Smart Warehouse Inventory Tracker

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***Abstract*—This paper presents the Smart Tracker project, focusing on developing a comprehensive Smart Warehouse Inventory Tracker for indoor environments. The system aims to provide precise location information, allowing the real-time tracking of assets in warehouses using Bluetooth Low Energy (BLE) and microcontroller units (MCUs) such as M5StickC Plus.**

***Index Terms*—Bluetooth Low Energy (BLE), Internet of Things (IoT), Location Tracking, Vertical Positioning**

I. Introduction

In the ever evolving landscape of logistics, the precise tracking of warehouse assets not only affords convenience, but is also strategically essential in the efficient warehouse operation. While various technologies like Ultra-Wideband (UWB), RFID, and Wi-Fi have made advancements in indoor positioning, accurately tracking an object's vertical location in indoor environments remains a challenge.

In this context, the paper presents the Smart Warehouse Inventory Tracker project, which aims to provide precise location information of assets within indoor environments in real time. The project employs Bluetooth Low Energy (BLE) and microcontroller units (MCUs) like M5StickC Plus to ensure accurate three-dimensional tracking of assets [1].

At the core of this system, BLE serves as the communication backbone by fostering connectivity between corner nodes and asset nodes, while MCUs serve as the brains of the operation by processing data, executing algorithms, and facilitating real-time communication [2]. By employing a trilateration algorithm and strategically placing BLE-enabled nodes in the indoor space, the Smart Warehouse Inventory Tracker aims to overcome the challenges associated with vertical tracking.

This paper outlines the system's objectives, addressing the limitations in current indoor tracking systems and presenting a solution that aims to enhance accuracy and efficiency in warehouse asset tracking.

II. Problem Statement

The primary challenge this project aims to address is the lack of accurate and reliable indoor asset tracking, particularly in the vertical dimension. Current indoor positioning technologies, such as RFID, Wi-Fi, and Bluetooth beacons, struggle to provide precise 3D location information, hindering effective warehouse management and asset visibility. Accurately tracking the vertical position of assets within a complex, multi-floor indoor environment remains a significant limitation that needs to be addressed.

III. Objectives

The primary objectives of the Smart Tracker project include:

- Establishing a network of BLE-enabled nodes for comprehensive coverage of the indoor area.
  - Vertical Location Tracking: The prevailing generation of IoT sensors grapples with challenges in effectively and accurately tracking objects vertically within an indoor environment. This limitation poses a substantial impediment to achieving precise and reliable tracking outcomes which this project is looking to solve.
- Developing algorithms for locating the position of assets based on signals received from these nodes.
  - Trilateration Algorithm: Utilizing signals from multiple strategically positioned BLE nodes, our algorithm accurately calculates asset positions by determining the intersection point of circles/spheres based on known distances between the asset and each node.
- Implementing real-time data processing mechanisms to accurately update asset positions.
- Evaluating the system's performance in terms of accuracy, reliability, and scalability.
  - Enhanced Accuracy: The proposed solution focuses on the reliability and accuracy of location tracking

within an indoor environment. An object/item will be attached to a corner node, and by utilising BLE beacons/nodes placed in the corners of the room, the corner node on the item will be able to calculate its position using trilateration.

IV. Literature Review

The study examines the utilisation of Ultra-Wideband (UWB) and barometers for indoor positioning. UWB technology, transmitting high-bandwidth pulses in short cycles, is explored for indoor navigation but faces challenges such as real-time calculation dependence on factors like Time-of-arrival (TOA) and environmental issues like Non-Line-of-sight (NLOS). Barometers, while affected by environmental factors like temperature, are combined with UWB to enhance vertical position accuracy. Despite potential inaccuracies, combining barometers with UWB improves vertical positioning, as observed in Li et al.'s study and similar findings from others integrating barometers with technologies like Wi-Fi and iBeacons [3][4][5][6][7][8].

RFID-based tool-tracking systems for construction sites can also be considered. RFID technology offers real-time tracking, but metal interference is a concern. Integration with sensor networks improves accuracy, yet deploying multiple IoT protocols may be complex. RFID tagging and mobile scanners enable data management, but economic and range limitations persist. Comparative analysis of tracking algorithms provides insights, but dynamic construction environments pose challenges. Despite RFID's promise, overcoming metal interference and deployment complexities is crucial. Further research is needed to optimize scalability, standardization, and data management in construction environments [9].

Yoo et al. (2018) studied real-time location systems (RTLS) in hospitals to improve productivity, using WiFi for general tracking and BLE beacons for precise areas. Their system integrates with the hospital's information system, enabling users to monitor asset location and battery status. Clear asset selection streamlines inventory, but technical challenges include occasional inaccuracies due to radio wave disruptions. Battery reliance poses issues with draining and replacement, while larger tags sacrifice adhesive power. These insights provide valuable guidance for implementing similar systems in warehouses, considering trade-offs between accuracy, energy, and tag size [10].

Nissen et al. apply Q-learning for cost minimization. Meller et al. use Linear Quantile Regression and Tree-Based Models considering factors like traffic and climate for better predictions. Haijema explores optimizing ordering and disposal policies based on stock age and demands and enforcing FIFO rules. Agrawal and Srikant utilize the Apriori Algorithm to predict item associations, enhancing inventory management efficiency. These methods prioritize products based on demand, crucial for sustaining perishable goods in inventory management [11].

Lee et al. (2019) explore a Bluetooth-based indoor positioning system for warehouse asset tracking, emphasizing BLE technology and introducing a Kalman-LULU filter for enhanced accuracy. Their system, employing beacons and Raspberry Pi, leverages RSSI for distance estimation. The study investigates metal attenuation effects and unexpected interference from nearby beacons. While effective, Lee et al.'s system lacks focus on vertical tracking and workshop tools. In contrast, the Smart Tracker project addresses these limitations, employing node augmentation for accuracy and scalability in 3D spaces. Tailored for workshop scenarios, it aims to provide a more holistic solution for indoor asset tracking [12].

V. Design, Implementation and Testing

Our proposed solution aims to utilise BLE connectivity to measure Received Signal Strength Indicator (RSSI) values to calculate and estimate the position of the tracked item within an indoor space.

The system architecture consists of three main components: the Asset Nodes, Corner Nodes and the Web Interface.

A. System Architecture

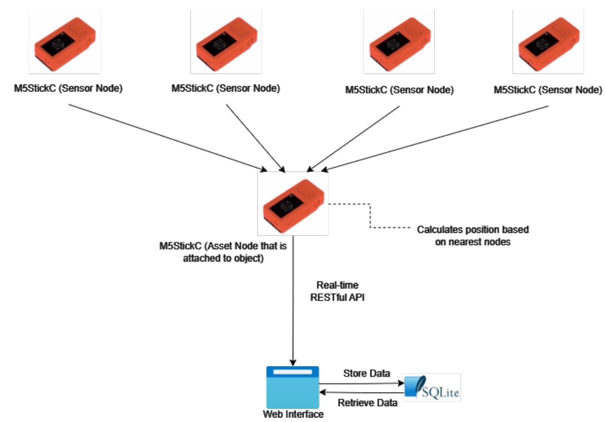

Fig. 1. Smart Warehouse Inventory Tracker System Architecture

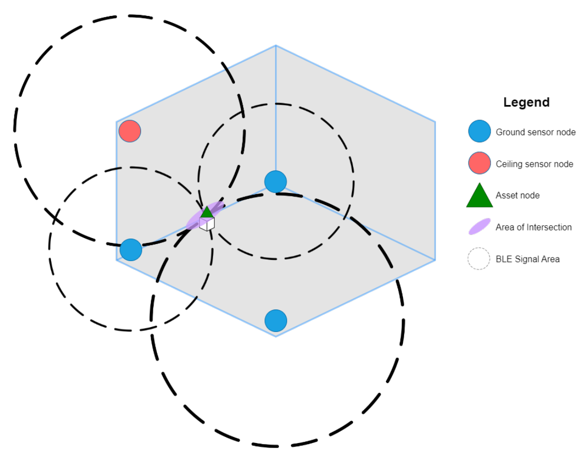

Fig. 2. Indoor Asset Tracking Layout

The system architecture, as depicted in Figure 1, illustrates the general layout of the proposed solution. Each Corner Node will be placed in each corner of a room. An additional Corner Node will be placed at the rooms tallest point. An object that is attached to an Asset Node will calculate its relative position based on trilateration. After its position has been determined, the Asset Node will send its locational data to an interface. Each Asset Node will send its locational data to the interface. This interface, as visualised in Figure 2, is designed to display the positions of all Asset Nodes in the rooms vicinity.

1) Asset Nodes: The item to be tracked is equipped with an Asset Node, which is a small, BLE-enabled device. The Asset Node uses BLE to actively scan for nearby Corner Nodes. Once connected to the Corner Nodes, it will periodically retrieve and record the RSSI values from the Corner Nodes within the indoor space. By retrieving these signals, the RSSI value can be measured for each respective ping from a Corner Node. The Asset Node will then be able to derive its own position relative to the fixed Corner Nodes. After deriving its own position, the Asset Node sends its own positional data to a web server through HTTP.

2) Corner Nodes: The system employs a network of strategically placed Corner Nodes throughout the indoor environment. The Corner Nodes broadcasts bluetooth signals periodically, transmitting these signals to any Asset Nodes that are in the vicinity. The Corner Nodes act as anchor points for the trilateration algorithm, providing the necessary reference points to determine the 3D position of the Asset Nodes.

3) Server: A server application handles any incoming JSON data sent over by the Asset Node over HTTP. The JSON data contains information such as Node ID, and the positional data of the Asset Node. This data is then stored in an SQLite database, so that positional data is readily available and can be easily fetched by the web interface.

4) Web Interface: The web interface displays the location of each Asset Node within the defined space of the Corner Nodes. It provides a visual representation of the position of each Asset Node in the indoor environment. The interface should also enable user interaction by allowing the rotation of the rooms axes. Locational data is updated in real-time, which shows the adjusted position of the Asset Node, if there is any change.

5) Architecture: The system architecture illustrates the general layout of the proposed solution. Each Corner Node will be placed in each corner of a room. An additional Corner Node will be placed at the rooms tallest point. The item to be tracked is attached to an Asset Node, which will calculate its relative position based on trilateration. After its position has been determined, the Asset Node will send its locational data to an interface via HTTP. Each Asset Node will send its locational data to the interface. The interface will then display the position of all Asset Nodes in the rooms vicinity.

B. Prototyping

1) Asset Nodes: The Asset Node is embodied by an M5StickC Plus. On initialisation, it sets itself in a scanning mode to scan and search for nearby Corner Nodes using BLE communication. The Asset Node systematically attempts to establish a BLE connection with each Corner Node it detects. Once it ensures that it has established a bluetooth connection with each of the Corner Nodes in the room, the Asset Node receives a bluetooth signal for each BLE link. The RSSI value measured from the signal Depends on the strength of the bluetooth signal. The RSSI value will then be used to calculate its position.

2) Corner Nodes: Four M5StickCPlus is used to represent the Corner Nodes. Each Corner Node is placed in a fixed corner of an indoor environment such as a room. On initialisation, each Corner Node will be set up as a BLE server, creating a unique service ID and characteristics ID. Once the bluetooth connection has been established, with the Asset Node(s), the Corner Node will periodically transmit a bluetooth signal to the Asset Node.

3) Position Calculation and Data Transmission: To calculate the position of the Asset Node, the Asset Node measures RSSI values from each Corner Node, and uses the Path Loss model and trilateration to calculate its relative position. Once the Asset Node calculates its position, it transmits this locational data to a central interface through a Wi-Fi connection. This step involves packaging the XYZ coordinates into a JSON format and sending them via HTTP POST requests to a Node Js server.

4) NodeJs Server: A server application handles any incoming JSON data sent over by the Asset Node over HTTP. The JSON data contains information such as Node ID, and the positional data of the Asset Node. This data is then stored in an SQLite database, so that positional data is readily available and can be easily fetched by the web interface.

5) Web Interface: The web interface utilises Three.js library to display a model of the indoor environment, showing the location of each Asset Node within the defined space of the Corner Nodes. Using WebGL, it provides an interface for users, allowing the rotation along the environments axes. The interface shows the Asset Nodes currently registered in the room, which are updated and displayed in the interface whenever there are changes. This shows the real-time location of each Asset Node.

The following steps describe the general process.

- Asset Node establishes bluetooth connection with the Corner Nodes
- Asset Node measure RSSI of each bluetooth signal from the Corner Nodes
- Using Path Loss Model, convert RSSI value to distance in metres
- Using the converted metres, perform trilateration with the trilateration algorithm
- Trilateration returns the XYZ coordinates of the Asset Node
- The XYZ coordinates will be sent to the server via HTTP.
- User Interface listens for any changes, and fetches the XYZ coordinates of the Asset Node.
- The position of the Asset Node is updated on the user interface

VI. Testing

To ensure the accuracy and reliability of our indoor positioning system, we conducted comprehensive testing procedures focusing on the Bluetooth signal strength (RSSI) measurement and its conversion to distance.

A. Testing Bluetooth Signal Strength

Initially, we evaluated the strength of the Bluetooth signal by measuring the Received Signal Strength Indicator (RSSI) between the asset node and the corner nodes. RSSI measurements were obtained by placing the asset node and corner nodes at various distances from each other and recording the corresponding RSSI values. The objective of this test was to assess the signal strength attenuation over distance and identify any potential signal degradation or interference.

B. Refinement of RSSI to Distance Conversion

Subsequently, we conducted tests to refine the conversion of RSSI values to distances, a crucial step in our trilateration algorithm.

1) Measured Power Determination: To establish the measured power parameter, representing the RSSI value at a distance of 1 meter from the corner node, we positioned the asset node and corner node exactly 1 meter apart.

Multiple RSSI values were recorded at this distance, and the average RSSI value was calculated to obtain an accurate representation of the measured power.

2) Environmental Factor Calibration: Another key constant in the distance conversion formula is the environmental factor, which accounts for environmental noise and interference. This factor typically ranges from 2 to 4, with 2 indicating a less noisy environment and 4 indicating a more noisy environment.

Through iterative testing and adjustments, we determined the most suitable environmental factor value that effectively captured the environmental conditions in our deployment environment.

C. Test Results

The culmination of our testing efforts yielded a refined distance conversion methodology that effectively translates RSSI measurements into accurate distance estimates for use in the trilateration algorithm. By precisely determining the measured power and calibrating the environmental factor, we achieved a robust and reliable distance conversion mechanism that enhances the accuracy of our indoor positioning system.

VII. Results and Analysis

In this section, we compare the pros and cons of our solution in comparison to other various technologies and solutions.

A. Comparison with BLE/Wi-Fi based asset tracking system

In a feasibility study conducted by Yoo et al (2018) [10], the utilisation of BLE/Wi-Fi-based tags can be compared with our implementation using M5StickC Plus devices as asset tags, considering factors such as tag size, adhesive durability, battery life, and beacon size. We discuss the observed differences in performance and their implications on the effectiveness of the respective tracking systems.

1) Tag Size and Adhesive Durability: The feasibility study employed tags with dimensions of 66x40x25mm, which were susceptible to detachment from tracked items due to adhesive issues, resulting in the loss of some tags and associated costs. In contrast, our M5StickC Plus devices, serving as asset tags, are compact with dimensions of 48.2x25.5x13.7mm and a weight of only 15g. Through rigorous testing, we have not encountered adhesive issues, ensuring secure attachment to tracked items.

2) Battery Life: The feasibility study prioritised extending battery life for both beacons and tags, utilising non-rechargeable batteries that require replacement annually for beacons and every 100 days for tags. Although our asset tags have a shorter battery life, lasting only a few days, they feature rechargeable batteries. While this necessitates more frequent recharging, it offers long-term cost savings and environmental benefits over the lifespan of the system.

3) Beacon Size and Signal Emission Frequency: The study's beacons are relatively large, measuring 120x120x30mm, potentially hindering discreet placement and visibility. Conversely, our beacon nodes, utilising M5StickC Plus devices, boast a more compact form factor, facilitating inconspicuous deployment for improved aesthetics and reduced risk of tampering. Additionally, the feasibility study configured tag location signals to emit at intervals ranging from 30 minutes to 2 hours, optimising battery longevity. In contrast, our system maintains continuous scanning for active beacons, ensuring real-time tracking capabilities.

4) Discussion: The differences observed in tag size, adhesive durability, and battery life between the feasibility study's approach and our implementation highlight distinct priorities and trade-offs in tracking system design. While our solution offers enhanced portability, reliability, and real-time tracking capabilities, the feasibility study emphasises battery longevity and tag visibility.

The utilisation of rechargeable batteries in our system mitigates long-term operational costs and environmental impact, despite requiring more frequent recharging intervals. The compact size of our beacon nodes facilitates discreet deployment, enhancing the overall aesthetics and security of the tracking infrastructure.

Ultimately, the selection of tracking technology and design considerations should align with the specific requirements, priorities, and constraints of the intended application environment and use case.

B. Comparison with UWB

1) Frequency Range: UWB frequency range for communication applications is 3.1 to 10.6 GHz, which operates at the same frequencies as popular communication products which may in turn interfere with systems such as third-generation 3G wireless systems. UWB positioning devices may also cause harmful interference to GPS and aircraft navigation radio equipment. This would in turn lead to weakened UWB positioning accuracy. The UWB receiver also requires signal acquisition, synchronisation and tracking which are time consuming. BLE frequency range on the other hand runs at 2.4-2.4835GHZ instead which does not interfere with those same communication products.

2) Discussion: While UWB offers superior accuracy, robustness, and security, it comes with higher complexity and cost. On the other hand, BLE presents a more cost-effective and widely supported alternative but sacrifices some accuracy and security.

The decision to adopt UWB or BLE depends on various factors, including the specific requirements of the warehouse environment, budget constraints, and the desired level of accuracy and security. For applications where precision localization and security are paramount, UWB may be the preferred choice. However, for cost-sensitive deployments requiring broader compatibility and scalability, BLE with RSSI-based localization offers a viable solution.

Thus, the choice between UWB and BLE technologies should be made based on a careful assessment of the application's needs, balancing accuracy, complexity, cost, and security considerations to achieve optimal performance in warehouse positioning systems.

VIII. Conclusion

In conclusion, the comparative analysis of different tracking technologies, including BLE/Wi-Fi-based tags, M5StickC Plus devices, and UWB, provides valuable insights into the diverse considerations and trade-offs inherent in designing effective asset tracking systems.

The utilisation of M5StickC Plus devices as asset tags in contrast to the larger tags employed in the feasibility study showcases advancements in technology, emphasising compactness, secure attachment, and real-time tracking capabilities. Despite shorter battery life, the incorporation of rechargeable batteries in M5StickC Plus devices aligns with long-term cost savings and environmental sustainability objectives.

Additionally, the comparison with UWB technology underscores the importance of considering factors such as frequency range, accuracy, complexity, and cost when selecting the most suitable tracking solution for specific applications. While UWB offers superior accuracy and security, it entails higher complexity and cost compared to BLE. The decision between the two technologies depends on the specific requirements, budget constraints, and desired performance metrics of the warehouse positioning system.

Ultimately, the proposed system architecture aims to optimise asset tracking efficiency by leveraging advanced corner nodes and trilateration techniques for precise localization. The interface designed to display the positions of all asset nodes further enhances the system's usability and functionality, providing real-time insights into asset locations within the warehouse environment.

By carefully weighing these considerations and leveraging technological advancements, organisations can design and implement asset tracking systems tailored to their unique needs, thereby improving operational efficiency, security, and cost-effectiveness in warehouse management scenarios.

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