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Latency-Optimized Kinematic Control and Real-Time Visual Feedback for Edge-Intelligence Surveillance Platforms

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ABSTRACT

This study presents the design and implementation of a standalone mobile surveillance robot that enables real-time visual monitoring and remote navigation through wireless communication. The system is built around the ESP32-CAM Microcontroller Unit (MCU – Microcontroller Unit), which integrates image capture, processing, and communication within a compact embedded platform. The onboard camera captures visual data in Joint Photographic Experts Group (JPEG – Joint Photographic Experts Group) format at Video Graphics Array (VGA – Video Graphics Array) resolution, while efficient buffering is achieved using internal memory supported by Pseudo-Static Random Access Memory (PSRAM – Pseudo-Static Random Access Memory) to ensure continuous frame transmission. A persistent communication channel is established using the WebSocket protocol (WebSocket – Full-Duplex Communication Protocol), enabling low-latency bidirectional exchange of control commands and video data. The robot's movement is controlled using dual Direct Current motors (DC – Direct Current), interfaced through General Purpose Input Output pins (GPIO – General Purpose Input Output), with Pulse Width Modulation (PWM – Pulse Width Modulation) applied for precise speed regulation and smooth navigation. The software architecture follows an asynchronous event-driven model implemented using ESPAsyncWebServer and AsyncWebSocket libraries, allowing simultaneous execution of streaming and control operations without delay. The system operates via a Wireless Fidelity Access Point (Wi-Fi – Wireless Fidelity, AP – Access Point), enabling direct device connectivity without relying on external internet infrastructure. Additionally, a safety mechanism is incorporated to automatically stop the robot in case of connection loss, preventing unintended motion. Overall, the system provides a compact, efficient, and cost-effective solution for real-time surveillance and remote robotic control applications.

Keywords: Wireless Surveillance System, ESP32-CAM MCU, Embedded Vision System, Wireless Control Interface, Uneven Terrain Navigation.

1. INTRODUCTION

The field of surveillance has undergone a substantial transformation with the integration of Internet of Things (IoT) technologies and advanced embedded systems, enabling the development of intelligent, interconnected monitoring platforms. Unlike traditional approaches that rely heavily on manual observation and passive recording, modern systems are designed to actively sense, process, and communicate information in real time. This shift has been driven by the growing need for continuous situational awareness, rapid response capabilities, and scalable deployment across diverse domains such as industrial automation, urban infrastructure, transportation systems, defense operations, and residential security. As environments become more dynamic and complex, the demand for systems that can operate autonomously while maintaining high reliability and adaptability has increased significantly.

In this context, mobile surveillance robots have emerged as a powerful alternative to fixed monitoring setups like Closed-Circuit Television (CCTV). Conventional systems are limited by their static

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positioning and restricted field of view, which often leads to blind spots and reduced coverage. In contrast, surveillance robots are equipped with onboard vision modules, embedded processing units, and communication interfaces that allow them to actively navigate and monitor their surroundings. Their mobility enables them to access confined or hazardous locations, dynamically adjust their viewpoint, and respond to specific monitoring requirements. By capturing live video streams and transmitting them to remote operators, these robots enhance visibility and operational efficiency. Furthermore, the integration of motor control systems and navigation algorithms supports both user-controlled and semi-autonomous movement, enabling flexible deployment in a wide range of scenarios. Wireless communication forms the backbone of such intelligent systems by facilitating seamless interaction between the robot and the end user. Technologies based on Wireless Fidelity (Wi-Fi) provide a practical and cost-effective solution for establishing connectivity without the need for physical infrastructure. Through browser-based control interfaces or dedicated applications, users can issue navigation commands and receive live visual feedback from the robot in real time. Advanced communication mechanisms such as WebSocket enable persistent, bidirectional data exchange, ensuring minimal latency and synchronized operation. This continuous flow of data is crucial for applications that demand immediate responsiveness, such as security monitoring or emergency inspection tasks.

To ensure efficient performance under continuous operation, modern surveillance robots adopt event-driven software architectures that support concurrent execution of multiple processes. Tasks such as video acquisition, data transmission, and command processing are handled simultaneously without blocking system resources, resulting in smooth and reliable operation. In addition, intelligent resource management techniques are employed to optimize memory usage and processing efficiency, particularly in resource-constrained embedded environments. Safety features are also incorporated to detect and handle abnormal conditions, such as communication loss or system faults, by triggering automatic stop mechanisms or fallback operations. Altogether, the integration of embedded intelligence, autonomous mobility, and real-time wireless communication establishes a robust and scalable surveillance framework capable of addressing the evolving demands of intelligent monitoring systems in real-world applications.

2. LITERATURE SURVEY

Chen, et al. [1] introduced a comprehensive motion planning strategy tailored for hexapod robots operating in irregular and rugged terrains. Their framework focused on coordinating the entire body of the robot rather than treating each leg independently, which significantly improved stability during locomotion. By dividing the walking cycle into support and swing phases, they optimized the robot's torso position to maintain a higher stability margin during transitions. The approach integrated terrain geometry into planning, ensuring that foot placements aligned with surface constraints. Smooth motion trajectories were generated using spline-based interpolation, while inverse kinematics translated these trajectories into precise joint movements. This method not only enhanced stability but also reduced unnecessary energy consumption, making it suitable for real-world terrain navigation where balance and efficiency were critical.

Qiao, et al. [2] developed a wheel–legged robotic platform that incorporated an active waist joint to improve mobility and adaptability in uneven environments. Unlike conventional rigid-body robots, their design introduced an additional articulation point that allowed the robot to dynamically adjust its body orientation during movement. This improved weight distribution across the legs and enhanced balance when traversing obstacles. The researchers formulated detailed kinematic and dynamic models to evaluate how the waist joint influenced motion stability and control accuracy. Experimental validation demonstrated that the robot performed smoother turns, better obstacle negotiation, and maintained stability on irregular surfaces. Their work highlighted how structural flexibility and body articulation significantly improved the performance of hybrid locomotion robots.

Mu, et al. [3] proposed an advanced hexapod robot design that emphasized lightweight construction and improved locomotion efficiency. Their approach involved the use of hollow structural components for the robot's legs, reducing overall weight without compromising strength or durability. This reduction in mass directly contributed to improved energy efficiency and faster response during motion. The authors conducted extensive gait simulations to analyze stability under different walking patterns and terrain conditions. The results indicated that the optimized structure enhanced dynamic stability and reduced power consumption, especially during continuous operation. Their study demonstrated that careful structural design played a vital role in improving both the mechanical performance and energy efficiency of multi-legged robotic systems.

Comin and Saaj, et al. [4] focused on understanding the interaction between robot locomotion systems and soft or deformable terrains by developing a slip estimation and terrain characterization model. Their work emphasized the importance of accurately predicting slip, which was a major factor affecting stability and control in real-world environments. By analyzing parameters such as ground reaction forces, friction behavior, and terrain deformation, they created mathematical models capable of estimating slip conditions during movement. The integration of this information into the control system allowed the robot to adjust its motion dynamically, improving traction and reducing the likelihood of instability. Their findings underlined the significance of terrain-aware control mechanisms in enhancing navigation performance in uncertain and challenging environments.

Zhao, et al. [5] presented a reconfigurable wheel–legged robot that was capable of adapting its structure based on terrain requirements through a metamorphic design approach. Their system allowed the robot to modify its configuration to switch between different locomotion modes, improving versatility. The study developed mathematical models to describe both the kinematics and dynamics of the robot during reconfiguration and movement. Control strategies were implemented to ensure that stability was maintained even when the robot changed its structure. Their results demonstrated that such adaptive systems significantly enhanced mobility and robustness, especially in environments where terrain conditions varied frequently. This work highlighted the importance of combining mechanical reconfiguration with intelligent control.

Wang, et al. [6] designed a deformable wheel–legged robot inspired by origami-based structural concepts to achieve flexible and adaptive locomotion. Their approach utilized foldable mechanisms that allowed the wheel structure to transform into leg-like configurations when required. This enabled the robot to seamlessly switch between rolling motion on flat surfaces and stepping motion when encountering obstacles. The study examined the kinematic behavior and deformation characteristics of the structure, as well as load distribution during movement. Experimental results showed that the robot achieved improved stability and obstacle-handling capability compared to traditional rigid designs. Their work demonstrated how integrating compliant structures with mechanical systems enhanced adaptability in complex and unstructured environments.

Park, et al. [7] presented a comprehensive review of transformable wheel mechanisms, examining their structural configurations, functional capabilities, and performance characteristics. Their study analyzed different transformation approaches such as folding, expansion, and hybrid configurations, evaluating them based on adaptability, mechanical complexity, and operational efficiency. They identified several challenges, including increased wear due to moving parts, higher control complexity, and the absence of standardized evaluation criteria for comparing different designs. The authors emphasized the need for unified benchmarking methods and optimization strategies to enhance the practicality and reliability of transformable wheel systems in real-world applications.

Cao, et al. [8] investigated the design and dynamic control of a wheel–legged separation quadruped robot, focusing on enabling smooth transitions between wheeled and legged locomotion modes. Their work introduced an adaptive control framework that ensured stability during the switching process, preventing abrupt changes that could destabilize the robot. They analyzed control algorithms responsible for maintaining balance and coordinating motion across different locomotion modes. Experimental observations demonstrated that intelligent control strategies significantly improved the robot's ability to operate efficiently across varying terrain conditions, highlighting the importance of control design in hybrid locomotion systems.

Liu, et al. [9] proposed a posture control strategy for hexapod robots navigating uneven terrains using a Layer Identification of Tracking (LIT) framework. Their method enabled the robot to classify terrain conditions into distinct categories and apply appropriate control strategies for maintaining stability. They developed a virtual suspension dynamic model to regulate torso orientation and minimize the impact of terrain irregularities. By integrating gait planning with adaptive posture control, the system maintained balance while reducing energy consumption. Experimental results confirmed improved locomotion stability and adaptability, demonstrating the effectiveness of combining terrain classification with dynamic control strategies.

Ma, et al. [10] introduced a six-link leg mechanism designed to amplify output motion from minimal actuator input, thereby improving locomotion efficiency and dynamic performance. Their design utilized a compact linkage system capable of converting small rotational movements into larger linear or angular displacements at the foot. Through experimental validation, they demonstrated that the robot achieved significant step height relative to its body size and exhibited high-speed locomotion. Their analysis of kinematic relationships and force transmission revealed that the mechanism enhanced energy efficiency while maintaining structural stability, highlighting the benefits of innovative mechanical design in robotic mobility.

Zhao, et al. [11] designed an all-terrain wheel–legged hybrid robot capable of adapting to diverse environmental conditions by switching between wheeled and legged locomotion modes. Their approach combined the advantages of both movement strategies, where wheeled motion provided speed and efficiency on flat surfaces, while legged motion enabled effective obstacle negotiation on rough terrains. They developed a detailed kinematic model to analyze both straight-line and turning movements and conducted obstacle-crossing analysis using mathematical modeling. Experimental evaluations demonstrated improved adaptability, stability, and mobility across different terrains, validating the effectiveness of hybrid locomotion systems.

Li, et al. [12] proposed a trajectory generation method for wheel–leg hybrid robots based on discrete mechanics and optimal control theory. Their approach focused on generating safe, collision-free, and energy-efficient motion paths in complex environments. They incorporated system constraints and environmental factors into the optimization process, ensuring stability and safety during operation. The results showed improved trajectory planning accuracy and robustness, making the method suitable for real-world applications where reliable navigation is essential. Their work emphasized the importance of integrating optimization techniques with motion planning for advanced robotic systems.

Tedeschi and Carbone, et al. [13] presented a comprehensive design methodology for hexapod walking robots, addressing critical aspects such as mechanical configuration, actuation systems, gait generation, and payload considerations. Their study systematically analyzed the key design constraints that influence robot performance, including stability, energy efficiency, and adaptability to different terrain conditions. They proposed a structured design framework that integrated mechanical architecture with control strategies to achieve optimal locomotion performance. The work also examined various leg configurations and movement patterns to enhance walking efficiency and balance. Their findings

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provided a strong foundational guideline for the development of reliable and efficient multi-legged robotic systems, emphasizing the importance of coordinated design and control integration.

3. PROPOSED SYSTEM

The system is designed as a comprehensive, event-driven embedded pipeline that integrates system initialization, wireless networking, web-based user interaction, asynchronous communication, real-time image streaming, and motor control using the ESP32 MCU as the central controller as illustrated in Figure. 1. During the initialization phase, the ESP32 enables PSRAM for extended memory capacity, configures GPIO pin modes for motor driver interfaces and peripherals, initializes the camera module via the esp_camera driver, and establishes a Wi-Fi SoftAP with defined SSID and credentials, allowing direct device-to-device connectivity. An asynchronous web server (AsyncWebServer) is launched to host the control interface, while WebSocket services (wsCarInput and wsCamera) are initialized to enable persistent, full-duplex communication channels for control commands and video streaming respectively. Once the user connects through a browser using the assigned IP address, the server delivers the HTML-based control interface, which includes directional controls, speed adjustment sliders, and a live video display panel.

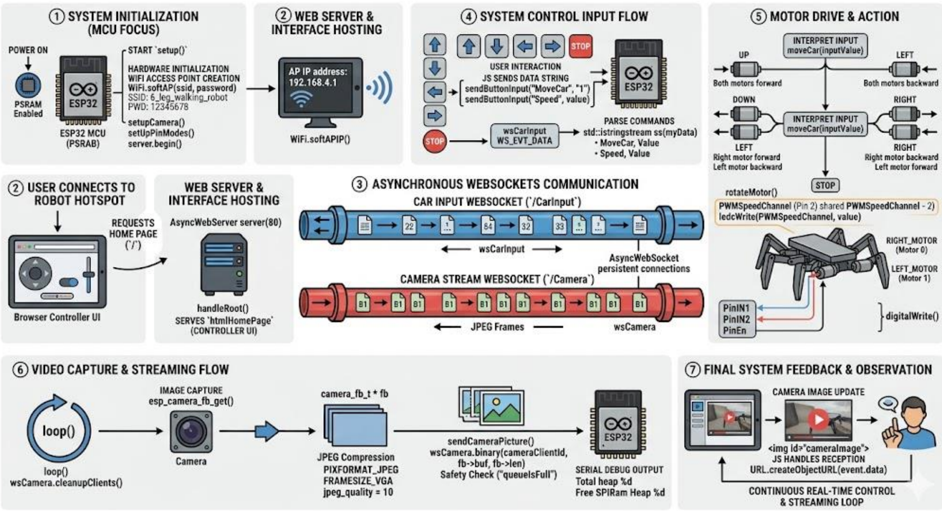

Figure. 1: Proposed system architecture.

User interactions such as movement commands (forward, backward, left, right, stop) and speed values are captured through JavaScript event handlers and transmitted as structured text messages via the wsCarInput WebSocket channel. These messages are received by the ESP32 through an event-driven callback function, where they are parsed into key-value pairs representing direction and speed parameters. The control logic processes these inputs using functions such as moveCar and rotateMotor, which determine the required motor actions and generate appropriate control signals. Motor actuation is achieved through an H-bridge motor driver interfaced via GPIO pins (IN1, IN2, EN), enabling bidirectional control and PWM-based speed modulation using LEDC channels configured with specific frequency and resolution. Simultaneously, the camera subsystem continuously captures frames using esp_camera_fb_get(), compresses them into JPEG format with defined quality settings, and stores them in PSRAM buffers to support uninterrupted streaming. These frames are transmitted through the wsCamera WebSocket channel to the client interface, ensuring real-time visual feedback.

The main loop operates continuously to manage WebSocket client connections, perform cleanup of inactive clients, process incoming control commands, and stream image data efficiently without blocking execution. The architecture also incorporates memory and queue management mechanisms to prevent buffer overflow and maintain stable performance during high-frequency data transmission.

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System feedback is achieved through live video updates and responsive control actions, allowing users to monitor and adjust robot behavior in real time. The modular separation of components such as initialization, communication, control processing, and streaming enhances scalability, maintainability, and performance optimization. The architecture demonstrates a tightly coupled integration of sensing, networking, processing, and actuation layers, enabling a robust, low-latency, and responsive robotic control system suitable for real-time applications.

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.

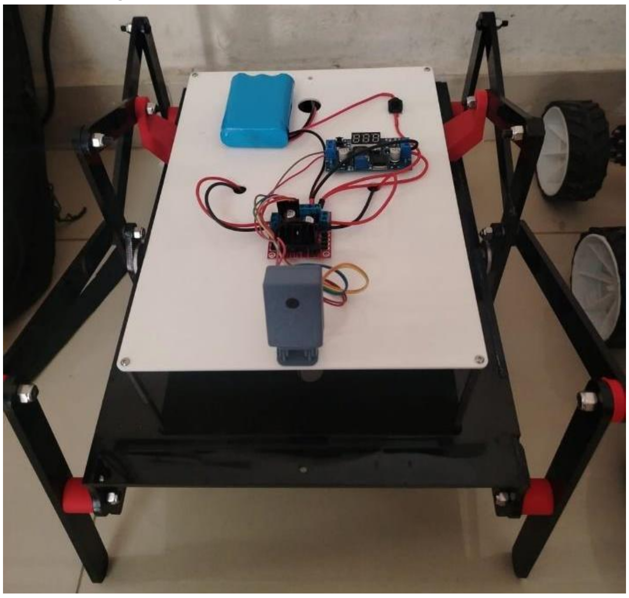

Figure 2: Experimental Setup of a Six-Legged Robot

Figure 3: Sensor Data Integration and Software Synchronization

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 4: Real-Time Sensor Output Visualization

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

5. CONCLUSION

This work demonstrates the design of a small-scale mobile monitoring robot capable of delivering real-time visual feedback while being controlled remotely over a wireless link. The system is built around an ESP32-CAM unit, which handles both image capture and communication, and is paired with a motor-driving setup to enable directional movement. Control is achieved through a web-based interface, allowing users to operate the robot directly from a browser without additional software. A WebSocket communication framework is employed to maintain a continuous, low-delay exchange of commands and video data, resulting in fluid navigation and uninterrupted streaming. The robot functions using its own Wi-Fi access point, eliminating reliance on external internet infrastructure. Careful management of processing and memory resources ensures that video transmission and motion control run in parallel without affecting performance. The overall architecture follows an event-driven approach, which helps maintain reliability and consistent operation even when multiple tasks are executed simultaneously.

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