Journal of Electronic Research and Application, 2025, Volume 9, Issue 6
http://ojs.bbwpublisher.com/index.php/JERA
ISSN Online: 2208-3510
ISSN Print: 2208-3502

An Intelligent Operation and Maintenance System for Photovoltaic Station

Qing Yi[1], Jiayou Sun[2], Shanying Su[1],Houzhi Wei[1], Ke Wang[1], Zhihui Qi[1], Siyu Teng[3]*

[1]China Resources New Energy (Chibi) Co., Ltd., Chibi 437300, Hubei, China
[2]Waytous, Shenzhen 518000, Guangdong, China
[3]Shenzhen University, Shenzhen 518060, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: The rapid expansion of photovoltaic (PV) deployment poses new challenges for large-scale and distributed maintenance, particularly in fishery-PV complementary plants where panels are deployed over water surfaces. This paper presents the design and implementation of an intelligent operation and maintenance (O & M) system that integrates a 3D holographic digital twin cloud platform with UAV-assisted inspection and localized cleaning. The proposed system supports multi-source data acquisition, including UAV imagery, infrared sensing, and DustIQ-based soiling monitoring, and provides real-time visualization of the PV plant through 1:1 3D reconstruction. UAVs are employed for both autonomous inspections, covering defects such as soiling, bird droppings, bypass diode faults, and panel disconnections and targeted cleaning in small water-covered areas. Field trials were conducted at Riyue and Chebu PV plants, with small-scale UAV cleaning validation in Chebu fish ponds. Results demonstrated that the system achieves efficient task scheduling, fault detection, and localized cleaning, thereby improving O & M efficiency, reducing costs, and enabling digitalized and intelligent management for large-scale PV stations.

Keywords: Photovoltaic station; Unmanned aerial vehicles; Operation and maintenance system

Online publication: December 16, 2025

1. Introduction

Photovoltaic (PV) power has grown into a major contributor to renewable generation worldwide [1,2]. The rapid scale-up of utility PV plants brings acute challenges for large-scale operation and maintenance (O&M), where modules are widely distributed, environments are harsh, and manual inspection or cleaning is time-consuming, costly, and often unsafe [3]. These challenges are amplified in fishery-PV complementary plants, where modules are deployed above ponds. While this co-location improves land-water utilization, it also increases O&M difficulty due to limited accessibility over water, high humidity, frequent soiling and bird droppings, and the need for frequent localized cleaning.

Unmanned aerial vehicles (UAVs) have emerged as a practical solution to these issues. They enable rapid, large-area data acquisition with flexible flight planning and multi-sensor payloads (RGB, infrared, LiDAR), supporting automated anomaly discovery and targeted maintenance. Beyond inspection, UAVs can execute localized cleaning in small pond areas where conventional ground systems are inefficient [4–8]. In parallel, advances in digital twin technology, real-scene 3D reconstruction, multi-source data fusion, and online analytics, make it feasible to build a cloud platform that virtualizes the entire plant for situational awareness, scheduling, and decision support. Integrating UAV-based inspection/cleaning with a holographic 3D cloud platform promises an end-to-end, data-driven O&M workflow [9,10].

This paper presents the design and implementation of an intelligent O&M system for fishery-PV plants. The composition are as follows:

(1) A real-scene 3D holographic cloud platform for IoT ingestion, GIS-based asset management, data cleansing, analytics, and EAM interfacing;
(2) A UAV inspection subsystem to detect visible anomalies and thermal faults;
(3) A UAV cleaning subsystem for targeted spraying in small pond regions with task scheduling and tracking.

The contributions of this paper are as follows:

(1) We develop a unified O&M framework coupling UAV inspection/cleaning with a 1:1 holographic 3D digital twin for real-time visualization, asset localization, and intelligent scheduling;
(2) We implement an end-to-end engineering system meeting data standardization and enterprise EAM integration requirements;
(3) We report field deployments at Riyue and Chebu plants, including small-pond UAV cleaning trials, showing improved inspection coverage, actionable fault localization, and efficient on-demand cleaning.

The presented system provides a practical blueprint for scalable, automated, and visualized PV O&M in complex water-land hybrid environments and offers a path for data-centric, predictive maintenance in large renewable assets.

2. System architecture

The proposed intelligent O&M system for fishery-PV complementary plants follows a layered architecture, integrating UAV-based inspection/cleaning subsystems with a holographic 3D cloud platform. As shown in **Figure 1**, the architecture consists of four key layers: data acquisition, platform management, intelligent application, and user interaction. Each layer is designed to ensure scalability, interoperability, and robustness under large-scale, distributed deployment.

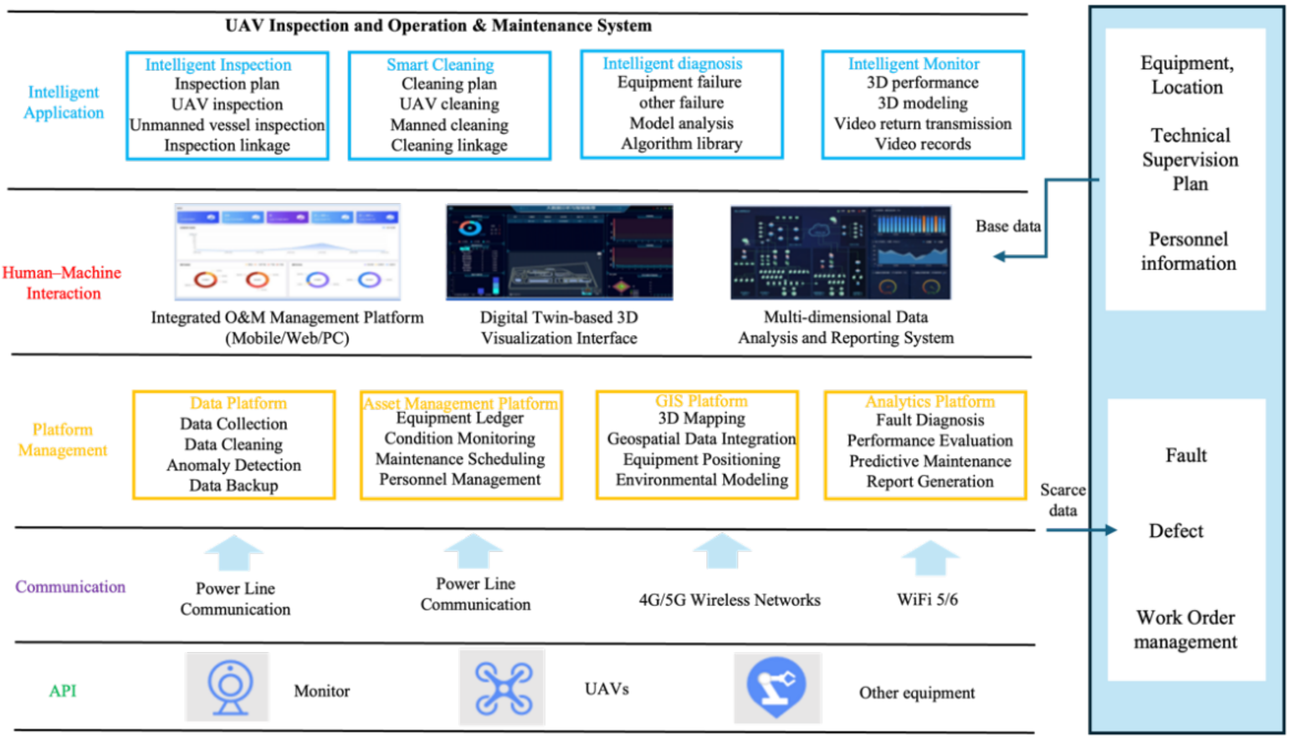

Figure 1. Schematic diagram of monitoring PV systems using UAVs.

2.1. Data acquisition layer

The lowest layer collects heterogeneous data from UAVs and IoT devices. UAVs are equipped with RGB and infrared cameras for surface and thermal inspection, and optionally LiDAR or oblique cameras for 3D reconstruction. In addition, environmental sensors (e.g., DustIQ for soiling level, meteorological sensors, and pond-level monitors) provide contextual data. All data streams are transmitted via 5G/WiFi or edge gateways to the cloud platform. This layer ensures multi-modal, real-time data ingestion for both inspection and cleaning scheduling.

2.2. Platform management layer

The platform management layer incorporates several coordinated sub-platforms that enable comprehensive data integration and infrastructure control. The IoT sub-platform manages edge device connectivity and protocol translation to ensure secure communication. The device sub-platform provides lifecycle management for UAVs and sensors, while the GIS sub-platform maintains accurate 3D PV plant models through coordinate integration and holographic modeling. The data sub-platform performs data cleansing, de-noising, and anomaly detection to ensure high-quality inputs for analysis. Building on this foundation, the analytics sub-platform applies machine learning and statistical models for tasks such as fault detection, loss estimation, and forecasting cleaning needs. Finally, the business middleware orchestrates operational workflows, including UAV inspections, cleaning dispatch, and fault reporting, and interfaces seamlessly with EAM systems. Collectively, this layer serves as the backbone of the O&M system, ensuring efficient coordination between hardware and software components.

2.3. Intelligent application layer

At the application layer, advanced functional modules provide intelligent decision-making support and enable automated O&M operations. 3D visualization capabilities create a digital twin of the PV plant, allowing real-time monitoring within a 1:1 holographic 3D environment. Inspection and cleaning scheduling modules dynamically allocate UAV tasks based on environmental conditions, equipment status, and operational priorities. Fault detection and alarming mechanisms automatically issue alerts when anomalies are identified, ensuring timely and targeted interventions. Additionally, extreme weather early-warning functions integrate meteorological data to generate predictive alerts and automatically suspend UAV operations under unsafe conditions. Overall, these capabilities convert raw data into actionable insights, enabling preventive and predictive maintenance across the entire system.

3. UAV inspection and cleaning system

Besides the cloud platform, UAVs are central to automating inspection and localized maintenance of fishery-PV complementary plants. The UAV subsystem has two components: an autonomous inspection platform for anomaly detection and a targeted cleaning platform for removing surface contamination in small pond regions. The cloud platform coordinates both subsystems via mission scheduling and real-time communication (**Figure 2**).

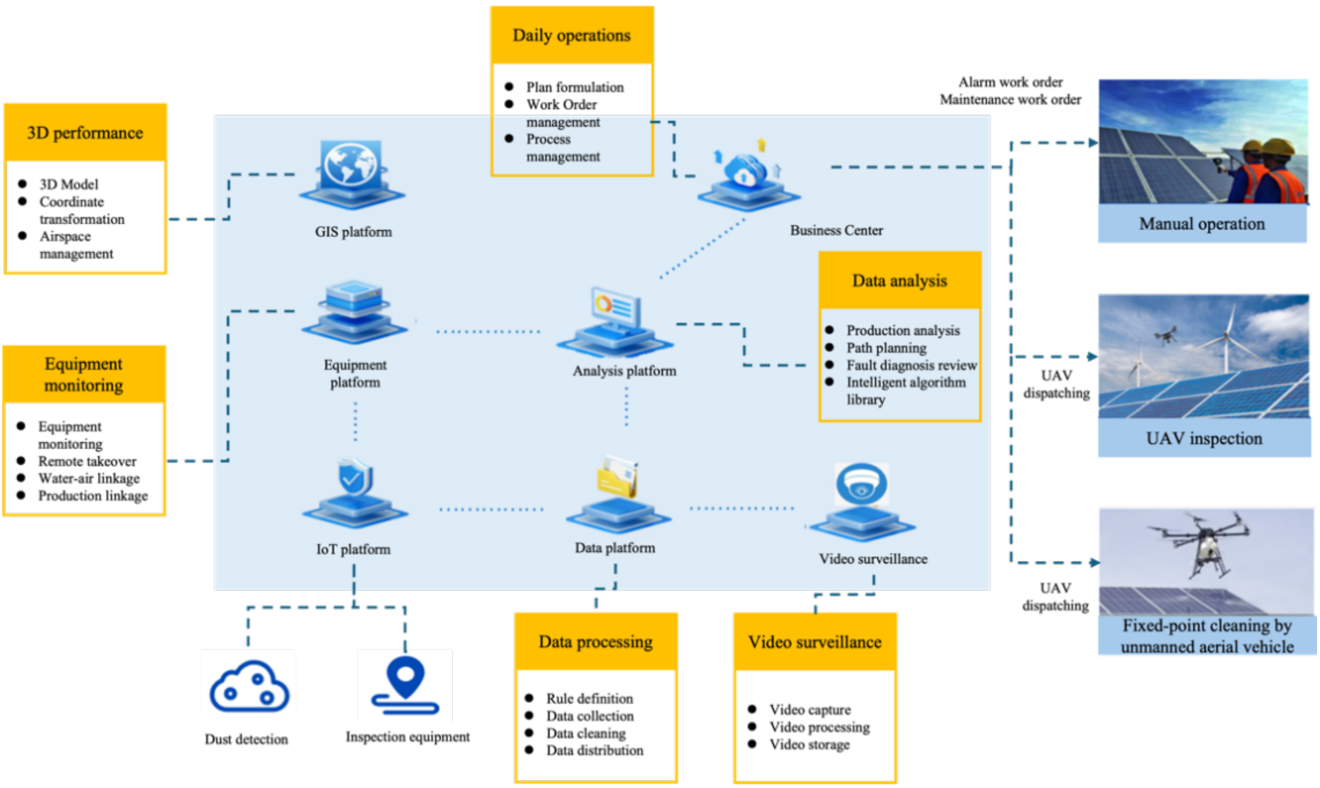

Figure 2. UAV inspection and cleaning system.

3.1. UAV inspection platform

The UAV inspection platform replaces traditional manual ground patrols with automated aerial surveys. It integrates docking stations, multi-rotor UAVs, and modular sensor payloads for comprehensive PV plant inspection. Each UAV has sensors for different tasks. RGB cameras detect surface anomalies like missing panels, and infrared cameras reveal hidden faults. LiDAR or oblique cameras can be mounted for 3D reconstruction.

3.2. UAV cleaning platform

UAVs also have localized cleaning capabilities for pond-covered PV regions where ground-based methods are inefficient. Each UAV has a detachable water tank and a spraying module to dispense cleaning fluid or pond water onto contaminated panels. Field trials confirmed its efficiency: a 15-minute sortie can clean 5–6 strings of panels (about 0.05 MW). A single UAV can clean up to 1.2 MW in 8 hours, showing its feasibility for medium- and large-scale PV plants.

3.3. Task scheduling and coordination

Inspection and cleaning UAVs are integrated into the platform's centralized scheduling system. The business middleware handles mission planning, generating tasks according to schedules, anomaly levels, or environmental sensor alerts. Dynamic dispatch mechanisms allocate tasks to available UAVs considering priority, UAV status, and weather, maximizing fleet efficiency and ensuring safety.

3.4. Safety and emergency handling

Due to risks of UAV deployment over water-covered PV plants, safety mechanisms are added. UAVs do pre-flight diagnostics to cut in-flight failures and have multiple emergency modes for unexpected events. Fail-safe mechanisms involve automatic return-to-home for communication loss, forced landing in safe zones for low battery, and trajectory correction for wind-induced drift. These features enhance mission robustness and safety for UAV operations in complex environments.

4. Field deployment and validation

To evaluate the feasibility and effectiveness of the proposed intelligent O&M system, a series of field trials were conducted in real PV plant environments featuring water-covered arrays and distributed module layouts. These scenarios provide representative challenges for UAV-based inspection and cleaning, including difficult access, high-frequency soiling, and thermal anomalies (Figure 3).

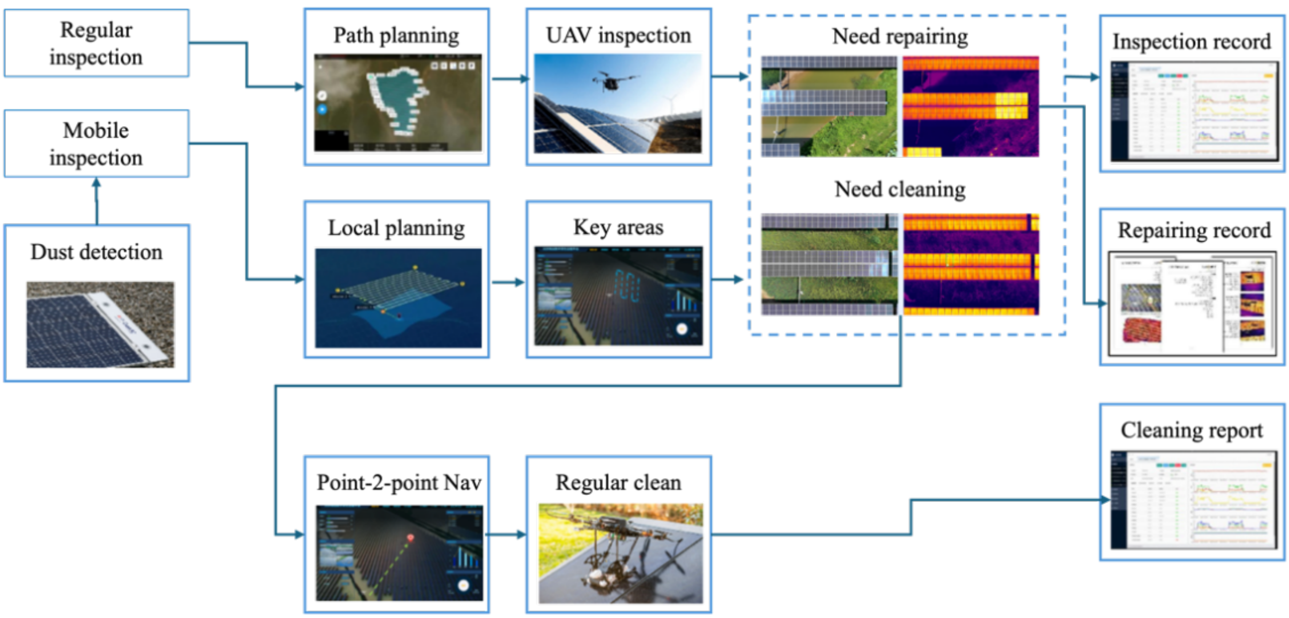

Figure 3. UAV cleaning/maintenance process.

4.1. Experimental phases

Validation of the proposed system was done in the following three progressive stages to ensure functional feasibility and system-level robustness.

(1) Small-scale pilot trials verified core subsystems' feasibility. UAV flight stability, image acquisition, anomaly detection, and cleaning tasks were tested under controlled conditions. The results confirmed basic components' reliable operation and laid a foundation for subsequent integration;

(2) Intermediate validation was carried out by end-to-end integration of UAV platforms with the cloud-based O&M system. Route planning, task transfer, and 3D visualization were evaluated. UAV missions were triggered by data-driven events, showing the system's adaptive response;

(3) Large-scale trials assessed the entire workflow in realistic PV plant environments. The cloud platform scheduled UAV missions for inspection, fault detection, and cleaning. Comprehensive metrics were measured, validating the framework's scalability and reliability for real-world deployment.

4.2. Inspection validation

UAVs with RGB and infrared cameras identified anomalies. Inspection results were processed, reported, and visualized on the 3D platform, facilitating confirmation and decision-making.

4.3. Cleaning validation

In field cleaning trials, UAV sorties were highly effective in removing localized PV module contamination. Each 15-minute sortie could clean about five to six panel strings, showing efficiency and feasibility for targeted cleaning. With periodic water-tank refilling and battery recharging over longer periods, a single UAV had a daily cleaning capacity exceeding 1~MW of installed capacity, indicating its potential to meet medium- to large-scale PV plant demands.

The trials also confirmed UAVs could effectively mitigate different contaminants. Bird-dropping contamination was fully removed, and dust soiling was reduced by over 90% under moderate accumulation. These results highlight the practicality of UAV-assisted cleaning, especially where conventional methods are inefficient or logistically difficult.

4.4. System performance and safety

The cloud platform demonstrated stable scheduling, real-time 3D visualization, and anomaly reporting. UAV operations were supported by automated return-to-home, emergency landing protocols, and weather-aware task suspension. These mechanisms ensured both operational reliability and flight safety.

5. Discussion

Field validation shows the effectiveness of integrating complementary sensing modalities for PV plant inspection. RGB imagery offers visual info to identify structural anomalies like panel misalignment, while infrared imaging is crucial for diagnosing latent thermal faults. Combining these two modalities enables more comprehensive anomaly detection than single-modality approaches.

Besides inspection, UAV-based cleaning is cost-effective and responsive for localized contamination, especially in areas with frequent soiling from bird activity or hard-to-access modules. Targeted cleaning reduces maintenance cycles and costs, and improves energy yield reliability, highlighting UAVs as both inspection and maintenance agents.

The validation confirms the scalability of the proposed framework. Its modular architecture allows seamless integration of more UAVs and sensors, and cloud-based scheduling ensures efficient task coordination, supporting the transition from small-scale trials to large-scale PV farms. These findings establish the framework as a reliable and scalable solution for PV plant operation and maintenance.

6. Conclusion

This paper presented an intelligent operation and maintenance system for PV plants, integrating a 3D holographic cloud platform with UAV-based inspection and cleaning. By combining RGB and infrared sensing, the system enables comprehensive detection of both visible and thermal anomalies, while UAV-mounted cleaning modules address localized contamination with high efficiency. Field validations confirmed reliable performance in inspection accuracy, cleaning effectiveness, and task scheduling, supported by safety mechanisms and real-time visualization. The results demonstrate that the proposed framework provides a scalable and practical solution for automated and intelligent O&M of large-scale and water-covered PV farms, contributing to improved reliability, efficiency, and sustainability of solar energy production.

Funding

Joint Innovation Program of Guangdong (Project No.: 2023A0505020003)

Disclosure statement

The authors declare no conflict of interest.

References

[1] Singh G, 2013, Solar Power Generation by PV (photovoltaic) Technology: A Review. Energy, 2013(53): 1–13.

[2] Parida B, Iniyan S, Goic R, 2011, A Review of Solar Photovoltaic Technologies. Renewable and Sustainable Energy Reviews, 15(3): 1625–1636.

[3] Hernandez-Callejo L, Gallardo-Saavedra S, Alonso-Gomez V, 2019, A Review of Photovoltaic Systems: Design, Operation and Maintenance. Solar Energy, 2019(188): 426–440.

[4] Laghari A, Jumani A, Laghari R, et al., 2023, Unmanned Aerial Vehicles: A Review. Cognitive Robotics, 2023(3): 8–22.

[5] Ahmed F, Mohanta J, Keshari A, Yadav P, 2022, Recent Advances in Unmanned Aerial Vehicles: A Review. Arabian Journal for Science and Engineering, 47(7): 7963–7984.

[6] Zeng Y, Zhang R, Lim Y, 2016, Wireless Communications with Unmanned Aerial Vehicles: Opportunities and Challenges. IEEE Communications Magazine, 54(5): 36–42.

[7] Zuo Z, Liu C, Han Q, et al., 2022, Unmanned Aerial Vehicles: Control Methods and Future Challenges. IEEE/CAA Journal of Automatica Sinica, 9(4): 601–614.

[8] Ashokkumara K, Srimonchaari B, Mayan J, 2025, Designing and Constructing a Versatile UAV System for Cleaning Applications. AIP Conference Proceedings, 2025(3257): 20163.

[9] Pires F, Cachada A, Barbosa J, et al., 2019, Digital Twin in Industry 4.0: Technologies, Applications and Challenges. 2019 IEEE 17th International Conference on Industrial Informatics (INDIN), 2019(1): 721–726.

[10] Wang X, Yang J, Han J, 2022, Metaverses and Demetaverses: From Digital Twins in CPS to Parallel Intelligence in CPSS. IEEE Intelligent Systems, 37(4): 97–102.