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Design and Development of a Smart Quadruped Spider Robot Using ESP32 with Obstacle Avoidance Vision-Based Face Detection and MQTT Control

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Abstract. Legged robotic platforms offer enhanced mobility in constrained indoor environments compared to wheeled systems, making them suitable for surveillance and inspection tasks. This work designs and builds a compact quadruped spider robot using the ESP32 embedded platform. This architecture integrates obstacle avoidance, vision-based face detection, live video streaming, and multi-modal communication control. The system employs eight MG90S servo motors configured in a two degree of freedom system per leg arrangement and implements a statically stable four-phase crawl gait using PWM based smooth interpolation at 50 Hz. Reactive ultrasonic-based obstacle avoidance ensures safe navigation, while the onboard ESP32-CAM module performs light- weight face detection and identity recognition for up to three registered users. Unknown face events trigger real-time alert notifications via a Telegram-based communication interface conceptually aligned with MQTT messaging principles. The robot further supports Bluetooth-based voice control for intuitive human–robot interaction. Experimental validation demonstrates 93% obstacle avoidance accuracy, 95% remote command execution success over 60 trials, 180 ms average control latency, 350 ms video streaming latency, 88% face detection accuracy, and stable locomotion under an additional 200 g payload. The proposed system provides a compact, low-cost, and energy- efficient mobile surveillance platform suitable for indoor monitoring applications.

Keywords: Quadruped Robot, ESP32-Based Embedded System, Obstacle Avoidance, Face Detection, Multi-Modal Communication, Indoor Surveillance

1 INTRODUCTION

Autonomous monitoring in enclosed environments such as laboratories, storage facilities, and restricted zones requires robotic platforms capable of reliable navigation and real-time surveillance. Wheeled robots are commonly used for indoor

S. Uppapalli and D. Chakraborty (eds.), *Proceedings of the International Conference on Mechanics, Materials and Mechatronics (ICM³ 2026)*, Atlantis Highlights in Engineering 47,
https://doi.org/10.2991/978-94-6239-764-4_14

monitoring, but their mobility is often limited by uneven surfaces and small obstacles. In comparison,quadruped robots offer better terrain adaptability and stable movement, making them suitable for inspection and surveillance tasks in confined indoor environments [2],[4]. Several high-performance quadruped systems achieve dynamic locomotion using advanced control algorithms and multi-sensor fusion techniques [1], [5]. However, these systems typically rely on powerful processors and complex actuation mechanisms, which increase cost and energy consumption. For structured indoor environments, microelectronic based robotic platforms provide a practical alternative by balancing locomotion capability with computational efficiency [3].

Recent advancements in embedded vision have enabled compact camera modules to perform real-time face detection on resource-constrained systems [6], [7]. In addition, communication protocols such as MQTT support scalable messaging in IoT enabled robotic systems [8],[9], while trust management mechanisms enhance secure communication among embedded devices [13]. However, the integration of locomotion, obstacle avoidance, face detection, live streaming, and human–robot interaction within a single embedded platform remains limited. This work presents the design and experimental validation of an ESP32-based quadruped spider robot for indoor surveillance.The proposed system integrates eight-servo locomotion, ultrasonic obstacle avoidance, onboard face detection with alert notification, live video streaming, and dual wireless control through Telegram and Bluetooth.

This paper describes

- Development of a compact ESP32-driven quadruped surveillance architecture utilising an eight-servo, two degree-of-freedom leg configuration.
- Implementation of a statically stable four-phase crawl gait integrated with reactive ultrasonic-based obstacle avoidance.
- Realisation of a dual-mode communication framework combining Telegram-based remote monitoring with Bluetooth-based voice command control.

2 LITERATURE SURVEY

Legged robots have been extensively studied due to their ability to navigate uneven terrain and maintain stability during locomotion. Several research studies have proposed quadruped robotic platforms that employ model-based control strategies, trajectory planning, and sensor fusion techniques to achieve agile locomotion [1], [5].These systems demonstrate high performance but require sophisticated hardware and high computational power. To reduce system complexity, researchers have explored simplified servo- driven quadruped architectures suitable for indoor environments. These designs typically use predefined gait patterns and micro-controller based control strategies to achieve stable movement while minimizing hardware requirements [2], [3].

In addition to locomotion, recent research has focused on integrating sensing and communication capabilities into robotic systems. Embedded vision platforms allow compact robots to perform tasks such as object detection and face recognition using lightweight processing algorithms [6],[7]. Communication protocols such as MQTT enable efficient data exchange in IoT- based robotic systems while maintaining low communication overhead [8],[9]. Bluetooth communication has also been widely used for local human–robot interaction and manual control [12]. Although these technologies have improved robotic monitoring systems, the integration of quadruped locomotion, embedded vision, obstacle avoidance and multi-modal communication within a single embedded platform remains relatively unexplored

Table 1. Comparative Analysis of Quadruped Robot Plat-forms

Platform	Dof	Actuation	Fabrication	Vision	Cost ($)	Web Control
Unitree	12	Brushless	Metal/Cnc	Optional	10,000	No
Boston	12	Hydraulic	Metal/Cnc	Yes	74,000	No
Padwq	12	Qdd	3D Print	Yes	3,000	No
Petoi Bittle	9	Servo	3D Print	Optional	300	Optional
Quadre	12	Servo	3D Print	Yes	800	Yes
Assistive Quadruped	4	Servo	3D Print	Yes	150	Yes
This Work	4	Servo	Plastic/Steel	Yes	65	Yes

3 SYSTEM ARCHITECTURE

The proposed surveillance robot is built around an ESP32 DevKit V1 microcontroller, which serves as the central control unit. The architecture consists of sensing, processing, actuation, communication and power management modules.

The ESP32 handles gait control, sensor processing, and communication management. An ultrasonic sensor continuously measures the distance to nearby obstacles and triggers avoidance behaviour when the measured distance falls below a predefined threshold.

The robot uses eight MG90S servo motors arranged in a two-degree- of-freedom configuration per leg. Pulse-width modulation (PWM) signals generated by the ESP32 control the joint angles. A statically stable four-phase crawl gait ensures that at least three legs remain in contact with the ground at any time, providing stable locomotion.

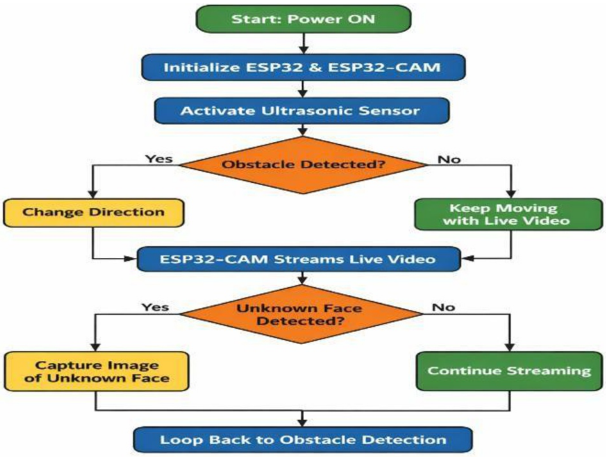

Fig. 1. *Flowchart illustrating the operational workflow of the ESP32-based quadruped spider robot for obstacledetection*
For monitoring tasks, an ESP32-CAM module captures video frames and performs onboard face detection. sent through a Telegram messaging interface Wi-FiCommunication supports the mobile application.

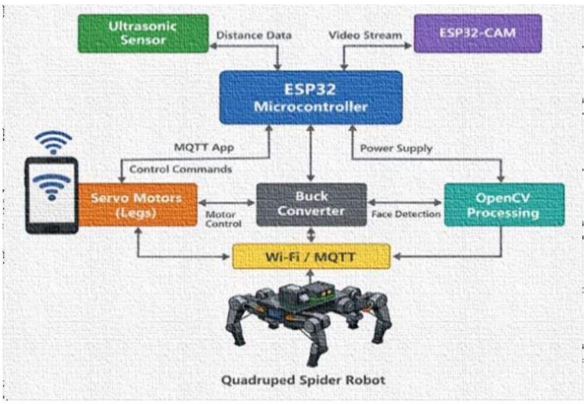

Fig. 2. *System architecture of the proposed ESP32-based quadruped surveillance robot.*

4 MECHANICAL STRUCTURE

The mechanical structure of the proposed quadruped robot is designed to achieve stable locomotion while maintaining compact embedded integration. The platform employs a four-leg configuration, with each leg providing two degrees of freedom corresponding to hip and knee joints. This configuration enables forward progression, elevation control, and obstacle negotiation.

Eight MG90S metal-gear servo motors rated at 6 V are used as joint actuators. Each leg incorporates one servo for hip rotation and one servo for knee articulation, resulting in a total of eight actuators. The 2-DOF arrangement provides sufficient motion flexibility for statically stable gait execution while reducing weight, power consumption, and control overhead compared to higher-degree-of-freedom implementations. Power is supplied using a 5 V (2S) lithium-ion battery rated at 2200 mAh. A buck converter regulates the voltage to 5 V for stable servo and microcontroller operation. The regulated power architecture ensures consistent torque delivery and prevents voltage fluctuations during simultaneous servo actuation.

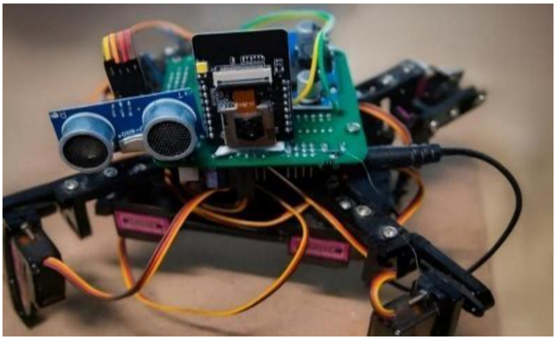

Fig.3. *Physical prototype of the proposed ESP-32-based quadruped surveillance robot*

5 GAIT PLANNING AND SERVO CONTROL

The robot uses a four-phase crawl gait, where only one leg moves at a time while the other three legs remain on the ground. This approach maintains stability during movement. Each leg is modelled as a two-link planar mechanism with link lengths 1and 2.

The foot position is defined as:

$$x = L1\cos\theta 1 + L2\cos(\theta 1 + \theta 2)\ y = L1\sin\theta 1 + L2\sin(\theta 1 + \theta 2)$$

Due to the computational limitations of the ESP32, joint angles are generated using pre-computed interpolation instead of real-time inverse kinematics.

5.1 EMBEDDED VISION AND FACE DETECTION

The ESP32-CAM module performs face detection using lightweight algorithms optimised for embedded systems. The robot can store up to three registered users, and unknown identities trigger alerts through the Telegram interface. Due to the memory and processing limitations of the ESP32 platform, lightweight face detection algorithms are used instead of deep neural network–based recognition frameworks. Experimental results showed an average face detection accuracy of 88% under controlled indoor conditions.

5.2 WIRELESS MONITORING AND CONTROL

Wi-Fi connectivity enables remote control and alert notifications through a Telegram bot interface. User commands are mapped to predefined robot actions such as forward, backwards, sit, stand, dance, and wave. Experimental tests over 60 trials achieved a 95% command execution success rate with an average control latency of 180 ms.

6. EXPERIMENTAL EVALUATION AND RESULTS

Experimental testing was carried out to evaluate the robot's navigation reliability, perception performance, communication latency, and operational stability under indoor conditions. The ultrasonic-based obstacle avoidance system was tested over 60 trials using a threshold distance of 15 cm.

***Table 2**. Experimental performance metrics of the proposed quadruped survey- lance system.*

Parameter	Measured value
Obstacle detection range	3-200cm
Obstacle avoidance accuracy	93%
Average walking speed	0.12m/s
Gait switching response time	0.45s
MQTT command latency	180ms
Video streaming latency	350ms
Face detection accuracy	88%
Command execution success	95%
Continuous operation time	35 min

The system achieved an obstacle avoidance accuracy of 93%, with an effective detection range between 3 cm and 200 cm. The average gait transition response time during directional changes was 0.45 seconds. Face detection performance was evaluated using three registered identities under indoor lighting conditions.

The ESP32-CAM module achieved an average detection accuracy of 88%, and unknown faces triggered alert notifications through the Telegram interface. The system achieved a 95% command execution success rate, with an average remote command latency of 180 ms. Additionally, live video streaming from the camera module showed an average delay of approximately 350 ms.

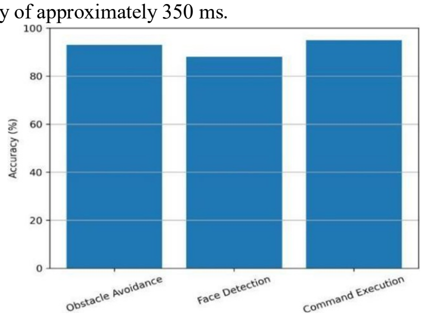

Fig. 4. Experimental performance metrics of the proposed quadruped surveillance system.

The robot maintained stable locomotion while carrying an additional 200 g payload and operated continuously for approximately 35 minutes using a 7.4 V, 2200 mAh Li-ion battery. The overall performed results are summarised in Table 1, while subsystem reliability is illustrated in Fig. 3. The obstacle avoidance module demonstrated high navigation accuracy during testing. The embedded face detection system provided reliable identification under indoor conditions. Communication experiments showed stable remote interaction with low command latency.

7. CONCLUSION

In this paper a compact ESP32-based quadruped spider robot is designed and experimentally tested for use in indoor surveillance applications. Experimental evaluation demonstrated reliable system performance with 93% obstacle avoidance accuracy, 88% face detection accuracy, and 95% command execution success across 60 experimental trials. The robot achieved stable locomotion with an average speed of 0.12 m/s and maintained continuous operation for approximately 35 minutes using a 7.4 V Li-ion battery. The results confirm that the integration of locomotion, perception, and communication modules within a resource-constrained embedded platform is feasible for indoor monitoring tasks. Future work may focus on improving gait efficiency, extending face recognition capability beyond limited stored identities, and optimising power management to increase operational endurance.

REFERENCES

1. Raibert, M., Blankespoor, K., Nelson, G., Playter, R.: BigDog, the rough-terrain quadruped robot. *Proceedings of the 17th World Congress of the International Federation of Automatic Control*, Seoul, Korea, pp. 10822–10825 (2008).
2. Kalakrishnan, M., Buchli, J., Pastor, P., Mistry, M., Schaal, S.: Learning, planning, and control for quadruped locomotion over challenging terrain. *International Journal of Robotics Research*, 30(2), 236–258 (2011).
3. Semini, C., Tsagarakis, N.G., Guglielmino, E., Focchi, M., Canella, F., Caldwell, D.G.: Design of HyQ – a hydraulically and electrically actuated quadruped robot. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, 225(6), 831–849 (2011).
4. Hutter, M., Gehring, C., Jud, D., Lauber, A., Bellicoso, C.D., Tsounis, V., Hwangbo, J., Bodie, K., Fankhauser, P.: ANYmal – a highly mobile and dynamic quadrupedal robot. *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 38–44 (2016).
5. Katz, B., Carlo, J.D., Kim, S.: Mini Cheetah: A platform for pushing the limits of dynamic quadruped control. *IEEE Interna- tional Conference on Robotics and Automation (ICRA)*, pp. 6295–6301 (2019).
6. Redmon, J., Farhadi, A.: YOLOv3: An incremental improve- ment. *arXiv preprint arXiv:1804.02767* (2018).
7. Viola, P., Jones, M.: Rapid object detection using a boosted cas- cade of simple features. *IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR)*, pp. 511–518 (2001).
8. Banks, A., Gupta, R.: MQTT Version 3.1.1. *OASIS Standard*, OASIS Open (2014).
9. Light, R.: Mosquitto: server and client implementation of the MQTT protocol. *Journal of Open Source Software*, 2(13), 265 (2017).
10. Espressif Systems: ESP32 Series Datasheet. Espressif Systems, Shanghai (2023).
11. Zhang, K., Zhang, Z., Li, Z., Qiao, Y.: Joint face detection and alignment using multitask cascaded convolutional networks. *IEEE Signal Processing Letters*, 23(10), 1499–1503 (2016).
12. Ghori, M.R., Wan, T.-C., Sodhy, G.C.: Bluetooth Low Energy Mesh Networks: Survey of Communication and Security Protocols**.** *Sensors*, 20(12), 3590 (2020)
13. Nagireddy, S., Venkata Rajasekhar Reddy, P., Padmaja, P., Mahdal, M., Seerangan, S., Vimal, V., Talasila, V., Cepova, L.: Hybrid fuzzy rule algorithm and trust planning mechanism for robust trust management in IoT-embedded systems integration. Mathematics 11(11), 2546 (2023). https://doi.org/10.3390/math11112546
14. Bharathiraja, N., Padmaja, P., Rajeshwari, S.B., Kallimani, J.S., Ahmed, M., Buttar, M., BheemaLingaiah, T.: Elite oppositional farmland fertility optimisation based node localization tech- nique for wireless networks. Wireless Communications and Mobile Computing, Article ID 5290028 (2022). https://doi.org/10.1155/2022/5290028
15. Sreenivasulu, M., Ashok, J., Godi, R.K., Padmaja, P., Ag- garwal, P.K., Kapila, D.: A novel framework for optimising the edge network node for wearable devices. Measurement: Sensors 27, 100740 (2023). https://doi.org/10.1016/j.measen.2023.100740