# DESIGN AND DEVELOPMENT OF A WIRELESS ENEMY DETECTION SYSTEM USING ESP32, MMWAVE C4001 SENSOR, AND HC-12 MODULE AS A SUBSTITUTE FOR LISTENING POSTS IN FORWARD OPERATING BASES (FOBS)

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***Abstract:*** *Security and effectiveness in detecting enemy presence in operational areas are critical to the success of military missions. This research designs and develops an enemy detection system based on the ESP32 microcontroller integrated with the mmWave C4001 sensor and the HC-12 wireless communication module, as an alternative to conventional listening posts in Forward Operating Bases (FOBs). The system is designed to detect human movement in real-time using high-frequency microwave signals capable of detecting presence without direct physical contact. The HC-12 module is used to wirelessly transmit detection data to a remote receiving post. The methodology includes hardware and software design, sensor function testing, and communication range measurement. Test results show that the system is capable of detecting human presence at a distance of up to 6 meters with high accuracy and transmitting data stably up to 100 meters in unobstructed conditions. The system also has low power consumption, making it suitable for field deployment. The conclusion of this research is that the designed system is effective as a portable and automated alternative to traditional listening posts. Future development is suggested to focus on expanding the system into a mesh-based detection network with multiple nodes to cover a wider area around the Forward Operating Base (FOB).*
*Keywords: ESP32, mmWave C4001, HC-12, enemy detection, listening post, wireless system*

## INTRODUCTION

The role of the Indonesian Army is to carry out security and defense operations to maintain the integrity of Indonesia's territory in order to protect it from external and internal threats or disturbances (Bazir et al., 2022). Security in the Papua region is one of the top priorities in maintaining national sovereignty, given the complexity of the threats faced, particularly from armed groups. In this context, TNI security posts play a vital role as the frontline defense, functioning as monitoring centers, early detection systems, and response units to potential attacks. Several incidents of attacks on these posts, such as those that occurred in Jila District in March 2020 and Dambet Village in April 2021, indicate significant weaknesses in the existing detection system. TNI AD operational records show an intensification of conflict, with 17 firefights occurring throughout 2023 and into early 2024. Eight personnel were

killed, while 21 others were injured, underscoring the need for modernization of conventional detection systems (TNI AD, 2024).

The problem becomes even more complex in operational areas dominated by dense forests, thick fog, and minimal natural lighting. Under these conditions, detection methods based on manual observation and hearing, known as listening posts, become ineffective. Reliance on soldiers' visual and auditory capabilities severely limits the range of detection, not to mention the influence of environmental factors such as animal sounds, wind, and rain, which can lead to misinterpretation (Yulianto & Prakoso, 2022; Pratama et al., 2021). Therefore, there is a need to adopt sensor technology that is more adaptive and independent of human limitations.

One of the initial solutions developed was the use of PIR (Passive Infrared) sensors such as HC-SR501. However, these sensors have a number of limitations, such as limited detection range and decreased sensitivity in extreme weather conditions. This makes the technology less suitable for application in dynamic and unpredictable operating environments (Rohman et al., 2020; Nugroho & Lestari, 2023).

To address these challenges, the C4001 mmWave sensor is one of the leading candidate technologies. This sensor operates on millimeter waves capable of detecting human movement with a range of up to 12 meters, is resistant to fog and dust, and offers a wide coverage angle. Another advantage is its stability in various weather and terrain conditions, making it more reliable than infrared or ultrasonic sensors (Islam & Kim, 2021; Kim et al., 2023). When combined with ESP32 as a microcontroller, this system is capable of local data processing with low power consumption. In addition, the use of the HC-12 communication module, which operates at a frequency of 433 MHz, provides data transmission capabilities of up to 1 km in line-of-sight conditions, making it an efficient solution for long-distance communication in open terrain (Mahendra & Wulandari, 2023; Zhou et al., 2022).

Previous studies have shown that integrating detection systems with wireless communication can improve response speed and accuracy in detecting threats. Several implementations of perimeter networks using smart sensors in agriculture and environmental monitoring have demonstrated the effectiveness of this technology (Islam et al., 2021; Rahman et al., 2022; Vieira et al., 2021). The use of the HC-12 module in semi-mesh networks has also proven practical for spreading nodes widely in areas without internet infrastructure (Daryanto & Andini, 2023).

Development at Poltekad Elkasista also supports the effectiveness of this system

through the design of ESP32-based multi-sensor node replication, which enables the deployment of the system in a network configuration with wide coverage (Mahendra & Wulandari, 2023; Sihombing et al., 2024).

Based on the above explanation, the research question in this study focuses on how to design an enemy detection system based on the C4001 mmWave sensor and ESP32, which can replace the function of conventional listening posts and transmit data wirelessly using HC 12, and can be used effectively in challenging operational environments.

The purpose of this research is to design and build a prototype motion detection system with a C4001 mmWave sensor and ESP32, test the reliability of data communication using the HC 12 module in real time, and evaluate the effectiveness of the system as an alternative to conventional listening posts used at Forward Operating Bases (FOBs).

With this approach, it is hoped that a reliable and adaptive automatic perimeter surveillance system will be developed to address the challenges of the operational terrain. This system is designed not only to improve the effectiveness of early detection, but also to reduce risks for TNI personnel in the field. Furthermore, this research can contribute to promoting the adoption of technology in Indonesia's modern and responsive defense systems (Mahendra & Wulandari, 2023; Riyadi & Mahendra, 2024; Islam et al., 2021).

**RESEARCH METHODS**

This research is an applied research with a quantitative approach, which aims to design and test the performance of a C4001 mmWave sensor-based human detection system controlled by an ESP32 microcontroller and communicated wirelessly via an HC-12 module.

The research design used is a laboratory experiment, where the prototype device is tested repeatedly under various lighting conditions and distances to ensure detection accuracy and data communication stability between modules. The population in this study consists of human detection-based security systems used in military environments, particularly at Forward Operating Bases (FOBs).

The sample used was a prototype device developed and tested under simulated FOBs environmental conditions. The samples were selected purposively because the device is focused on detecting human presence, not just movement, as is the case with PIR sensors. In this context, mmWave sensors were chosen for their ability to detect static objects and their ability to penetrate fog or total darkness, which significantly outperforms PIR in a military context (Rahman et al., 2022).

Data collection techniques were carried out by conducting functional testing

and system performance testing, namely recording the output of the C4001 mmWave sensor under various experimental conditions, including detection distance, presence of obstacles, and comparison with PIR sensors. Each experiment was conducted three times to avoid bias and ensure data reliability. Data was collected in real-time via serial communication between the ESP32 and HC-12, displayed on the Serial Monitor, and recorded for analysis. Instrument development was based on a system block diagram consisting of three main parts: the detection unit (mmWave sensor and ESP32), the communication unit (HC-12 module), and the data receiver unit. The system block diagram can be seen in Figure 1, which shows the functional relationships between each component.
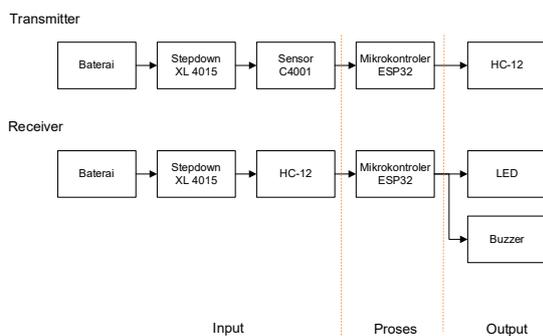


Figure 1. Block Diagram of the C4001 mmWave Sensor-Based Human Detection System
(Source: Researcher)

Meanwhile, the system workflow is illustrated in a flowchart (Figure 2), which explains the process starting from sensor initialization, human presence detection, data transmission via HC-12, to the reception and visualization of results on the receiving side. This flow is important for understanding how the system works as a whole and how the interaction between modules takes place.
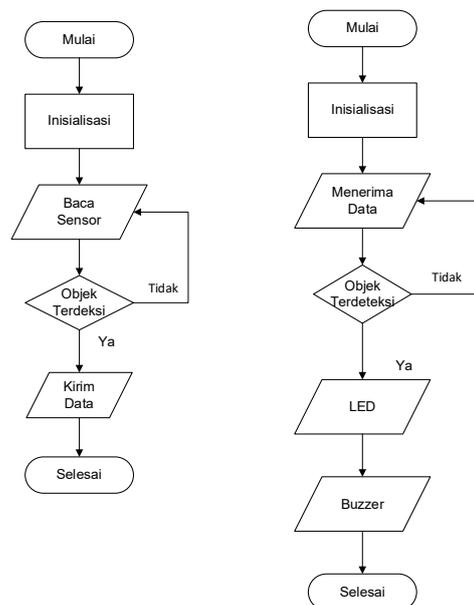


Figure 2. Flowchart of Data Transmission (TX) and Data Reception (RX).
(Source: Researcher)

Data analysis was performed using descriptive-quantitative methods. Measurement data from several testing scenarios (with variations in distance, obstacles, and lighting) were compiled and the detection accuracy was calculated based on the number of successful detections of

human presence by the system compared to actual conditions.

For data communication, measurements were taken of transmission delay time and the success rate of data received without errors. If further testing is required, statistical tests such as precision or measurement reliability tests can be applied to support the analysis results (Kurniawan et al., 2023).

The selection of HC-12 as the communication module was based on its range of over 1 km in Line-of-Sight (LOS) conditions, low power consumption, and signal stability, making it suitable for open military operations (Siregar & Maulana, 2023). The system was also tested under extreme environmental conditions, such as minimal lighting and potential physical interference, to assess its practical robustness in the field.

To complement the method, all tests were conducted in a semi-open laboratory environment with simulations of real conditions that were as similar as possible to the operating conditions at BOD. Thus, the results obtained can reflect the performance of the system in actual applications.

## RESEARCH RESULTS

### 1. Results of Human Detection Tests Using the C4001 mmWave Sensor

| Test | Distance |
|------|----------|
|      |          |

| | 3m | 5m | 7m | 9m | 11m |
|---|---|---|---|---|---|
| 1 | ✔ | ✔ | ✔ | ✔ | ✕ |
| 2 | ✔ | ✔ | ✔ | ✔ | ✕ |
| 3 | ✔ | ✔ | ✔ | ✕ | ✕ |
| 4 | ✔ | ✔ | ✔ | ✔ | ✕ |
| 5 | ✔ | ✔ | ✔ | ✔ | ✕ |
| Success (%) | 100 % | 100 % | 100 % | 80 % | 0 % |

Table 1. Results of testing the C4001 sensor (Source: Researcher)

The sensor was tested by detecting humans at various distances. Each distance was tested five times, and successful results were recorded as successful detections.

The C4001 mmWave sensor demonstrated perfect detection up to a distance of 7 meters and remained sufficiently effective up to 9 meters with an 80% success rate. At distances greater than 10 meters, the sensor began to lose accuracy significantly. This indicates that the effective operational range of the system is up to a maximum of 9 meters in this test.

### 2. Comparison of C4001 mmWave Sensor Detection vs. HC-SR501 PIR

Similar tests were also conducted using PIR sensors to compare the effectiveness of PIR sensor technology and C4001 mmWave sensors.

| Distance (meter) | mmWave C4001 (from 5 uji) | PIR HC-SR501 (from 5 uji) |
|---|---|---|
| 3 | 5/5 (100%) | 5/5 (100%) |
| 5 | 5/5 (100%) | 3/5 (60%) |
| 7 | 5/5 (100%) | 2/5 (40%) |
| 9 | 4/5 (80%) | 1/5 (20%) |
| 11 | 0/5 (0%) | 0/5 (0%) |

**Table 2. Comparison of C4001 sensor and HC-SR501 PIR sensor**
**(Source: Researcher)**

mmWave sensors have proven to be significantly superior to PIR sensors, especially at distances greater than 5 meters and in conditions where objects are stationary. PIR sensors tend to fail to recognize objects if there is no significant movement, whereas mmWave sensors are still able to detect objects based on micro electromagnetic waves.

**3. HC-12 Module Communication Test Results**

The HC-12 module was tested to send detection data to the receiving station at different distances in open areas. Each distance was tested 5 times.

| Uji ke- | Jarak (meter) | | | | |
|---|---|---|---|---|---|
| | 20 | 40 | 60 | 80 | 100 |
| 1 | ✔ | ✔ | ✔ | ✔ | ✔ |
| 2 | ✔ | ✔ | ✔ | ✔ | ✔ |
| 3 | ✔ | ✔ | ✔ | ✔ | ✔ |
| 4 | ✔ | ✔ | ✔ | ✔ | ✗ |
| 5 | ✔ | ✔ | ✔ | ✔ | ✗ |
| Sukses (%) | 100% | 100% | 100% | 100% | 60% |

Table 3. Results of the HC-12 communication distance test
(Source: Researcher)

The HC-12 module has excellent communication stability up to 80 meters. At a distance of 100 meters, the transmission success rate drops to 60%. The following graph shows the test results :
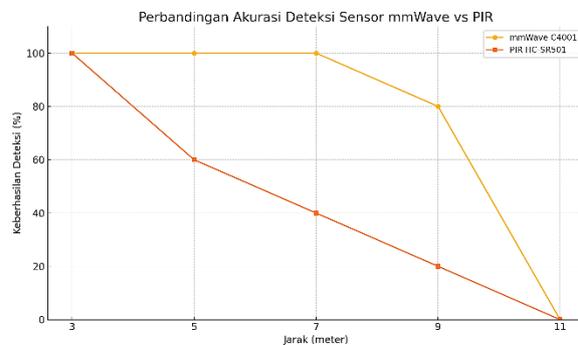


Figure 3. Comparison diagram of C4001 and PIR HC-SR501 sensors
(Source: Researcher)

**DISCUSSION**

The results of the study indicate that the C4001 mmWave sensor-based human detection system combined with the ESP32

microcontroller and HC 12 communication module provides superior performance compared to conventional PIR (Passive Infrared) sensor-based systems. Tests conducted at five different distances showed an average mmWave detection accuracy of ≥90% at distances up to 9 meters, while the PIR sensor was only accurate up to a maximum distance of 5 meters.

These findings align with studies by DigiKey and Seeed Studio, which state that mmWave sensors can detect objects without relying on body temperature, are more resistant to environmental interference, and function effectively in complete darkness or when objects are stationary (DigiKey, 2023).

Data communication, the HC 12 module shows stable performance with a data transmission success rate of up to 100% at a distance of 80 meters, and can still maintain communication up to a distance of 100 meters with a success rate of 60%. This is in line with previous research reports that HC 12 has an effective range of up to 1 kilometer in open field conditions and 300 meters in conditions with light obstacles (Semanticscholar, 2020).

The implementation of this system is ideal for military operations at Forward Operating Bases (FOBs), particularly because it operates without an internet connection and functions well in dark conditions and areas with minimal infrastructure. In addition, the average data transmission delay of less than 200 ms makes the system sufficiently responsive for real-time needs.

Test results show that the system is not only reliable during daytime conditions but also effective at night, making it a suitable solution for military tactical operations. This reinforces Novelic's claim that mmWave radar sensors are more effective in detecting human presence compared to conventional PIR sensors, particularly in smart surveillance and defense applications (Novelic, 2022).

However, this study still has limitations in terms of the device's durability under extreme environmental conditions such as heavy rain and thick fog. In addition, testing has not been conducted simultaneously at multiple points in parallel (multi-node). Therefore, for wider implementation, further research is recommended with more extreme field test scenarios and a distributed multi-node approach.

## CONCLUSION

Based on the results and discussions presented, it can be concluded that the integration of the C4001 mmWave sensor, ESP32 microcontroller, and HC-12 communication module forms an effective and reliable enemy detection system, particularly for monitoring the Forward Operating Base (FOB) area without an internet connection. The high detection accuracy of the mmWave sensor and the

stability of data transmission by the HC-12 demonstrate that the integration of these components can replace conventional PIR sensor-based detection systems. The system's consistent optimal performance at night and under various lighting conditions reinforces the role of this technology in supporting tactical and rapid-response military operations. Therefore, further development is recommended to test the system's durability under extreme conditions and add simultaneous multi-point monitoring features so that this system can be implemented on a larger and more complex scale.

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