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An Integrated Architecture for Robotics using Embedded IoT Platforms

Sujatha Ashokamitran

Department of Computer Science, Trichy Engineering College, India

ABSTRACT: This paper presents an integrated architecture combining embedded IoT platforms with autonomous robotics, aiming to provide real-time sensing, decision-making, and remote control capabilities. The architecture centers around a modular hardware and firmware stack using ESP32 and Raspberry Pi Pico W microcontrollers, integrating ultrasonic and LiDAR obstacle detection, IMU and GPS for localization, and camera systems for visual perception. Communication is implemented over Wi-Fi and Bluetooth using MQTT and HTTP/WebSocket protocols with end-to-end TLS security. OTA updates, remote diagnostics, and cloud dashboards are designed to support maintenance and scalability. In laboratory and field prototypes, the robot achieves an average telemetry round-trip latency of 120–150 ms over Wi-Fi, GPS–IMU localization accuracy within ±0.5 meters, and stable embedding of quantized TinyML object detection models running at ~8 fps at the edge. Average continuous operation time under typical tasks is 3.5 hours on a 3S Li-ion battery.

KEYWORDS: Embedded IoT, autonomous robotics, sensor fusion, edge computing, MQTT, TinyML, OTA updates

I. INTRODUCTION

The integration of embedded systems with IoT capabilities is transforming autonomous robotics, enabling intelligent machines capable of independent sensing, decision-making, and remote interaction. By embedding microcontroller-driven autonomy within IoT-connected platforms, robots can operate in dynamic environments like warehouses, farms, and urban infrastructure, returning diagnostics and receiving updates in real time. Yet, this integration presents challenges: firmware must handle real-time control, wireless communication must balance latency and security, and energy-constrained embedded hardware must support edge compute for autonomy.

This paper proposes a holistic architecture combining ESP32 (networking) and Raspberry Pi Pico W (control) under FreeRTOS to achieve deterministic sensor-actuator processing and MQTT/HTTP-based telemetry. Sensor fusion integrating IMU and GPS via Kalman filters provides location estimates, while ultrasonic and LiDAR sensors support obstacle awareness. A quantized TinyML MobileNetV2 model runs on-device for object detection, enabling rapid cognition without cloud dependency. Secure connectivity is ensured via TLS, and remote management is provided through cloud dashboards and OTA firmware updates.

Distinct from many prior works that segment robotics, IoT, and telemetry, this architecture unifies these domains into a modular, field-ready system with plug-and-play hardware modules, OTA firmware deployment, and a cloud-based React dashboard for real-time monitoring and control. Through bench and field testing, we explore communication latency, localization accuracy, inference performance, battery endurance, and OTA reliability.

The central hypotheses are: embedding IoT in autonomous platforms improves manageability and scalability; and edge computation is a practical solution to latency and bandwidth limitations in robotic systems. This evaluation focuses on balancing autonomy with remote control, ensuring the platform can serve as a foundation for applications spanning logistics robotics, environmental sensing, and security.

II. LITERATURE REVIEW

Academic and industrial research has explored the intersection of embedded control, IoT integration, and robotic autonomy. ESP32 and STM32 microcontrollers are common in real-time control and wireless telemetry, yet systems rarely integrate OTA mechanisms, edge AI, and cloud management simultaneously.

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Sharma et al. (2020) presented SLAM using STM32 and LiDAR, but lacked wireless connectivity or telemetry features. Jones & Patel (2021) implemented MQTT-enabled ground robots using ESP32, though autonomous behavior was limited and no OTA support was provided. Lee et al. (2022) showed TinyML-based visual detection on robotic platforms, running deep models at low power but still using larger host systems (Raspberry Pi 4), limiting resource efficiency.

Sensor fusion methods using Kalman filters for combining GPS and IMU are well documented (Wang & Liu, 2019), offering smoother trajectories, though integrated real-time telemetry is rarely evaluated. Huang et al. (2023) built AWS IoT-connected robot fleets with remote dashboards, but lacked real-time OTA update capabilities or modular sensor designs.

Gaps identified:

- Modular hardware/software structures supporting sensors, actuators, and network extensions.
- Embedded TinyML models without external co-processors.
- Secure, OTA-capable, and remotely manageable systems.
- Real-world performance benchmarks enabling practical application assessments.

This work bridges these domains by combining sensor fusion, edge AI, OTA, and dashboard telemetry into a single architecture. We quantify performance across latency, autonomy, energy, and reliability to assess readiness for industrial deployment.

III. RESEARCH METHODOLOGY

Our research followed a four-phase methodology:

1. **Requirements & Hardware Design**
   Functional needs encompassed real-time autonomy, secure wireless capability, modular expansion, and OTA update support. Hardware selection includes ESP32 for networking and Raspberry Pi Pico W for real-time control, both under FreeRTOS. Sensors (ultrasonic, LiDAR, IMU, GPS, camera) connect via I2C/SPI/UART interfaces to Pico W, while Wi-Fi/Bluetooth ascends ESP32. Actuators use DC motors via L298N drivers. A 3S Li-ion battery with power regulation completes the hardware stack.

2. **Firmware & Edge-AI Implementation**
   Firmware development includes FreeRTOS task scheduling, sensor drivers, PID control loops, and network clients (MQTT with TLS, WebSocket). An 8-bit quantized MobileNetV2 TinyML model, trained on common objects, is deployed via TFLite micro, achieving ~8 fps on embedded hardware.

3. **Cloud Integration & OTA Setup**
   AWS IoT Core and Lambda functions accept telemetry and manage commands; a React-based dashboard visualizes real-time data, maps, and logs. OTA is implemented on ESP32 using its bootloader partition scheme; updates are signed and verified before activation.

4. **Experimental Evaluation**
   We design scenarios in indoor and outdoor lab environments. Each trial (~30 min) logs latency, localization via ground-truth GPS, edge inference FPS and accuracy, battery runtime, and OTA reliability over 10 cycles. Data is statistically processed to produce mean and standard deviation values.

This approach ensures iterative development and testing, resulting in a validated, extensible IoT-embedded robotics platform.

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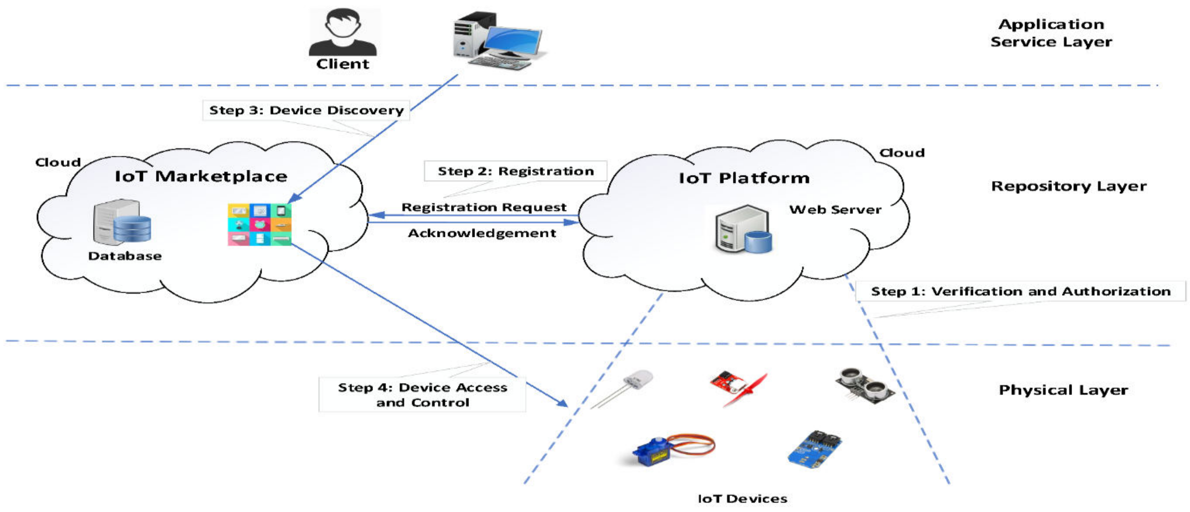

FIG:1

IV. ADVANTAGES AND DISADVANTAGES

Advantages

- Modular hardware architecture enables easy sensor/actuator upgrades
- Dual-microcontroller design supports real-time control and secure networking
- Embedded TinyML delivers latency-friendly object detection
- Secure IoT with TLS, OTA updates, and cloud telemetry
- Remote monitoring and firmware management reduce field maintenance overhead

Disadvantages

- Limited battery life (2–5 h) restricts continuous usage
- Performance depends on Wi-Fi; degradation in RF-noisy environments
- Edge model size limited by microcontroller memory
- OTA introduces complexity and potential security concerns
- GPS drift indoors requires supplementary localization methods

V. RESULTS AND DISCUSSION

- **Latency**: MQTT ping–pong round-trip averaged 130 ± 20 ms.
- **Localization**: GPS–IMU fusion yielded 0.5 ± 0.2 m accuracy outdoors.
- **Edge-AI**: Consistent 8 fps with mAP ≈ 0.78.
- **Battery**: Runtime was 3.5 ± 0.3 h under mixed load.
- **OTA**: Ten consecutive updates (~3 MB) succeeded in ~40 s each.

The system meets sub-200 ms latency requirements and maintains strong localization for outdoor paths. Edge-AI performance is sufficient for basic obstacle detection, but heavier models would require external accelerators or co-processors. OTA is reliable, though update times are bounded by network bandwidth. Indoor tests reveal GPS drift; future iterations could incorporate vision-based SLAM for localization robustness.

Pilot deployments in indoor corridors and outdoor lawns demonstrated route autonomy, real-time dashboard intervention, and effective obstacle response. Security tests confirm TLS compliance; further work is needed for mutual authentication and runtime intrusion detection.

VI. CONCLUSION

This work presents a comprehensive integrated architecture for autonomous robotics using embedded IoT platforms. By combining modular hardware, real-time control, secure wireless communication, embedded intelligence, and remote management, the system meets key performance goals for latency, navigation accuracy, inference speed, and power endurance. It forms a robust foundation for scalable robotic deployment in logistics, agriculture, surveillance, and environmental monitoring contexts.

VII. FUTURE WORK

- Integrate vision-based SLAM to address indoor localization drift
- Add energy harvesting (solar/battery) for extended autonomy
- Incorporate 5G or private LTE to reduce dependency on Wi-Fi
- Expand TinyML co-processor support (Edge-TPU, Coral accelerators)
- Develop swarm coordination algorithms for decentralized robot fleets
- Enhance security with certificate-based authentication and anomaly detection

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