

IoT-Based ESP32-CAM Surveillance Robot for Wireless Real-Time Video Monitoring and Control

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Abstract

This research discusses the designing and implementation of an IoT-based ESP32-CAM surveillance robot which offers real-time video monitoring and remote robot navigation capabilities wirelessly. The design utilizes ESP32-CAM module, L298N motor driver, DC motors, and WiFi connectivity which enables the robot to stream live videos and be remotely navigated via a browser using a mobile device. The ESP32-CAM module serves as both processor and image capture component which ensures live video streaming and WiFi connectivity. Robot movement control is achieved using PWM motor control which allows the robot to move forwards, backwards, left, and right smoothly. In addition, IR LEDs are installed to improve performance during low-light surveillance. WebSocket communication protocol is also used to reduce delay times during communications. The experimental findings show that there is stable video transmission, reliable wireless connectivity, effective navigation control, and monitoring capacity in low light conditions. The system that has been designed serves as an economical, compact and efficient surveillance system.

Keywords: ESP32-CAM Module, Surveillance Robot, Internet of Things (IoT), Wireless Communication Control, Real-Time Video Streaming, Embedded Systems Design.

1. Introduction

The rising need for intelligence in monitoring systems has driven the development of wireless surveillance systems which are used for applications involving security, industrial inspections, and distant observations. Conventional surveillance systems normally struggle with problems like poor coverage, lack of mobility, and more complex infrastructures, which limit their performance in variable environments.

New developments in embedded systems and Internet of Things (IoT) technology have made it possible to design surveillance devices that are portable, affordable, and energy-efficient, and able to communicate in real time. Wireless surveillance robots that are fitted with cameras and wireless connections offer more flexibility and convenience as they can monitor remote environments without difficulty. Applications of these types of surveillance devices include industrial safety, disaster control, military surveillance, and hazardous environment inspections. Also, the use of embedded control of motors and wireless communications increases the efficiency of controlling robots remotely.

The objective of this project is to design an IoT-enabled ESP32-CAM surveillance robot that can stream video live and navigate remotely using a web page interface.

2. Literature Review

There has been increased focus on developing surveillance robots owing to the high demand for intelligent security systems, automation in industries, and remote monitoring. The emergence of Internet of Things technology and embedded system has made it possible for developers to come up with compact and affordable wireless surveillance robots that can perform navigation and real-time monitoring [1], [2]. ESP32-CAM-based robots are highly favored due to the presence of Wi-Fi connectivity, an in-built camera, and low power consumption. They offer live video transmission and navigation from a remote location making them useful in dangerous and inaccessible locations where human operation may be difficult [3], [4].

Most surveillance robots rely on motor driver chips like L298N and L293D to enable navigation by moving forward, backwards, left, and right. Communication between the user and the robot is usually done using HTTP or WebSockets protocol [5], [6]. Moreover, infrared LED and sensors are employed to improve the functioning of the robot in dark environments.

Emerging trends in the field of surveillance robotics include the incorporation of machine learning and computer vision algorithms like object detection, facial recognition, and motion tracking to improve autonomy [7], [8]. Wireless surveillance robots are now used in industries for inspection purposes, warfare surveillance operations, and smart security environments [9], [10].

However, current surveillance robots have some constraints such as low range of communications, dependence on Wi-Fi connectivity, lag in networking, and lack of sufficient energy storage units [6], [7]. Research will be carried out on how to optimize surveillance robots using edge computing, long-range communication systems, LoRa, and RF modules for power consumption optimization and multiple robot coordination [6], [7].

Generally, the literature review shows that ESP32-CAM-based surveillance robots are an efficient and cost-effective system for wireless surveillance robots.

3. Proposed System

The proposed system entails the design and implementation of an IoT based ESP32-CAM surveillance robot that is capable of performing real-time wireless video monitoring and remote navigation via a web-based control interface. It consists of embedded components and systems, as well as intelligent monitoring capabilities, providing a compact, cost-efficient, and advanced monitoring platform that can be used in various areas such as security monitoring, military reconnaissance, industrial inspections, or exploratory operations in hazardous environments.

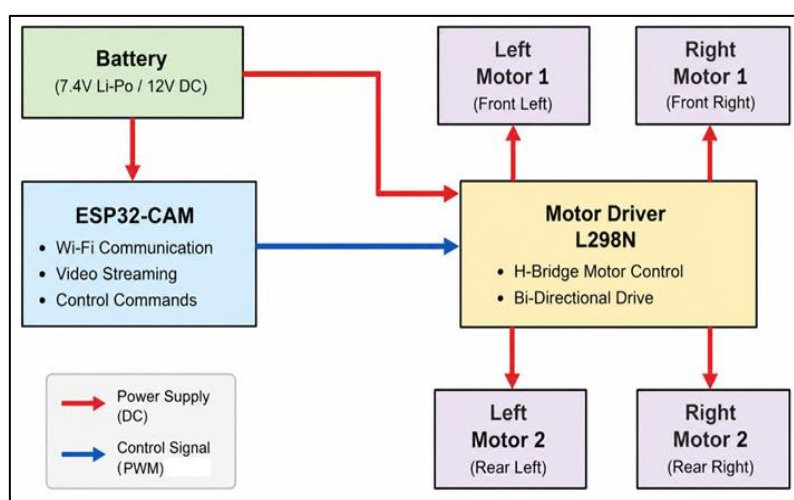


Figure 1. Simplified Block Diagram of the Proposed Surveillance System

As seen from the illustration in Figure 1, the ESP32-CAM acts as the core component of the system responsible for image processing and capturing. It is comprised of an ESP32 processor and an onboard camera that has Wi-Fi connectivity. The ESP32-CAM forms a wireless connection with a nearby Wi-Fi hotspot and assigns an IP address to facilitate remote access to the security bot from a phone, tablet, or computer browser. This process means there is no need for extra modules for connectivity and special software packages for controlling the system.

The movement of the robot surveillance is done with the use of L298N motor driver that works with DC motors. User commands that are sent from the web-based interface are used by the ESP32-CAM to send control commands to the motor driver. The motor driver works on the H-bridge principle (refer figure 2) that makes it possible for the robot to have bidirectional motion, that means the robot can move in forward, backward, left and right motions. The speed of the robot is determined by the PWM signals issued from the ESP32-CAM that makes navigation easy, directional and controlled. A re-chargeable battery powers the whole system during surveillance tasks.

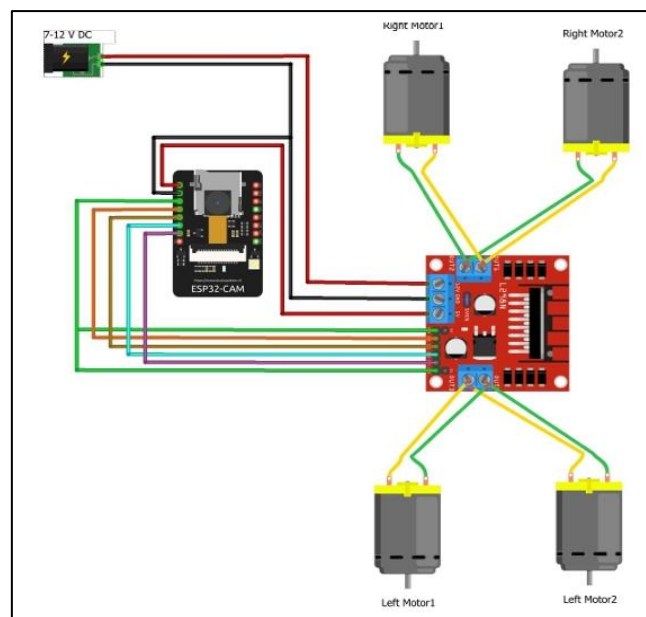


Figure 2. Circuit Diagram of the ESP32-CAM Surveillance Robot

In order to optimize the efficiency of surveillance at night-time, IR LEDs are installed on the robot's frame. IR LEDs help improve visibility in images captured by the camera and provide basic night-vision capability without making any substantial changes to the system complexity or energy requirements. Furthermore, WebSocket communication is established

between the website and ESP32-CAM to reduce latency and increase the speed of commands compared to traditional HTTP protocols.

The overall workflow of the suggested surveillance system is shown in Figure 3. First, initialization of the system takes place, whereby the ESP32-CAM module, Wi-Fi communication channel, and motor controller are activated by applying power to the robotic platform. After that, the ESP32-CAM establishes connection with the Wi-Fi network and starts streaming video in real time through a browser-based web application interface. At this stage, the system remains idle and awaits user's commands. Upon receiving navigation commands, for example forward, backward, left, right, or stop, the ESP32-CAM executes the commands and controls the L298N motor driver, thus regulating robot movements. Meanwhile, continuous updates of video streaming continue for ensuring real-time observation of the environment around the robot.

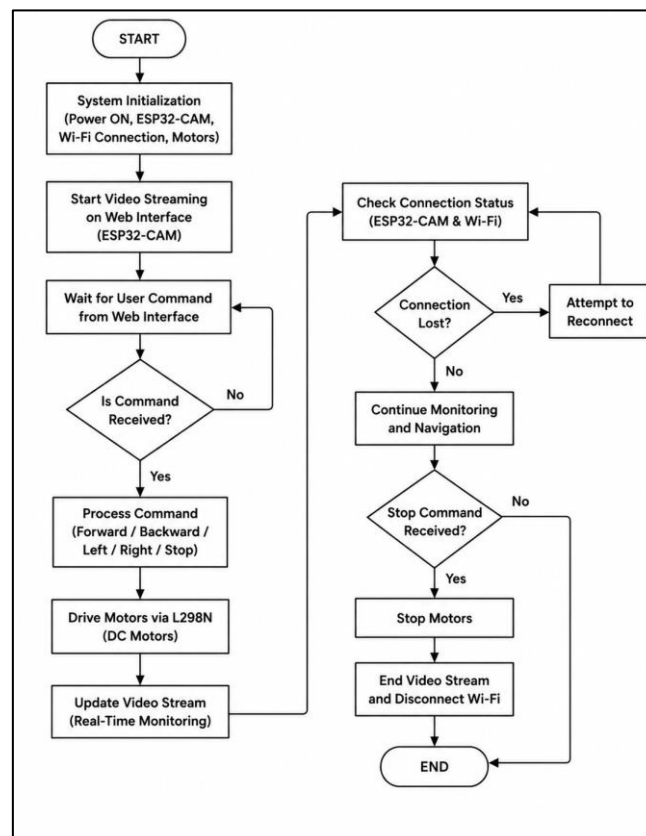


Figure 3. Flowchart of the Surveillance Robot Operation

Throughout the process, the system constantly monitors the status of the Wi-Fi connection in order to maintain communication with the user. If the connection is broken for some reason, it will attempt to reconnect automatically. Surveillance activities will be carried

on until a stop command is sent to the robot at which point the system disconnects and stops video streaming.

Table 1 below shows the hardware and software elements used in designing the proposed surveillance robot based on ESP32-CAM as well as their specifications and functions. It clearly indicates that the design involves the use of embedded control, wireless technology, motor control, and real-time video transmission technologies for remote surveillance operations.

Table 1. Hardware and Software Specifications of the Proposed System

Component	Specification	Function
ESP32-CAM Module	ESP32 microcontroller with OV2640 camera and IR LEDs	Captures live video, processes commands, and provides Wi-Fi communication
L298N Motor Driver	Dual H-Bridge Motor Driver	Controls motor direction and PWM-based speed regulation
DC Motors	12V Geared DC Motors	Enable robot movement in forward, backward, left, and right directions
Rechargeable Battery	Portable DC power supply	Provides power to the surveillance robot system
Wi-Fi Communication	IEEE 802.11 Wireless Network	Enables wireless monitoring and remote navigation
Web-Based Interface	HTML, CSS, JavaScript	Provides browser-based robot control and live monitoring
WebSocket Protocol	Real-time communication protocol	Reduces communication delay and improves response time
Arduino IDE	Embedded system programming platform	Used for ESP32-CAM programming and firmware upload
PWM Control	Pulse Width Modulation Technique	Ensures smooth motor speed and directional control
Video Streaming	Real-time IP-based streaming	Supports continuous live surveillance monitoring

4. Results and Discussion

The proposed ESP32-CAM surveillance robot was tested for its capabilities in wireless video surveillance, remote manoeuvring, effective communication, and low-light surveillance applications. The robot demonstrated good connectivity by establishing a strong Wi-Fi network and transmitting video via the web browser interface with minimum latency. The robot could be remotely controlled in real time using the L298N motor controller and DC motors to move forward, backward, left, and right. The robot's motion stability was enhanced using a PWM technique that limited drastic changes in direction during navigation. Figure 4 presents the developed prototype of the developed surveillance robot.

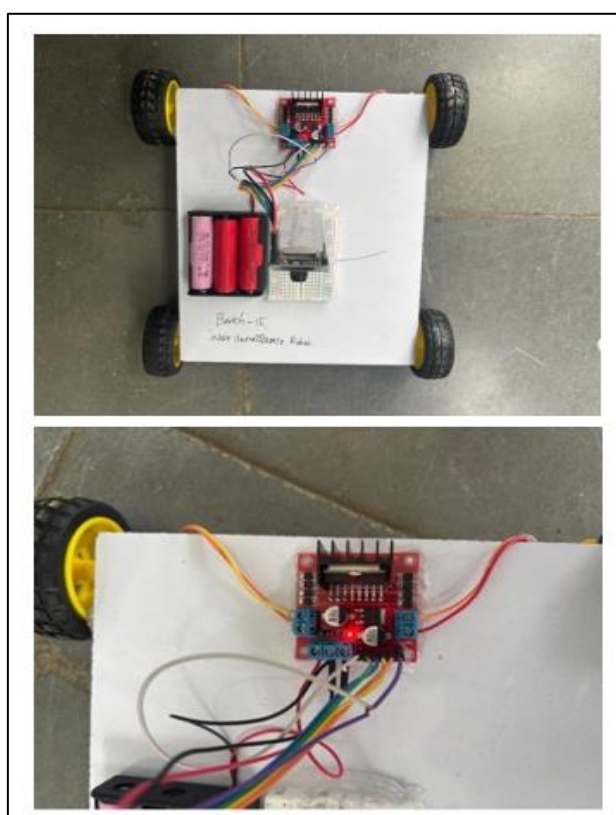


Figure 4. Prototype Model of Surveillance Robot

The adopted WebSocket communication protocol increased the efficiency of the system by minimizing command lag when running the system in real-time mode. The robot acted promptly on navigation instructions that were sent from the web application, thus indicating smooth coordination of wireless communication and movement of motors. The ESP32-CAM worked efficiently to provide high-quality video streams in an indoor environment, whereas the built-in IR LEDs facilitated video streaming in low-light settings, allowing night vision to

some extent. Figure 5 presents the developed web application used to control the robot and monitor videos in real-time.

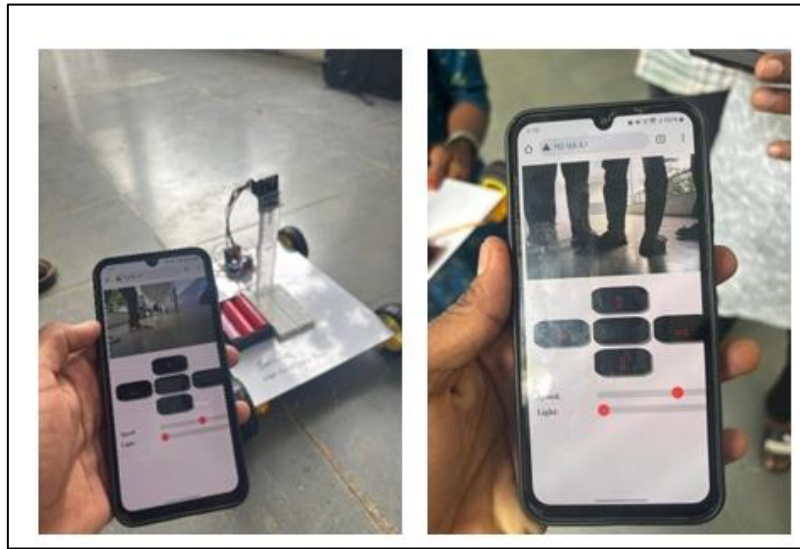


Figure 5. User Interface to Control the Surveillance Robot

Table 2. Performance Analysis of the Proposed Surveillance Robot

Parameter	Observed Performance	Remarks
Video Streaming	Stable real-time transmission	Low latency within Wi-Fi range
Robot Navigation	Smooth directional control	Accurate forward/backward/turning movement
Communication Method	WebSocket-based control	Faster response compared to HTTP
Night Vision Capability	Functional under low-light conditions	Enabled using IR LEDs
Wi-Fi Communication Range	Moderate indoor coverage	Performance decreases with distance
Power Consumption	Moderate	Motors consume higher power than ESP32-CAM
User Interface Response	Fast and reliable	Minimal delay during command execution

The performance of the proposed ESP32-CAM-based surveillance robot has been evaluated based on Table 2 which shows the experimental outcomes of its operation under real-

time conditions. The results show that the surveillance robot functioned effectively in the zone of effective Wi-Fi coverage. Frame drop and delay occurred when the robot was far from the wireless access point due to reduced signal strength. From the power analysis carried out, it was found that more power was utilized by the motors during movement than the ESP32-CAM processor. Despite this, the overall functioning of the robot remained stable with reasonable power consumption and low complexity of components.

5. Conclusion

This research has successfully integrated embedded technology, wireless communication and real-time monitoring techniques to create a surveillance robot with ESP32-CAM module. This implemented system was able to provide live video streaming, stable wireless communication and proper robot navigation using a web interface. The usage of PWM method in controlling motors ensured proper movement whereas the use of WebSocket ensured proper communication and increased response time of commands sent. It has been proved that this implemented system runs very effectively under the condition of indoor Wi-Fi connection with moderate energy efficiency. This designed surveillance robot provides an inexpensive, lightweight and compact approach for different applications including industrial inspections, security monitoring, military surveillance, and environmental observation.

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