Design of 6-Legged Robot with Adaptive Gait and Obstacle Sensing for Rugged Terrain Mobility

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ABSTRACT

This work presents the development of a Wi-Fi enabled intelligent surveillance robot built on the Espressif Systems Processor ESP32-CAM Microcontroller Unit (MCU), designed to provide real-time monitoring and remote mobility through a web-based control system. The robot integrates a compact 32-bit embedded controller with an onboard camera module capable of capturing and transmitting images in Joint Photographic Experts Group (JPEG) format at Video Graphics Array (VGA) resolution. Efficient handling of image data is achieved using internal memory along with Pseudo-Static Random Access Memory (PSRAM), enabling smooth frame buffering and continuous transmission via WebSocket protocol for low-latency feedback. The locomotion system is driven by dual Direct Current (DC) motors interfaced through General Purpose Input Output (GPIO) pins, where Pulse Width Modulation (PWM) is employed to regulate motor speed and ensure controlled navigation. Directional commands including forward, reverse, left, right, and halt are executed through digital signal control of motor drivers. The software framework follows an asynchronous event-driven architecture implemented using ESPAsyncWebServer and AsyncWebSocket libraries, allowing concurrent processing of video streaming and user commands without execution delays. The system operates using a Wireless Fidelity (Wi-Fi) Access Point (AP), enabling direct device-to-robot communication without reliance on external internet connectivity. Continuous video acquisition and command execution are maintained in real time, ensuring responsive operation. A built-in safety mechanism automatically stops the robot upon connection loss, preventing unintended movement. This system demonstrates a compact, reliable, and cost-effective solution for embedded surveillance and remote robotic control applications.

Key words: a Wi-Fi Enabled Surveillance Robot, ESP32-CAM MCU, Real-Time Monitoring, Remote Navigation, Terrain Navigation, JPEG Image Transmission.

1. INTRODUCTION

The domain of intelligent surveillance has expanded rapidly with the convergence of Internet of Things (IoT) technologies and embedded system design, enabling the creation of autonomous, connected, and highly responsive monitoring solutions. In modern scenarios, there is a strong demand for systems that can continuously observe environments, process information in real time, and assist in decision-making without requiring direct human presence. Such systems are increasingly deployed across industrial automation, smart cities, transportation hubs, defense applications, and residential security, where continuous monitoring, anomaly detection, and rapid response are essential. The shift from traditional monitoring to intelligent surveillance is driven by the need for scalability, flexibility, and real-time situational awareness.

A surveillance robot represents a significant advancement over conventional fixed monitoring systems such as Closed-Circuit Television (CCTV). It is a mobile robotic platform integrated with vision sensors, embedded processors, and communication modules, enabling it to actively explore and monitor environments. Unlike static cameras with limited field of view, these robots can navigate through complex and dynamic spaces, access hard-to-reach areas, and adjust their position based on monitoring requirements. They are capable of capturing real-time video, performing basic onboard processing, and transmitting data to remote users. This mobility not only improves coverage but also enhances the ability to respond to specific events or threats dynamically. In addition, the integration of motor control systems and navigation logic allows these robots to operate autonomously or semi-autonomously depending on the application.

Wireless communication is a critical enabler for such systems, as it allows seamless interaction between the robotic platform and the operator. Technologies based on Wireless Fidelity (Wi-Fi) provide reliable connectivity over short to medium distances, eliminating the need for wired infrastructure and enabling flexible deployment. Through browser-based interfaces or dedicated applications, users can remotely control the robot’s movement and access live video feeds. Advanced communication protocols such as WebSocket enable continuous, bidirectional data exchange between the robot and the client, ensuring minimal latency and synchronized control. This is particularly important for real-time applications where delays can impact system performance and user responsiveness.

Furthermore, modern surveillance robots often adopt event-driven software architectures that allow simultaneous handling of multiple processes such as video streaming, command execution, and sensor data acquisition. This ensures that the system remains responsive even under continuous operation. Safety mechanisms are also integrated to handle communication failures or unexpected conditions, preventing unintended behavior. Overall, the combination of embedded processing, mobility, and real-time wireless communication creates a robust and scalable surveillance framework, capable of meeting the growing demands of intelligent monitoring systems in diverse real-world environments.

2. LITERATURE SURVEY

Wang, et al. [1] developed a deformable wheel–legged robot incorporating origami-inspired structural mechanisms to achieve dynamic reconfiguration. Their design enabled the transformation of wheel geometry to switch between rolling and stepping locomotion modes, allowing the robot to adapt effectively to varying terrain conditions. The study focused on kinematic modeling, structural flexibility, and motion efficiency, demonstrating how foldable mechanisms can reduce mechanical complexity while enhancing adaptability. They also analyzed load distribution and deformation behavior during locomotion, showing that the reconfigurable design improves obstacle negotiation and stability. Their work highlighted that integrating compliant structures with mechanical intelligence significantly enhances the robot’s capability to operate in unstructured environments. Chen, et al. [2] proposed an advanced whole-body motion planning framework for hexapod robots navigating rugged terrain, addressing the challenge of maintaining stability during locomotion. Their method decomposed motion planning into support and swing phases, where the torso pose was optimized by maximizing the stability margin at the support–swing transition. They incorporated terrain geometry constraints and aligned the torso orientation with the support polygon formed by footholds. Smooth trajectories were generated using cubic spline interpolation, and inverse kinematics was applied to convert task-space trajectories into joint-space commands. Their approach ensured coordinated leg movement, improved stability, and reduced energy consumption, making it highly effective for uneven terrain navigation. Comin and Saaj, et al. [3] investigated slip estimation and terrain characterization for multi-legged wheel–legged robots operating on soft and deformable terrains. Their study developed mathematical models to estimate slip based on wheel–terrain interaction and sensor feedback. By analyzing parameters such as contact force, friction coefficients, and terrain deformation, they demonstrated that accurate slip estimation can significantly improve control strategies. Their results showed that integrating terrain-aware feedback into the control loop enhances traction, reduces instability, and improves navigation accuracy. This work emphasized the importance of adaptive control systems for reliable operation in challenging and uncertain environments. Ma, et al. [4] introduced a six-link leg mechanism designed to amplify output displacement from minimal actuator input, thereby improving locomotion efficiency and dynamic performance. Their mechanism utilized a compact linkage system that converts small rotational inputs into larger linear or angular outputs at the foot. Experimental validation demonstrated that the robot achieved significant step height relative to its body size and exhibited high-speed locomotion capabilities. The study also analyzed the kinematic relationships and force transmission characteristics of the linkage system, showing that it enhances energy efficiency while maintaining structural stability. Their work highlighted the role of innovative mechanical design in improving robotic mobility.

Park, et al. [5] presented a comprehensive review of transformable wheel mechanisms, focusing on their classification, structural design, and functional capabilities. They analyzed various transformation strategies, including folding, expanding, and hybrid mechanisms, and evaluated their performance based on adaptability, mechanical complexity, and efficiency. The study identified key challenges such as increased mechanical wear, control complexity, and lack of standardized evaluation metrics. They emphasized the need for unified performance benchmarks and optimization techniques to improve the practicality of transformable wheel systems. Their work provided critical insights into the design trade-offs involved in developing hybrid locomotion platforms. Liu, et al. [6] proposed a posture control strategy for hexapod robots navigating rugged terrain using a Layer Identification of Tracking (LIT) framework. Their method enabled the robot to classify terrain conditions into different categories and apply corresponding control strategies for stability maintenance. They developed a virtual suspension dynamic model to regulate torso orientation and reduce the impact of terrain irregularities. By combining gait planning with adaptive posture control, their system maintained balance while minimizing energy consumption. Their experimental results demonstrated improved locomotion stability and adaptability, highlighting the effectiveness of integrating terrain classification with control strategies. Qiao, et al. [7] designed a wheel–legged robot incorporating an active waist joint to enhance maneuverability and adaptability in uneven terrains. Their study focused on improving the robot's kinematic flexibility by introducing an additional degree of freedom at the torso, allowing better distribution of forces during locomotion. They developed a comprehensive kinematic and dynamic model to analyze the influence of the waist joint on stability and motion control. Experimental results demonstrated improved obstacle negotiation, smoother turning capability, and enhanced adaptability in complex environments, highlighting the importance of body articulation in multi-modal locomotion systems. Cao, et al. [8] investigated the mechanism design and dynamic switching control of a wheel–legged separation quadruped robot. Their work emphasized the transition between wheel-based and leg-based locomotion modes through adaptive control strategies. They developed a dynamic switching framework that ensured smooth transitions without compromising stability or efficiency. The study also analyzed control algorithms for maintaining balance during mode transitions, demonstrating that intelligent control plays a crucial role in hybrid locomotion systems operating in variable terrains. Tedeschi and Carbone, et al. [9] provided a systematic design methodology for hexapod walking robots, focusing on mechanical configuration, actuation systems, gait generation, and payload considerations. Their work addressed critical design constraints such as stability, energy efficiency, and terrain adaptability. They proposed a structured design process that integrates mechanical design with control strategies, ensuring optimal performance across different operating conditions. Their study serves as a foundational guideline for developing efficient and reliable multi-legged robotic systems.

Zhao, et al. [10] developed a modeling and stability control framework for wheel–legged metamorphic robots capable of reconfiguration. Their research focused on steering dynamics and structural transformation, enabling the robot to adapt its configuration based on terrain requirements. They formulated mathematical models to describe the robot's motion and implemented control strategies to maintain stability during reconfiguration. Their results demonstrated improved locomotion versatility and robustness, emphasizing the importance of adaptive control in reconfigurable robotic systems. Mu, et al. [11] proposed a bionic hexapod robot design that improved locomotion stability through structural optimization and lightweight design. Their approach incorporated hollow leg structures to reduce overall weight while maintaining mechanical strength. They conducted gait simulation studies to evaluate stability and energy efficiency, showing that reduced weight leads to improved responsiveness and reduced power consumption. Their work highlighted the significance of structural design optimization in enhancing robot performance. Li, et al. [12] introduced a safe trajectory generation method for wheel–leg hybrid robots using discrete mechanics and optimal control theory. Their approach focused on generating collision-free and energy-efficient trajectories in complex environments. They incorporated system constraints and environmental factors into the optimization process, ensuring both safety and stability during motion. Their results demonstrated improved trajectory planning accuracy and robustness, making their method suitable for real-world robotic applications requiring reliable navigation. Zhao, et al. [13] designed and developed an all-terrain wheel–legged hybrid robot capable of adapting to diverse environmental conditions by switching between wheeled and legged locomotion modes. Their work focused on integrating the advantages of both locomotion strategies, where wheeled motion provided speed and energy efficiency on flat surfaces, while legged motion enabled effective obstacle negotiation in rough terrains. They developed a comprehensive kinematic model to analyze both straight-line and turning motions, ensuring precise control of the robot in different operating modes. Additionally, they conducted obstacle-crossing analysis by formulating mathematical models for front-wheel interaction with terrain obstacles, allowing the robot to dynamically adjust its movement strategy. Experimental evaluations demonstrated improved adaptability, stability, and mobility across varying terrains, highlighting the effectiveness of hybrid locomotion systems in real-world robotic applications.

3. PROPOSED SYSTEM

The system architecture as illustrated in Fig. 1, is designed as a distributed embedded control and vision framework that integrates wireless communication, real-time image streaming, memory optimization, and multi-actuator control using the ESP32-CAM board as the central unit. The ESP32-CAM (AI-Thinker variant) interfaces with the OV2640 camera sensor, which captures image frames using the esp_camera driver configured with parameters such as pixel format (JPEG), frame size (e.g., VGA), and buffer location in PSRAM to ensure efficient handling of continuous image streams.

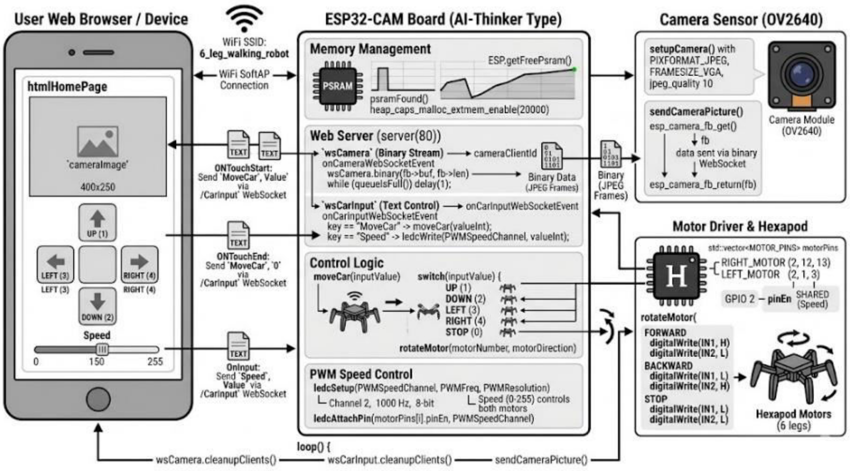

Fig. 1: Proposed system architecture.

The device operates in Wi-Fi SoftAP mode, allowing a user web browser or mobile device to establish a direct connection through a defined SSID, enabling standalone operation without external network dependency. The web server layer is implemented using asynchronous WebSocket communication, where two channels—wsCamera for binary image streaming and wsCarInput for control commands—enable simultaneous, non-blocking data exchange between client and server. The user interface provides a control panel with directional inputs (forward, backward, left, right), speed adjustment sliders, and live camera feed visualization, where user actions are encoded into structured text commands and transmitted via WebSocket events. These commands are processed by event handlers such as onCarInputWebSocketEvent, where parsing, validation, and key-value extraction are performed before mapping inputs to control logic. The control subsystem implements movement functions such as moveCar and rotateMotor, which translate user commands into motor actions using GPIO-based digital signals and PWM outputs. Motor control is achieved through an H-bridge motor driver interfaced with multiple GPIO pins, enabling bidirectional movement and speed regulation of the hexapod or multi-motor system. PWM-based speed control is implemented using LEDC channels, where parameters such as frequency and resolution are configured to achieve precise motor velocity adjustments. The firmware architecture includes memory management mechanisms that utilize PSRAM for frame buffering and heap allocation, ensuring stable performance during continuous streaming and control operations. The main execution loop handles client cleanup, WebSocket communication, and periodic image transmission through functions such as sendCameraPicture, maintaining real-time responsiveness. The routing and processing layers are designed to separate concerns between image streaming and control handling, reducing latency and improving system scalability. Overall, the architecture demonstrates seamless integration of perception, communication, memory management, and actuation, enabling efficient real-time remote monitoring and control of a multi-motor robotic system.

3.1 ESP32-CAM

The ESP32-CAM is a compact microcontroller module that integrates Wi-Fi connectivity and a camera interface, making it suitable for real-time surveillance and IoT applications. It is built on the ESP32 chipset, which provides processing capability along with wireless communication features. The module includes an OV2640 camera sensor for capturing images and streaming video. It supports external memory (PSRAM), enabling efficient handling of image data. Due to its low cost and multifunctionality, it is widely used in embedded vision systems.

Initialization: The ESP32-CAM initializes its internal components, including GPIO pins, camera configuration, and memory allocation.

Camera Configuration: The OV2640 camera sensor is configured with parameters such as frame size, pixel format (JPEG), and resolution.

Wi-Fi Setup: The module creates a Wi-Fi access point, allowing user devices to connect directly to the system.

Web Server Activation: An internal web server is started to host the control interface and manage client connections.

Frame Capture: The camera captures image frames continuously and stores them in the frame buffer.

Image Processing and Buffering: Captured frames are processed and prepared for transmission using available memory (PSRAM).

Data Transmission; The ESP32-CAM sends image frames to the connected client using WebSocket communication.

Command Reception: It receives control commands from the user interface for robot movement and speed control.

Processing and Execution: The received commands are processed, and corresponding actions are performed such as motor control.

Continuous Operation: The module continuously performs streaming and control operations in a loop for real-time monitoring.

4. RESULTS AND DISCUSSION

The figure 2 shows the 6-legged robotic system designed for rugged terrain mobility, built on a sturdy rectangular chassis with a multi-link leg mechanism on both sides that mimics walking motion. At the top, a compact control unit is mounted, consisting of a rechargeable battery pack (blue), a voltage regulator module with a digital display, and a motor driver circuit interconnected through organized wiring. The front section houses a sensor module (likely for obstacle detection), enabling environmental awareness, while the leg assemblies are mechanically linked with joints and supports to facilitate adaptive gait movement. The overall design reflects a combination of mechanical stability and embedded control integration, demonstrating the robot’s capability for coordinated locomotion, power management, and real-time sensing in uneven terrain conditions.

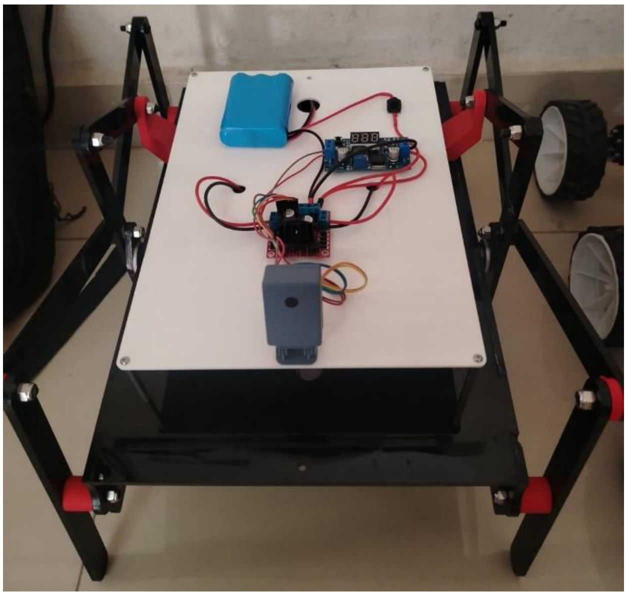

Figure 2: Experimental Setup of a Six-Legged Robot

The figure 3 shows the fully assembled and connected six-legged robotic prototype, where all electronic components are integrated and operational on the chassis. The control board, motor driver module, voltage regulator with display, and battery pack are properly wired and mounted on the top platform, indicating a completed hardware setup. The leg mechanisms on both sides are connected to the actuation system, ready for coordinated movement, while the front-mounted sensor module is positioned for obstacle detection. This stage represents the post-integration phase, where power distribution, control signaling, and mechanical linkages are successfully established, enabling the robot to perform adaptive locomotion and real-time sensing.

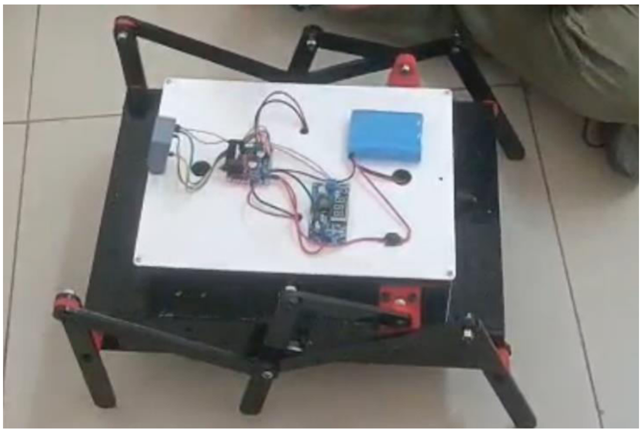

Figure 3: Sensor Data Integration and Software Synchronization

The figure 4 illustrates the successful execution stage of the six-legged robotic system, where sensor–software integration is fully established and functioning correctly. The onboard control unit, along with the connected sensor module, is actively transmitting data, which is visibly displayed on the digital voltage/sensor output screen, confirming real-time data acquisition and processing. The wiring and components appear stable and operational, while the robotic leg structure is ready for coordinated movement based on sensor inputs. This stage validates that the system has achieved reliable communication between sensors and embedded software, enabling effective monitoring and supporting adaptive locomotion decisions

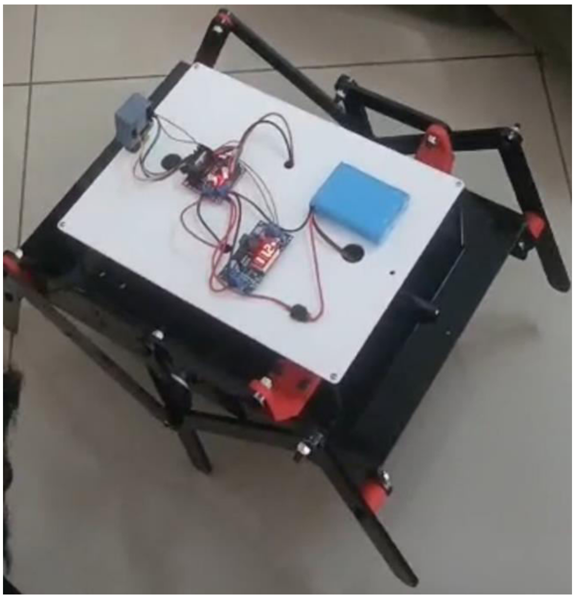

Figure 4: Real-Time Sensor Output Visualization

5. CONCLUSION

The study presents the development of a compact robotic surveillance system that enables live video transmission and remote mobility through wireless connectivity. By utilizing the ESP32-CAM module along with motor control mechanisms, the robot can be navigated in real time via a browser-based interface. A WebSocket-based communication layer supports fast and continuous data exchange, ensuring responsive control and smooth video streaming. The system operates through a self-hosted Wi-Fi Access Point, removing dependency on external networks. Efficient resource management allows simultaneous handling of image streaming and motion control without performance degradation. An event-driven design architecture maintains system stability during concurrent operations.

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