis-Aligned Bounding Boxes (AABB) establish accurate spatial awareness and define and monitor hazard zones, such as elevated drop-offs, machinery operational paths, and restricted access areas. The bounding volumes dynamically interact with the actual positions of the tracked machines and workers in real-time, providing immediate detection of unsafe proximity or collision threats.

3 OPTIMIZATION OF UWB DATA THROUGH EXTENDED KALMAN FILTER

To enhance 3D positioning accuracy, an Extended Kalman Filter (EKF) was implemented to fuse Ultra-Wideband (UWB) trilaterated positions with Inertial Measurement Unit (IMU) data [29]. In this research, the EKF state includes position $x \in R^3$, velocity $v \in R^3$, and orientation $q \in R^4$, represented as a unit quaternion. In the prediction step, angular velocity measurements $\omega \in R^3$ from the IMU are integrated to update orientation:

$$q_k = q_{k-1} \otimes \text{quat}(\omega \cdot \Delta t) \tag{5}$$

where $\otimes$ denotes quaternion multiplication and quat( ) converts a small rotation into a quaternion. The body-frame acceleration $\mathbf{a}_b$ is then rotated into the world frame:

$$a_w = q_k \cdot a_b \cdot q_k^{-1} \tag{6}$$

Velocity and predicted position are updated using Newtonian motion:

$$v_k = v_{k-1} + a_w \cdot \Delta t = x_{k-1} + v_k \cdot \Delta t \tag{7}$$

In the update step, the UWB measurement $\mathbf{z}_k$ is used to compute the innovation

$$a_w = q_k \cdot a_b \cdot q_{k^{-1}} \tag{8}$$

A scalar Kalman gain K_k is calculated from process noise Q and measurement noise R:

$$K_k = \frac{Q}{Q+R} \tag{9}$$

The final state update is performed as:

$$x_k = \widehat{x_k} + K_k \cdot r_k, \quad v_k = v_k + K_k \cdot \frac{r_k}{\Delta t} \tag{10}$$

In summary, Figure 8 illustrates that the EKF process begins with initialization using the first UWB measurement for position and assumes zero velocity and neutral orientation. IMU data are used in the prediction step: gyroscope readings update orientation, and accelerometer data (rotated to world coordinates) predict velocity and position. Using a Kalman gain, new UWB position measurements are applied to the subsequent predicted state in the update step. The accuracy of real-time tracking is improved and drift is decreased by this fusion process.

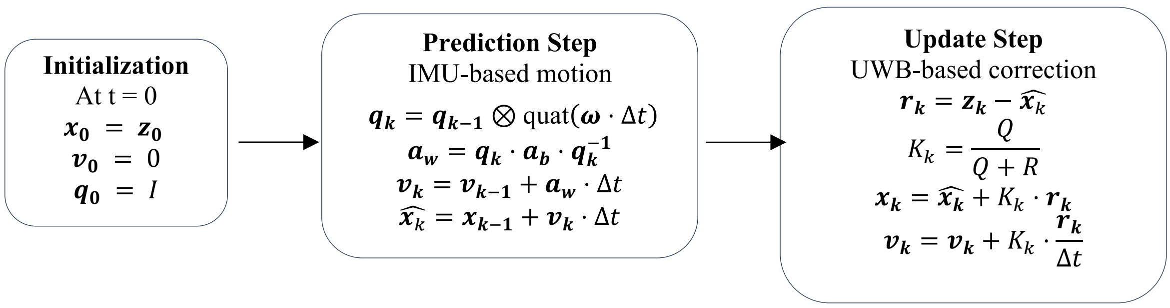

Figure 8: Extended Kalman Filter Process for UWB-IMU Sensor Fusion

4 RESULTS AND DISCUSSION

The proposed system was evaluated in a controlled laboratory environment, wherein dynamic construction environments were simulated. The results demonstrate the effectiveness of optimized localization and digital twin in improving worker and vehicle localization, exposure hazard reduction, and active safety support management.

4.1 Improved Localization Accuracy with Sensor Fusion

The comparison on Figure 10, 11, 12 demonstrate the impact of the Extended Kalman Filter (EKF) on refining UWB-based position estimates under static conditions. Meanwhile, Figure 13 provides a 2D visualization of raw versus EKF-filtered position data in the X-Y plane. Across all three axes (X, Y, Z), EKF-filtered positions show notably reduced variance and tighter clustering around the expected true position, reflecting effective noise attenuation. To quantitatively assess this enhancement, the Root Mean Square Error (RMSE) between raw UWB data (based on trilateration) and EKF-optimized outputs was computed. The resulting RMSE values—approximately 0.0787 m (X), 0.0648 m (Y), and 0.0826 m (Z)—confirm a substantial improvement in positional accuracy. These findings underscore the effectiveness of EKF in fusing UWB and IMU data to suppress noise and more reliable localization.

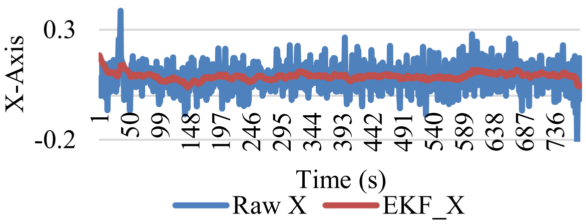

Figure 10: Comparison of Raw vs EKF X-Axis Position at Static Condition

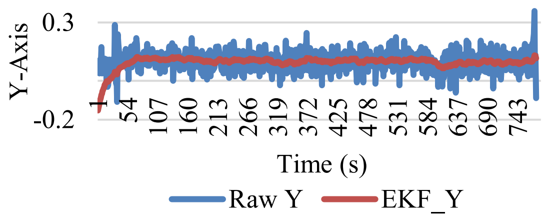

Figure 11: Comparison of Raw vs EKF Y-Axis Position at Static Condition

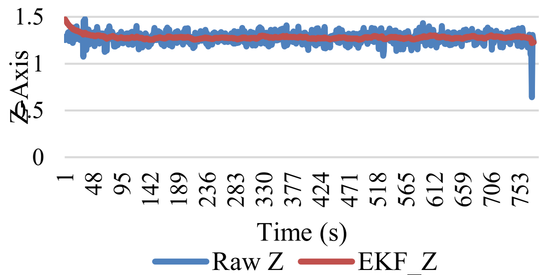

Figure 12: Comparison of Raw vs EKF Z-Axis Position at Static Condition

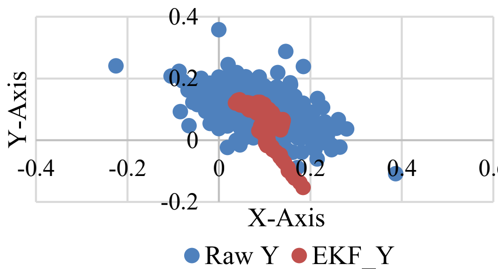

Figure 13: Comparison of Raw vs EKF Z-Axis Position at Static Condition

In dynamic conditions, the Extended Kalman Filter (EKF) maintained consistent improvements in positional accuracy despite rapid motion and increased UWB measurement noise. As shown in the comparative line plots(Figure 14, 15, 16), the raw UWB data exhibited pronounced fluctuations across the X, Y, and Z axes, reflecting typical instability in moving scenarios while the EKF-refined path outlines a coherent and continuous motion pattern that aligns more closely with expected movement behavior. The trajectory plot (X-Y plane) shown in Figure 17, further underscores this improvement.

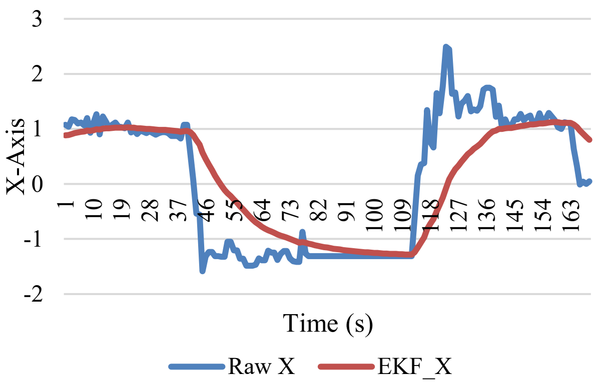

Figure 14: Raw vs EKF-Filtered X-Coordinates at Moving State

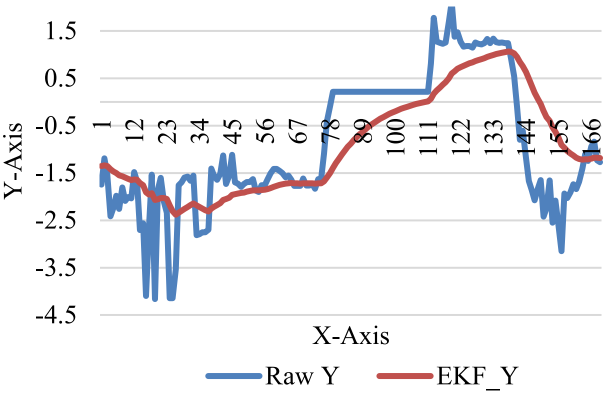

Figure 15: Raw vs EKF-Filtered Y-Coordinates at Moving State

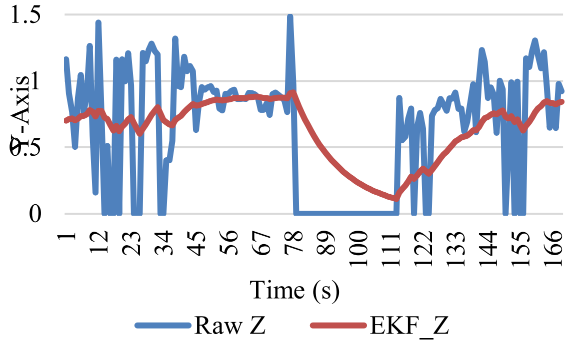

Figure 16: Raw vs EKF-Filtered Z Coordinates at Moving State

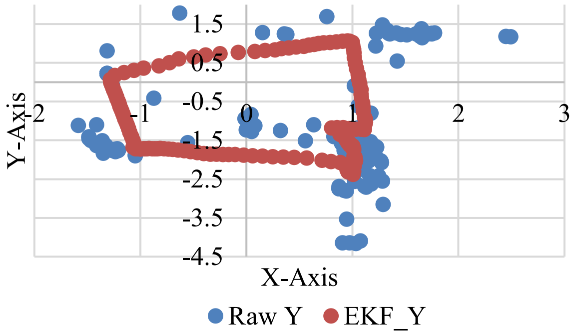

Figure 17: X–Y Trajectory: Raw vs EKF

4.2 Real-Time Hazard Detection in Digital Twin Environment

Figure 18 illustrates the proposed real-time hazard detection system developed within the Unity game engine, which serves as a platform for both visualization and automated hazard analysis. The system visualizes 3D localization data derived from UWB and IMU sensors: a UWB tag (ESP32-DW3000) is mounted on a safety helmet, while four UWB anchors are positioned strategically around the test area. The IMU module (MKR WAN 1310) transmits inertial data via LoRa, and the UWB module communicates distance data via Wi-Fi to a host PC running Unity. Within this environment, Unity enables the integration of sensor data, hazard detection logic, and real-time visual feedback.

In Unity, the system computes the optimized position of the worker and overlays a virtual bounding box (AABB) onto the tracked object. Hazard zones—such as operating machinery and restricted areas—are represented by static colliders. The system detects collision events between the bounding box of the worker and hazardous areas using AABB intersection logic. A notification message is triggered in real time when contact occurs, alerting the user to a potential safety breach. This integration enables continuous monitoring, spatial awareness, and dynamic risk detection, making it suitable for safety planning and incident prevention in innovative construction environments.

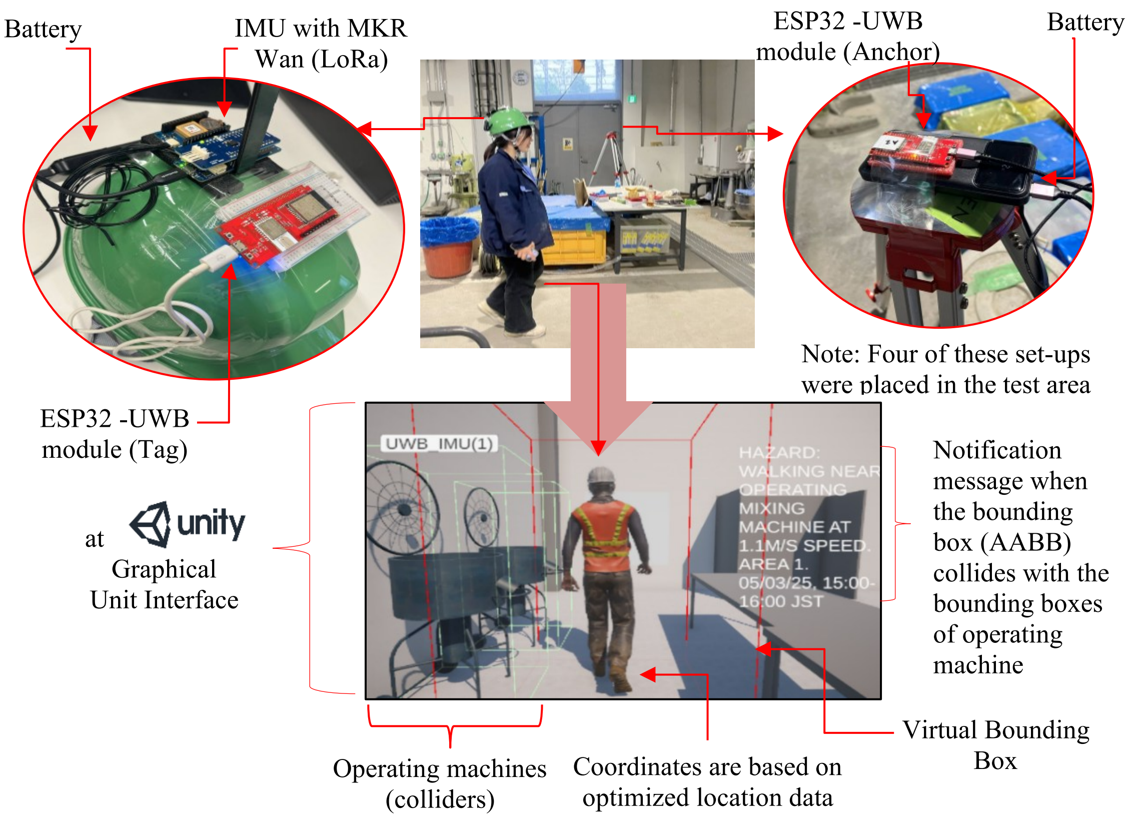

Figure 18: UWB-IMU System Deployment and Digital Twin Integration for Safety Monitoring

5 CONCLUSIONS

This study presents a novel framework for improving construction site safety monitoring and management by integrating UWB-IMU sensor fusion with BIM modeling and game engine simulation. By applying an Extended Kalman Filter (EKF), the system significantly improved localization accuracy in both static and dynamic conditions. Real-time hazard detection was implemented in Unity using Axis-Aligned Bounding Boxes (AABB), enabling automated recognition of unsafe proximity and enhanced spatial awareness.

A key contribution of this research is the development of a more reliable Real-Time Location System (RTLS) through the fusion of UWB and IMU data, supported by a dual communication architecture—LoRa for inertial signals and ESP32-based Wi-Fi for UWB data. This setup enabled simultaneous, low-latency data transmission in obstructed environments, addressing a significant challenge in real-time multi-sensor integration.

By embedding this sensing and localization system and automated hazard identification within a BIM-based digital twin, the framework enhances proactive safety monitoring, reduces manual observation dependency, and mitigates oversight and environmental complexity risks.

Future development will explore the integration of Long-Short-Term Memory (LSTM) neural networks to improve the temporal prediction of movement and position under signal degradation. Field deployment in real construction environments will also be pursued to validate the system's scalability and reliability under practical conditions, including dynamic interference and multi-agent activity.

6 ACKNOWLEDGEMENT

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