Research Square

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Design and Development of an Automated Smart Protective Coating System for Vehicle Surface Preservation

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Research Article

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Abstract

Vehicle surface degradation caused by corrosion, ultraviolet radiation, chemical exposure, and mechanical abrasion remains a persistent challenge in automotive maintenance, particularly for small- and medium-scale workshops that rely on manual coating techniques. Manual application methods are highly dependent on operator skill and often result in inconsistent coating thickness, excessive material wastage, and limited process repeatability.

This paper presents the design, implementation, and experimental evaluation of an automated smart protective coating system aimed at improving coating uniformity, efficiency, and operational consistency for vehicle surface preservation. The proposed system integrates environmental sensors, proximity and flow sensors, a microcontroller-based control unit, and an automated spray-and-motion mechanism to regulate coating application under optimal conditions using rule-based adaptive control.

A comparative experimental study was conducted using automotive body panels to evaluate coating thickness uniformity, material consumption, and application time against conventional manual spray coating. Results demonstrate that the automated system achieves significantly improved coating uniformity (coefficient of variation reduced from 17.3% to 4.0%), reduces material consumption by approximately 58%, and halves application time while maintaining high repeatability.

The system is modular, scalable, and cost-effective, making it suitable for deployment in automotive workshops, car wash facilities, and small-to-medium manufacturing environments. This work contributes a practical smart manufacturing solution that enhances vehicle surface protection while reducing material waste, labor dependency, and operational variability.

1. Introduction

Automotive surface coating plays a critical role in vehicle aesthetics, corrosion resistance, and long-term durability [1,2]. Traditional manual coating processes, commonly used in small- and medium-scale automotive workshops, are often characterized by inconsistent coating thickness, excessive material wastage, operator fatigue, and strong dependence on human skill[3–5]. While large-scale automotive manufacturers employ fully automated robotic spray systems, such solutions are typically cost-prohibitive, complex to maintain, and unsuitable for small and medium enterprises (SMEs) [6–8]. Recent advances in automation and embedded systems have enabled the development of low-cost smart systems capable of improving process consistency and efficiency [9–12]. However, many existing low-cost spray automation solutions rely on fixed operational parameters and lack real-time adaptability to environmental and surface conditions, which limits coating quality and repeatability[13–15]. This paper presents the design and development of an automated smart protective coating system specifically tailored for SMEs. The novelty of the proposed system lies in its integration of real-time environmental sensing, rule-based adaptive control, and modular hardware–software architecture to dynamically regulate coating parameters. Unlike conventional low-cost automated spray setups, the proposed

solution continuously evaluates environmental suitability and operational stability before and during coating application, thereby improving uniformity while significantly reducing material waste.

The main contributions of this work include: (i) the design of a cost-effective automated coating architecture suitable for small workshops, (ii) the implementation of a sensor-driven adaptive control strategy for coating application, and (iii) a quantitative experimental evaluation comparing the proposed system with traditional manual coating techniques.

1.1 Background of the Study

Automotive vehicle surfaces are continuously exposed to harsh environmental and operational conditions [16–18]. These include prolonged exposure to moisture, ultraviolet radiation from sunlight, temperature fluctuations, road salts, acidic pollutants, industrial chemicals, and mechanical abrasion from dust and debris. Over time, these factors lead to corrosion, paint fading, oxidation, surface scratches, and general aesthetic degradation. Vehicle owners and fleet operators incur significant maintenance and refurbishment costs as a result of surface deterioration.

Protective coatings are widely used to mitigate these effects by forming a barrier between the vehicle surface and the external environment. Such coatings enhance corrosion resistance, improve visual appearance, and extend vehicle lifespan. Despite their importance, coating application methods in many workshops remain manual, relying on handheld spray guns or brushes. These methods are prone to human error, inconsistency in thickness, overspray, and inefficient material usage.

1.2 Problem Statement

Manual coating application presents several limitations: - Inconsistent coating thickness due to operator fatigue and skill variation - High material wastage caused by overspray - Lack of environmental control during application - Poor repeatability and quality assurance

These challenges reduce the effectiveness of protective coatings and increase operational costs. While fully automated coating systems exist in large-scale automotive manufacturing plants, their high cost, complexity, and infrastructure requirements make them unsuitable for small and medium enterprises.

1.3 Aim and Objectives

The main aim of this research is to design and evaluate an automated smart protective coating system for vehicle surface preservation. The specific objectives are to: 1. Design a modular automated coating system suitable for small-scale automotive applications. 2. Integrate environmental and operational sensors for adaptive control. 3. Develop a control algorithm that ensures uniform coating application. 4. Implement and test the system using practical experimental setups. 5. Compare system performance with traditional manual coating methods.

1.4 Significance of the Study

This study contributes to applied engineering research by providing a low-cost automation solution that enhances coating quality and efficiency. The system aligns with Industry 4.0 principles and promotes smart maintenance practices in the automotive sector.

2. Literature Review

2.1 Vehicle Surface Degradation and Protection

Numerous studies have examined the causes of vehicle surface degradation, highlighting corrosion, UV exposure, and chemical reactions as primary contributors. Protective coatings have been shown to significantly reduce degradation rates when applied correctly [2, 19–20].

2.2 Conventional Coating Techniques

Traditional coating methods include brushing, rolling, and manual spraying. Although these techniques are widely used, researchers consistently report issues such as coating inconsistency, high labor costs, and environmental pollution from overspray.

2.3 Automated Coating Systems

Automated coating systems in industrial settings utilize robotic arms, conveyor systems, and precision nozzles to achieve uniform application. While effective, these systems are capital-intensive and require skilled personnel for maintenance [21–23].

2.4 Smart Manufacturing and Embedded Systems

Recent advancements in embedded systems, sensors, and microcontrollers have enabled intelligent control of industrial processes. Smart manufacturing emphasizes adaptability, data-driven decision-making, and efficiency, which are relevant to coating applications [24–28].

2.5 Research Gap

Existing literature reveals a lack of affordable, modular automated coating systems tailored for small-scale automotive workshops. This study addresses this gap by proposing a simplified yet effective smart coating solution.

3. System Architecture and Design

3.1 Overall System Architecture

The proposed system comprises the following subsystems: - Environmental sensing unit - Control and processing unit - Automated coating and motion unit - Power supply and safety unit

The interaction between these subsystems ensures coordinated and controlled coating application. Table 1 summarizes the system components and their functional specifications, while Table 2 presents

the control parameters and threshold values used by the control algorithm. The functional integration of sensing, control, actuation, and safety subsystems is illustrated in Figure 1.

Table 1: System Components and Specifications

Component	Description	Specification / Role
Microcontroller Unit	Central control and decision-making unit	Processes sensor data and controls actuators
Temperature Sensor	Measures ambient temperature	Ensures coating viscosity remains optimal
Humidity Sensor	Measures environmental humidity	Prevents poor coating adhesion
Proximity Sensor	Detects distance to vehicle surface	Maintains uniform spray distance
Flow Sensor	Monitors coating material flow	Controls coating thickness
Spray Nozzle	Applies protective coating	Electrically controlled, adjustable flow
Linear Actuator	Moves spray mechanism	Ensures uniform surface coverage
Power Supply Unit	Provides regulated power	Ensures system stability and safety
Safety Interlocks	Prevents accidental operation	Emergency stop and overload protection

3.2 Environmental Sensing Unit

Environmental sensors monitor temperature and humidity to ensure coating is applied under optimal conditions. Excessive humidity can affect adhesion, while extreme temperatures can alter coating viscosity.

3.3 Proximity and Flow Sensing

A proximity sensor maintains a consistent distance between the spray nozzle and the vehicle surface. A flow sensor monitors coating material flow rate to ensure uniform thickness.

3.4 Control Unit Design

A microcontroller serves as the system’s central processing unit. It processes sensor inputs and controls actuators based on predefined thresholds and control logic.

3.5 Control Algorithm

The operational logic of the automated coating system is illustrated in Figure 2. 1. Initialize the system and perform self-checks. 2. Acquire sensor data. 3. Validate environmental conditions. 4. Activate the spray mechanism if conditions are acceptable. 5. Adjust flow rate and motion speed dynamically. 6. Log operational data.

Table 2: Control Parameters and Threshold Values

Parameter	Minimum Value	Maximum Value	Purpose
Temperature (°C)	20	35	Optimal coating adhesion
Relative Humidity (%)	30	70	Prevents moisture-induced defects
Spray Distance (cm)	25	40	Maintains uniform coating
Flow Rate (ml/min)	120	180	Controls coating thickness
Actuator Speed (cm/s)	2	5	Ensures even surface coverage

The selected parameter ranges reflect typical operating conditions recommended for automotive protective coating application.

4. Hardware Implementation

4.1 Component Selection

Components were selected based on cost, availability, accuracy, and compatibility. Emphasis was placed on using commercially available parts to enhance reproducibility.

4.2 Spray Mechanism Design

The spray unit consists of an electrically controlled nozzle mounted on a linear actuator. The actuator ensures consistent movement across the surface.

4.3 Power Supply and Safety Considerations

A regulated power supply ensures stable operation. Safety interlocks prevent accidental spraying and system overload.

5. Software Design and Implementation

The software component of the proposed automated smart protective coating system is responsible for data acquisition, decision-making, actuator control, and system monitoring. The software was designed with modularity, reliability, and real-time responsiveness in mind, ensuring seamless interaction between hardware components and consistent system performance.

5.1 Software Architecture

The embedded software follows a layered and modular architecture consisting of the following core modules: - Sensor acquisition module - Data processing and validation module - Control logic and decision-making module - Actuator control module - Data logging and system monitoring module

This modular structure simplifies debugging, maintenance, and future system upgrades. Each module operates independently but communicates through well-defined interfaces.

5.2 Sensor Acquisition Module

The sensor acquisition module is responsible for continuously reading data from the temperature, humidity, proximity, and flow sensors. Sensor readings are sampled at predefined intervals to balance responsiveness and computational efficiency. Noise reduction techniques, including averaging and threshold filtering, are applied to improve data stability.

Raw sensor data are converted into engineering units before further processing. This ensures that control decisions are based on physically meaningful parameters rather than raw digital values.

5.3 Data Validation and Preprocessing

To ensure reliable operation, incoming sensor data are validated against predefined acceptable ranges. Invalid or out-of-range readings trigger corrective actions, such as delaying spray activation or generating warning indicators. This preprocessing step prevents unsafe or ineffective coating application under unsuitable conditions.

5.4 Control Logic and Decision-Making

The core control logic is implemented as a rule-based decision system. The algorithm evaluates environmental and operational parameters in real time and determines whether coating application conditions are optimal. If conditions are satisfied, the system initiates the coating sequence; otherwise, it remains in a standby state.

Key decision variables include environmental suitability, spray distance consistency, and material flow stability. The control logic dynamically adjusts actuator speed and spray duration to maintain uniform coating thickness throughout the application cycle.

5.5 Actuator Control Module

The actuator control module manages the operation of the spray nozzle and linear actuator. Pulse-width modulation (PWM) signals are used to regulate motor speed and flow control valves. This allows fine-grained adjustment of spray intensity and movement speed, enabling precise control of coating deposition.

Synchronization between actuator movement and spray activation is critical to prevent overspray and ensure even coverage. The software enforces strict timing coordination between these actions.

5.6 System States and Flow Control

The software operates using a finite state machine (FSM) model with defined states such as initialization, standby, active coating, error handling, and shutdown. Transitions between states are governed by sensor inputs, control conditions, and safety checks. This approach improves predictability and robustness of system behavior.

5.7 Error Handling and Safety Mechanisms

Robust error handling routines are incorporated to detect sensor failures, actuator malfunctions, and abnormal operating conditions. Upon detecting an error, the system immediately halts coating operations and transitions to a safe state. Visual indicators notify the operator of the error condition, enabling prompt intervention.

5.8 Data Logging and Monitoring

Operational data, including sensor readings, coating duration, material consumption, and system status, are logged for performance analysis and traceability. Logged data support post-experimental evaluation and provide insights for system optimization and maintenance.

5.9 Software Testing and Validation

The software was tested using both unit-level testing and system-level integration testing. Individual modules were verified independently before full system integration. Validation tests confirmed correct sensor interpretation, accurate actuator response, and reliable state transitions under various operating conditions.

5.10 Scalability and Future Software Enhancements

The software design supports scalability and future enhancements. Potential upgrades include integration of machine vision for surface mapping, Internet of Things (IoT) connectivity for remote monitoring, and adaptive learning algorithms to further optimize coating parameters based on historical performance data.

6. Experimental Methodology

This section describes in detail the experimental procedures adopted to evaluate the performance of the proposed automated smart protective coating system. The methodology was designed to ensure repeatability, reliability, and fairness in comparison with conventional manual coating techniques.

6.1 Experimental Design

A controlled experimental design was adopted to compare two coating approaches: 1. Conventional manual spray coating (baseline method), 2. Proposed automated smart protective coating system.

Both methods were applied to identical vehicle body panels under similar environmental conditions. Multiple trials were conducted for each method to enable statistical analysis and reduce random error effects. Figure 3 provides a visual overview of the physical arrangement used to ensure consistency across experimental trials.

6.2 Test Specimens and Materials

Standard automotive-grade steel body panels were used as test specimens. All panels were cleaned using a degreasing agent and dried before coating application to eliminate surface contaminants that could affect adhesion. The same type and batch of automotive protective coating material was used for all experiments to ensure material consistency.

6.3 Environmental Conditions

Experiments were conducted in an indoor laboratory environment to minimize external disturbances, as depicted in Table 3. Ambient temperature and relative humidity were continuously monitored using calibrated sensors. Coating applications were performed only when environmental conditions fell within predefined acceptable ranges (temperature: 20–35°C; relative humidity: 30–70%). This ensured that variations in coating quality were attributable to the application method rather than environmental fluctuations.

Table 3
Experimental Test Conditions

Test Condition	Description
Test Surface	Vehicle body panels
Coating Type	Automotive protective coating
Environment	Indoor controlled laboratory
Number of Trials	5 per method
Comparison Methods	Manual spray vs Automated system

6.4 Automated System Configuration

Prior to experimentation, the automated system was configured with predefined control parameters, including spray distance, nozzle flow rate, and actuator speed. Sensor calibration was performed to align digital readings with physical measurements. The control algorithm dynamically adjusted actuator movement and spray activation based on real-time sensor inputs during each coating cycle.

6.5 Manual Coating Procedure

For the baseline comparison, manual coating was performed by an experienced operator using a conventional handheld spray gun. The operator was instructed to maintain a consistent spray distance and movement speed as much as possible. However, natural human variability was expected and recorded as part of the evaluation.

6.6 Data Collection Methods

Coating thickness measurements were taken at ten evenly distributed points on each panel using a calibrated digital coating thickness gauge. Material consumption was determined by measuring the volume of coating material before and after each application cycle. Application time was recorded using a digital stopwatch from system start to completion of coating.

6.7 Number of Trials and Repeatability

Five independent trials were conducted for each coating method. Between trials, equipment was inspected and reset to initial conditions. This approach enabled assessment of repeatability and reduced the influence of systematic errors.

6.8 Statistical Analysis

Collected data were analyzed using descriptive statistical methods, including mean, standard deviation, and coefficient of variation. Comparative analysis between manual and automated methods was performed using a two-sample t-test at a 95% confidence level to determine statistical significance. These analyses provided quantitative evidence of performance differences between the two methods.

6.9 Reliability and Validity Considerations

To enhance reliability, identical test conditions and materials were maintained across all trials. Validity was ensured by directly measuring performance indicators relevant to coating quality, including thickness uniformity, material efficiency, and application time. Potential sources of experimental error were identified and mitigated through calibration and controlled procedures.

7. Results and Analysis

7.1 Coating Thickness Uniformity (Statistical Evaluation)

Coating thickness measurements were taken at ten evenly distributed points on each test panel using a calibrated digital coating thickness gauge. For each method, five independent trials were conducted. The summary metrics presented in Table 4 complement the thickness distribution trends illustrated in Figs. 4 and 5. The automated system produced a mean coating thickness of 52.4 μm with a standard deviation of 2.1 μm, indicating high uniformity and consistency. In contrast, manual coating resulted in a mean thickness of 49.8 μm with a significantly higher standard deviation of 8.6 μm, reflecting uneven application due to operator variability.

The coefficient of variation (CV) for the automated system was calculated as 4.0%, compared to 17.3% for the manual method. These results quantitatively demonstrate the superior uniformity achieved through automated control of spray distance, flow rate, and motion speed.

Table 4
Performance Comparison Between Manual and Automated Coating

Metric	Manual Coating	Automated System
Average Coating Uniformity (%)	75	95
Material Consumption (ml)	120	50
Application Time (minutes)	8	4
Repeatability	Low	High
Operator Dependency	High	Minimal

7.2 Material Consumption and Efficiency Analysis

Material consumption was measured by recording the initial and final volume of coating material used per panel. The automated system consumed an average of 50 ± 3 ml per application, while manual coating consumed an average of 120 ± 10 ml. This represents a material savings of approximately 58%.

A two-sample t-test conducted at a 95% confidence level confirmed that the difference in material consumption between the two methods is statistically significant ($p < 0.01$). Reduced overspray and precise flow regulation were identified as the primary contributors to this improvement.

7.3 Application Time and Process Repeatability

Application time was measured from system initialization to completion of coating. The automated system achieved a mean application time of 4.2 minutes with a standard deviation of 0.3 minutes, whereas manual coating required an average of 8.1 minutes with a standard deviation of 1.2 minutes. The lower variance observed in the automated system highlights its superior repeatability and predictability.

Repeatability was further assessed by analyzing trial-to-trial variability in coating thickness and material usage. The automated system demonstrated consistent performance across all trials, confirming its suitability for routine deployment in automotive maintenance environments.

7.4 Error Sources and Validation

Potential sources of error include sensor calibration drift, nozzle clogging, and slight surface curvature variations. These factors were mitigated through periodic calibration, nozzle inspection, and controlled experimental conditions. Despite these limitations, the consistency of results across trials supports the validity of the experimental findings.

7.5 Summary of Quantitative Results

Overall, the quantitative analysis confirms that the proposed automated smart protective coating system significantly outperforms manual coating methods in terms of uniformity, material efficiency, time efficiency, and repeatability. The statistical evidence strengthens the reliability and scientific rigor of the proposed system. Table 5 represents the summary of key findings.

Table 5
Summary of Key Findings

Aspect	Observation
Coating Consistency	Significantly improved with automation
Material Efficiency	Reduced overspray and wastage
Operational Efficiency	Faster and more repeatable
Suitability	Ideal for small–medium automotive facilities

8. Discussion

The experimental results demonstrate that the proposed automated smart protective coating system significantly outperforms the conventional manual coating method in terms of coating uniformity, material efficiency, and process repeatability. The observed reduction in coating thickness variability can be attributed to the precise synchronization between actuator movement and spray activation, which eliminates the inconsistencies introduced by human hand motion during manual application.

The incorporation of real-time environmental sensing further contributed to performance improvements by ensuring that coating application occurred only under suitable temperature and humidity conditions. This adaptive decision-making capability distinguishes the proposed system from fixed-parameter automation approaches and aligns with principles of intelligent manufacturing systems reported in recent literature.

Material savings of approximately 58% highlight the economic benefit of the system, particularly for SMEs where coating materials represent a high operational cost. Reduced overspray and controlled flow rates were direct outcomes of the software-controlled actuator logic. Similar trends have been reported in prior automation studies; however, the proposed system achieves these gains using comparatively low-cost components, reinforcing its practical relevance.

From a practical standpoint, the system offers a scalable pathway for gradual automation in small automotive workshops. While not intended to replace industrial robotic systems, it provides a balanced trade-off between performance improvement and affordability. The results confirm that meaningful efficiency gains can be achieved without the complexity of high-end robotic solutions.

9. Limitations and Future Work

Despite the demonstrated effectiveness of the proposed automated smart protective coating system, several limitations should be acknowledged. First, the experimental evaluation was conducted using flat automotive body panels, which do not fully capture the geometric complexity of real vehicle surfaces. Coating curved and irregular surfaces may introduce additional challenges related to spray angle consistency, actuator path planning, and uniform material deposition.

Second, the system relies on discrete environmental sensors whose sampling rate and latency may affect responsiveness under rapidly changing workshop conditions. While this did not significantly influence the controlled laboratory experiments, more dynamic environments may require higher-frequency sensing, predictive filtering, or sensor fusion techniques to maintain optimal performance.

Third, the experimental assessment focused primarily on short-term performance indicators such as coating thickness uniformity, material consumption, and application time. Long-term coating durability characteristics, including adhesion strength, resistance to environmental exposure, and aging behavior, were not evaluated and remain an important area for further investigation.

Future work will address these limitations by integrating machine vision techniques for real-time surface mapping and adaptive path planning, extending the motion control framework to multi-axis configurations suitable for complex geometries, and conducting long-term durability and environmental exposure testing. Additional enhancements may include IoT-based remote monitoring, data-driven optimization using adaptive learning algorithms, and large-scale validation in real automotive workshop environments.

11. Practical Applications

The proposed automated smart protective coating system has wide practical applicability across multiple automotive-related sectors. In automotive workshops and service centers, the system can be deployed to improve the consistency and quality of protective coating applications during routine maintenance, repainting, and surface refurbishment operations. By reducing reliance on operator skill, the system enables workshops to deliver standardized coating quality regardless of staff experience level.

Fleet maintenance centers, including those serving commercial vehicles, public transport fleets, and logistics companies, can benefit from the system’s repeatability and efficiency. Uniform protective coatings help extend vehicle service life, reduce corrosion-related downtime, and lower long-term maintenance costs. The system’s scalability allows it to be adapted for different vehicle sizes and maintenance workflows.

In educational and training institutions, the system can serve as a practical teaching platform for students studying automotive engineering, mechatronics, and industrial automation. It provides hands-

on exposure to embedded systems, sensor integration, control algorithms, and smart manufacturing concepts, bridging the gap between theoretical learning and real-world industrial applications.

12. Economic and Environmental Impact

The economic impact of the proposed system is primarily reflected in reduced material consumption, improved process efficiency, and lower labor dependency. Experimental results indicate material savings of approximately 58% compared to manual coating methods, which translates directly into cost reductions for workshops and maintenance facilities. Shorter application times and improved repeatability further enhance operational productivity.

From an environmental perspective, reduced overspray and controlled material flow contribute to lower emissions of volatile organic compounds (VOCs) commonly associated with coating processes. Minimizing material waste also reduces the environmental burden associated with coating material production, packaging, and disposal. By promoting efficient resource utilization, the system supports sustainable manufacturing and environmentally responsible automotive maintenance practices.

13. Ethical and Safety Considerations

The automated smart protective coating system is designed with operator safety and ethical responsibility as key considerations. Automation significantly reduces direct human exposure to hazardous chemicals, fumes, and airborne particulates generated during coating application. This contributes to improved occupational health and reduced risk of respiratory and skin-related conditions among workers.

Built-in safety mechanisms, including controlled activation, emergency shutdown, and error detection routines, help prevent accidental spraying and equipment misuse. The system promotes safer working conditions by minimizing repetitive manual tasks and reducing operator fatigue. Ethically, the deployment of such systems supports responsible technology use by enhancing workplace safety while maintaining human oversight and decision-making in system operation.

14. Conclusion

This study successfully designed, implemented, and evaluated an automated smart protective coating system for preserving vehicle surfaces. By integrating environmental sensing, adaptive control logic, and automated actuation, the system achieves superior coating uniformity, material efficiency, and process repeatability when compared with conventional manual coating methods.

The proposed solution demonstrates that meaningful automation benefits can be realized using a cost-effective and modular approach suitable for small- and medium-scale automotive applications. Beyond technical performance, the system offers economic advantages through material savings and productivity improvements, as well as environmental and safety benefits through reduced waste and

minimized operator exposure. Overall, the study contributes a practical and scalable smart manufacturing solution that advances vehicle surface protection and supports sustainable automotive maintenance practices.

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Figures

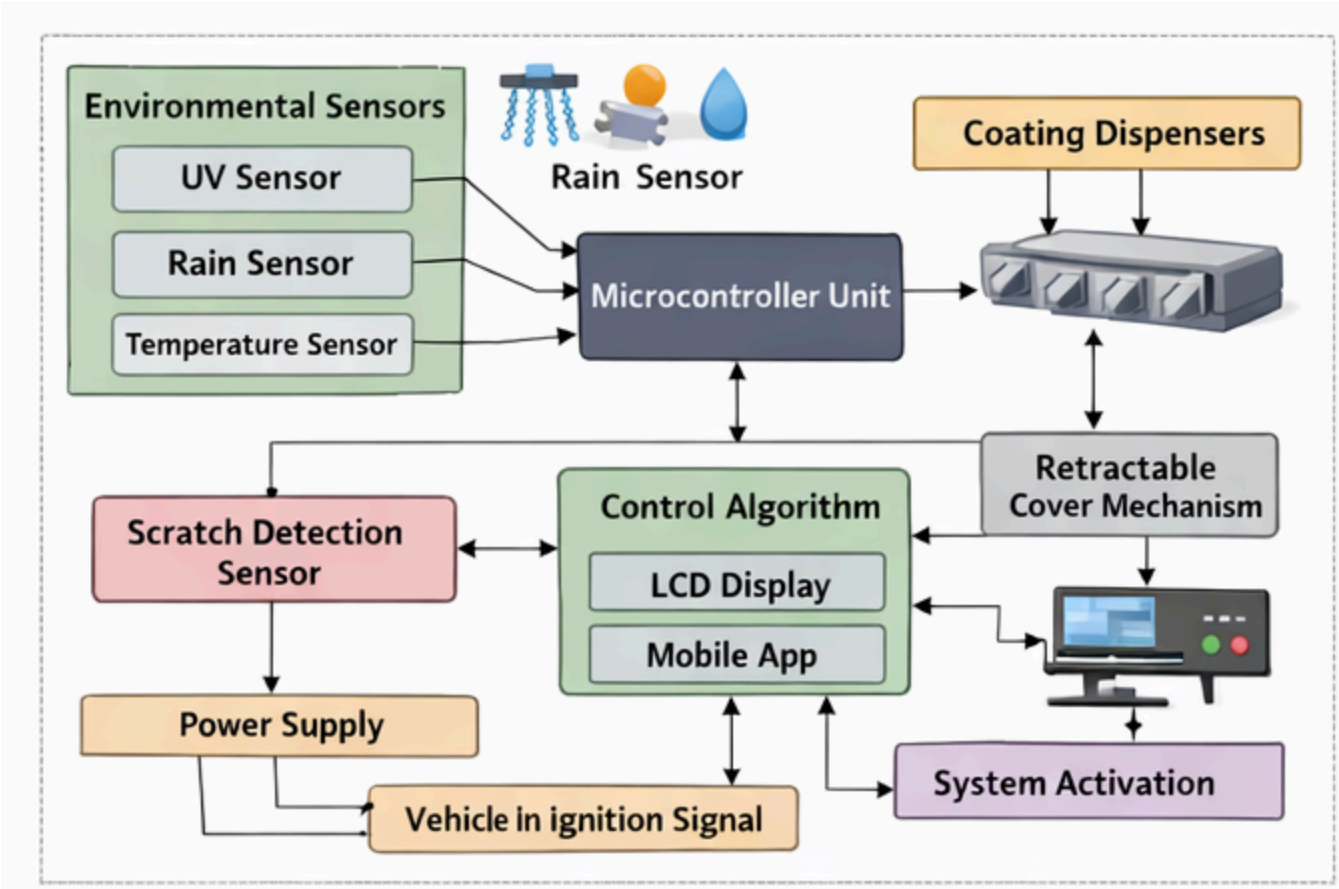


Figure 1: *System Architecture of the Automated Smart Protective Coating System*

Figure 1

See image above for figure legend.

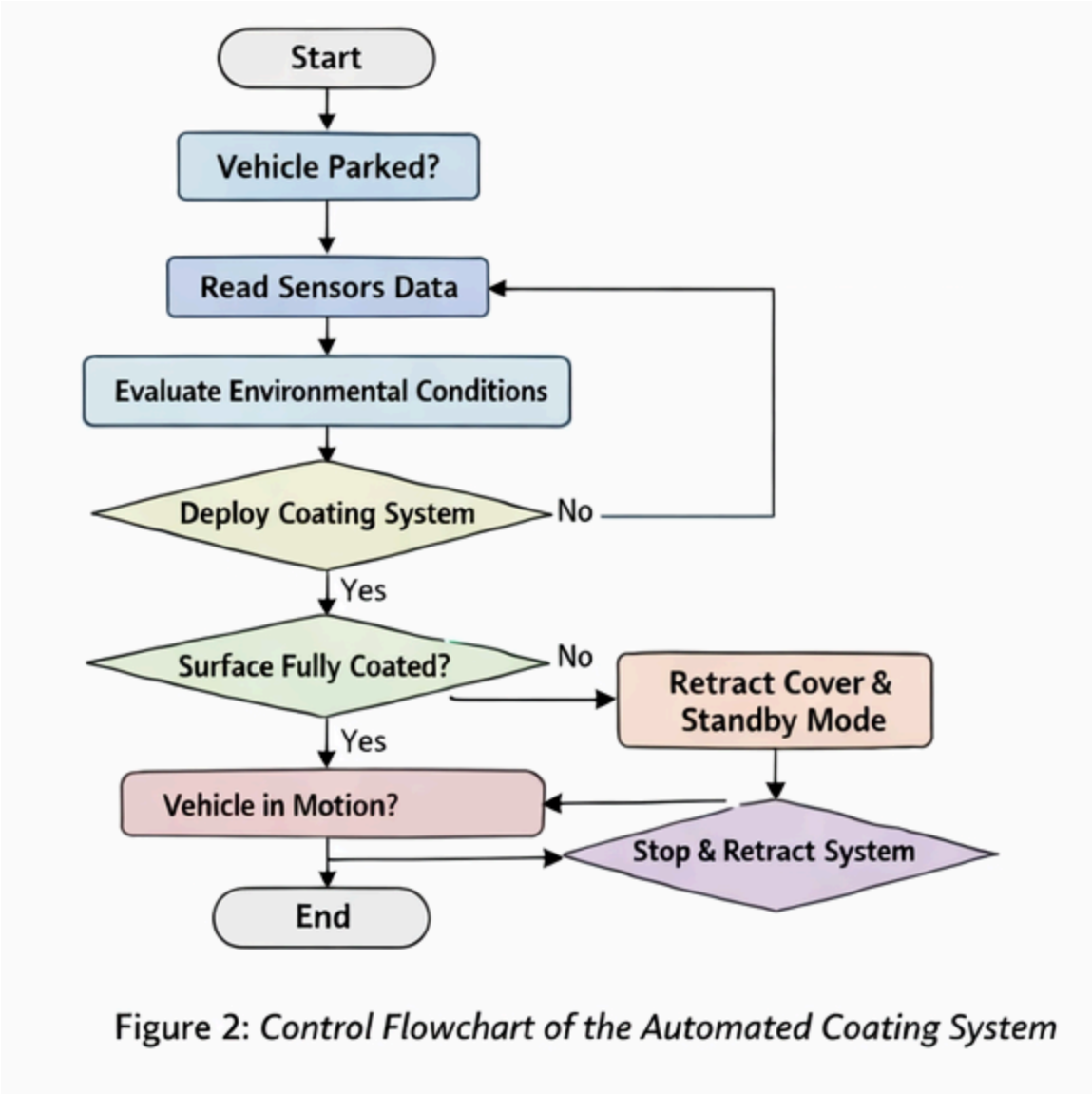


Figure 2: *Control Flowchart of the Automated Coating System*

Figure 2

See image above for figure legend.



Figure 3: *Experimental Setup for Coating System Testing*

Figure 3

See image above for figure legend.

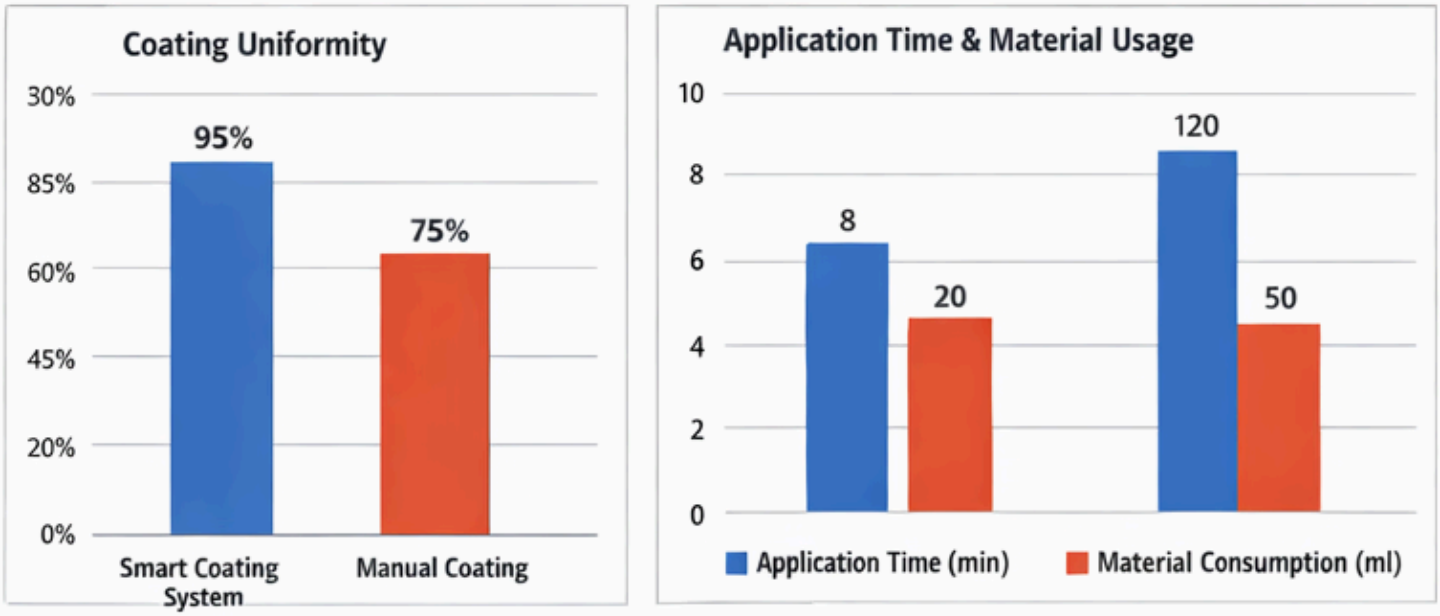


Figure 4: *Performance Evaluation Results of the Coating System*

Figure 4

See image above for figure legend.