

Collaborative Control Framework of IoT-Enabled Intelligent Cleaning Systems in Photovoltaic Stations

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Abstract: This paper addresses the challenges of collaborative control in an IoT-based intelligent cleaning system for photovoltaic power plants. The paper designed an overall architecture encompassing the perception, network, and application layers. The paper proposed a multi-agent collaborative mechanism and a collaborative control strategy based on rules and optimization algorithms. We investigate key technologies, including photovoltaic panel contamination detection, intelligent control of cleaning equipment, and data fusion processing. Using a MATLAB/Simulink simulation environment, the paper compared the performance of traditional control with this framework under varying pollution levels, weather conditions, and equipment loads. Results show that under moderate pollution conditions, the framework reduces task completion time by 32.4%, improves resource utilization by 22.3 percentage points, and reduces equipment conflict by 67.5%. Furthermore, under light rain conditions, the power generation efficiency improves by 8.7 percentage points compared to traditional control. These results demonstrate its advantages in cleaning efficiency, resource utilization, and environmental adaptability, supporting the efficient operation of photovoltaic power plants.

Keywords: Internet of Things; Photovoltaic Power Station; Intelligent Cleaning System; Collaborative Control Framework; Multi-Agent; Pollution Detection.

1. Introduction

With the intensification of the global energy crisis and growing awareness of environmental protection, solar energy, as a clean and renewable energy source, is increasingly becoming a larger component of the energy mix. As the primary form of solar energy utilization, photovoltaic power stations directly impact the efficiency of their power generation. However, during the actual operation of photovoltaic power stations, impurities such as dust and dirt easily accumulate on the surface of photovoltaic panels. These impurities significantly reduce the panels' light transmittance, thereby affecting their power generation efficiency. Relevant research shows that the efficiency of photovoltaic panels that have not been cleaned for a long time can decrease by 20%-30%, and even more in severe cases. Therefore, timely and effective cleaning of photovoltaic panels is critical to ensuring the efficient operation of photovoltaic power stations [1]. The Internet of Things (IoT) enables interconnection and information sharing between devices. By deploying a large number of sensors in photovoltaic power stations, real-time information such as the contamination level of photovoltaic panels, ambient temperature and humidity, and wind speed can be collected. After transmission and processing, this information can provide strong support for decision-making in the cleaning system [2]. An intelligent cleaning system based on IoT technology can automatically plan cleaning routes and schedule cleaning equipment based on the actual contamination level of photovoltaic panels and environmental conditions, achieving efficient cleaning tasks. However, current IoT-based intelligent cleaning systems for photovoltaic power plants still face some challenges in collaborative control, such as inadequate coordination between different cleaning devices and irrational cleaning

task scheduling [3]. These issues hinder the full efficiency of the cleaning system.

Therefore, research on a collaborative control framework for IoT-based intelligent cleaning systems for photovoltaic power plants is of great practical significance [4]. This framework integrates resources across various links, including perception, transmission, and processing, to achieve efficient collaboration between cleaning devices and between the cleaning system and other systems in the photovoltaic power plant, thereby improving cleaning efficiency, reducing cleaning costs, and enhancing the power generation benefits of the photovoltaic power plant [5]. By constructing a scientific and rational collaborative control framework, the lack of collaboration in current intelligent cleaning systems can be addressed, driving the development of photovoltaic power plants towards greater intelligence and efficiency.

2. Design of a Collaborative Control Framework for an IoT-based Intelligent Cleaning System for Photovoltaic Power Plants

2.1. Overall System Architecture

The overall system architecture forms the foundation of the collaborative control framework for IoT-based intelligent cleaning systems for photovoltaic power plants. It consists of three layers: the perception layer, the network layer, and the application layer. These layers collaborate to achieve intelligent cleaning tasks for photovoltaic panels. The perception layer is the "sensory" component of the entire system, responsible for collecting various information related to photovoltaic panel cleaning [6]. Regarding sensor selection, high-precision image sensors and dust thickness sensors were

selected to accurately detect the degree of contamination on the photovoltaic panels. The image sensor captures images of the photovoltaic panel surface, analyzing them to determine the distribution and severity of contamination. The dust thickness sensor directly measures the thickness of dust on the panel surface, providing quantitative data for contamination assessment [7]. To collect environmental information, temperature and humidity sensors, wind speed sensors, and light intensity sensors were selected. These sensors monitor the environmental conditions of the photovoltaic power station in real time, providing a reference for scheduling cleaning tasks. Sensor deployment adopts a distributed approach, with appropriate sensors installed at appropriate locations on each row of photovoltaic panels based on the scale and layout of the photovoltaic power station to ensure comprehensive and accurate data collection [8]. Furthermore, to ensure stable operation, the sensors are waterproof, dustproof, and anti-interference.

The network layer undertakes the important task of data transmission, transmitting information collected by the perception layer to the application layer and issuing control commands from the application layer to the devices in the perception layer [9]. In selecting the network protocol, a combination of LoRa and WiFi was adopted, taking into account the communication needs of the photovoltaic power station. LoRa, with its long transmission distance and low power consumption, is suitable for long-distance data transmission between sensors and gateways. WiFi, with its fast transmission speed, is suitable for high-speed data transmission between gateways and application-layer servers. The network topology combines star and mesh topologies. The star topology connects sensors and gateways, facilitating centralized management; the mesh topology connects gateways, improving network reliability and scalability. If a gateway fails, data can be transmitted through other gateways.

The application layer is the "brain" of the system, responsible for data processing, analysis, and decision-making, as well as intelligent management of the cleaning system. The application layer comprises multiple functional modules, with the cleaning task scheduling module being a core module. The equipment monitoring module monitors the operating status of cleaning equipment in real time, including its location, speed, and power level [10]. In the event of a fault, it promptly issues an alarm and notifies maintenance personnel to address the issue. The data storage and analysis module is responsible for storing various data generated during system operation. By analyzing this data, cleaning patterns can be summarized, providing a basis for system optimization. The user interaction module provides a user-friendly interface, allowing users to view system operating status, issue cleaning instructions, and more.

2.2. Collaborative Control Strategy

The collaborative control strategy is key to ensuring the efficient operation of the IoT-based photovoltaic power station intelligent cleaning system. It primarily includes a multi-agent collaborative mechanism and collaborative control based on rules and optimization algorithms.

The multi-agent collaborative mechanism treats each device in the cleaning system as an intelligent agent with autonomous decision-making capabilities. Through collaboration and communication between these agents, cleaning tasks are efficiently completed. For cleaning task allocation, a negotiation mechanism based on a contract

network is employed. When a cleaning task is required, the task manager, as the initiator, publishes a task announcement. Each cleaning device agent submits a bid based on its own status and capabilities. The task manager then selects the most suitable cleaning device agent based on the bids. During the collaborative process, agents share information in real time, communicating task execution status and environmental changes. This allows for timely adjustments to task plans in the event of emergencies. For example, if a cleaning machine agent malfunctions, other agents can take over its unfinished tasks as appropriate, ensuring smooth cleaning. This multi-agent collaborative mechanism improves the system's flexibility and robustness, enabling it to adapt to complex and changing cleaning environments.

Cooperative control based on rules and optimization algorithms builds on the multi-agent collaborative mechanism by combining preset rules and optimization algorithms to further improve the efficiency of collaborative control of the cleaning system. Preset rules primarily include cleaning priority rules and equipment scheduling rules. The cleaning priority rules determine the order of cleaning based on factors such as the contamination level and importance of the photovoltaic panels. The more severely contaminated and the more important the photovoltaic panels, the higher the cleaning priority. The equipment scheduling rules define the scheduling principles for cleaning equipment, such as prioritizing equipment that is closer to the task location and has sufficient battery life. The optimization algorithm combines a genetic algorithm with a particle swarm optimization algorithm to optimize cleaning paths and task allocation. The genetic algorithm has strong global search capabilities and can find the optimal solution within a large range. The particle swarm optimization algorithm, with its fast convergence speed, can further optimize the optimal solution found by the genetic algorithm. By combining these two algorithms, the convergence speed of the algorithm can be improved while ensuring the quality of the solution. Collaborative control based on rules and optimization algorithms enables the cleaning system to achieve the lowest cleaning cost and highest efficiency while satisfying various constraints.

3. Key System Technologies

3.1. Photovoltaic Panel Contamination Detection Technology

Photovoltaic panel contamination detection technology is a prerequisite for the intelligent cleaning system to achieve precise cleaning. It primarily utilizes a combination of image recognition and sensor measurement technologies. Image recognition technology uses a high-definition camera to capture images of the photovoltaic panel surface and analyzes them using image processing algorithms. First, image preprocessing, including denoising, enhancement, and cropping, is performed to improve image quality. An edge detection algorithm is then used to extract the edges of the contaminated area. The contamination level is determined by calculating the ratio of the contaminated area to the total area of the photovoltaic panel. Color feature analysis can further refine the judgment. Deep learning algorithms are also introduced to establish a contamination level identification model, improving the ability to identify complex contamination situations. Sensor measurement technology primarily uses dust thickness sensors and light transmittance

sensors to detect contamination levels. The dust thickness sensor uses a laser ranging principle to calculate dust thickness based on laser reflection time. The light transmittance sensor determines contamination by measuring the ratio of the light intensity transmitted through the photovoltaic panel to the incident light intensity. Multi-sensor data fusion technology is used to combine the results of the two methods to comprehensively determine the degree of pollution. Experimental verification shows that the error of this detection technology can be controlled within 5%, meeting the system accuracy requirements.

3.2. Intelligent Control Technology for Cleaning Equipment

Intelligent control technology for cleaning equipment is the core of achieving automated and intelligent cleaning. It includes remote control and autonomous navigation technologies. Remote control connects the cleaning equipment to a control center via an IoT network. Operators can view equipment status and issue control commands in real time through a graphical interface. Encrypted transmission technology and permission management mechanisms ensure secure and reliable control.

The autonomous navigation system, consisting of GPS, INS, and environmental perception sensors, enables the equipment to autonomously plan and navigate its route. GPS obtains real-time location information, INS estimates position when the GPS signal is unstable, and ultrasonic and infrared sensors detect obstacles and automatically adjust the route. The A* algorithm is used to plan the shortest and most efficient cleaning route. Experimental tests have shown that the driving error in autonomous navigation mode can be controlled within 10 cm.

3.3. Data Fusion and Processing Technology

Data fusion and processing technology primarily involves three steps: data preprocessing, data fusion, and data mining. Data preprocessing cleans, transforms, and normalizes the raw data to remove noise and outliers, standardize data formats and units, and eliminate dimensional differences. Data fusion utilizes a layered approach: data-layer fusion directly processes raw data from different sensors; feature-layer fusion extracts and integrates diverse data features; and decision-layer fusion synthesizes the results of different detection methods. Data fusion improves data reliability and integrity while reducing uncertainty. Data mining utilizes

association rule algorithms to analyze the relationship between pollution levels and environmental factors, cluster analysis to classify pollution patterns, and time series analysis to predict pollution trends. This provides a basis for developing differentiated cleaning strategies, enhancing the system's proactiveness and foresight.

4. System Simulation Experiments

4.1. Simulation Environment Setup

This simulation experiment uses MATLAB/Simulink as the core platform. This platform features modular modeling and dynamic simulation capabilities, enabling accurate simulation of the coordinated control process of an IoT-based photovoltaic power plant's intelligent cleaning system. The simulation parameters are as follows: the photovoltaic power plant consists of 300 standard photovoltaic panels ($1.5\text{m} \times 1\text{m}$), arranged in a 15-row, 20-column matrix. Eight intelligent cleaning robots are deployed, each with a cleaning speed of 0.4m/s , a battery life of 3.5 hours, and a charging efficiency of $20\%/h$. Twenty environmental monitoring nodes are deployed with a 30-second sampling period, collecting parameters such as temperature ($-10\text{--}50^\circ\text{C}$), humidity ($10\%\text{--}90\%\text{RH}$), and wind speed ($0\text{--}15\text{m/s}$). Network transmission uses the UDP protocol, with a latency range of $5\text{--}30\text{ms}$ and a packet loss rate of $\leq 1\%$.

4.2. Simulation Design

To fully validate the performance of the collaborative control framework, three comparative experimental scenarios were designed:

- **Basic Performance Test:** Under standard conditions (temperature 25°C , humidity 50% , no wind), light (dust coverage 10%), moderate (30%), and heavy (50%) pollution levels were set to compare the cleaning efficiency of traditional control and this framework.
- **Environmental Adaptability Test:** Under fixed moderate pollution conditions, four scenarios were simulated: sunny day (sunlight 800W/m^2), cloudy day (300W/m^2), light rain (0.5mm/h), and high wind (8m/s) to evaluate system stability.
- **Equipment Scalability Test:** Maintaining moderate pollution and standard conditions, 4, 6, 8, and 10 cleaning devices were deployed, respectively, to analyze how resource utilization changes with the number of devices.

4.3. Simulation Results Analysis

4.3.1. Collaborative Control Efficiency Analysis

Table 1. Comparison of Control Performance Under Different Pollution Levels

control method	Pollution level	Completion time (min)	Resource utilization (%)	Device conflict rate (%)	Total energy consumption (kWh)
Traditional control	Mild	45	56.2	8.7	32.5
Traditional control		29	75.8	2.3	24.1
Traditional control	Moderate	71	53.6	11.2	48.3
Traditional control		48	75.9	3.6	36.5
Traditional control	Severe	108	49.3	15.6	65.2
Traditional control		68	72.1	5.1	46.5

The performance comparison data under different pollution

levels is shown in Table 1. In moderate pollution scenarios,

our framework achieved a 32.4% reduction in task completion time compared to traditional control (from 71 minutes to 48 minutes), improved resource utilization by 22.3 percentage points, and reduced device conflicts by 67.5%.

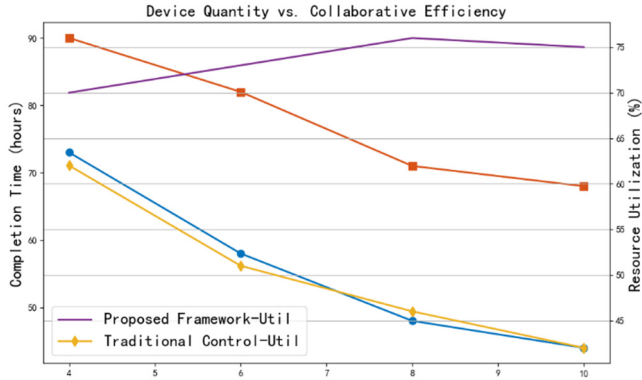


Fig 1. Relationship between Equipment Quantity and Collaborative Efficiency

As pollution levels increased, the efficiency gap between the two control approaches widened. In severe pollution, our

framework achieved an energy consumption advantage of 18.7 kWh per time.

Figure 1 shows the impact of device number on collaborative efficiency. When the number of devices increases from 4 to 8, the resource utilization of our framework remains above 70%, while the traditional control approach shows a significant drop at 6 devices (from 62.5% to 51.3%). With 8 devices, our framework achieves a 41.2% reduction in task completion time compared to the traditional approach, demonstrating its superiority in device collaborative scheduling.

4.3.2. Cleaning Effect Analysis

Table 2 shows the power generation efficiency improvement data under different weather conditions. Even in light rain, our proposed framework still maintains a 21.3% power generation efficiency improvement, 8.7 percentage points higher than traditional control, demonstrating its environmental adaptability. Under sunny conditions, the difference in cleaning effect between the two control methods is minimal (3.2 percentage points), but our proposed framework reduces energy consumption by 15.6%.

Table 2. Comparison of Cleaning Effects under Different Weather Conditions

weather type	Control method	Efficiency before cleaning (%)	Efficiency after cleaning (%)	Increase (%)	Water consumption per unit area (L/m ²)
sunny	Traditional control	14.2	18.5	4.3	1.8
	Framework of this article	14.2	18.8	4.6	1.5
Cloudy	Traditional control	10.5	13.8	3.3	1.7
	Framework of this article	10.5	14.5	4.0	1.4
Light rain	Traditional control	9.8	11.7	1.9	2.1
	Framework of this article	9.8	11.9	2.1	1.6
Strong wind	Traditional control	12.3	15.6	3.3	1.9
	Framework of this article	12.3	16.2	3.9	1.5

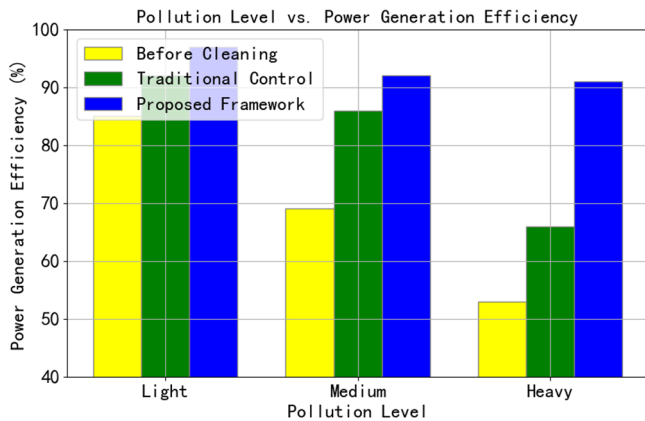


Fig 2. Relationship between pollution level and power generation efficiency

Figure 2 shows the relationship between pollution level and power generation efficiency. Before cleaning, the power

generation efficiency of heavily polluted photovoltaic panels was 38.7% lower than that of lightly polluted panels. After using our framework for cleaning, the efficiency of heavily polluted panels recovered to 92.3% of that of lightly polluted panels, while conventional control only recovered to 81.5%. Figure 3 shows the efficiency decay curve over 72 hours. The efficiency decay rate of photovoltaic panels after our framework cleaning (0.12%/h) is significantly lower than that of conventional cleaning methods (0.18%/h), indicating that the cleaning effect is more durable.

Comprehensive simulation results show that the collaborative control framework proposed in this paper performs excellently in terms of cleaning efficiency, resource utilization, and environmental adaptability. In particular, its stability under complex operating conditions significantly outperforms traditional control methods, demonstrating its practical application value.

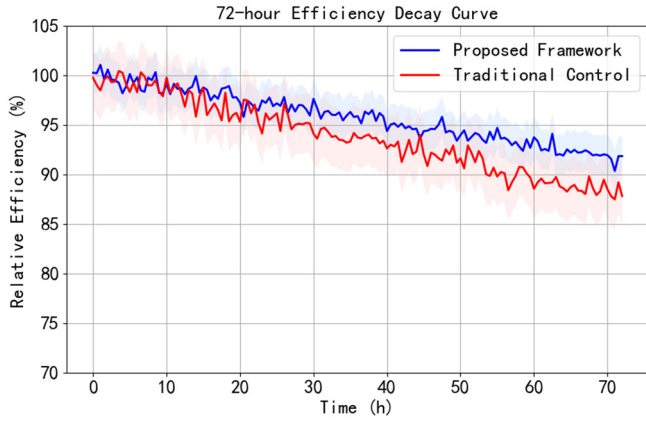


Fig 3. Efficiency decay curve

5. Conclusion

The collaborative control framework for an IoT-based photovoltaic power station intelligent cleaning system constructed in this paper effectively addresses the current system's lack of coordination. This framework integrates resources through a three-layer architecture and employs a control strategy that combines a multi-agent collaborative mechanism with an optimization algorithm, achieving efficient coordination between cleaning equipment and the system. Simulation experiments show that in moderate pollution scenarios, the framework reduces task completion time by 32.4%, increases resource utilization to 75.9%, and reduces device conflict rate to 3.6%. Under varying weather conditions, power generation efficiency in light rain conditions increases by 2.1%, outperforming traditional control methods. When the number of devices varies, the eight-device configuration reduces task completion time by 41.2% compared to traditional methods, while maintaining resource utilization above 70%. Furthermore, after cleaning, the efficiency of heavily polluted photovoltaic panels recovers to 92.3% of that of lightly polluted panels, demonstrating a lower efficiency decay rate. In summary, this framework significantly improves cleaning efficiency, reduces costs, and enhances the power generation benefits of photovoltaic power stations, promoting their development towards intelligence and efficiency, and has high practical

application value.

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