Grenze International Journal of Engineering and Technology, June Issue

IoT-Enabled Height and Zone Detection System for Worker Safety in Vertical Construction using RF Signal Strength and Alternative Sensing Approaches

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***Abstract*— Fall from heights remains the leading cause of fatalities in the construction sector, especially where work at elevated places is involved. In India, approximately 42 fatalities occur on a daily basis, which highlights the need for improving safety measures. Conventional monitoring system is dependent on manual intervention, which has proved to be error prone. This study proposes a novel IoT enabled system that integrates multiple technologies to triangulate the worker position. The proposed system utilises RF signal strength measurements, voltage variations and time-of-flight measurements for identifying the workers' movement when he surpasses the critical height of >6ft. The system was validated using MATLAB simulations, and the results indicated an accuracy of 98.78%. The system was found to be a viable approach to ensure compliance with safety protocols.**

***Keywords*— Construction Safety, Sensor-Based Monitoring, Real-Time Detection, Occupational Safety.**

I. INTRODUCTION

Accidents in construction account for approximately 22% of global accident statistics, with India reporting around 42 fatalities daily, and the accident rate is 4 to 5 times higher than that of the other sectors, which involve manual labour. [1].

There are various reasons for accidents identified by researchers, out of which fall from heights remain the most common cause of accidents. [10] [11] [12], These accidents are a result of poor working conditions, lack of use of PPE and many other factors that stress the need for ensuring accident protection measures [2]. These incidents lead to severe medical, financial, and legal repercussions, along with significant project delays and reputational damage for stakeholders [3].

OSHA mandates strict safety protocols to ensure there are minimum accidents at the workplace [5]. The national construction code and ISO 45001 followed in India reiterates similar guidelines for minimising accidents and mandates proactive safety measures that are meant to be implemented when working at elevated platforms. [4]. Construction monitoring relies on manual inspection techniques, which are error prone. In order to overcome these issues, the intervention of technology becomes important.

Grenze ID: 01.GIJET.11.2.728

Technological advancements especially, for real-time monitoring advocate automation process that is capable of detecting safety violations [7] IoT devices like RFID tags [13], Bluetooth sensors and wireless communication devices, [8] [16] [17]] have displayed great potential in minimising risks associated with working in elevated platforms. Zigbee technology [4]], on the other hand, is widely popular due to its strong communication capabilities [14] [15] as it utilises RSSI based measurements, it is widely used for asset tracking and height tracking applications [18] [29]. Though there are many advantages in this technique, there are issues with signal transfer and signal loss which greatly impact accuracy of the system [28]. [23], [24]. [27].

Studies by [25] explored application of RSSI system to detect environmental influence on signal strengths and found out that with appropriate filtering techniques such as Kalman filtering methods [27]. and data fusion methods, errors can be minimised but the issues with privacy and user acceptance of these technologies always remain a challenge [26].[21], [22].

Alternate technologies like Bluetooth , ultrasonic sensors, IR systems and LiDAR can be applied for monitoring worker movements due to their low power-consumption nature [25].Studies show that LiDAR (Light Detection and Ranging) technology) is highly effective in identifying changes in worker positions, making it suitable for construction sites. Although many technologies enhance the accuracy and efficiency of safety monitoring, challenges like signal interference integration of various sensors, environmental factors, and computational complexity persist.

Through extensive literature review, it was found that most of the literature highlights primarily RSSI-based height detection, which has limited adaptability. However, alternate approaches like integrating BLE, ultrasonic, IR and LiDAR-based techniques have not been comprehensively integrated and explored for real-time worker height and position tracking of working, making way for the present research to address this gap by introducing multi-technology and IoT-based systems that depend on multiple zone detection methods to enhance accuracy.

The proposed objectives of this study are to design and implement an integrated system for identifying the height and location of a construction worker on the scaffold environments with technologies like BLE beacons, ultrasonic sensors, IR sensors, and LiDAR for real-time worker monitoring. These systems apply signal strength, time-of-flight, and voltage variations to determine the height and location of the worker accurately.

II. Methodology

To overcome the limitations of the existing monitoring systems, this study proposes a new integrated system to monitor construction worker's location and height. The methodology adopted is described below, in Figure 1.

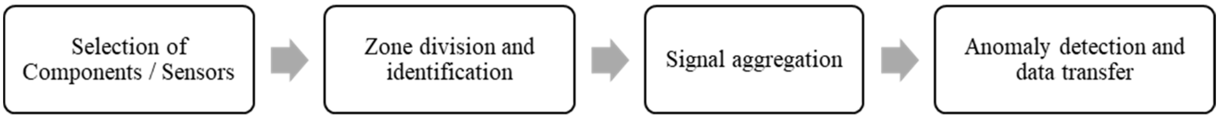

Figure 1: Process chart - Proposed Zone Detection System

For zone-based detection, the proposed system uses Bluetooth beacons to monitor the proximity data by analysing signal strength and enabling interaction with workers who are equipped with trans-receivers. Ultrasonic sensors are placed strategically at pre-determined critical zones for triangulating the workers' position with precision. IR sensors are used for continuous monitoring of worker movements, and the LiDAR sensors are applied for spatial analysis of worker activity.

Dividing the scaffold structures into pre-defined zones become essential for accurate tracking of worker movements, these zones are segmented as critical (>6ft) and non- critical (<6ft) zones based on height. The selected components or sensors are strategically placed on the scaffold framework to enhance accuracy. The signals received from LiDAR, ultrasonic sensors and IR transmitters are integrated to identify worker height and location as it interacts with the sensors worn by the workers. Upon detection non-compliance the system generates alerts in real-time and transmit the collected data to a central control system for further analysis. The accuracy is calculated through a weighted data fusion (WDF) approach to combine the data obtained from various sensors dynamically by assigning a weight to each sensor based on its reliability and the aggregated signal strength. Through Bayesian models, the system predicts the most likely zone and height based on sensor input and signal strength, this approach helps to reduce the effect of multi-path propagation.

A. Working setup

The working setup of the proposed system, which is based on RF signal strength, BLE, Ultrasonic, IR, and LiDAR sensors, is built on the assumption that all RF transmitters transmit signals at a constant power level and the received signal strength decreases proportionally as the distance increases, the transmitters which are placed at pre-determined heights are correctly aligned to each other to reduce errors. The signal reflection and multi-path effects have minimum impact on the signal strength, and at any given time, the receiver can pick up signals from at least 2-4 transmitters, facilitating accurate measurements. The working of the entire system assumes that the zone layout and grid are pre-calibrated with known transmitter positions. The pseudo-code for the proposed system and its relevant code is mentioned below.

```
FUNCTION generate_vertical_zones(num_floors, step_height):
DEFINE zones AS EMPTY DICTIONARY
FOR m FROM 0 TO (num_floors - 1):
SET zone_name TO CONCATENATE("Z_", m)
SET floor_height TO m * step_height
SET zones[zone_name] TO floor_height
RETURN zones
FUNCTION calculate_BLE_signal_strength(x_b, y_b, h_b, x_r, y_r, h_r, P_b = 1):
CALCULATE d_br AS sqrt((x_b - x_r)^2 + (y_b - y_r)^2 + (h_b - h_r)^2)
RETURN P_b / d_br^2
FUNCTION calculate_ultrasonic_distance(x_u, y_u, h_u, x_r, y_r, h_r):
RETURN sqrt((x_u - x_r)^2 + (y_u - y_r)^2 + (h_u - h_r)^2)
FUNCTION detect_IR_motion(worker_ID, zone_name):
IF IR_DETECTED_IN_ZONE(zone_name):
RETURN "Movement Detected"
ELSE:
RETURN "No Movement"
FUNCTION track_real_time_LiDAR(worker_ID, receiver_coords):
RETURN GET_LiDAR_POSITION(worker_ID, receiver_coords)
FUNCTION calculate_zone_strength(transmitter_coords, receiver_coords, sensor_weights):
SET zone_strength TO 0
# BLE signal contribution
FOR EACH (x_b, y_b, h_b) IN transmitter_coords["BLE"]:
ADD sensor_weights["BLE"] * calculate_BLE_signal_strength(x_b, y_b, h_b, receiver_coords[0], receiver_coords[1], receiver_coords[2]) TO zone_strength
# Ultrasonic sensor contribution
FOR EACH (x_u, y_u, h_u) IN transmitter_coords["Ultrasonic"]:
ADD sensor_weights["Ultrasonic"] / calculate_ultrasonic_distance(x_u, y_u, h_u, receiver_coords[0], receiver_coords[1], receiver_coords[2]) TO zone_strength
RETURN zone_strength
FUNCTION determine_height_and_zone(num_floors, step_height, receiver_coords, sensor_weights):
SET zones TO generate_vertical_zones(num_floors, step_height)
SET max_strength TO 0
SET best_zone TO None
FOR EACH zone_name, floor_height IN zones:
SET transmitter_coords TO GET_TRANSMITTERS_AT_HEIGHT(floor_height)
CALCULATE strength AS calculate_zone_strength(transmitter_coords, receiver_coords, sensor_weights)
IF strength > max_strength:
SET max_strength TO strength
SET best_zone TO zone_name
RETURN best_zone, zones[best_zone]
FUNCTION trigger_alert(worker_ID, best_zone, height, critical_height):
IF height >= critical_height:
SEND_ALERT(worker_ID, "Critical Zone Entry Detected! Ensure Safety Measures.")
TRANSMIT_DATA_TO_CCS(worker_ID, best_zone, height, "CRITICAL")
ELSE:
TRANSMIT_DATA_TO_CCS(worker_ID, best_zone, height, "NORMAL")
FUNCTION transmit_data_to_CCS(worker_ID, best_zone, height, status, ZigBee_worker_ID, ZigBee_CCS_ID):
SET data TO {worker_ID, best_zone, height, status}
```

TRANSMIT data FROM ZigBee_worker_ID TO ZigBee_CCS_ID
FUNCTION monitor_worker_activity(worker_ID, num_floors, step_height, receiver_coords, critical_height, sensor_weights, ZigBee_worker_ID, ZigBee_CCS_ID):
Track real-time position with LiDAR
SET receiver_coords TO track_real_time_LiDAR(worker_ID, receiver_coords)
Determine best zone and height based on sensor data
SET best_zone, height TO determine_height_and_zone(num_floors, step_height, receiver_coords, sensor_weights)
Detect IR motion and log activity
SET motion_status TO detect_IR_motion(worker_ID, best_zone)
# Trigger alerts and transmit data to CCS
trigger_alert(worker_ID, best_zone, height, critical_height)

This code helps calculate the distances between transmitters and receivers, evaluate the strength of received signals, and aggregate these signals across different zones.

To validate the proposed zonal tracking system (pseudo code), a simulation was conducted using MATLAB software version R2024a, using the provided pseudo-code, to assess the system's accuracy. For simulation, the below considerations were made.

- Each scaffold has one transmitter.
- The receiver receives the signal from all the transmitters
- The strongest signal has the least dBm
- The least dBm value received will the worker's zone/ position

It is quite interesting to identify the exact height and location of the construction worker since the RF receiver will receive signals from all the transmitters at once. To decrease the errors in the execution of the code, a mathematical model-based approach is described below which helps in methodical quantification and establishing interrelationships among various parameters.

B. Mathematical modelling

Calculation of distance between the worker and the nearest BLE beacon based on signal strength (RSSI).

To identify the zone where the worker is located, the distance between the worker and the nearest BLE beacon is calculated using the equation (1)

$$d_{BLE} = 10\frac{(P_{tx} - RSSI)}{10xn}$$

Where

- d_{BLE} = distance between the beacon and receiver
- Ptx = Transmitted power (in dBm)
- n = Path loss exponent (typically 2 for free space)

Zone detection calculation: The time of flight of sound waves is measured through an ultrasonic sensor to determine the distance between the worker and the ultrasonic sensor to identify the worker's zone based on the distance as specified in equation (2)

$$d_{ultra} = \frac{v\ x\ t}{2}$$

Where

- d_{ultra} = Distance from the ultrasonic sensor
- v = Speed of sound in air (~343 m/s)
- t = time taken for the ultrasonic wave to return

IR sensor-based detection: The distance between the worker and the IR sensor is measured through IR signal response, which is calculated using the equation (3).

$$d, R = K\frac{V_{in}}{v_{out}}$$

Where

- d_{IR} = distance from the IR sensor
- K = Calibration constant based on IR emitter power
- Vin and Vout = Input and output voltages

Lidar-based determination: LiDAR helps in generating a 3D view of the scaffold layout for tracking the worker's exact height and zone in real-time by calculating the distance between the nearest reference point and the worker. This is given by

$$d_{LiDAR} = \sqrt{(x_r - x_i)^2 + (y_r - y_i)^2 + (h_r - h_i)^2}$$

Where

- d_{LiDAR} = Distance between the LiDAR and the worker
- (x_r, y_r, h_r) = Coordinates of the worker
- (x_i,y_i, h_i) = Coordinates of the LiDAR reference

Aggregated Signal Strength for Zone Detection: Measuring aggregate signals from multiple transmitters helps to recognise the zone with the highest signal strength. This necessitates reducing the errors caused by multi-path propagation. This is measured by

$$s_{agg} = \sum_{i=1}^{n} \frac{Pi}{d_1^2}$$

Where

- Sagg = Aggregated signal strength in a given zone
- Pi = power of the iii-th transmitter
- di = distance between the transmitter and the receiver

Zone determination and vertical zone calculations for nxn scaffold layout: For the N x N scaffold layout, the zonal assignment, as mentioned above, would remain the same. However, the distance between the worker and the transmitter in a grid layout is given by

$$dmn = \sqrt{(x_m - x_r)^2 + (y_m - y_r)^2}$$

Where

- dmn = distance between the worker and the transmitter at position (m,n)
- Xm, Yn = Coordinates of the transmitter
- Xr, Yr = Coordinates of the worker

Zone Identification from Aggregated Signal: Identifying the zone with the highest aggregated signal strength is critical for indicating the worker's most likely position and is given by

$$z_{best} = \text{ar}\, g_{zm}{}^{Max} \sum_{i=1}^{n} S_i$$

Where

- Zbest = Zone with the highest signal strength
- Si = signal strength received by the worker from the iii-th transmitter in zone Zm

Vertical division of scaffolds: Mathematically, the vertical division of scaffolds based on fixed height intervals is calculated by

$$Z_m = \frac{H\ (total)}{n}$$

Where

- Zm = height of zone mmm
- Htotal = Total height of the scaffold
- n = number of vertical zones

Zone Assignment Based on Signal Strength

The zonal assignment of the worker by comparing the received signal strengths from adjacent zones is measured by

$$Zone = arg \underset{m}{\text{Max}}(S_m)$$

Where:

- Zone = Identified zone of the worker
- Sm = Aggregated signal strength for zone mmm

The mathematical equations are important for precisely establishing the location of construction workers in scaffold systems.

III. Results

A. Validation of the pseudo-code

The test results of measuring the effectiveness and accuracy of the proposed system are presented in Table 1, Table 2, and Table 3 below.
Table 1 shows the input data that is provided for the MATLAB simulation, which indicates the number of workers, floor heights, and actual worker height from ground level.

TABLE I: INPUT DATA FOR SIMULATION USING MATLAB

Enter the number of workers	10
Enter the Number of Floors	17
Height of Each floor	3 meters
Enter the Actual height for Workers (in meters)	
Worker ID	**Floor height in meters**
Worker 1	18
Worker 2	34
Worker 3	9
Worker 4	50
Worker 5	24
Worker 6	32
Worker 7	12
Worker 8	4
Worker 9	37
Worker 10	44

Output from the simulation

Table 2 demonstrates the calculated heights, received signal strengths, and identified zones for each worker based on aggregated signal data from BLE beacons, ultrasonic sensors, LiDAR, and IR transmitters. The system was successful in identifying the zones by measuring the strongest signal received from the respective height and zone sensor. It was found that the calculated heights nearly matched the actual worker heights from ground level, with a minimal difference ranging from 0.00 meters to 0.40 meters.

TABLE II: TABLE INDICATING THE ZONE NUMBERS AND HEIGHT OF THE WORKER

Worker ID	**Actual Height of the Worker (m)**	**Calculated Worker Height (m)**	**Received signal strength (dBm)**	**Zone identified (strongest signal)**
W1	18.00	17.80	-65.12, -63.98, -62.50, -61.30, -60.02, **-59.19**, -59.45, -60.33, -61.80, -63.25, -64.62, -65.90, -67.05, -68.08, -69.01, -69.87, -70.66	Zone 6
W2	34.00	33.90	-71.02, -70.35, -69.50, -68.58, -67.62, -66.55, -65.35, -64.00, -62.53, -61.05, -59.70, **-58.91**, -59.08, -60.10, -61.53, -63.05, -64.48	Zone 12
W3	9.00	8.90	-59.30, -57.50, **-56.20**, -56.50, -58.12, -60.19, -62.05, -63.70, -65.10, -66.38, -67.55, -68.55, -69.45, -70.25, -71.00, -71.70, -72.35	Zone 3
W4	50.00	49.60	-74.10, -73.50, -72.90, -72.40, -71.80, -71.10, -70.30, -69.50, -68.60, -67.50, -66.35, -65.05, -63.50, -61.70, -59.45, -56.70, **-54.00**	Zone 17
W5	24.00	23.70	-67.75, -66.70, -65.55, -64.30, -62.95, -61.55, -60.40, **-59.70**, -59.90, -60.75, -62.00, -63.35, -64.70, -65.90, -67.05, -68.10, -69.05	Zone 8
W6	32.00	31.80	-70.30, -69.60, -68.70, -67.85, -66.90, -65.80, -64.75, -63.70, -62.80, -62.10, **-61.90**, -62.10, -62.80, -63.70, -64.75, -65.80, -66.85	Zone 11
W7	12.00	11.90	-60.85, -58.35, -55.30, **-52.80,** -53.40, -56.35, -59.20, -61.50, -63.40, -65.00, -66.35, -67.50, -68.55, -69.50, -70.35, -71.15, -71.85	Zone 4
W8	4.00	4.00	-60.50, **-60.38**, -60.95, -62.00, -63.20, -64.50, -65.70, -66.80, -67.85, -68.75, -69.60, -70.40, -71.10, -71.80, -72.45, -73.05, -73.60	Zone 2
W9	37.00	36.60	-71.70, -71.00, -70.25, -69.40, -68.50, -67.50, -66.40, -65.20, -63.80, -62.25, -60.60, -59.05, **-58.10**, -58.30, -59.50, -61.10, -62.75	Zone 13
W10	44.00	43.90	-72.95, -72.35, -71.70, -71.00, -70.30, -69.50, -68.65, -67.75, -66.75, -65.70, -64.60, -63.50, -62.45, -61.70, **-61.42**, -61.70, -62.45	Zone 15

Table 3 below indicates the overall performance of the system by comparing the actual and measured heights, identifying the best zones for each worker. During testing, it was found that the system identified the construction worker zones accurately, and the accuracy of the system was found to be 98.78%. This high accuracy indicates that the system can be adaptable for more complex environments.

TABLE III: ACCURACY MEASUREMENT OF THE SYSTEM

Worker ID	Actual height (meters)	Calculated height (meters)	Best Zone (Floor)	Difference (meters)	Accuracy (%)
W1	18.00	17.80	Zone 6	0.20	98.89
W2	34.00	33.90	Zone 12	0.10	99.71
W3	9.00	8.90	Zone 3	0.10	98.89
W4	50.00	49.60	Zone 17	0.40	99.20
W5	24.00	23.70	Zone 8	0.30	98.75
W6	32.00	31.80	Zone 11	0.20	99.38
W7	12.00	11.90	Zone 4	0.10	99.17
W8	4.00	4.00	Zone 2	0.00	100.00
W9	37.00	36.60	Zone 13	0.40	98.92
W10	44.00	43.90	Zone 15	0.10	99.77
Average Accuracy					98.78

Tables 1, 2 and 3 above validates the accuracy of the proposed system. with a minimum error margin, the system was proven to be more suitable and scalable for real-time height and location monitoring of workers.

IV. CONCLUSION

The IoT-enabled height and zone detection system using an alternate sensing approach was effective in identifying the location and zone of construction workers across elevated workspaces. The system integrated Bluetooth technology, ultrasonic sensors, IR sensors, and LiDAR technologies for triangulating the data. When the system was tested with multiple workers who were placed at different heights and locations, the system performed as expected and displayed an error margin of 0.4m. The system was effective in triggering alerts in real-time in case of detection of non-compliance and transmitted the data to the central control system in real-time for further analysis. The system was validated using MATLAB simulations, which demonstrated 98.78% accuracy. Though the system is effective, user acceptance remains a challenge.

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