

Smart IoT-Enabled Solar-Powered Automated Car Wash System

Adsure Atharv Sandip¹, Kakad Anuj Sopan², Punde Atharva Ramesh³,
Shinde Prasad Chandrakant⁴, Prof. P. B. Wakchaure⁵

^{1,2,3,4,5} UG Scholars, Dept. of Automation and Robotic Engineering,
Amrutvahini College of Engineering, Sangamner, India

Abstract: This paper presents the design, development, and evaluation of a Smart IoT-Enabled Solar-Powered Automated Car Wash System — an intelligent, eco-friendly vehicle cleaning solution that integrates the Internet of Things (IoT), computer vision, embedded systems, and renewable solar energy. Conventional car washing systems suffer from high water and electricity consumption, reliance on manual labor, and lack of real-time monitoring. The proposed system addresses these limitations by employing an ESP32 microcontroller as the central control unit, an ESP32-CAM for adaptive dirt detection using HSV color-space segmentation, and IoT platforms (Blynk and ThingSpeak) for remote monitoring and control. A 100W solar panel with a PWM charge controller and 12V battery bank provides a sustainable energy source. QR-code-based authentication ensures secure user access. Experimental results demonstrate up to 70% reduction in water usage, 60% reduction in wash duration, 91% dirt detection accuracy, and complete elimination of manual labor — validating the system as a scalable and sustainable alternative to traditional car washing methods.

Keywords: IoT, ESP32, Car Wash Automation, Solar Energy, Computer Vision, Dirt Detection, Blynk, ThingSpeak, QR Authentication, Sustainable Automation.

I. INTRODUCTION

The rapid expansion of the global automobile industry has created an escalating demand for efficient, affordable, and sustainable vehicle maintenance solutions. With millions of vehicles requiring regular cleaning, traditional car washing methods — primarily manual and semi-automated — are becoming increasingly inadequate. These methods are characterised by heavy reliance on unskilled labor, inconsistent cleaning quality, excessive consumption of water and grid electricity, and a complete absence of intelligent monitoring capabilities.

The emergence of the Internet of Things (IoT), embedded computing, and renewable energy technologies has opened new avenues for intelligent automation in everyday industrial applications. Smart automation systems can now adaptively respond to environmental conditions, transmit real-time operational data to cloud platforms, and be remotely monitored and controlled — all while operating on green energy sources such as solar power.

This research proposes a fully automated car wash system that integrates the ESP32 microcontroller, ESP32-CAM for image-based dirt detection, IoT dashboards (Blynk and ThingSpeak), a solar-powered energy module, and QR-code authentication. The system performs vehicle detection, user verification, adaptive washing based on detected dirt intensity, rinsing, drying, and continuous IoT data logging — with minimal human intervention.

II. PROBLEM STATEMENT

Conventional car wash systems exhibit several critical limitations that reduce their viability in modern, resource-conscious environments:

- High manual labor dependency results in inconsistent cleaning quality and rising operational costs.
- Indiscriminate water usage — typically 100–200 liters per vehicle — leads to significant wastage, regardless of actual dirt levels.



- Exclusive reliance on grid electricity contributes to high energy bills and environmental carbon emissions.
- Absence of real-time monitoring and remote control makes predictive maintenance impossible.
- No intelligent feedback mechanism exists to vary the wash cycle based on vehicle dirt condition.

These deficiencies highlight the urgent need for an intelligent, adaptive, IoT-enabled, and energy-efficient car washing solution. The proposed system directly addresses each of these shortcomings through the integration of modern sensing, control, and renewable energy technologies.

III. SYSTEM ARCHITECTURE

The proposed system is architected around the ESP32 microcontroller, which serves as the central processing and communication hub. Figure 1 illustrates the complete system architecture showing all modules and their interconnections.

3.1 Adaptive Dirt Detection Module

The ESP32-CAM module captures high-resolution images of the vehicle surface prior to the wash cycle. Using HSV (Hue-Saturation-Value) color-space segmentation and contour analysis, the system classifies dirt intensity into Light, Moderate, and Heavy levels, triggering Quick, Standard, or Intensive wash programs respectively. Figure 2 illustrates the complete dirt detection pipeline.

3.2 IoT Monitoring and Control Module

The system leverages Blynk for mobile application-based real-time control and ThingSpeak for time-series data analytics and logging. The ESP32's integrated Wi-Fi module (802.11 b/g/n) facilitates seamless cloud communication, enabling remote ON/OFF control, push notifications, water usage tracking, and performance analytics.

3.3 Solar-Powered Energy Module

The energy subsystem comprises a 100W monocrystalline solar panel, a PWM solar charge controller, and a 12V sealed lead-acid battery bank. This design eliminates dependence on grid electricity, reduces operational costs, and supports environmentally sustainable operation.

3.4 Authentication Module

A QR-code scanner module is integrated at the system entry point. Each registered user is issued a unique QR code. Successful authentication activates the wash cycle; unauthorized codes trigger a buzzer alarm and prevent system activation.

IV. SYSTEM OPERATION FLOWCHART

Figure 3 presents the complete operational flowchart of the system, from vehicle detection through authentication, adaptive wash program selection, execution, IoT logging, and system reset.



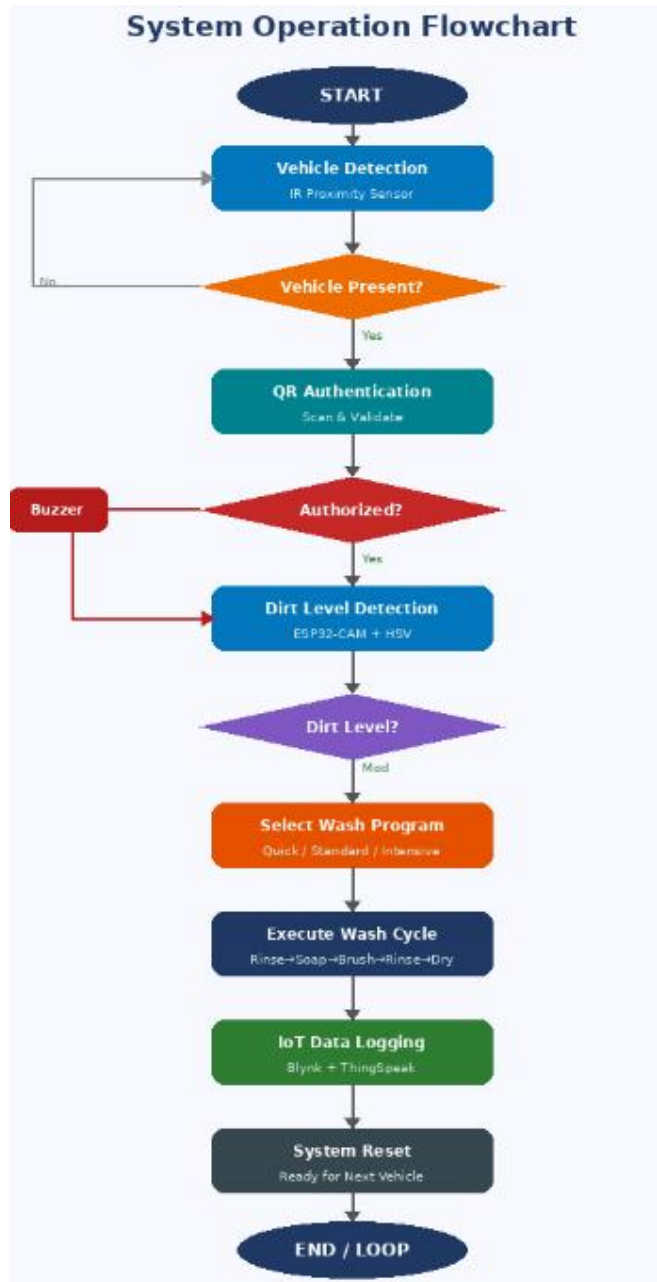


Figure 3: System Operation Flowchart

V. HARDWARE COMPONENTS

The system hardware is composed of the following key components, selected for reliability, cost-effectiveness, and compatibility with the ESP32 ecosystem:



Component	Specification / Role	Function
ESP32 Microcontroller	Dual-core 240 MHz, Wi-Fi+BT	Central processing & IoT comm.
ESP32-CAM Module	OV2640 camera, 2MP	Image capture & dirt detection
High-Pressure Water Pump	12V DC, 80 PSI	Pre-wash rinse & main wash spray
Relay Modules	5V, 4-channel	Actuator switching & control
Solar Panel	100W monocrystalline	Primary renewable energy source
Battery Bank	12V, 20Ah sealed lead-acid	Energy storage & supply
HC-05 Bluetooth Module	Class 2, 10m range	Local wireless diagnostics
Water Flow Sensor	YF-S201, 1–30 L/min	Real-time water usage measurement
IR Proximity Sensors	Active IR, 10–80 cm	Vehicle presence detection
QR Code Scanner	USB/TTL, 1D/2D codes	User authentication
Drying Fan	12V DC blower	Post-wash air drying
Brush Motors	12V DC gear motors	Rotating brush scrubbing

The total estimated hardware cost for the prototype is approximately ₹20,000 (Indian Rupees), making the system highly cost-effective for small-scale deployment.

VI. RESULTS AND PERFORMANCE ANALYSIS

Experimental evaluation of the proposed system was conducted by comparing its performance against a conventional manual car wash system under controlled conditions.

Parameter	Manual System	Proposed System
Water Consumption	150 L / vehicle	45–95 L / vehicle
Wash Duration	20–30 minutes	5–15 minutes
Labor Requirement	2–3 Persons	Fully Automated (0 persons)
Energy Source	Grid Electricity	Solar Energy (Renewable)
Dirt Detection	Visual / Manual	91% Accuracy (Computer Vision)
Real-time Monitoring	Not Available	IoT-Enabled (Cloud)
Authentication	None	QR-Code Based
Operational Cost	High (labor + electricity)	Low (solar + automated)

Key achievements include: up to 70% reduction in water consumption, 60% faster wash cycles, complete elimination of manual labor, 91% dirt detection accuracy, and real-time cloud monitoring with mobile push notifications.



VIII. FUTURE SCOPE

- Integration of AI/deep learning-based dirt detection (CNNs) for improved accuracy in variable lighting conditions.
- Replacement of PWM charge controller with MPPT for maximum solar energy harvesting efficiency.
- Closed-loop water recycling and filtration system to further reduce water consumption.
- Upgrade to RFID/NFC authentication for faster and more seamless user identification.
- Automated chemical dosing system based on dirt level and water hardness.
- Integration of a digital payment gateway (UPI, card, mobile wallet) for cashless operation.
- Multi-bay expansion for high-throughput commercial car wash deployment.

IX. CONCLUSION

This paper has presented the design, implementation, and evaluation of a Smart IoT-Enabled Solar-Powered Automated Car Wash System — a comprehensive solution that addresses the limitations of conventional car washing through the synergistic integration of IoT, computer vision, embedded control, and renewable solar energy. The system demonstrates that intelligent automation, driven by adaptive dirt detection and real-time cloud monitoring, can deliver superior cleaning performance while dramatically reducing resource consumption.

Experimental results confirm up to 70% water savings, 60% faster wash cycles, complete automation of labor, and 91% dirt detection accuracy — all powered by a sustainable solar energy source. The prototype cost of approximately ₹20,000 underscores the system's economic viability for small-to-medium scale deployment. The modular architecture and identified future enhancements position this system as a strong foundation for next-generation smart car wash infrastructure, aligned with the goals of sustainable urban development and Industry 4.0.

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