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Design and Development of a Portable Surveillance Robot with Wireless Control Using ESP32-CAM for Tactical Intelligence Purposes

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Abstract

This research aims to design and develop a portable surveillance robot with wireless control using the ESP32-CAM module as an innovative solution to support tactical intelligence needs in high-risk environments. Through the prototype research method, this system is developed to facilitate real-time surveillance without requiring personnel to be directly present in dangerous locations, thereby minimizing risks to human safety. The robot integrates major components such as the ESP32-CAM as the main control center and video transmission medium, the L298N motor driver, and four DC motors that enable mobility across various urban and open-field terrains. Supported by a Li-ion battery power source, the device is capable of transmitting visual data efficiently through a Wi-Fi network to the control device, which is expected to improve operational effectiveness and decision-making accuracy in surveillance and security missions.

Keywords Surveillance Robot, ESP32-CAM, Wireless Control, Tactical Intelligence, Real-time Streaming.

INTRODUCTION

The rapid advancement of technology has had a significant impact on various aspects of human life, including the fields of security and intelligence. One of the primary needs in the military and law enforcement sectors is efficient real-time surveillance. However, direct surveillance by human personnel often involves high safety risks and requires substantial resources. Therefore, the development of automated surveillance systems using wireless technology has become an important solution to implement. The implementation of autonomous robotic systems in security operations has been proven to reduce dependence on the physical presence of personnel in dangerous zones (Chen, 2021). Surveillance robots have emerged as an innovation for monitoring areas that are difficult to access or dangerous for humans.

The main advantage of this surveillance robot is its ability to operate in high-risk environmental conditions. The robot can be deployed in contaminated areas, battlefields, or other locations with serious threats. The use of wireless technology in this device enables far more flexible control and communication for operators. Wireless connection stability is crucial to maintain smooth control in tactical terrains(Wijaya et al., 2026). This ensures that data can be transmitted quickly without relying on physical cable connections. As a result, the effectiveness of surveillance operations can be significantly improved through the assistance of modern robotics technology.

ESP32-CAM is a camera-integrated microcontroller module that has proven to be efficient for various IoT-based applications. This advanced module is capable of transmitting real-time video through a Wi-Fi network to user devices. The use of edge image processing using ESP32 can accelerate object detection before visual data is sent to the operator(Chang et al., 2025; Widiatmoko et al., 2024) In addition, the device can be remotely controlled using web-based applications or mobile devices. Cloud-based control architectures also allow for the management of robot units from very long distances (Wang et al., 2010). These capabilities make ESP32-CAM highly suitable for use in surveillance robot systems, especially in the context of tactical intelligence. The module serves as the core component that ensures the surveillance system operates practically and reliably(Nur et al., 2026).

The development of a portable surveillance robot based on ESP32-CAM aims to provide an advanced solution for monitoring in challenging situations. This system is expected to be used for monitoring restricted areas, border surveillance, and covert reconnaissance operations in the field. The use of robots becomes the preferred option when direct involvement of human personnel is considered impossible or too risky. In addition, the robot is designed to operate effectively in various terrains, such as urban environments and natural outdoor areas. Proper DC motor torque settings on the robot chassis are vital for movement stability on uneven surfaces(Artikel, 2024). Efficient battery power management is also key to ensuring that reconnaissance missions can last longer(Zhao et al., 2023). Navigation flexibility is a key factor in ensuring that the robot can perform surveillance missions optimally.

By combining robotics technology and wireless communication, this project successfully creates an efficient and functional device. Optimizing Wi-Fi data packet delivery significantly affects the quality of the received video streaming(Dharuman et al., 2024). The project not only focuses on technological sophistication but also on the potential to improve the effectiveness of security operations. The integration of smart navigation algorithms and ultrasonic sensors can help the robot avoid obstacles automatically (Li et al., 2023). The research and development of this robot represent a strategic step toward a more modern and secure surveillance system. Furthermore, securing video streams through data encryption is essential to prevent interception of tactical information(Toma et al., 2022). With this technology, intelligence data collection can be carried out more flexibly without endangering personnel safety. Implementation of artificial intelligence on micro-devices is expected to become a future standard in automatic motion detection(Device et al., 2024; Rachman et al., 2024). Overall, this innovation provides a meaningful contribution to the advancement of future security technology. The paradigm shift from manual control to intelligent autonomous systems will continue to evolve in the coming years(Memoye & Ph, 2024).

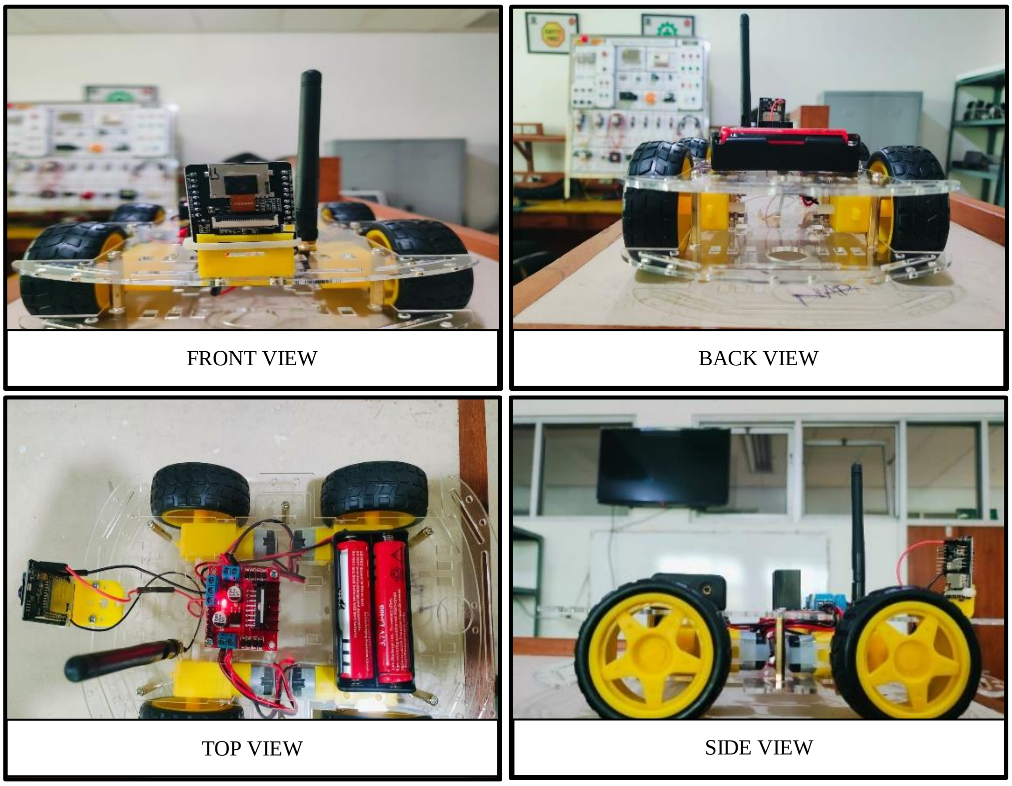
FRONT VIEW
BACK VIEW
TOP VIEW
SIDE VIEW

Figure 1. Robot with Wireless Control Using ESP32-CAM.

METHODS

Design of the Portable Surveillance Robot

The system design was carried out comprehensively for the integrated camera monitoring and motor control system. This system is intended to provide real-time visual feedback and remote control of a DC motor using an ESP32 microcontroller with Wi-Fi connectivity. The ESP32 serves as the main control unit, processing camera inputs and managing motor output. The interconnection between the core modules is illustrated in Figure 2 below.

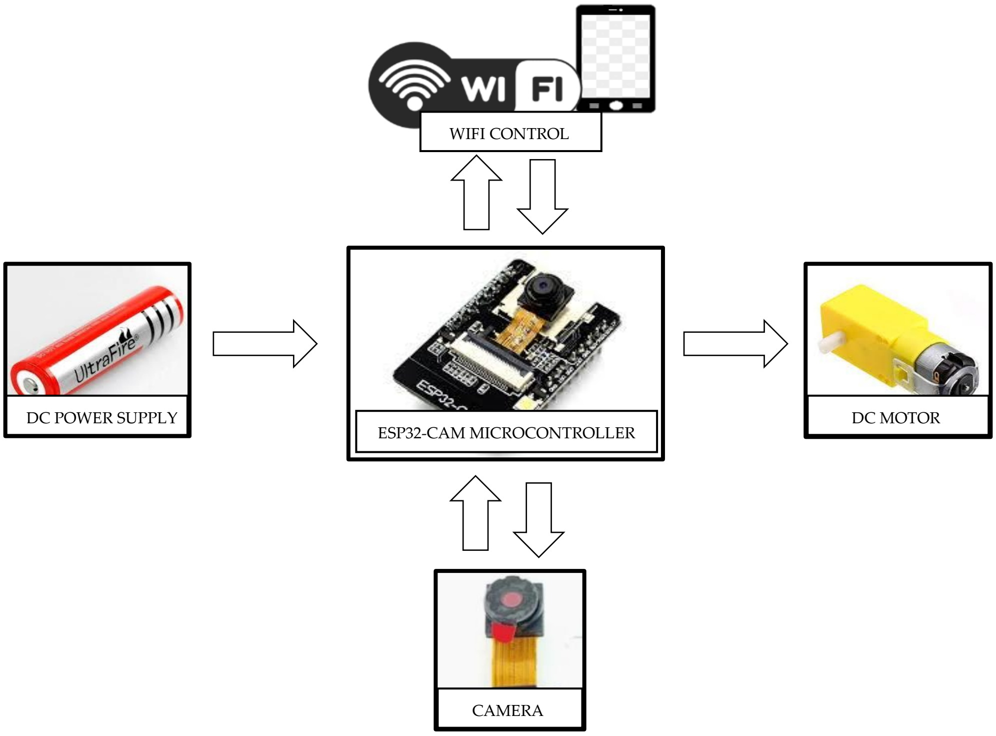

Figure 2. Diagram of the Portable Surveillance Robot Blocks

The control system shown in Figure 2 below manages the surveillance robot operation using an automated microcontroller-based approach. The ESP32-CAM serves as the main control unit, which establishes a connection via Wi-Fi Control to receive navigation commands and transmission requests from a smartphone or remote interface. For environmental sensing, the integrated Camera captures real-time visual data, allowing the operator to monitor the robot's surroundings during maneuvers. The Arduino-compatible ESP32 processes these inputs and modulates the signals sent to the DC Motor to control the robot's speed and direction. A stable DC Power Supply provides the necessary electrical energy to ensure the reliability of the wireless link and the consistent torque of the motor. Through the continuous feedback of the camera stream and the responsive execution of wireless commands, the system keeps the robot’s movement precise and the surveillance data accurate based on the user's remote inputs.

Mechanical Design of the Portable Surveillance Robot.

Besides control system design, the mechanical design of the robot is an essential component to ensure mobility and durability in various operational environments. The robot structure is designed to support tactical intelligence missions in a stable and reliable manner under various terrain conditions. Therefore, high-quality acrylic and lightweight composite materials were selected as the primary materials for the robot's chassis.

The selection of these materials is based on several technical considerations. Acrylic provides a rigid yet lightweight structure, allowing the robot to maintain high speed and agility without consuming excessive battery power. Furthermore, the transparent nature of the chassis facilitates easy internal component inspection and troubleshooting during development. The portability of the robot is maintained through this compact design, especially for deployment in narrow or hard-to-reach areas. Functionally, the mechanical design ensures structural stability to protect sensitive electronic components, such as the ESP32-CAM and motor drivers, from physical impact. In addition, the chassis provides dedicated mounting points for the DC motors, power source, and the camera module. The mechanical layout must be capable of balancing the weight distribution to prevent tipping during rapid maneuvers and providing an unobstructed field of view for the camera. Properly designed mechanically, movement precision and wireless signal stability are achieved more effectively. The mechanical configuration of the designed robot, showcasing the various perspectives, is illustrated in Figure 3.

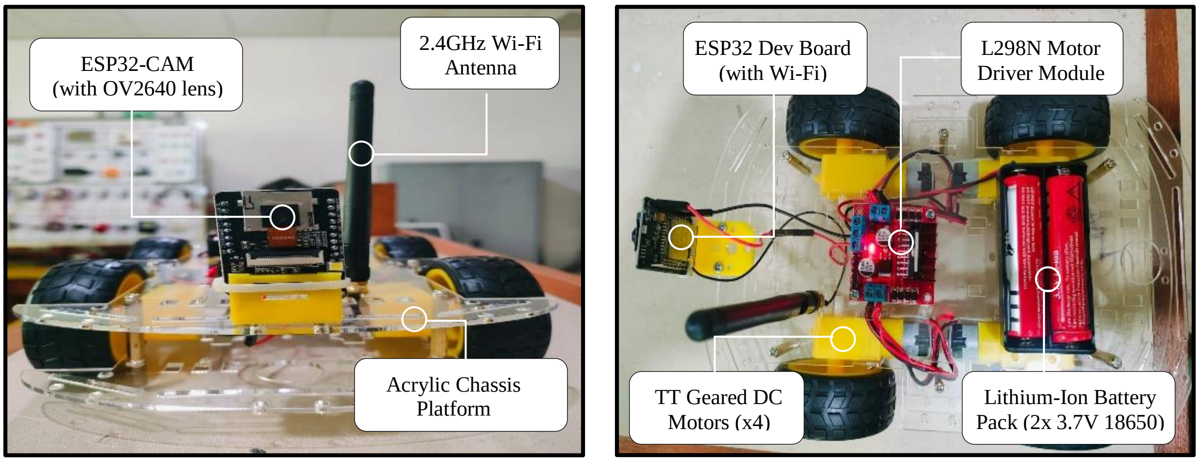

Figure 3. Mechanical Design of the Portable Surveillance Robot

Wiring of the Portable Surveillance Robot

The ESP32-CAM acts as the main controller or the "brain" of the circuit in the portable surveillance robot system. This module is responsible for coordinating all input, processing, and output operations, including capturing visual data through the integrated camera sensor and receiving operational parameters and directional commands wirelessly via a Wi-Fi connection. The use of ESP32-CAM ensures that instructions from the smartphone interface can be processed rapidly to produce accurate mechanical responses.

The system is powered by a stable DC power supply, which in the schematic is shown as a 7V–12V voltage input typically sourced from a lithium-ion battery. The red wiring line distributes positive power to the motor driver input terminals and the ESP32-CAM power pins, while the black wiring line functions as a common ground to maintain electrical stability throughout the entire circuit. Separate power regulation between the control logic and motor operation is essential to prevent signal interference while the robot is actively moving during surveillance tasks.

For mobility, the robot utilizes an L298N motor driver to regulate the speed and direction of four DC motors divided into the right motor group (Right Motor 1 & 2) and the left motor group (Left Motor 1 & 2). The motor driver receives control signals from the ESP32-CAM through a series of colored wires (green, brown, blue, and purple) connected to the input and enable pins to ensure precise robot movement. Figure 4 illustrates the complete wiring diagram of all modules used in the portable surveillance robot system. The synergy between all these components enables the monitoring process to operate stably and wirelessly, providing real-time video feedback to the user according to tactical field requirements.

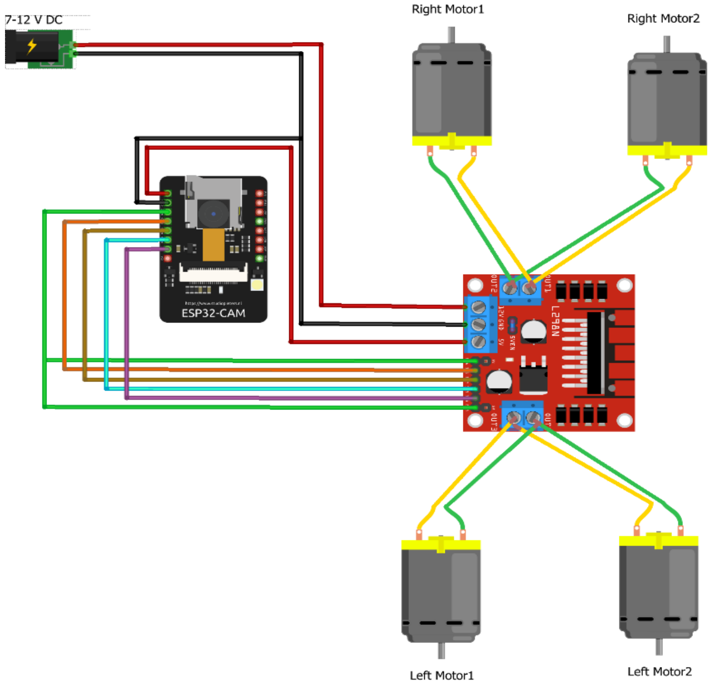

Figure 4. Wiring of the Portable Surveillance Robot

Wiring for Uploading Code to the Portable Surveillance Robot

This circuit configuration is used to upload program code (firmware) to the ESP32-CAM using an Arduino Uno as a USB-to-Serial intermediary. In this configuration, the Arduino Uno does not function as the main controller, but only as a communication bridge between the computer and the ESP32-CAM. To enable upload mode, GPIO 0 on the ESP32-CAM must be connected to GND (indicated by the short black wire on the module), which instructs the microcontroller to enter bootloader mode during startup.

Data communication is carried out through cross-serial connections represented by the orange and purple wires. The U0R (Receive) pin on the ESP32-CAM is connected to the RX (0) pin on the Arduino, while the U0T (Transmit) pin is connected to the TX (1) pin on the Arduino. In addition, the Reset (RST) pin on the Arduino Uno must be connected to GND to disable the onboard ATmega328P chip, allowing serial signals from the computer to be forwarded directly to the ESP32-CAM module without interference from the Arduino processor. The power aspect of this circuit is managed through the red wire for positive voltage and the black wire for the negative or ground line. The 5V pin on the Arduino Uno supplies voltage to the 5V/VCC pin on the ESP32-CAM to ensure that the module receives sufficient power during the data transfer process. Figure 5 illustrates the complete wiring configuration for uploading firmware to the ESP32-CAM module. The entire circuit must share a properly connected common ground to maintain stable serial communication signals, ensuring that the upload of tactical code for surveillance and Wi-Fi communication functions can be completed successfully.

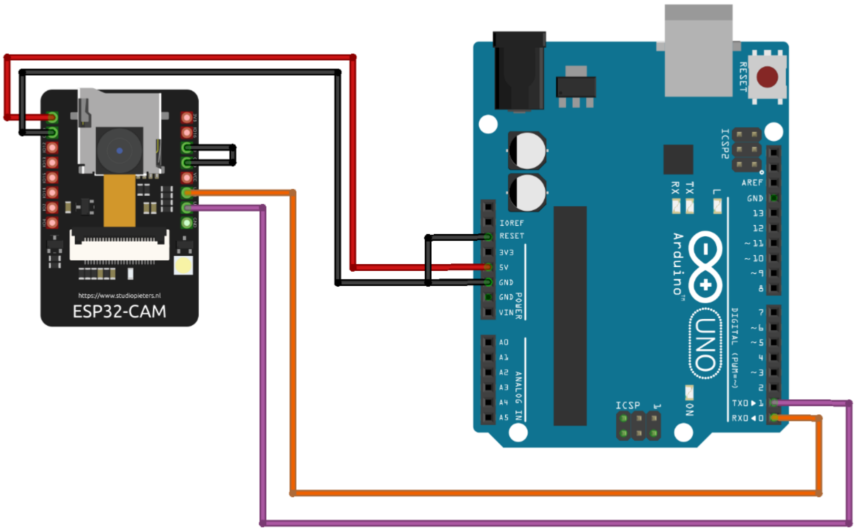

Figure 5. Wiring for Uploading Code to the Portable Surveillance Robot

Flowchart of the Portable Surveillance Robot

The surveillance robot system begins with hardware initialization when the power supply is activated, where the ESP32-CAM performs the booting process to prepare the camera module and enable wireless connectivity features. After the system becomes active, the robot attempts to establish a connection to a Wi-Fi network in order to communicate with the smartphone control interface. This initial stage is very crucial to ensure that the data communication pathway between the robot and the user is fully prepared before the robot receives further operational commands.

Once the connection is established, the system enters the main operational cycle involving visual data transmission and command reception. The ESP32-CAM module captures images through the camera sensor and transmits them as real-time video feedback to the user, enabling the monitoring of high-risk areas from a safe distance. At the same time, the user can send directional commands through the application, which are then processed by the controller to determine the robot's tactical movement in the field.

The final stage of this workflow is mechanical execution, where control signals from the ESP32-CAM are forwarded to the L298N motor driver to move the robot wheels. The motor driver regulates power distribution to four DC motors, allowing the robot to move forward, backward, or turn according to the received instructions. Figure 6 illustrates the operational workflow of the portable surveillance robot system. This process continuously repeats in a loop, maintaining stable visual data transmission and robot mobility until the user decides to terminate the surveillance session.

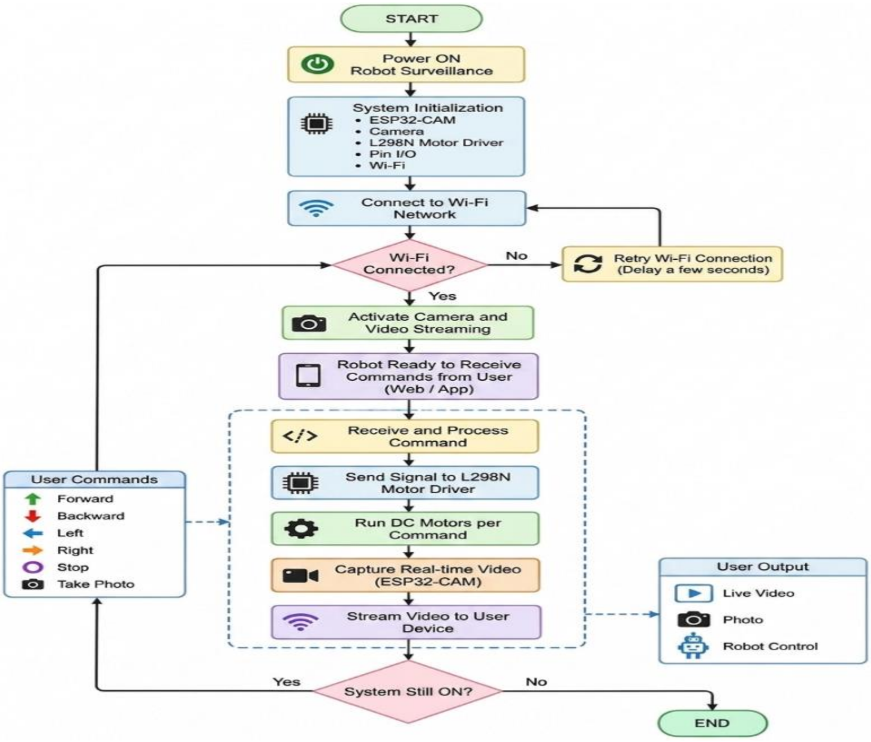

Figure 6. Flowchart of the Portable Surveillance Robot

Packet Loss

$$\text{Packet Loss} = \left(\frac{packets\ sent - packets\ received}{packets\ sent}\right) \times 100\%$$

Table 1. Packet Loss Category

Packet Loss Category	Packet Loss (%)	Index
Excellent	0-2%	4
Good	3-14%	3
Fair	15-24%	2
Poor	>25%	1

Delay

Average Delay = Total Delay : Total Received Packets

Table 2. Delay Category

Latency Category	Delay Value	Index
Excellent	< 150ms	4
Good	150ms – 300ms	3
Fair	300ms – 450ms	2
Poor	> 450ms	1

FINDINGS AND DISCUSSION

Quality of Service (QoS) Testing Page

Packet Loss The calculation for packet loss is as follows:

$$\text{Packet Loss} = \left(\frac{packets\ sent - packets\ received}{packets\ sent}\right) \times 100\%\ [cite: 159,160,168,169]$$

$$\text{Packet Loss} = \left(\frac{15.204 - 15.201}{15.204}\right) \times 100\% = 0.1\%\ [cite: 169,170,171]$$

A packet loss of 0.01% is classified as Excellent.

Delay The Average delay is calculated as follows:

$$\text{Average Delay} = \left(\frac{789.346.622}{213.646}\right) = 3.694\ ms\ [cite: 175,176]$$

An average delay of 3.694 ms is classified as Excellent.

Black Box Testing Results

Table 3. Black Box Testing Results

No.	Number of Tests	Expected Realization	Test Results	Success Percentage

1	10X	Move forward	Worked well	100%
2	10X	Move backward	Worked well, despite collisions	93%
3	10X	Move left	Worked well, but too fast when turning	87%
4	10X	Move right	Worked well, despite slight delay	98%

After obtaining the results from 10 testing trials, it can be concluded that the control system was sufficiently successful in performing movement activities on the robot.

Robot Camera Black Box Results

After obtaining the results from 10 testing trials, it can be concluded that the camera system on the robot was sufficiently successful in performing object monitoring and visual observation activities.

Table 4. Robot Camera Black Box Testing Results

No.	Number of Tests	Expected Realization	Test Results	Success Percentage
1	10X	Camera moves right	Worked well, despite slight buffering	79%
2	10X	Camera moves left	Worked well, despite buffering	85%
3	10X	Camera moves up	Worked well, despite packet loss and buffering	79%
4	10X	Camera moves down	Worked well, despite shuttering and slight vibration	84%
5	10X	Camera moves right	Worked well, despite slight buffering	96%

CONCLUSION

This research successfully designed and developed a portable surveillance robot prototype with wireless control based on the ESP32-CAM module as an innovative solution to support tactical intelligence needs in high-risk environments. Through the integration of major components such as the ESP32-CAM microcontroller as the main control center and video transmission medium, the L298N motor driver, and four DC motors, the robot is capable of performing real-time surveillance and demonstrates good mobility across various urban and open-field terrains. The use of an acrylic chassis provides a lightweight yet durable structure, maintaining agile navigation without excessive battery consumption. Based on the Quality of Service (QoS) testing results, the system demonstrated highly stable performance with a packet loss value of 0.1% and an average delay of 3.694 ms, both categorized as Excellent. In addition, Black Box testing confirmed that the robot's movement control system and camera functions operated successfully with a high average success rate, although minor issues such as video transmission buffering and the need for smoother mechanical response during turning maneuvers were still observed. Overall, this innovation provides a significant contribution to improving the effectiveness of security operations by enabling flexible intelligence data collection without endangering personnel safety. For future development, improvements in camera stabilization systems and the addition of automatic obstacle avoidance features are recommended.

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