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Design and Implementation of a Low-Cost Wi-Fi-Based Smart Surveillance Vehicle Using ESP32 Modules

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Abstract—*Conventional fixed surveillance systems are limited by restricted coverage, high deployment cost, and poor adaptability to dynamic environments. To address these challenges, this paper presents the design and implementation of a low-cost Wi-Fi-based smart surveillance vehicle capable of real-time remote monitoring. The system employs a dual-ESP32 architecture, where one ESP32-CAM module handles live video streaming while a second ESP32 microcontroller manages motor control and wireless command processing. The surveillance vehicle operates as a standalone Wi-Fi access point, enabling direct communication with a remote user interface without reliance on external network infrastructure. Motor drivers and a chassis platform are integrated to achieve controlled mobility, allowing the system to navigate and monitor environments that are inaccessible or unsafe for static cameras. Experimental evaluation demonstrates stable real-time video transmission, responsive vehicle navigation, and reliable wireless control within the designed operating range. The results confirm that separating video processing and motion control tasks improves system responsiveness and reliability. The developed system offers a cost-effective, portable, and scalable solution for real-time surveillance applications in security, agriculture, and industrial monitoring.*

Keywords— Smart Surveillance Vehicle, ESP32-CAM, Wireless Video Streaming, Pulse Width Modulation, Robotics car, Internet of Things.

1. INTRODUCTION (*Heading 1*)

The demand for reliable and adaptable surveillance systems has increased significantly due to rising security concerns in agricultural, industrial, and logistics environments. Conventional surveillance systems primarily rely on fixed cameras, which are limited by restricted coverage areas, blind spots, complex wiring infrastructure, and limited adaptability to dynamic environments. These constraints reduce their effectiveness in applications such as perimeter monitoring, warehouse inspection, and farmland surveillance, where mobility and flexibility are essential. Recent advancements in embedded systems and wireless communication technologies have enabled the development of mobile surveillance platforms capable of real-time remote monitoring with improved coverage and responsiveness.

Several studies have explored Internet of Things (IoT)-based surveillance systems to enhance monitoring efficiency and accessibility. Vivek and Kaur (2025) developed an IoT-enabled surveillance robot using an ESP32-CAM module for real-time video streaming and wireless navigation. Okokpujie et al. (2023) presented a cost-effective ESP32-based wireless surveillance system, demonstrating the feasibility of low-cost embedded monitoring solutions. Similarly, Koneru et al. (2020) integrated camera modules with mobile robotic platforms to reduce human exposure in hazardous environments. Despite these advancements, many existing systems employ single-controller architectures, where video streaming and motion control tasks compete for limited processing resources, potentially leading to reduced system responsiveness and operational instability.

This study aims to design and implement a low-cost Smart Surveillance Vehicle (SSV) capable of real-time video transmission and remote navigation using Wi-Fi communication (to achieve what). To enhance system reliability, a dual-ESP32 architecture is proposed, where an ESP32-CAM module handles video streaming while a separate ESP32 development board manages motor control and navigation. This task separation minimises processing overload and improves real-time responsiveness and system stability. The main contributions of this work include the development of a standalone Wi-Fi-enabled (to achieve what) mobile surveillance vehicle, the implementation of a distributed dual-microcontroller architecture for efficient task management.

2. THEORETICAL ANALYSIS

At the computational level, the architecture employs a distributed embedded system model. The ESP32-CAM module functions as the vision-processing unit responsible for real-time image acquisition and wireless video streaming. A secondary ESP32 development board (ESP32-D) manages motion control, signal coordination, and navigation. By separating vision and actuation tasks, the architecture minimises processor overload and latency, thereby improving real-time responsiveness. The Smart

Surveillance Vehicle system operates based on wireless local area network (WLAN) principles using Wi-Fi protocols. The ESP32-CAM establishes a wireless hotspot or connects to an existing network, enabling bidirectional communication between the vehicle and the user interface. Data transmission follows standard TCP/IP communication models, ensuring reliable packet exchange for control commands and video streaming. The motion subsystem operates under fundamental DC motor theory. The L298N motor driver regulates current and direction to the four N20 DC motors using pulse-width modulation (PWM). The SSV functions as a human-in-the-loop feedback system. User commands transmitted via Wi-Fi initiate vehicle motion through the actuation subsystem. Simultaneously, real-time video feedback is streamed back to the user, enabling continuous environmental monitoring. The user interprets visual data and provides corrective control inputs, forming a dynamic feedback loop.

3. MATERIALS AND METHODS

3.1 SYSTEM DESIGN AND ARCHITECTURE

The Smart Surveillance Vehicle (SSV) was designed as a mobile embedded system capable of real-time video transmission and remote navigation via Wi-Fi communication. The operational structure of the SSV is illustrated in Fig. 1. The ESP32-CAM captures live video and streams it wirelessly to the user interface via Wi-Fi. Simultaneously, the control ESP32 receives navigation commands and generates Pulse Width Modulation (PWM) and direction signals for the motor driver. Power distribution and signal routing are coordinated to ensure stable real-time operation.

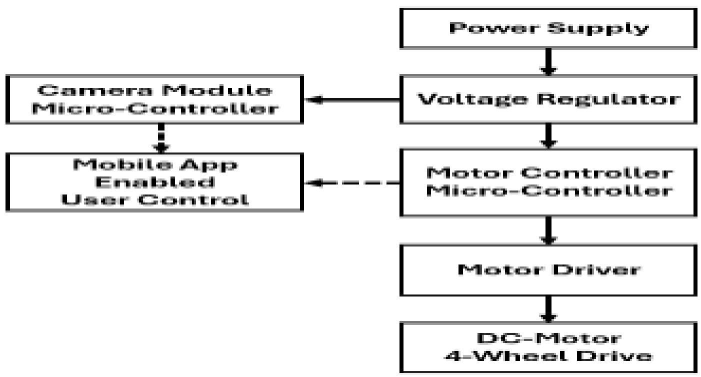

Fig. 1: Block Diagram

3.2 Mechanical Platform

The mechanical configuration of the SSV is shown in Fig. 2. The system employs a four-wheel-drive (4WD) chassis powered by four N20 DC motors. The chassis provides structural rigidity and ensures stable mobility across flat indoor and moderately uneven outdoor surfaces.

Fig. 2: 4-WD Car Chassis

3.3 Circuit Diagram

The complete electrical configuration of the Smart Surveillance Vehicle is presented in Fig. 3. The battery output is divided into two paths: Direct supply to the L298N motor driver and Regulated 5 V supply (via 7805) to both ESP32 modules. The ESP32-CAM operates as a Wi-Fi access point and streams live video. The ESP32-D receives motion commands and outputs PWM signals to the L298N driver. Fly-back diodes are connected across motor terminals to prevent voltage spikes, and filtering capacitors stabilize the power lines.

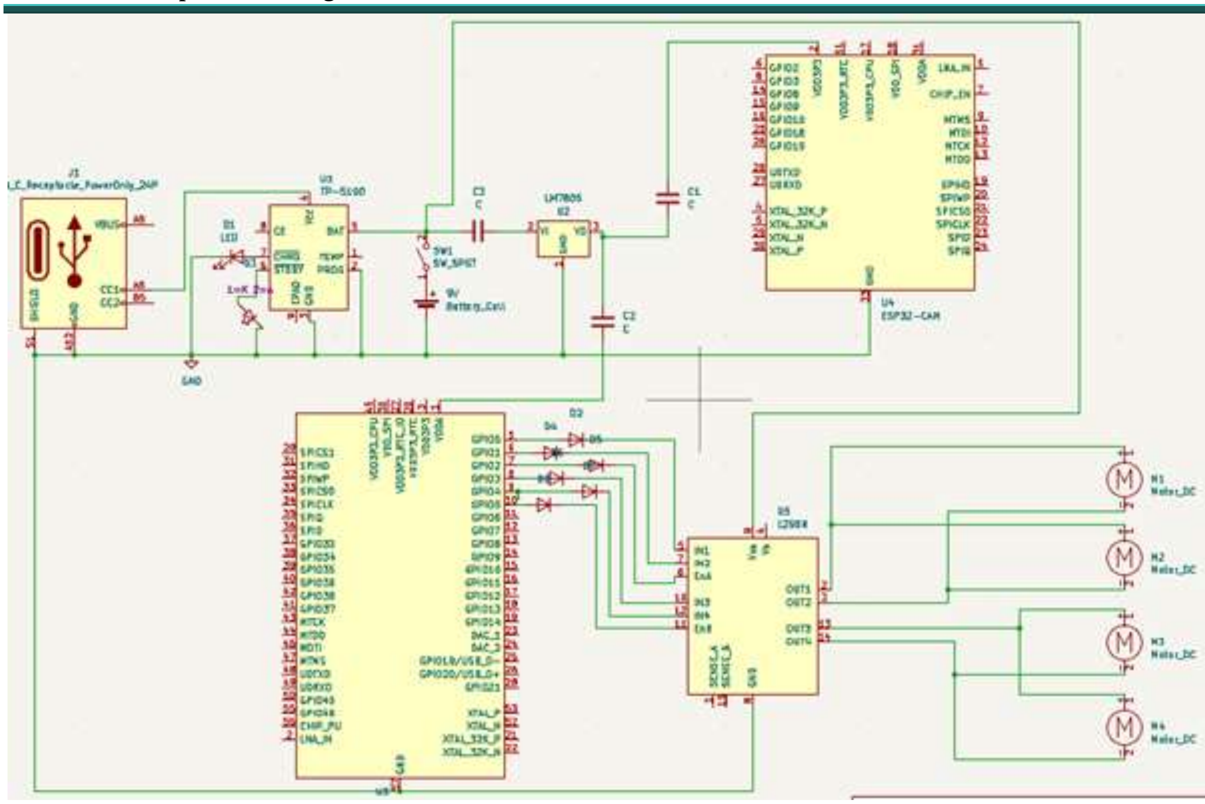

Fig. 3: Circuit Diagram

3.4 Flow Chart of System Operation

The operational logic of the Smart Surveillance Vehicle is illustrated in Fig. 4.

Fig. 4: Flow chart Diagram

3.5 Software Implementation

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The software was developed using embedded C/C++ within the Arduino Integrated Development Environment (IDE). Separate firmware programs were deployed for the ESP32-CAM and ESP32-D modules.

The ESP32-CAM firmware handles:

i. Camera initialization
ii. Wi-Fi configuration
iii. MJPEG video streaming
iv. Reception of navigation commands

The ESP32-D firmware handles:

i. Command decoding
ii. PWM signal generation
iii. Motor direction control

This modular programming approach improves system reliability and simplifies debugging and upgrades.

4. RESULTS AND DISCUSSION

This section presents and discusses the results obtained from implementation of the Smart Surveillance Vehicle (SSV). The performance of the system was evaluated in terms of real-time video transmission, and wireless control responsiveness.

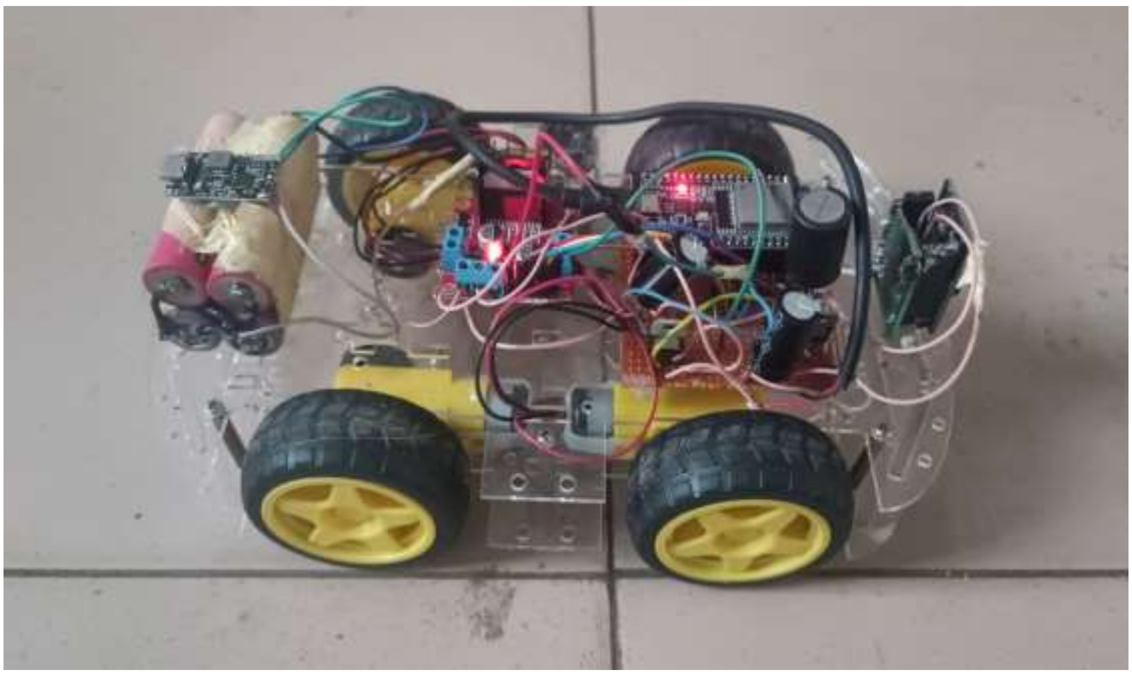

Fig. 5: Fully assembled Smart Surveillance Vehicle showing camera placement and chassis configuration.

Fig. 6: Smart Surveillance Vehicle during field testing in an open environment.

4.1 Discussion of Results

The experimental findings demonstrate that the developed Smart Surveillance Vehicle meets the design objectives outlined in this study. The use of a dual-ESP32 architecture significantly improved system performance by preventing task interference between video streaming and motor control processes. This architectural decision enhanced responsiveness and ensured reliable real-time operation.

The motor control performance aligns with the theoretical analysis presented in Section 2, where PWM duty cycle variation was shown to directly influence effective motor voltage and speed. The observed smooth navigation behavior validates the DC motor control equations previously discussed.

The inclusion of flyback diodes and decoupling capacitors proved highly effective in suppressing voltage spikes and electromagnetic interference. Prior to their inclusion, occasional resets were observed during motor activation. After implementing the protection circuitry, system stability improved considerably.

Although the system performed effectively within the tested range, performance was influenced by Wi-Fi signal strength and environmental obstructions. Additionally, the linear 7805 regulator resulted in some energy loss through heat dissipation. Future improvements may include the use of a switching buck converter and a MOSFET-based motor driver to enhance power efficiency.

Overall, the results confirm that the proposed system provides a cost-effective and reliable solution for real-time mobile surveillance, particularly in environments where fixed camera installations are impractical.

5. CONCLUSION

This study presented the design and implementation of a low-cost Wi-Fi-based Smart Surveillance Vehicle capable of real-time video monitoring and remote navigation. A dual-ESP32 architecture was adopted to separate video streaming and motion control tasks, thereby improving system responsiveness and operational stability. Experimental evaluation showed that the ESP32-CAM provided stable real-time video transmission with minimal latency, while the control ESP32 ensured smooth and reliable vehicle navigation through pulse width modulation–based motor control. The main contribution of this work was the development of a standalone mobile surveillance system that operates independently of external internet infrastructure, making it suitable for deployment in remote or resource-constrained environments. The results demonstrated that distributing tasks between two microcontrollers enhanced performance and reduced processing interference compared to single-controller implementations. The developed system is applicable to security monitoring, agricultural field inspection, warehouse surveillance, and other scenarios where mobility and flexibility are essential.

Future improvements may include enhancing communication range, replacing linear power regulation with more efficient switching converters, and integrating autonomous navigation features. The incorporation of intelligent capabilities such as obstacle detection, motion tracking, and object recognition could further improve the effectiveness and scalability of the surveillance platform.

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