ESP32-Powered Web-Controlled Surveillance Robot with Camera

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Abstract. This project focuses on the development of a low-cost, web-controlled surveillance robot using the ESP32microcontroller, which offers Wi-Fi capabilities for real-time remote access. The robot is equipped with a camera module that streams live video to a web interface, allowing users to monitor and control the robot's movements from a browser. The system integrates motor drivers for mobility, a pan-tilt mechanism for dynamic camera positioning, and various sensors for obstacle detection and environmental monitoring.

Through the ESP32's web server functionality, users can issue commands to control the robot's direction, speed,and camera angle, enabling flexible surveillance in real-time. The design prioritizes low power consumption, wireless operation, and ease of use, making it suitable for applications in home security, remote monitoring of inaccessible areas, and educational purposes. Key challenges include ensuring a stable video feed over Wi-Fi,low-latency control responses, and efficient battery management.

This project demonstrates the potential of the ESP32 as a platform for robotics and IoT, emphasizing the simplicity of integrating web-based control with real-time data streams in cost-effective surveillance solutions

Keywords—ESP32-CAM,USB to TTL, Car chassis, Motor driver, servomotors, jumper wires and Power bank.

I. INTRODUCTION

With the rapid advancements in the Internet of Things (IoT) and embedded systems, real-time remote surveillance has become increasingly accessible and cost-effective. Traditional surveillance systems often rely on stationary cameras with limited coverage, requiring significant infrastructure and investment. To address these limitations, this paper presents the design and implementation of a low-cost, web-controlled surveillance robot utilizing the ESP32 microcontroller with integrated Wi-Fi capabilities.

The proposed system leverages the ESP32-CAM module to provide live video streaming over a web interface, allowing remote users to monitor and control the robot from any device with an internet connection. Unlike conventional CCTV systems, this mobile platform enhances surveillance flexibility by incorporating a motorized chassis for movement and a servo-driven pan-tilt mechanism for dynamic camera positioning. Additionally, the system integrates obstacle detection sensors to improve navigation and autonomous operation.

Through the embedded web server functionality of the ESP32, users can issue real-time commands to control the robot's speed, direction, and camera orientation, ensuring

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efficient remote monitoring. The primary challenges addressed in this work include maintaining a stable video feed over Wi-Fi, minimizing control latency, and optimizing power consumption for extended operation.

This paper demonstrates the ESP32's potential as a powerful platform for robotics and IoT applications, showcasing a compact, cost-effective solution for home security, industrial monitoring, and remote exploration. The proposed system provides an accessible and scalable approach to real-time, wireless surveillance, offering significant advancements in modern security and monitoring technologies.

II. EASE OF USE

One of the key advantages of the proposed ESP32-powered web-controlled surveillance robot is its user-friendly design, making it accessible to a wide range of users, including home security personnel, industrial operators, and hobbyists. The system is designed with simplicity in mind, ensuring seamless setup, intuitive controls, and minimal maintenance.

- Web-Based Interface for Remote Access

The ESP32's built-in web server eliminates the need for additional applications or complex software installations. Users can control the robot and monitor the live video stream directly from a standard web browser on a smartphone, tablet, or computer. The web interface provides an intuitive control panel for real-time navigation, speed adjustment, and camera positioning via pan-tilt controls.

- Wireless and Flexible Operation

Unlike wired surveillance systems, this mobile platform operates entirely over Wi-Fi, providing greater flexibility in deployment. Users can remotely control the robot from anywhere within the network's range without requiring direct physical access. Additionally, the use of wireless communication protocols eliminates cable clutter and simplifies the installation process.

- Minimal Hardware Complexity and Easy Assembly

The system integrates off-the-shelf components, including the ESP32-CAM module, motor driver, servo motors for pan-tilt control, and ultrasonic sensors. These components are widely available and can be assembled with minimal technical expertise. The plug-and-play nature of the hardware ensures that users can set up and configure the system without specialized knowledge of embedded electronics.

- Low Maintenance and Power-Efficient Design

The system is designed for low power consumption, making it suitable for battery-operated applications. Power management techniques, such as deep sleep mode in the ESP32, extend battery life, reducing the need for frequent recharging. Additionally, the reliable wireless communication and self-contained web server minimize the risk of system failures, ensuring long-term usability with minimal maintenance requirements.

- Versatile Applications and Scalability

Due to its modular design, the system can be easily customized and expanded. Users can integrate additional sensors, upgrade the camera, or enhance the robot's mobility by incorporating GPS modules, AI-based motion tracking, or solar-powered charging systems. This scalability makes the system adaptable to various use cases, from home security and industrial surveillance to remote exploration and educational projects.

III. DESIGN & IMPLEMENTATION

- Hardware Overview The hardware implementation of the proposed ESP32-powered surveillance robot consists of several key components, each contributing to the overall functionality of the system. The main hardware components include:

1. **ESP32-CAM Module**: The primary controller for the system, responsible for image capture, Wi-Fi communication, and web server functionality.

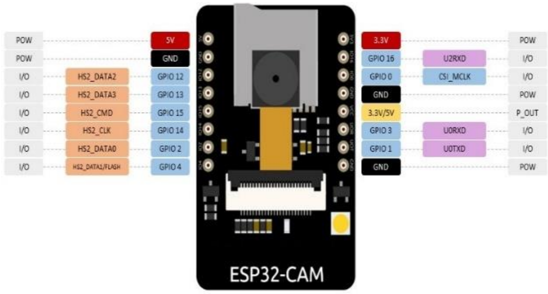

Fig. 1. Block Diagram

2. **Motor Driver (L298N)**: Used to control the motion of the robot's chassis, enabling forward, backward, left, and right movements.

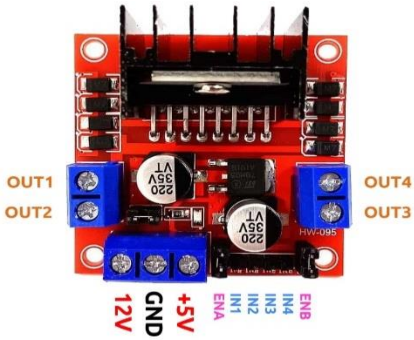

Fig. 2. Motor Driver

3. **Servomotors (SG90)**: Responsible for the pan-tilt mechanism of the camera, allowing dynamic positioning and improved field of view.

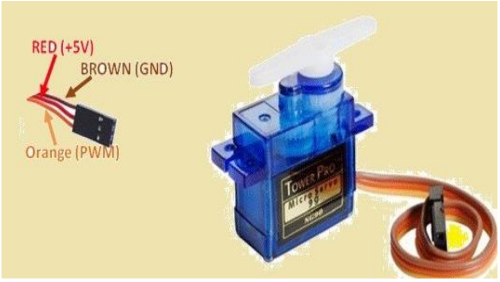

Fig. 3. Servomotors

4. **USB to TTL Converter**: Used for flashing the ESP32-CAM module with firmware.

Fig. 4.USB to TTL Converter

5. **Power Bank (5V/2A)**: Provides power to the ESP32 and motor driver for wireless operation.

Fig. 5.Power Bank

6. **Car Chassis**: The base structure that houses all electronic components and provides mobility to the robot.

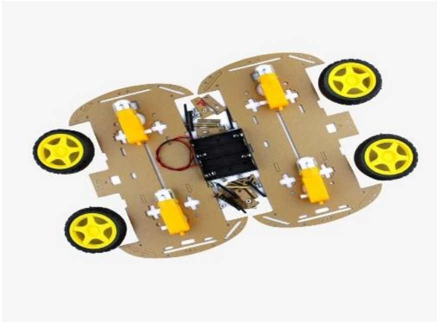

Fig. 6.Car Chassis

B. Software Implementation The software implementation involves firmware development for the ESP32-CAM module, integrating web-based control, video streaming, and real-time sensor data acquisition. The following steps outline the software design:

1. **ESP32 Firmware Development**:
   - The firmware is written in C++ using the Arduino IDE.
   - The ESP32 is programmed to establish a Wi-Fi hotspot or connect to an existing network.
   - The onboard web server is implemented using the ESPAsyncWebServer library to provide a real-time interface for user control.
   - The camera module captures and streams video using the ESP32-CAM library.
   - PWM signals control motor speed and servo positioning.

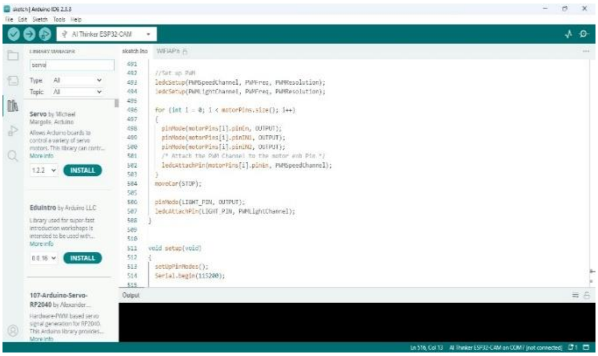

Fig. 7.Development IDE.

2. **Web Interface Development**:
   - A simple HTML and JavaScript-based interface is created to allow users to issue movement commands.

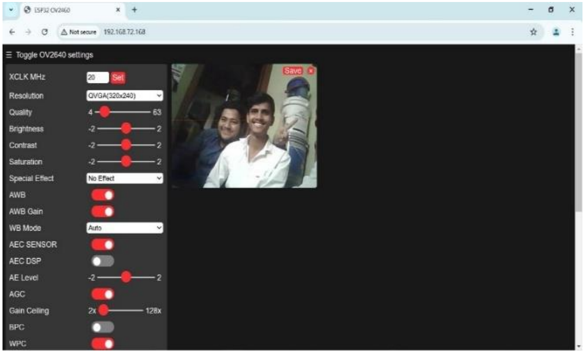

Fig. 8.Web Interface Development IDE.

- The interface updates video streams dynamically without lag.
- Control buttons enable movement and camera adjustments

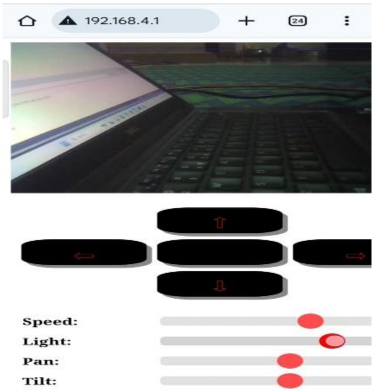

Fig. 9.Web Interface Control.

IV. RESULTS& DISCUSSION

A. System Performance The developed ESP32-powered surveillance robot was tested under various conditions to evaluate its performance. The key observations include:

1. **Video Streaming Quality**:
   - The ESP32-CAM module successfully streams live video at 320x240 resolution with minimal latency.
   - Performance slightly degrades with increased Wi-Fi distance.

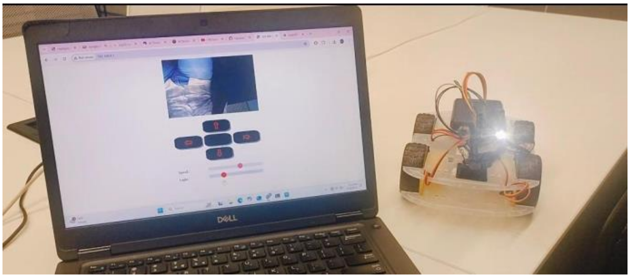

Fig. 10.Video Streaming Quality.

2. **Robot Navigation**:
   - The robot moves smoothly with precise directional control.
   - The motor driver and servos function effectively, allowing seamless movement transitions.

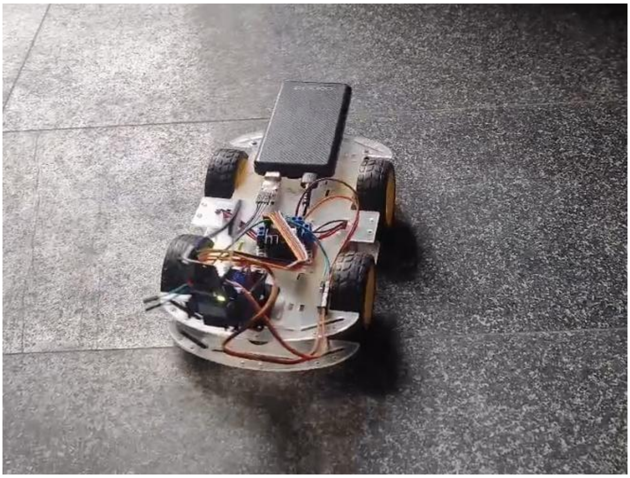

Fig. 11.Robot Navigation.

3. **Power Consumption**:
   - The system operates efficiently on a standard 5V power bank.
   - Battery life extends up to 2 hours under continuous operation.

B. Limitations Despite its effectiveness, the system has a few limitations:

- Wi-Fi range is limited, affecting remote operation capabilities.
- Video streaming resolution is restricted due to ESP32-CAM hardware limitations.

V. CHALLENGES& SOLUTIONS

A. Wi-Fi Connectivity Issues

- Problem: Limited range affecting remote access.
- Solution: Implementing an external Wi-Fi module or integrating 4G connectivity for extended control range.

B. Latency in Video Streaming

- Problem: Occasional lag in video transmission.
- Solution: Optimization of video encoding parameters and reducing frame rate for smoother transmission.

C. Power Efficiency

- Problem: Limited battery life.
- Solution: Implementing a solar charging mechanism or using higher capacity Li-ion batteries.

VI. FUTURE SCOPE

A. Integration with AI for Smart Surveillance

- Implement AI-based object detection for automated threat identification.
- Use facial recognition to enhance security features.

B. GPS-Based Tracking

- Incorporating a GPS module to track the robot's location remotely.
- Useful for security and rescue operations.

C. Autonomous Path Planning

- Enhancing the robot's navigation system with SLAM (Simultaneous Localization and Mapping) for autonomous movement.

D. Mobile App Development

- Creating a dedicated mobile application for enhanced control and monitoring.

VII. CONCLUSION

The ESP32-powered web-controlled surveillance robot successfully demonstrates the feasibility of using low-cost hardware for real-time remote monitoring. By leveraging the ESP32's Wi-Fi capabilities, motorized mobility, and camera streaming, the system provides an effective solution for home security, industrial monitoring, and educational projects. The project highlights the ESP32's potential in IoT applications and paves the way for further enhancements, including AI integration and GPS tracking.

The experimental results validate the effectiveness of the proposed system, showcasing its ability to stream live video, respond to user commands in real-time, and navigate autonomously. Future work will focus on expanding connectivity options, improving video quality, and integrating AI-driven features for smarter surveillance.

This research contributes to the field of embedded systems and robotics, providing a scalable, cost-effective, and practical solution for modern security challenges.

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