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Edge Based Dual Axis Smart Surveillance System

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Abstract: Surveillance systems now move faster than before, leaving behind old cloud-heavy cameras. Instead of sending everything online, small smart gadgets handle tasks right where they happen. One example uses the tiny ESP32 chip, turning it into a watcher that moves two ways while spotting things. Vision jobs run light and quick on board, avoiding heavy data loads. A compact form of machine learning, powered by TensorFlow Lite for Microcontrollers, helps spot objects without delay. Messages go out efficiently when needed, thanks to MQTT's lean communication method. Speed improves, internet traffic drops, personal information stays safer. Earlier designs get examined here alongside decisions made during building. Choices about parts and code shape what each system can do. Some compromises appear necessary between power needs, accuracy, and cost. The setup described guides movement with servos, keeping eyes on moving targets in real time.

Keywords: ESP32, TensorFlow Lite for Microcontrollers, MQTT, Smart Surveillance, Edge Computing, Real-Time Object Tracking, Embedded Vision, Dual-Axis Tracking, IoT.

I. INTRODUCTION

Most video monitoring systems use set-in-place cameras. These often run nonstop or send clips far away for checking later. That setup works everywhere now, yet shows problems plainly. Too much network space gets eaten up. Reactions lag when things happen. The system needs constant web access. People worry more about their private details being exposed. Places like houses, dorms, science rooms, schools, farms - they feel these limits hard. Old-style security cams turn out pricey there. They also perform poorly under such conditions.

Now devices handle smarts themselves thanks to progress in edge computing and TinyML. Rather than pushing live footage offsite, cameras spot movement right where they sit. A built-in brain judges if someone appears or something matters. That moment it shifts from just capturing clips to making choices changes everything. Deciding locally - right inside the hardware - is what we now call edge intelligent surveillance.

One big upgrade for edge monitoring? Adding a motorized base that moves side to side and up down. Instead of staying locked in one direction, it shifts position automatically. A regular camera just sees whatever happens to pass in front. But when attached to two small motors, it gains motion - swiveling left or right, angling high or low. That shift lets it chase moving objects smoothly. Suddenly, one basic unit covers far more ground. No extra hardware needed. It watches like something much more complex, yet stays simple underneath. The whole setup turns stillness into motion, quietly expanding its reach.

Video surveillance begins easily on the ESP32. Its small size hides strong abilities - Wi-Fi and Bluetooth come standard, removing extra parts. Instead of separate controllers, pulse signals drive servos directly through built-in PWM pins. Cameras plug into models like the ESP32-CAM without hassle, capturing images right away. Processing happens onboard when TinyML methods run via TensorFlow Lite for Microcontrollers. Rather than sending everything upstream, decisions form locally based on what the model sees. Messages travel out only when needed, routed by MQTT to alert systems or devices. Between sensing, thinking, moving, and signaling, the cycle completes entirely within the board

A. *Problem Statement*

Most old-style security cameras just send live footage. Watching them means someone must always pay attention. Smarter features often depend on distant servers. A lot of internet-connected cameras miss built-in smarts. Following movement automatically? Rarely happens onboard. What fills this gap is a unified solution. Intelligence sits right inside the hardware. It spots people instantly. Tracking runs without delays. All processing stays local. The device handles decisions alone.

B. *Objectives*

1) Design a dual-axis smart surveillance system using ESP32-CAM capable of live video capture and remote monitoring. (Phase 1 — Completed)

2) Integrate basic automation using servo motors for pan-tilt camera movement. (Phase 1 — Completed)
3) Implement Edge-AI based person detection and automatic tracking on the device. (Planned — Phase 2)
4) Enhance the system towards a fully autonomous, intelligent CCTV with real-time local decision making. (Future Work)

C. Scope
1) Develop a compact IoT-based surveillance camera without dependence on cloud processing.
2) Implement autonomous camera movement using servos based on detection results.
3) Reduce the need for continuous human monitoring in surveillance.
4) Design a modular and scalable system that supports future AI upgrades.
5) Promote low-cost, smart, and energy-efficient surveillance for homes, labs, campuses, and offices.

II. LITERATURE SURVEY
Several researchers have explored IoT-based surveillance, embedded vision, and edge intelligence using low-power camera modules. The following section reviews key related works and identifies the research gap addressed by this project.

A. Review of Related Work
Espressif Systems [1] introduced the ESP32-CAM, a low-cost Wi-Fi camera module widely adopted for IoT surveillance and live video streaming applications, proving the feasibility of compact embedded vision devices. Pete Warden and Daniel Situnayake [2] demonstrated TinyML concepts using TensorFlow Lite for Microcontrollers, showing that machine learning inference can run directly on microcontrollers without cloud dependency. Zach Shelby et al. from Edge Impulse [3] developed an embedded ML platform that enables real-time image classification and object detection on resource-constrained hardware, simplifying Edge-AI deployment. Neil Kolban [4] illustrated practical implementation of camera web servers and servo motor control using ESP32, highlighting integration of video streaming with actuator mechanisms. Massimo Banzi and David Cuartielles from Arduino [5] promoted open-source servo-based pan-tilt mechanisms for expanding camera field of view in DIY surveillance projects. Researchers at MIT Media Lab [6] explored embedded vision and real-time object tracking on low-power devices, emphasizing local processing for faster response and enhanced privacy. Dustin Franklin, David Hall, and the NVIDIA Jetson Research Team [7] demonstrated edge-based vision processing for surveillance using embedded GPUs, reinforcing the effectiveness of performing real-time object detection locally without cloud dependency. Eben Upton and the Raspberry Pi Foundation [8] showcased camera modules integrated with servo pan-tilt assemblies for smart monitoring projects, validating the use of low-cost hardware for intelligent surveillance prototypes. Werner Vogels and the Amazon Web Services IoT Research Group [9] emphasized edge analytics for video streams to minimize latency and bandwidth, supporting the importance of on-device processing in surveillance systems.

B. Identified Research Gap
Most existing works focus separately on video streaming, servo-based camera movement, or embedded machine learning. There is no unified low-cost system that integrates IoT video streaming, dual-axis camera control, and on-device Edge-AI based person detection with automatic tracking using a single embedded platform. This gap motivates the proposed smart surveillance project.

Table I: Comparative Study of Related Works

Reference	Video Streaming	Dual-Axis Control	Edge AI Detection	Integration
Espressif Systems [1]	Yes	No	No	Partial
Pete Warden & Daniel Situnayake [2]	No	No	Yes	Partial
Zach Shelby et al., Edge Impulse [3]	No	No	Yes	Partial
Neil Kolban [4]	Yes	Yes	No	Partial
Massimo Banzi & David Cuartielles, Arduino [5]	No	Yes	Yes	Partial
MIT Media Lab Researchers [6]	No	No	Yes	Partial
Proposed System	Yes	Yes	Yes	Full

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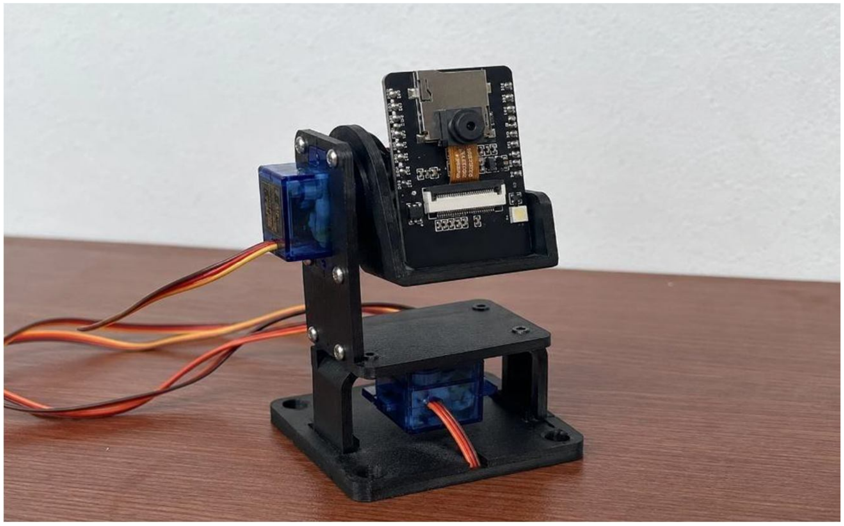
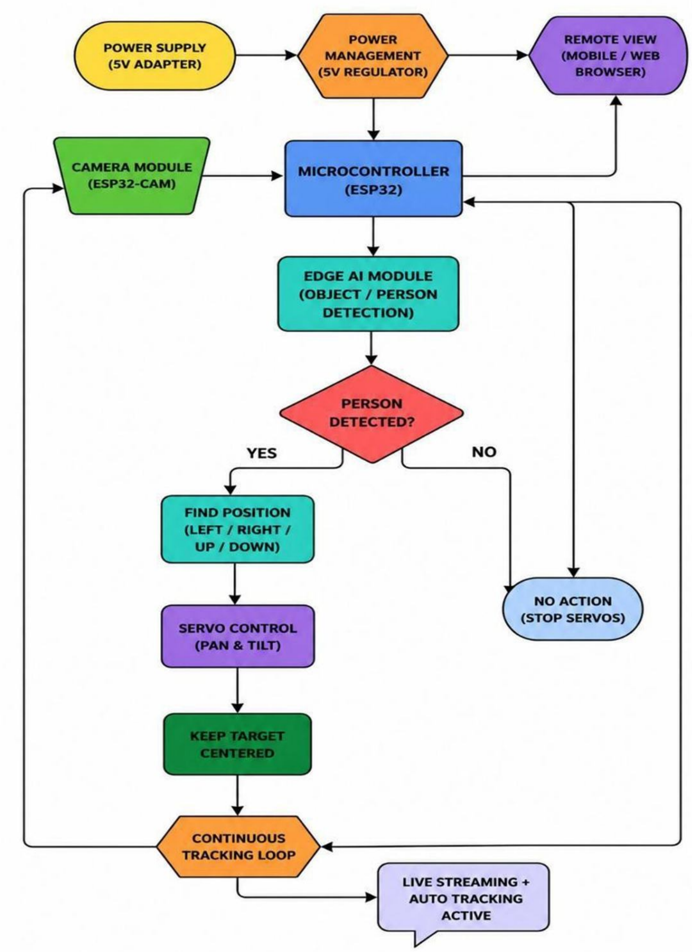
III. ESP32 CAMERA MODULE



IV. METHODOLOGY

A. System Architecture



B. Phase-wise Development Plan

Table II: Phase-wise Development Plan

Phase	Name	Key Components	Status
Phase 1	Video Streaming & Pan-Tilt Control	ESP32-CAM, servo motors (pan & tilt), 5V regulator, Wi-Fi streaming	Completed
Phase 2	Edge-AI Person Detection & Auto Tracking	Edge AI model using Edge Impulse, on-device inference, position logic	Planned
Phase 3	Intelligent Surveillance Enhancements	Alert system, recording, mobile notifications, advanced tracking features	Future Work

V. RESULTS AND DISCUSSION

A. Phase 1 Design Specifications

Table III: Phase 1 Component Specifications

ESP32-CAM	Specification	Function
ESP32-CAM	Wi-Fi camera module with OV2640	Video capture and streaming
Servo Motors (2×)	SG90/MG90S, 180° rotation	Pan and tilt camera movement
5V Regulator	ESP32 (Wi-Fi/BT)	Stable power supply to system
ESP32 (on-board)	AMS1117 / Buck converter	Central control and processing
Camera Mount	Wi-Fi / Bluetooth	Central control and processing
Power Supply	Dual-axis pan-tilt bracket	Primary power source
Wi-Fi Network	5V adapter / power bank	Remote live monitoring via browser

The Phase-1 prototype of the smart surveillance system was tested in indoor and lab conditions and demonstrated the following results:

1) Live video streaming: The ESP32-CAM successfully streamed real-time video to a mobile/web browser over Wi-Fi with stable connectivity.
2) Pan-tilt movement: Servo motors accurately controlled horizontal and vertical camera movement, increasing the field of view.
3) System stability: The 5V regulated power supply ensured uninterrupted operation during continuous streaming and servo actuation.
4) Camera performance: The OV2640 camera module captured clear frames suitable for real-time monitoring and Edge-AI processing.
5) Remote monitoring: Users were able to access and monitor the camera feed wirelessly without physical interaction with the device

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B. Comparative Analysis

Compared with existing systems, the proposed Phase-1 prototype focuses on live video streaming with dual-axis camera control using the ESP32-CAM, which many basic IoT camera projects do not combine effectively. Most reviewed works focus either on video streaming, servo-based movement, or Edge-AI independently. The proposed system establishes a strong foundation for an integrated solution that combines streaming, pan-tilt control, and on-device Edge-AI tracking in the upcoming phases.

VI. CONCLUSION AND FUTURE SCOPE

A. Conclusion

This paper presented the design, development, and testing of an Edge-AI enabled smart surveillance system as Phase 1 of a modular, multi-phase project. The prototype successfully integrates live video streaming and dual-axis camera movement using the ESP32-CAM. Testing confirmed reliable performance for real-time monitoring and remote access over Wi-Fi, establishing a strong foundation for adding on-device intelligence in the next phase. The system demonstrates a practical application of IoT, embedded systems, and Edge AI in intelligent surveillance, with relevance for homes, laboratories, campuses, and office environments.

B. Future Enhancements

1) Phase 2: Implement Edge-AI based person detection and automatic tracking using Edge Impulse for on-device inference.
2) Phase 3: Add alert system, image/video recording, and mobile notifications for enhanced security features.
3) Long-term: Integration with smart surveillance networks and advanced object tracking with improved accuracy and response time.

VII. ACKNOWLEDGMENT

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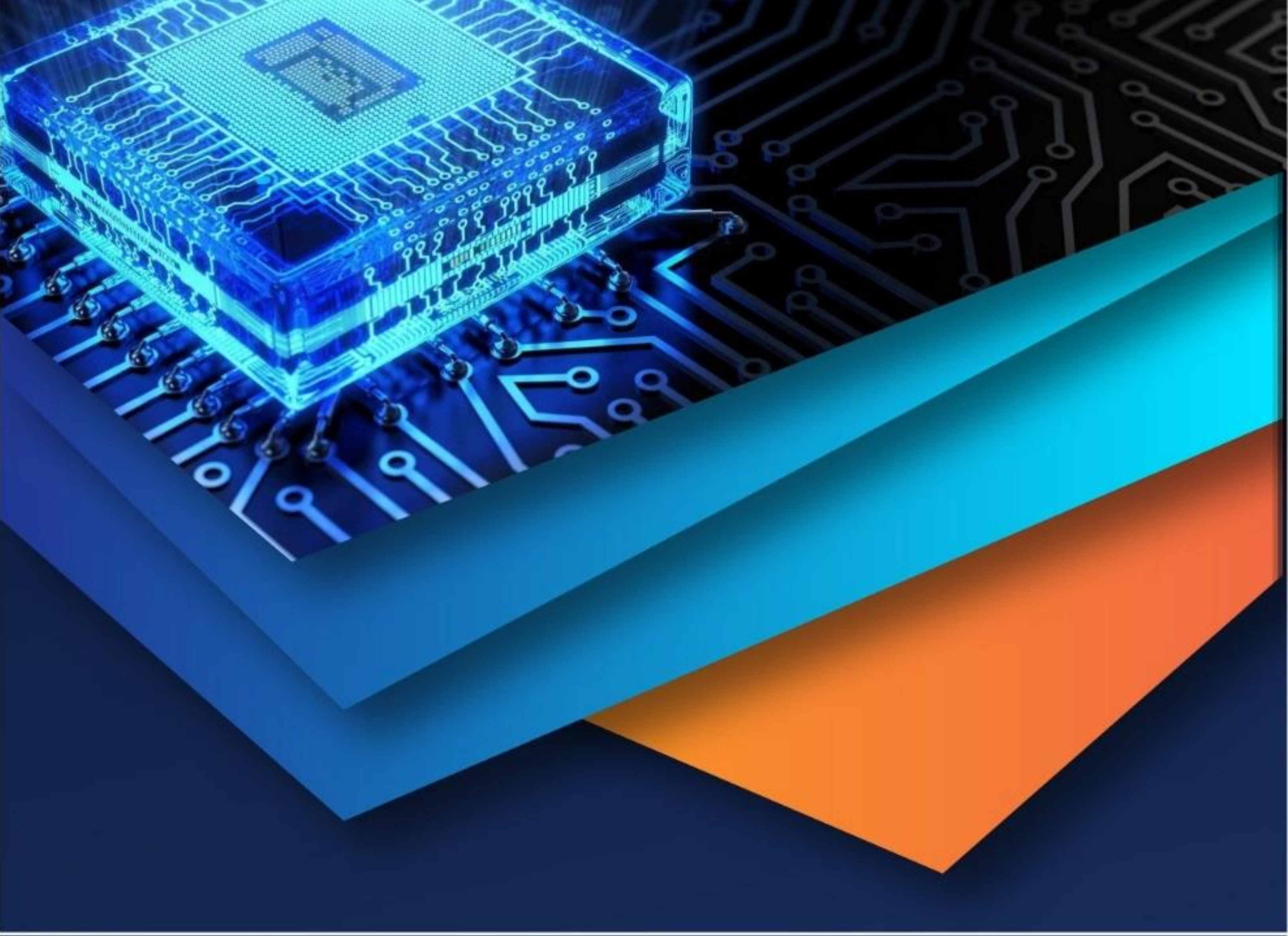

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