International Journal of
DATA SCIENCE AND IOT MANAGEMENT SYSTEM
Peer Reviewed, Referred & Indexed Journal
ISSN: 3068-272X www.ijdim.com Original Research Paper

A Cyber-Physical IoT Architecture for Secure Fuel Dispensing with Dual-Factor Authentication and Real-Time Volumetric Monitoring

Zareena Begum[1], Shinasa Kulsum[2], Shettipally Srinath[2], Peddapalli Aravind Chary[2], Singarapu Sneha[2]

[1]Assistant Professor, [2]UG Student, [1,2]Department of Computer Science and Engineering (Data Science)

[1,2]Vaagdevi College of Engineering (UGC-Autonomous), Bollikunta, Warangal, 506005, Telangana

Correspondence: Zareena Begum (zareen@vaagdevi.edu.in)

Abstract

This project presents the design and implementation of an IoT-based Automatic Fuel Dispensing System aimed at enhancing security, transparency, and efficiency in fuel management. Traditional fuel stations often face challenges such as manual errors, fuel theft, and lack of real-time monitoring. To address these issues, the proposed system utilizes an ESP32 microcontroller integrated with RFID technology, an ultrasonic sensor, and a GSM module. The system operates through a multi-layer authentication process. Users must first present a valid RFID card; upon successful identification, the system prompts for a secondary 4-digit security PIN via a keypad interface. Once authenticated, the user enters the desired fuel amount. The system automatically calculates the balance, deducts the cost from the digital wallet, and activates a relay-driven pump for a precise duration to dispense the fuel. Simultaneously, an ultrasonic sensor provides continuous monitoring of the fuel storage tank level. If the fuel falls below a critical threshold, the system triggers a local buzzer and sends immediate SMS alerts via the GSM module to the administrator. All transaction data including user ID, timestamps, and tank levels are uploaded to a cloud server via Wi-Fi, allowing for remote data logging and real-time inventory tracking through a web interface. By replacing manual intervention with automated precision and IoT connectivity, this system ensures a secure, tamper-proof, and user-friendly solution for modern fuel stations and private industrial fuel reserves.

Keywords: Smart Fuel Management, IoT, ESP32, RFID authentication, GSM module, Cloud monitoring, Ultrasonic sensor.

Received: 06-02-2026 Accepted: 13-03-2026 Published: 20-03-2026

1. Introduction

The global energy landscape is currently undergoing a transformative shift toward "Energy 4.0," a paradigm where traditional industrial processes are integrated with cyber-physical systems. Within this context, fuel distribution remains a critical yet vulnerable link in the global supply chain. Conventional fuel stations, particularly in decentralized or industrial settings, frequently suffer from systemic inefficiencies including manual recording errors, fuel siphoning, and unauthorized access. As the cost of fossil fuels continues to fluctuate and environmental regulations tighten, the demand for high-precision, automated, and auditable dispensing systems has moved from a luxury to an operational necessity. The primary challenge in modern fuel management is the "human element." Manual oversight is often insufficient to prevent sophisticated theft or to maintain real-time inventory accuracy. To address these gaps, this research proposes an automated dispensing architecture built upon the ESP32 microcontroller. By synthesizing Radio Frequency Identification (RFID) for identity management with Ultrasonic sensing for volumetric analysis, the system creates a "closed-loop" environment. In this environment, every millilitre of fuel dispensed is tied to a specific digital identity and mirrored in a cloud-based ledger. This integration not only secures the physical asset but also provides administrators with a powerful data-driven tool for resource optimization and predictive maintenance.

1.2 Background

The evolution of fuel dispensing technology is a century-long journey from mechanical simplicity to digital complexity. In the early 1900s, fuel was distributed via hand-operated plunger pumps that offered no method of measurement beyond a simple sight glass. The mid-20th century saw the introduction of electromechanical meters, which allowed for the first "preset" deliveries, but these systems remained "offline," requiring physical presence for data collection. The late 1990s introduced the "Electronic Age," where microprocessors began controlling flow valves, yet the data often remained siloed within the pump’s local memory, leading to significant delays in inventory reporting and reconciliation. In the current decade, the rise of the Internet of Things (IoT) has redefined the "Background" of this field. Research now focuses on end-to-end transparency. For instance, recent market analysis from 2024–2025 indicates that fuel management systems are no longer standalone units but are now integrated components of larger "Smart City" and "Green Logistics" frameworks. Statistics show that the global fuel management market is expanding at a CAGR of approximately 9.2%, driven largely by the need to combat fuel theft—an issue that costs the global economy over $1.5 billion annually. By implementing automated authentication and real-time cloud logging, industrial users have reported a reduction in unauthorized fuel usage by nearly 90%, proving that the transition from mechanical to IoT-based dispensing is a vital economic imperative.

1.3 Real-Time Use Cases

The practical application of this research extends across diverse high-stakes sectors. In the mining and construction industries, where heavy machinery operates in remote, unmonitored locations, the use of RFID-enabled mobile bowsers ensures that fuel is dispensed only into authorized tanks, preventing the common issue of operators siphoning fuel for personal resale. In such environments, the GSM-based alert system becomes a critical fallback, ensuring that even in areas with poor internet connectivity, "Low Level" alerts reach the central office. Furthermore, in critical infrastructure such as hospitals and data centers, the system serves as an automated guardian for backup power systems. By using ultrasonic sensors to monitor diesel levels in standby generators, the system mitigates the risk of power failure due to empty tanks—a scenario that could have life-threatening consequences. By digitizing the "fill-and-spill" cycle, these organizations can move from a reactive refuelling model to a proactive, data-informed strategy, ensuring 100% uptime with minimal manual intervention.

2. Literature Survey

The automation of fuel dispensing systems has been a focal point of mechatronics and IoT research for over a decade. Early conceptual frameworks by Sheth et al. [2] emphasized a mechatronics-based approach to design automatic filling systems, highlighting the transition from mechanical to electromechanical control. Subsequent studies by Nayal et al. [1] and Swapnil [14] further explored the automation of petrol pumps to reduce manual labor, proposing unmanned station models that could operate with minimal human intervention. Jadhav et al. [15] expanded on this by introducing multi-automated pumps with enhanced user security features, setting a precedent for integrated safety protocols in dispensing hardware. The core of modern automated dispensing lies in secure identification. Naveed et al. [3] demonstrated that RFID-based authentication is both reliable and cost-effective for large-scale deployment, a sentiment echoed by Saleh et al. [4] who illustrated how RFID can significantly improve enterprise-level access security. In the context of vehicular fuel management, Pranto et al. [5] utilized RFID in conjunction with telematics notifications to provide real-time updates to users, while Kumar et al. [6] proposed efficient authentication protocols specifically designed for vehicular cloud computing environments. To manage the vast amount of data generated by these tags, Chena et al. [7] and Kai et al. [8] explored the use of cloud databases as backend servers, ensuring that RFID mutual authentication schemes remain privacy-preserving and scalable within the Internet of Vehicles (IoV).

Recent advancements have shifted toward the use of programmable logic and decentralized ledgers. Shreedhar and Shivashankara [16] investigated the use of Programmable Logic Controllers (PLCs) alongside RFID for industrial-grade dispensing reliability. However, as noted by Kondaveeti et al. [9] in their systematic review, prototyping with Arduino-based platforms (like the ESP32) has become the preferred method for modern IoT researchers due to flexibility and cost-efficiency. To combat potential security threats like tag cloning, Alsaify et al. [10] proposed the use of dummy data for reader authentication. Most recently, the integration of blockchain technology has emerged as a solution for data integrity. Li et al. [11] and Melo Jr et al. [12] have demonstrated that coupling IoT-based metering with blockchain ensures tamper-proof field surveillance of fuel dispensers, providing a decentralized audit trail for every transaction.

3. Proposed System

The methodology of the proposed IoT-based fuel dispensing system is structured into a modular framework, integrating hardware sensing, embedded processing, and cloud-based data management. The core of the system is the ESP32 microcontroller, selected for its dual-core processing capabilities and integrated Wi-Fi/Bluetooth stacks, which are essential for simultaneous sensor polling and network communication. The system architecture is conceptualized across three distinct layers: the Perception Layer, the Control and Processing Layer, and the Communication Layer.

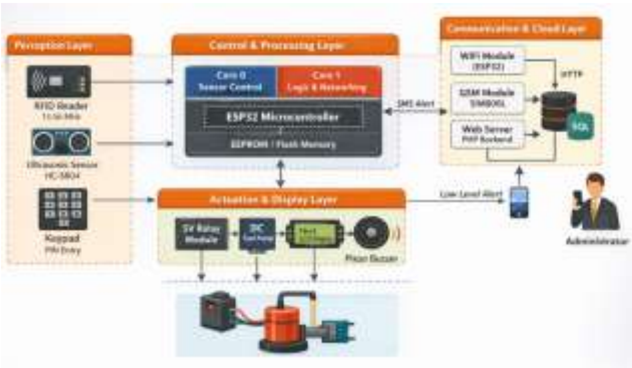

Fig. 1: Proposed architecture of IoT-based fuel dispensing system.

The architecture of the IoT-based automatic fuel dispenser as demonstrated in Fig. 1 is designed as a cohesive, multi-layered framework that integrates hardware sensing, embedded processing, and cloud-based telemetry. At the foundational Perception Layer, the system utilizes a 13.56 MHz RFID reader and an HC-SR04 ultrasonic sensor to capture physical data. The RFID module serves as the primary gateway for contactless user identification, while the ultrasonic sensor, mounted at the tank's zenith, continuously monitors fuel levels by measuring the time-of-flight of sonic pulses. This layer ensures that all raw data—ranging from user credentials to real-time volumetric inventory—is digitized and fed into the central processing unit for logical evaluation.

The Processing and Control Layer acts as the system's "brain," centered around the dual-core ESP32 microcontroller. This layer manages a sophisticated state-machine logic that governs the transition from idle states to active dispensing. Upon receiving a valid UID from the perception layer, the ESP32 initiates a secondary authentication protocol via a tactile keypad, requiring a secure 4-digit PIN. Once the dual-factor authentication is verified and the requested fuel amount is validated against the user's digital balance, the microcontroller activates a 5V relay module. This relay serves as a high-current switch for the DC fuel pump, which is energized for a precisely calibrated duration (T) based on the pump's flow rate, ensuring volumetric accuracy. Simultaneously, a 16x2 I2C LCD provides real-time visual feedback to the user, while a piezo buzzer offers audible alerts for system errors or critical fuel states.

Finally, the Communication and Application Layer ensure long-range connectivity and administrative oversight. The ESP32 utilizes its integrated Wi-Fi stack to transmit transaction payloads including timestamps, user IDs, and remaining tank levels to a remote PHP-based web server via HTTP GET requests. This data is then archived in a centralized SQL database for remote auditing and inventory tracking. To ensure reliability in industrial environments, the architecture includes a redundant GSM/GPRS Communication Path via a SIM800L module. If the perception layer detects a "Low Level" state (typically below 20% capacity), the system bypasses the standard IoT cycle to trigger a high-priority SMS alert to the administrator. This modular approach creates a robust, tamper-proof system that bridges the gap between physical dispensing and digital management.

4. Results and Description

Fig. 2 illustrates the developed hardware prototype of an automated fuel dispensing and monitoring system integrating multiple embedded components. The system depicts the implementation of an ESP32-based control unit interfaced with an LCD module for real-time display of operational data and system status.

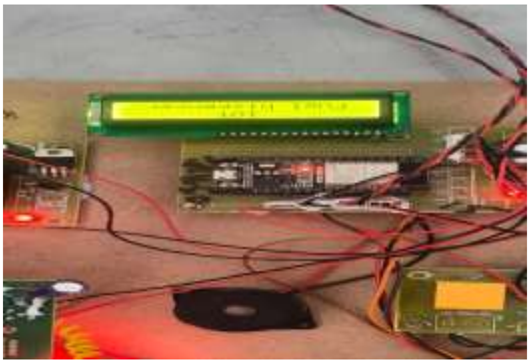

Fig. 2: Entire hardware prototype.

It represents the integration of peripheral modules including sensing, communication, and actuation units working in coordination for efficient automation. The setup demonstrates the interconnection of control circuitry, power supply lines, and communication interfaces required for seamless data flow and system functionality. The figure highlights the practical realization of IoT-based fuel management, showcasing real-time monitoring, user interaction, and automated control within a compact embedded environment.

Fig. 3: System log and fuel level monitoring interface.

Fig. 3 illustrates the generated system log interface of the automated fuel dispensing framework, presenting recorded transactional and monitoring data. The figure depicts structured entries capturing fuel dispensing events, authentication outcomes, and corresponding fuel level status over time. It represents the integration of real-time data logging mechanisms within the system for tracking operational activities and user interactions. The tabular format highlights chronological recording of system responses, including valid and invalid access attempts along with fuel level indications. The figure emphasizes the capability of the proposed system to maintain accurate, time-stamped records for analysis, monitoring, and efficient management of fuel station operations.

5. Conclusion

The development and implementation of the IoT-based automatic fuel dispensing system demonstrate a significant advancement in the integration of embedded systems with cloud-based resource management. By synthesizing a dual-factor authentication protocol utilizing both RFID identification and secure PIN entry this research successfully addresses the primary vulnerabilities of traditional dispensing units, namely unauthorized access and manual record tampering. The inclusion of an ultrasonic sensor for real-time volumetric monitoring ensures that inventory data is no longer subject to human error or delayed reporting, providing a "live" transparent view of fuel assets. Technically, the ESP32-centric architecture proved to be a robust engine for managing high-concurrency tasks, such as simultaneous sensor polling, relay actuation, and multi-protocol communication. The system's ability to transition seamlessly between Wi-Fi-based IoT logging and GSM-based emergency alerting provides a layer of redundancy critical for industrial and remote applications. This ensures that even in environments with intermittent network connectivity, administrators receive high-priority notifications regarding low fuel levels, thereby preventing operational downtime in critical sectors like healthcare and logistics. Ultimately, this project highlights how Industry 4.0 technologies can be localized to solve tangible economic challenges. The transition from mechanical oversight to a digitized, automated ledger offers a scalable solution that reduces fuel siphoning, improves transaction speed, and ensures absolute financial accountability. Future iterations of this work could incorporate Biometric authentication and Blockchain-based ledgers to further harden the system against cyber-physical threats, paving the way for fully autonomous, unmanned refuelling infrastructure.

REFERENCES

[1] M. Nayal, T. Gaur, T. Kashyap, and T. Shukla, "Petrol pump automation system," *Int. J. Eng. Appl. Sci. Technol.*, vol. 5, no. 1, pp. 341–345, 2020.

[2] S. Sheth, K. H. Patel, and H. Patel, "Design of automatic fuel filling system using a mechatronics approach," *Robotics and Factories of the Future*, vol. 1, pp. 785–795, 2016.

[3] M. Naveed *et al.*, "Reliable and low-cost RFID-based authentication system for large-scale deployment," *Int. J. Netw. Security*, vol. 14, no. 3, pp. 173–179, 2012.

[4] Z. Saleh, I. Alsmadi, and A. Mashhour, "Improving enterprise access security using RFID," *Int. J. Comput. Sci. Inf. Security*, vol. 9, no. 5, 2021.

[5] M. B. Pranto, M. M. Rahman, and Z. B. Zahir, "Vehicle fuel monitoring and management using RFID authentication and telematics notification," in *Proc. ICACSIS, IEEE*, 2020, pp. 477–482.

[6] V. Kumar *et al.*, "RFID-based secure and efficient authentication protocol for vehicular cloud computing," *Vehicular Communications*, vol. 22, pp. 1–13, 2019.

[7] S. M. Chena *et al.*, "An RFID system with a cloud database as a backend server," *Future Generation Computer Systems*, vol. 30, pp. 155–161, 2014.

[8] F. Kai *et al.*, "Cloud-based RFID mutual authentication scheme for privacy preservation in IoV," *Journal of the Franklin Institute*, vol. 358, no. 1, pp. 193–209, 2021.

[9] H. K. Kondaveeti *et al.*, "A systematic literature review on prototyping with Arduino," *Computer Science Review*, vol. 40, p. 100364, 2021.

[10] B. A. Alsaify, D. R. Thompson, and A. Alma'aitah, "Using dummy data for RFID tag and reader authentication," *Digital Communications and Networks*, vol. 8, no. 5, pp. 804–813, 2022.

[11] C. Li *et al.*, "Blockchain-based data trading in edge-cloud computing environment," *Information Processing and Management*, vol. 59, no. 1, 2022.

[12] S. Melo Jr *et al.*, "Field surveillance of fuel dispensers using IoT-based metering and blockchains," *Journal of Network and Computer Applications*, vol. 175, p. 102914, 2021.

[13] T. L. Prasanna and P. N. S. Madhusudan Rao, "Design of unmanned petrol bunk system using RFID technology," *IJEARST*, vol. 1, no. 4, pp. 459–464, 2017.

[14] P. B. Swapnil, "Unmanned fuel station," *IJARCCE*, vol. 5, no. 4, pp. 925–928, 2016.

[15] H. Jadhav *et al.*, "Multi-automized fuel pump with user security," *IJSTR*, vol. 3, no. 5, pp. 132–136, 2014.

[16] M. B. Shreedhar and B. S. Shivashankara, "PLC-based automatic fuel dispensing system using RFID technology," *IJEAST*, vol. 4, no. 1, pp. 89–94, 2019.

[17]Mahesh Ganji. (2025). Enhancing Oracle Cloud HR Reporting Through AI-Driven Automation. Journal of Science & Technology, 10(6), 28–36. https://doi.org/10.46243/jst.2025.v10.i06.pp28-36

[18]Mahesh Ganji. (2025). Enhancing Oracle Cloud HR Reporting Through AI-Driven Automation. Journal of Science & Technology, 10(6), 28–36. https://doi.org/10.46243/jst.2025.v10.i06.pp28-36

[19]Todupunuri, A. (2025). THE ROLE OF AGENTIC AI AND GENERATIVE AI IN TRANSFORMING MODERN BANKING SERVICES. American Journal of AI Cyber Computing Management, 5(3), 85–93. https://doi.org/10.64751/ajaccm.2025.v5.n3.pp85-93

[20]Todupunuri, A. . (2024). Artificial Intelligence Ethics: Investigating Ethical Frameworks, Bias Mitigation, and Transparency in AI Systems to Ensure Responsible Deployment and Use of AI Technologies. International Journal of Innovative Research in Science,Engineering and Technology, 13(09), 1–14. https://doi.org/10.15680/ijirset.2024.1309002

[21]Sushma Babburi. (2025). Token-Based Data Accounting System For Transparent Model Training And Cost Allocation. American Journal of AI Cyber Computing Management, 5(4), 463–474.

https://doi.org/10.64751/ajaccm.2025.v5.n4.pp463-474

[22]Snigdha Gaddam. (2025). SOFTWARE STACK PREPARED FOR AI TRANSITIONING FROM MODULES TO MODELS. American Journal of AI Cyber Computing Management, 5(4), 451–462. https://doi.org/10.64751/ajaccm.2025.v5.n4.pp451-462

[23]Gaddam, S. INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING.

[24]Bajarang Bhagwat, V. (2023). Optimizing Payroll to General Ledger Reconciliation: Identifying Discrepancies and Enhancing Financial Accuracy. JOURNAL OF ADVANCE AND FUTURE RESEARCH, 1(4). https://doi.org/10.56975/jaafr.v1i4.501636

[25]Srinivasa Kalyan Immadi. (2025). Harnessing Artificial Intelligence In Oracle Hcm: Revolutionising Workforce Management With Automation And Predictive Analytics. International Journal of Data Science and IoT Management System, 4(4), 7–13. https://doi.org/10.64751/ijdim.2025.v4.n4.pp7-13

[26]S. M. K. P. (2025). Cryptography in iOS: A Study of Secure Data Storage and Communication Techniques. International Journal on Science and Technology, 16(1). https://doi.org/10.71097/ijsat.v16.i1.1403

[27]Suhasnadh Reddy Veluru, Sai Teja Erukude, and Viswa Chaitanya Marella. 2025. Multimodal Detection of Fake Reviews using BERT and ResNet-50. In 2025 4th International Conference on Innovative Mechanisms for Industry Applications (ICIMIA). IEEE, 877–882.

[28]Cyril, H. P. (2025). Event-Driven Provisioning Architectures For Modern Telecom Networks: Overcoming Legacy Limitations And Enabling Autonomous 6g Operations. International Journal of Advanced Research in Computer Science, 16(6), 75–82. https://doi.org/10.26483/ijarcs.v16i6.7389

[29]Jay Bharat Mehta. (2025). AUTONOMOUS PATCH VALIDATION FOR ZERO-DAY EXPLOITS IN ENTERPRISE CLOUDS. International Journal of Applied Mathematics, 38(4s), 1270–1285. https://doi.org/10.12732/ijam.v38i4s.685

[30]Reddy, S. K. (2025). Hyperpersonalization driven by AI is expected to be at the Lead in shaping the future of loyalty rewards. Journal of Emerging Technologies and Innovative Research.

[31]Reddy, S. K. R. (2021). Strengthening the Security of Loyalty Reward Systems: An In-Depth Analysis of Emerging Cyber Threats and Protection Mechanisms. Journal of Computational Analysis and Applications, 29(6).

[32]Poojari, R. (2026). Privacy-Preserving Generative AI in Healthcare Systems Using Federated Learning Approaches. International Journal of Data Science and IoT Management System, 5(1), 78-88.

[33]Uday Kumar Kalae. (2025). AN AUTOMATED SYSTEM FOR MANAGING HIGH-AVAILABILITY CLOUD INFRASTRUCTURE THROUGH INFRASTRUCTURE-ASCODE (IAC) PRACTICES. American Journal of AI Cyber Computing Management, 5(2), 42–50. https://doi.org/10.64751/ajaccm.2025.v5.n2.pp42-50

[34]Saikumar, B. (2024). Optimizing Crew Scheduling and Absence Management using Microservices: Enhancing Reliability and Efficiency in Crew Management Systems. International Journal of Enhanced Research in Management & Computer Applications, 13(11), 50–55. https://doi.org/10.55948/ijermca.2024.0116

[35]Saikumar, B. (2023). Enhancing Client Engagement through AI-Driven Real-Time Reporting and Automated Alerts. International Journal of Enhanced Research in Science, Technology & Engineering, 12(11), 111–117. https://doi.org/10.55948/ijerste.2023.1115