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Real-time Individual Tracking Solution for Intrusion Detection and Monitoring System using 24-GHz mm Wave Radar Technology

Nghiem Le Phan Gia[1], Linh Ho Khanh[1], Tuan Do-Hong[1]
[1]*Department of Telecommunication Engineering, Faculty of Electrical and Electronics Engineering, Ho Chi Minh City University of Technology - Vietnam National University Ho Chi Minh City, 268 Ly Thuong Kiet street, Dien Hong ward, Ho Chi Minh city, 700000, Viet Nam*

Abstract: Now a days, a wide range of solutions is available for monitoring and tracking human within a defined area, employing diverse technologies. Among these, solutions that utilize cameras or image sensors are predominant, owing to their straight forward integration, scalability, and ease of development, particularly with the remarkable advancements in Artificial Intelligence (AI) algorithms for visual data processing. However, these vision-based approaches pose inherent risks related to the theft or unauthorized disclosure of sensitive data. In this study, the design of a novel solution for effective intrusion detection and monitoring system using 24 GHz mm Wave radar technology is presented. The proposed system incorporates advanced edge-based signal processing and machine learning algorithms to achieve high accuracy while facilitating easy integration, scalability, and future development. This approach also ensures the information security and confidentiality of sensitive user data.

Keywords: mmWave, radar, HLK-LD2410, IoT, individual monitoring, edge processing.

I. Introduction

The Internet of Things (IoT) is revolutionizing numerous aspects of modern life by interconnecting billions of devices, from sensors and machinery to everyday objects, thereby creating a vast, intelligent network.

In this context, the detection and monitoring of human presence within environments such as homes, offices, and healthcare facilities have gained significant importance. This capability serves multiple essential purposes, including smart home automation (controlling lighting and HVAC systems), enhancing security, providing safety alerts (such as fall detection for the elderly), and enabling efficient resource management. However, traditional solutions exhibit several limitations. Camera-based systems frequently raise privacy concerns, while ubiquitous passive infrared (PIR) sensors lack the sophistication to differentiate between humans and other objects or to detect stationary individuals. Consequently, there is a critical need for an alternative solution that is cost-effective, preserves user privacy, and can reliably detect human presence, even when objects are motionless or exhibit only minimal movement. Millimeter-wave (mmWave) radar technology has emerged as a promising candidate due to its capacity to detect subtle motions (such as the minute physiological oscillations on an object's body surface) and its robust performance under various environmental conditions, mitigating the privacy risks associated with cameras.

Motivated by these practical requirements and technological opportunities, this study investigates the design and implementation of a "Real-time Individual Tracking Solution for Intrusion Detection and Monitoring System using 24-GHz mmWave Radar Technology". The objective of this system is to deliver a real-time solution for monitoring human presence and position, establishing a foundational platform for future smart automation and management applications while ensuring the protection of personal privacy.

II. Review of Literature

Presently, the remote management and monitoring for security, safety, and health risk alerts is of paramount importance. To address these critical applications, numerous research studies and practical solutions have been developed and implemented globally.

The most prevalent approaches currently rely on cameras integrated with image processing algorithms. A significant body of research focuses on enhancing camera effectiveness in low-light conditions through advanced image processing techniques. Some systems leverage the continuously updated tools available in the OpenCV library, while others develop superior features for event detection using models like You Only Look Once (YOLO) to improve the overall accuracy of the recognition system.[1]

Furthermore, some studies integrate auxiliary modules, such as infrared (IR) sensors, to enhance the night-vision capabilities of cameras and extend the system's operational range for continuous monitoring. [2]

In practical applications, human detection, management, and tracking systems are often built upon a multi-layered architecture that combines multiple sensor types using different technologies, including laser. However, while these applications are equipped with advanced algorithms to maximize efficacy and compensate for mutual shortcomings, the inherent technical limitations of these technologies persist. These limitations introduce vulnerabilities that can be exploited by malicious actors; for instance, a hacker could infiltrate a system to acquire private footage from its cameras.

Currently, millimeter-wave (mmWave) detection technology is primarily utilized in smart home applications, either for automatic device control based on a subject's detected position or in voice-controlled systems to distinguish between human speech and electronic audio sources by leveraging its ability to detect micro-vibrations. In the security domain, the application of this technology has been largely confined to reflection-based metal scanners.

To date, few models or applications for civilian security monitoring, including intruder detection and tracking, have been developed using mmWave radio technology. The study, "Real-time Individual Tracking Solution for Intrusion Detection and Monitoring System using 24-GHz mmWave Radar Technology", aims to exploit the potential strengths of mmWave waves to enhance the security of existing systems or to serve as a viable replacement under specific conditions.

Table 1: Reflection parameters for 100 GHz mmWave signals [3]

Sample		Thickness (mm)	Reflection (dB)	Transmission (dB)
Clothing	Wool	1.4	-13	-0.8
	Nylon	0.1	-23	-0.1
	Flannel	0.5	-18	-0.3
	Denim	1.0	-30	-0.3
	Leather	0.8	-18	-0.7
	Corduroy	0.6	-16	-0.4
Skin	Calf	Null	-11.3	Null
	Forearm	Null	-8.4	Null
	Jowl	Null	-15.0	Null
	Chest	Null	-8.8	Null
Contrabands	Ceramic	2.6	-4.5	-3.0
	Polycarbonate	5.5	-8.5	-1.8
	Polypropylene	1.5	-8.8	-0.8
	Metal	Null	0	Null

III. Overview

The "Real-time Individual Tracking Solution" utilizes 24-GHz millimeter-wave (mmWave) technology for presence detection and object tracking. This solution is implemented as a hardware suite comprising two critical components: a central node and multiple sensor nodes.

The sensor nodes function as environmental scanners responsible for detecting oscillating objects. They perform on-board pre-processing to reject noise and enhance the probability of human identification. Subsequently, each node measures its distance to an object classified as human and transmits this ranging data to the central node. The central node serves as the system's edge computing hub. It employs a combination of advanced processing algorithms, statistical signal analysis, and machine learning models to determine the probabilistic region of human presence within the monitored 3D space. It applies further high-level algorithms for noise cancellation to increase the accuracy of the detection and localization processes.

The system is architected for scalability, allowing a single central node to support an expandable network of sensor nodes, and for seamless integration into existing IoT management platforms.

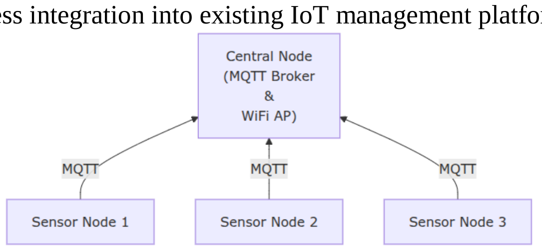

Fig 1: Device set connection schematic

IV. System Design and Algorithms

Sensor Node

The sensor nodes are tasked with scanning the environment with 24-GHz mmWave signals to identify oscillating objects. Through internal processing and calculation, each node determines which objects are likely human and transmits the measured distance to those targets to the central node. This communication is handled via the Message Queuing Telemetry Transport (MQTT) protocol over a local Wi-Fi network managed by the central node.

Each sensor node is constructed from two primary components: an ESP32 microcontroller, which serves as the node's processor, and an HLK-LD2410-24G module, which functions as the environmental sensor. The module sends data to the ESP32 microcontroller for processing through the Universal Asynchronous Receiver-Transmitter (UART) protocol.

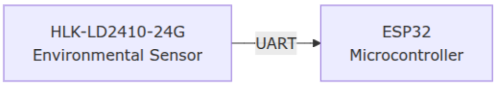

Fig 2: Sensor node connection schematic

The HLK-LD2410-24G radar module operates on the principle of Frequency Modulated Continuous Wave (FMCW). FMCW radar emits a continuous signal whose frequency is modulated over time, typically in a linear fashion, to create a waveform known as a "chirp." This signal reflects off an object and returns to the receiver. By comparing the frequency of the received signal with the frequency of the transmitted signal at that same instant, a "beat frequency" is generated. The module processes this beat frequency to determine the distance to the object. The range resolution of an FMCW radar is determined by the bandwidth (BW) of the chirp's frequency sweep. Furthermore, by analyzing the phase variations or the Doppler frequency shift of the reflected signal across successive chirp cycles, the module can also detect movement and estimate its motion energy.

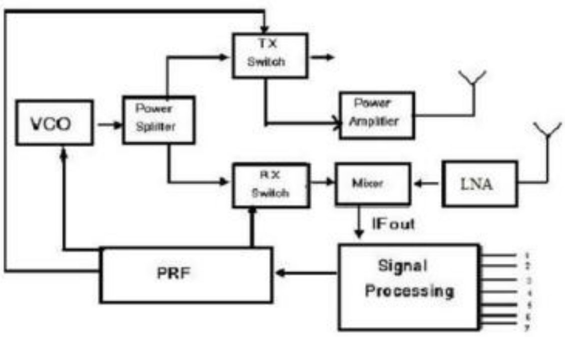

Fig 3: FMCW radar operating principle [4]

Following the working principle of FMCW radar described, the HLK-LD2410-24G radar module identifies clusters of motion within its monitored field of view. Subsequently, the module determines the maximum oscillation amplitude for each cluster based on the amplitudes of its constituent motion points. Using this amplitude, the module classifies an object as either "moving" or "stationary". It also determines (i) the object's ranges characterized by "moving distance" (*Md*) and "stationary distance" (*Sd*), and (ii) its energies characterized by "moving energy" (*Me*) and "stationary energy" (*Se*). These energies are directly proportional to the object's oscillation amplitude.

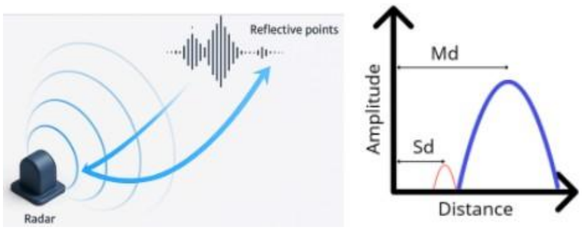

Fig 4: Target detection and classification principle of HLK-LD2410-24G

After the parameters (*Me, Se, Md, Sd*) are determined, the noise filtering algorithm (Algorithm 1) is executed using the ESP32 microcontroller. This process involves comparing the measured *Me* and *Se* values for a given object against their respective pre-set environmental thresholds, *Me_threshold* and *Se_threshold*. Only values that exceed these thresholds are utilized in subsequent computational steps. Subsequently, the distance from the sensor node to the detected target is computed based on the *Md* and *Sd* parameters.

Algorithm 1 Determine the Distance to Detected Target

Require: The calculated sensor values: Md, Me, Sd, Se
The calibrated environment thresholds: $Me\_threshold$, $Se\_threshold$
Ensure: The estimated distance d

```
if (Md ≈ Sd) and (Me > Me_threshold) and (Se > Se_threshold) then
    d ← (Md + Sd)/2
else
    d ← 0
end if
```

In addition to the inherent oscillations within the monitored space—which are already filtered by comparing the *Me* and *Se* values against the *Me_threshold* and *Se_threshold* (environment noise thresholds)—the environment can also be affected by "ghost objects". These artifacts are typically caused by vibrations from other objects within the same space.

Therefore, to eliminate the influence of these “ghost objects”, a subsequent algorithm (Algorithm 2) is executed on the sensor node. This algorithm determines the state of the monitored person and performs noise filtering based on both the "current distance" and the "distance history".

Algorithm 2 Detect the Target's Activity State

Require: The current sensor values: $Current\_Md$, $Current\_Me$, $Current\_Sd$, $Current\_Se$
The sensor value from the previous time step: $Previous\_Sd$
Ensure: The classified state of the target: $State$

```
function is_acting_human(Md, Me, Sd, Se)
    ▷ This function implements the logic from Algorithm 1
if (Md ≈ Sd) and (Me > Me_thr) and (Se > Se_thr) then
        return True
else
        return False
end if
end function
if is_acting_human(Current_Md, ..., Current_Se) then
    State ← "ActingHuman"
else
    if Current_Sd ≈ Previous_Sd then
        State ← "Non-ActingHuman"
    else
        State ← "Noise"
    end if
end if
```

Central Node

Due to hardware constraints from the manufacturer, the HLK-LD2410-24G module can only provide data to the ESP32 microcontroller for calculating the scalar distance (*d*) to a monitored object. Consequently, a system with a single sensor node cannot determine the position and the probabilistic presence region of an object in the monitored 3D space.

Therefore, the system architecture requires each central node (using another ESP32 microcontroller) to manage at least three sensor nodes. These nodes must be installed in a coplanar arrangement (e.g., on the same ceiling) and must be non-collinear. With the respective distance value, *d*, reported by each sensor, the central node can then compute the 3D position (*x-y-z* coordinates) of the monitored object by applying the Trilateration algorithm.

After the 3D position of the monitored object is computed at successive intervals, a probabilistic presence region is determined. This region is calculated based on an aggregation of the object's positions recorded over a configurable reporting cycle. It is important to note that this cycle—used for calculating the presence region and sending data from the central node to the server—is distinct from the more frequent cycle used for individual 3D position calculations.

During this process, a linear regression machine learning algorithm (Algorithm 3) is employed to eliminate outliers. These outliers are suspected to be noise artifacts from "ghost objects" captured by the system during the reporting cycle. This step enhances the accuracy of the final probabilistic presence region data that the central node transmits to the server.

Algorithm 3 Outliers Filtering and Probabilistic Presence Region Detecting

Require: A set of sensors with known positions: $S = \{S_1, S_2, ..., S_n\}$
The duration of the observation cycle: T_{cycle}
Ensure: The probability region R, defined by a center R_{center} and a radius R_{radius}

Initialize an empty list: $List\_Positions \leftarrow []$ {Begin observation cycle to collect position data}
for $t \leftarrow 1$ **to** T_{cycle} **do**
  Obtain the set of distances D_t from all sensors in S at time t
  Estimate target's position: $P_t \leftarrow CalculatePosition(D_t, S)$
  Append P_t to the list: $List\_Positions.add(P_t)$
end for{Compute the probability region from the collected data}
Calculate the mean position to serve as the region's center:
$R_{center} \leftarrow CalculateMeanPosition(List\_Positions)$
Calculate the standard deviation of positions from the center for the radius:
$R_{radius} \leftarrow CalculateStandardDeviation(List\_Positions, R_{center})$
return (R_{center}, R_{radius})

V. Result and Discussion

The device system is mounted on a plane parallel to the floor and at a height greater than that of the targets to be monitored. The results presented below are the average values obtained from multiple experimental runs conducted under various conditions. The parameter *r* represents the radius of the probabilistic presence region.

Table 2: Experimental results under quiet conditions

	Coordinates (in cm)				
x (actual)	**50**	**60**	**80**	**100**	**120**
x (measured)	55	58	88	103	123
y (actual)	**50**	**85**	**80**	**90**	**110**
y (measured)	52	89	83	86	108
z (actual)	**50**	**50**	**50**	**50**	**50**
z (measured)	54	50	56	49	52
r	48	59	47	35	51

Table 3: Experimental results in a cluttered environment with low obstacles and loud music

	Coordinates (in cm)				
x (actual)	**50**	**80**	**90**	**100**	**120**
x (measured)	52	75	89	92	115
y (actual)	**50**	**80**	**90**	**100**	**120**
y (measured)	57	86	85	106	116
z (actual)	**20**	**20**	**20**	**20**	**20**
z (measured)	41	47	42	31	38
r	64	58	51	49	35

Table 4: Experimental results in a cluttered environment with low obstacles and an active fan

	Coordinates (in cm)				
x (actual)	**60**	**80**	**90**	**100**	**120**
x (measured)	75	99	103	108	112
y (actual)	**60**	**80**	**90**	**90**	**90**
y (measured)	71	75	82	83	82

z (actual)	**40**	**40**	**100**	**140**	**140**
z (measured)	64	68	129	155	161
r	65	68	51	42	45

The preceding experimental results indicate that the system achieves high accuracy for monitoring and measurement on the *xy*-plane (which is the plane parallel to the ground where the three sensor nodes are mounted). Errors along the *z*-axis, however, can be mitigated by adjusting the installation height of this plane relative to the ground.

VI. Conclusion

In this study, the "Real-time Individual Tracking Solution for Intrusion Detection and Monitoring System using 24-GHz mmWave Radar Technology" is successfully designed and implemented, featuring a hardware suite that utilizes 24-GHz mmWave radar technology. Experimental results demonstrate that the system achieves a commendable degree of accuracy for real-time detection and monitoring tasks in a 3D space. This work thereby establishes a foundational platform based on mmWave technology for the development of more advanced applications, such as intrusion detection and monitoring or proximity smart health tracking.

VII. Acknowledgements

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