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AI-ASSISTED TARGETED DRONE RE-INSPECTION OF PHOTOVOLTAIC PLANTS USING PHOTOGRAMMETRIC 3D MODELS – A PRACTICAL WORKFLOW

Summary

This work presents an automated end-to-end workflow for PV plant inspections using Unmanned Aerial Vehicles (UAVs). By integrating real-time photogrammetry with AI-driven anomaly detection, the system generates a georeferenced 3D digital twin during flight. A key innovation is the autonomous "double-pass" logic: the system identifies thermal anomalies and string faults in real-time, automatically calculating optimized waypoints for a secondary, high-resolution re-inspection. This eliminates manual data post-processing and ensures precise localization of defects via GPS-linked 3D reports. Initial results show significant reductions in inspection and analysis time and improved accuracy in fault-to-module assignment.

Keywords: photovoltaic inspection, infrared thermography, drone inspection, photogrammetry, AI defect detection, PV monitoring, automated drone missions and documentation, simulation of revenue loss

Field of application for the findings: Operation and maintenance (O&M) of photovoltaic systems, thermographic drone inspection, automated PV monitoring and reporting.

Addressed audience: Researchers in solar energy systems, PV plant operators, drone inspection service providers, asset managers, and developers of AI-based monitoring and thermography solutions.

1. Introduction

The rapid expansion of photovoltaic (PV) capacity globally necessitates highly efficient Operation and Maintenance (O&M) strategies to ensure optimal energy yields and system longevity. Aerial thermography using Unmanned Aerial Vehicles (UAVs) has become a standard tool for detecting anomalies such as hotspots, bypass diode failures, and string faults. However, conventional workflows often suffer from significant manual post-processing efforts, delayed reporting, and challenges in precisely localizing defects within large-scale utility plants.

The research presented here addresses these inefficiencies by introducing an integrated system for real-time thermographic evaluation and autonomous re-inspection. By combining computer vision-based module segmentation with simplified, high-speed photogrammetry, the proposed workflow generates a georeferenced 3D digital twin during the flight. Unlike traditional methods where data is analyzed offline, this approach enables immediate identification and 3D-mapping of thermal anomalies.

A novel feature of this system is the closed-loop automation: detecting a high-level anomaly triggers an immediate calculation of optimized waypoints, allowing the UAV to perform autonomous close-up captures for detailed diagnostic verification before the initial mission ends. This "report-ready upon landing" capability significantly reduces the "Mean Time to Repair" (MTTR). To date, the system has been validated through field tests on three utility-scale plants and ten residential installations, demonstrating its robustness in diverse operational environments.

2. Methodology

The proposed technical workflow is divided into four integrated modules: automated data acquisition, real-time 3D reconstruction, AI-based diagnostics, and automated reporting.

2.1. Computer Vision and Module Segmentation

The system processes synchronized RGB and Long-Wave Infrared (LWIR) streams. A customized Convolutional Neural Network (CNN) is employed to segment individual PV module surfaces within the image frames (Fig. 1). This segmentation allows for the isolation of active solar areas, excluding mounting structures and background noise, allowing for an accurate thermal delta-T (ΔT) calculation in accordance with IEC 62446-3 (2017)

2.2. Real-Time Photogrammetry and Coordinate Mapping

To achieve real-time 3D reconstruction without the computational overhead of traditional Structure-from-Motion (SfM) algorithms, the system utilizes a disparity-based approach. By leveraging the UAV's onboard LiDAR or the optical displacement between consecutive frames, a simplified photogrammetric mesh is generated. Each detected PV module is assigned a unique ID and localized within a global coordinate system (*lat, lon, alt*) (Fig. 1).

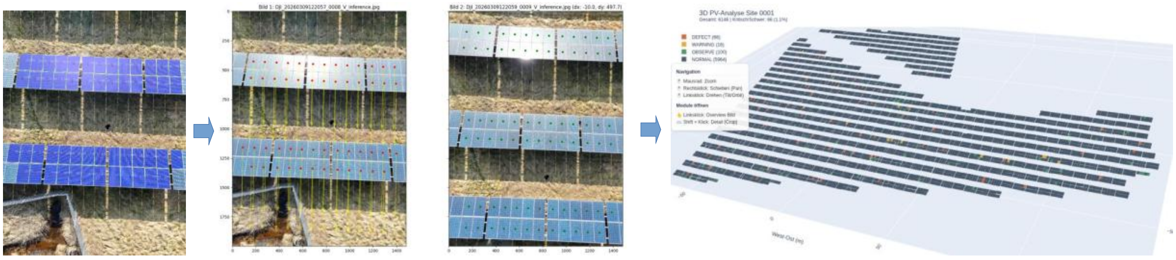

Fig. 1: From module segmentation via disparity-based photogrammetry to real-time 3D digital twin

2.3. Thermal Anomaly Detection and Pixel-Level Analysis (Fig. 2)

A secondary AI model identifies thermal signatures associated with common PV defects, such as hotspots, bypass diode failures, and string anomalies. For each flagged module, the system performs a pixel-precise temperature distribution analysis. By normalizing thermal data against ambient conditions, the software quantifies the severity of the defect.

2.4. Autonomous Flight Path Optimization

A key innovation is the feedback loop to the UAV's flight controller. Upon detecting a high-priority anomaly, the software dynamically generates a secondary mission plan. The UAV autonomously navigates to the precise 3D coordinates of the defect to capture high-resolution macro-imagery, ensuring a comprehensive diagnostic dataset before the aircraft lands.

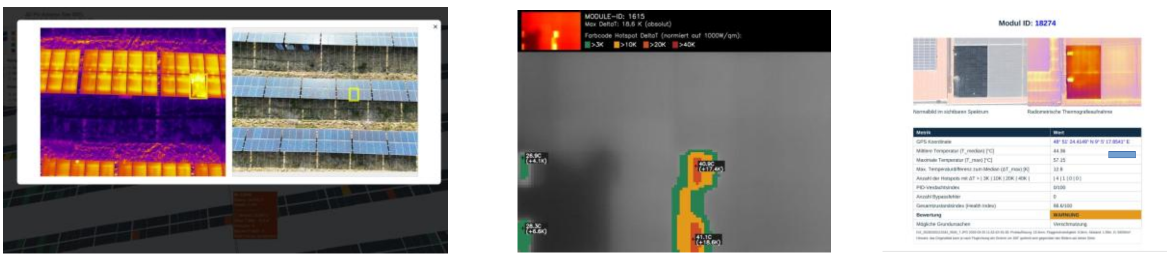

Fig. 2: Representative results from three different PV plants illustrating automated defect localization within the 3D model and corresponding pixel-based thermographic analysis

3. Results and Discussion

The integrated workflow was evaluated through field tests on 13 PV installations, ranging from residential rooftop systems to utility-scale plants. The primary objective was to validate the technical feasibility of the real-time coupling between 3D reconstruction, AI diagnostics and automated report generation.

3.1. Technical Validation of the 3D-Reporting Loop

The tests confirmed that the simplified photogrammetry approach provides sufficient spatial accuracy to distinguish individual modules within the digital twin. While the absolute georeferencing precision depends on the UAV's GNSS quality, the relative localization of anomalies within the plant layout was consistently achieved. This allows for a significant reduction in the cognitive load for maintenance teams, as thermal defects are no longer presented as isolated images but as interactive elements within a spatial context.

3.2. Observations on Workflow Efficiency

Although a full statistical time-motion study has not yet been conducted, preliminary observations indicate a substantial acceleration of the end-to-end process. The elimination of manual data sorting and the generation of structured reports immediately upon landing represent a major shift from reactive to proactive data management. The automated re-inspection ("double-pass") successfully captured detailed imagery of detected anomalies, proving that the closed-loop communication between the diagnostic engine and the flight controller is robust in real-world conditions.

3.3. Expert Feedback and Practical Utility

Preliminary inspection reports were presented to certified PV experts and potential industry clients for qualitative assessment. The feedback emphasized the high value of the GPS-linked 3D models and the pixel-precise thermal segmentation for professional documentation. A major advantage identified by practitioners is the ability to generate a comprehensive 3D digital twin from standard grid-based survey flights, which allows for the unambiguous assignment of anomalies to specific modules within the plant layout. Furthermore, experts highlighted that the automation of data evaluation and report generation significantly reduces the lead time between the drone flight and the final delivery of results. The depth of detail in the automated reports—specifically the integration of pixel-level thermal analysis and estimated yield loss simulations—was found to meet the requirements for high-quality technical audits.

4. Conclusion and Outlook

The transition from manual data evaluation to an integrated, real-time 3D diagnostic workflow represents a significant advancement in PV O&M digitalization. The developed system proves that AI-driven anomaly detection, when coupled with autonomous flight path optimization, can provide immediate, actionable data for maintenance teams.

Future work will focus on expanding the AI training datasets, particularly for complex string-fault signatures, to further increase detection precision in high-density utility plants. Furthermore, the development of adaptive, real-time path-planning strategies based on live AI detections will be explored to optimize data acquisition independently of pilot intervention, ensuring consistent high-quality imagery across complex plant geometries. The integration of automated yield loss simulations based on detected thermal anomalies will further assist operators in prioritizing maintenance tasks based on economic impact.

5. References

IEC 62446-3:2017, Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 3: Photovoltaic modules and plants - Outdoor infrared thermography.