AI-Based Autonomous Drone System for Solar PV Panel Fault Detection Using RGB, Thermal Camera

Pranali Nitnaware[1], Anshul R Mankar[2], Abhay R Dhakade[3], Achal R Kawde[4], Purva P Thaokar[5]
[1,2,3,4,5]*Priyadarshini College of Engineering, Hingana, Maharshtra*

***Abstract*—The increasing deployment of photovoltaic (PV) systems has created a need for efficient inspection methods capable of identifying panel defects at an early stage. This work presents an autonomous UAV-based inspection architecture using RGB visual imaging, MLX90640 thermal sensing, a custom ultraviolet (UV) sensor, GPS localization, ESP32-based embedded control, and MAV link communication. The system follows a quadcopter platform equipped with a multisensory payload to capture surface-level, temperature-related and electrical-discharge-related indications. The proposed hardware uses an ESP32 Hybrid Cam, 1000KV brushless motors, ESCs, a KK2.1.5 flight controller, GPS, SIM module, buck converter, servo motors, radio controller and receiver, with three 1200mAh lithium batteries. MAV link is used for structured flight telemetry, status information, GPS-related data and command communication. Image data is treated separately from MAV link telemetry so that the communication protocol is not incorrectly used as an image-processing or image-storage method. The design is intended to reduce manual inspection effort and support cost-efficient monitoring of large solar farms.**

***Index Terms*—Solar panel inspection, UAV, MAV link, ESP32, RGB imaging, thermal imaging, ultraviolet sensing, GPS localization, photovoltaic monitoring.**

I. INTRODUCTION

The rapid growth of solar photovoltaic (PV) installations has increased the need for reliable, efficient, and automated inspection methods capable of identifying panel defects at an early stage. Defects such as cracks, dust accumulation, physical damage, discoloration, and other visible abnormalities can reduce the performance and reliability of PV modules. Manual inspection of large-scale solar farms is often labour-intensive, time-consuming, and difficult to perform at regular intervals. UAV-based inspection provides a flexible aerial platform for systematic image acquisition and can significantly reduce the effort required for repeated manual surveying of extensive photovoltaic installations [1], [2]. RGB-based visual inspection provides valuable surface-level information that can be used to identify visible abnormalities in PV modules. In the proposed system, an ESP32 Hybrid Cam is used to capture RGB images of solar panels during UAV flight. The captured images are analyzed using the YOLOv8 object-detection framework to automatically identify and classify visible panel defects. This AI-based approach enables the inspection system to process captured visual information and identify potential faulty regions without relying entirely on manual examination. GPS localization is incorporated to associate detected defects with their corresponding positions within the solar farm, allowing identified panels to be located for subsequent maintenance. The proposed system uses an economical quadcopter architecture consisting of a quadcopter frame, 1000KV brushless motors, ESCs, a KK2.1.5 flight controller, ESP32 Hybrid Cam, GPS module, SIM module, buck converter, radio controller and receiver, and three 1200mAh lithium batteries. The flight-control subsystem manages UAV movement, while the camera and YOLOv8-based analysis subsystem perform visual inspection and defect detection. MAVLink is used as the structured communication layer for flight telemetry, system status, GPS-related information, and command communication between the UAV and the ground station. Importantly, MAVLink is not treated as an image-processing algorithm, image codec, or image-storage mechanism; image acquisition and YOLOv8-based analysis remain separate from the flight-telemetry communication layer.The overall objective of the proposed architecture is to develop a cost-effective and automated UAV inspection platform capable of capturing solar-panel images, detecting

visible defects using AI-based image analysis, associating detected faults with GPS coordinates, and transmitting relevant flight and inspection information to a monitoring system. By combining autonomous aerial inspection, RGB imaging, YOLOv8-based defect detection, GPS localization, embedded control, and MAVLink-based telemetry, the proposed system aims to reduce manual inspection effort and support efficient monitoring of large-scale solar PV farms [1], [2].

II. MATH

1. UAVs for inspection and fault detection in photovoltaic arrays

A. Al Mamun and F. M. Gonzalez-Longatt studied the use of UAVs for inspection and fault detection in photovoltaic arrays. Their work highlights the usefulness of aerial inspection for covering large photovoltaic installations while reducing the time and human effort associated with conventional manual inspection.

UAV-based imaging provides a practical method for collecting information from PV modules and identifying abnormalities across large areas. The study establishes the importance of combining UAV platforms with suitable sensing technologies for efficient photovoltaic monitoring. This work provides an important foundation for developing an autonomous solar-panel inspection system because it demonstrates how UAVs can be used as mobile inspection platforms.

2. UAV-based approaches for photovoltaic plant diagnosis

A. Michail and A. Livera presented a comprehensive review of UAV-based approaches for photovoltaic plant diagnosis. The study examines different PV degradation mechanisms, failure modes, diagnostic techniques, sensors, operating conditions and UAV-based inspection approaches. It also discusses the importance of locating faulty PV modules accurately after detection. The authors emphasize that a complete UAV diagnostic system requires suitable imaging sensors, data-processing methods and location information. This research is particularly relevant to the proposed system because it supports the integration of visual/thermal sensing with UAV positioning and automated inspection, providing a foundation for combining RGB, thermal, GPS and communication technologies.

3. Investigated autonomous monitoring of photovoltaic systems from a multidisciplinary perspective involving UAVs, artificial intelligence and future inspection technologies

J. Aghaei and P. Kosmopoulos investigated autonomous monitoring of photovoltaic systems from a multidisciplinary perspective involving UAVs, artificial intelligence and future inspection technologies. The research emphasizes that autonomous PV monitoring requires the integration of aerial platforms, sensing, data analysis and operational decision-making. UAVs can improve the scalability of inspection by covering large solar farms, while intelligent processing can assist in identifying abnormal conditions. The study also highlights challenges associated with achieving complete autonomy, particularly in real-time processing and interpretation of inspection data. These findings support the development of a UAV architecture in which sensing, navigation and communication are integrated into a single inspection platform.

4. Reviewed faults and infrared thermographic diagnosis in operating crystalline-silicon photovoltaic modules.

J. A. Tsanakas and L. Ha reviewed faults and infrared thermographic diagnosis in operating crystalline-silicon photovoltaic modules. Their work demonstrates the importance of infrared thermography for identifying temperature-related abnormalities in PV modules. Thermal patterns can provide information about faults that may not be clearly visible through conventional RGB imaging. However, thermal inspection is influenced by factors such as operating and environmental conditions, making appropriate measurement and interpretation important. The study therefore establishes thermal imaging as an important sensing technology for PV fault diagnosis and supports the inclusion of a thermal sensor such as the MLX90640 in a UAV-based inspection system.

5. Effect of infrared image blurring on UAV-based solar power-plant inspectio

T. A. Solend and A. Rødningsby investigated the effect of infrared image blurring on UAV-based solar

power-plant inspection. Their research shows that UAV flight speed, navigation performance, camera characteristics and image resolution can influence the quality of collected thermal imagery. Motion blur can obscure important thermal details and consequently affect the efficiency of inspection. The authors developed a simulation approach that considers navigation precision and different camera configurations to determine suitable operating conditions. This research is important for the proposed UAV because it shows that simply installing a thermal camera is not sufficient; flight speed, stability, camera resolution and data-acquisition rate must also be considered during system design.

6. Radiometric infrared thermography for solar photovoltaic inspection with an emphasis on explainable intelligent

A. E. Alnajjar and D. Issa investigated radiometric infrared thermography for solar photovoltaic inspection with an emphasis on explainable intelligent inspection.

Radiometric thermal imaging provides temperature-related information that can be used to understand abnormal thermal behavior in PV systems. The research demonstrates the importance of obtaining reliable thermal measurements rather than treating thermal images only as visual representations. This approach can support more explainable interpretation of PV faults and improve the usefulness of thermal inspection data. For the proposed UAV system, this research supports the use of thermal sensing as a complementary inspection channel alongside RGB and other sensors.

7. Thermographic inspection of PV modules using UAVs and deep learning for automated fault classification

H. Bommes and F. Gaede investigated thermographic inspection of PV modules using UAVs and deep learning for automated fault classification. Their work combines aerial thermal imaging with machine-learning techniques to automate the identification of PV faults. This demonstrates how UAV-collected thermal data can be processed automatically instead of requiring complete manual interpretation of every captured image.

The study is relevant to the development of automated PV inspection because it connects three major components: UAV-based data acquisition, thermal imaging and automated fault analysis. It also demonstrates the potential of intelligent image-processing techniques for reducing manual inspection requirements.

8. Real-time object-detection approach for autonomous solar-farm inspection using UAVs.

J. Rodríguez-Vázquez and I. Prieto-Centeno proposed a real-time object-detection approach for autonomous solar-farm inspection using UAVs. Instead of relying only on conventional bounding-box or segmentation approaches, their work focuses on detecting the vertices of solar panels using a keypoint-based method.

The proposed architecture is designed for embedded computing and was evaluated on an NVIDIA Jetson AGX Orin, achieving close to 60 frames per second at a reported image resolution of 1024 × 1376 pixels. The study also considers active learning to reduce annotation requirements.

This research demonstrates the importance of real-time processing and computational efficiency when autonomous UAV inspection is intended for practical deployment.

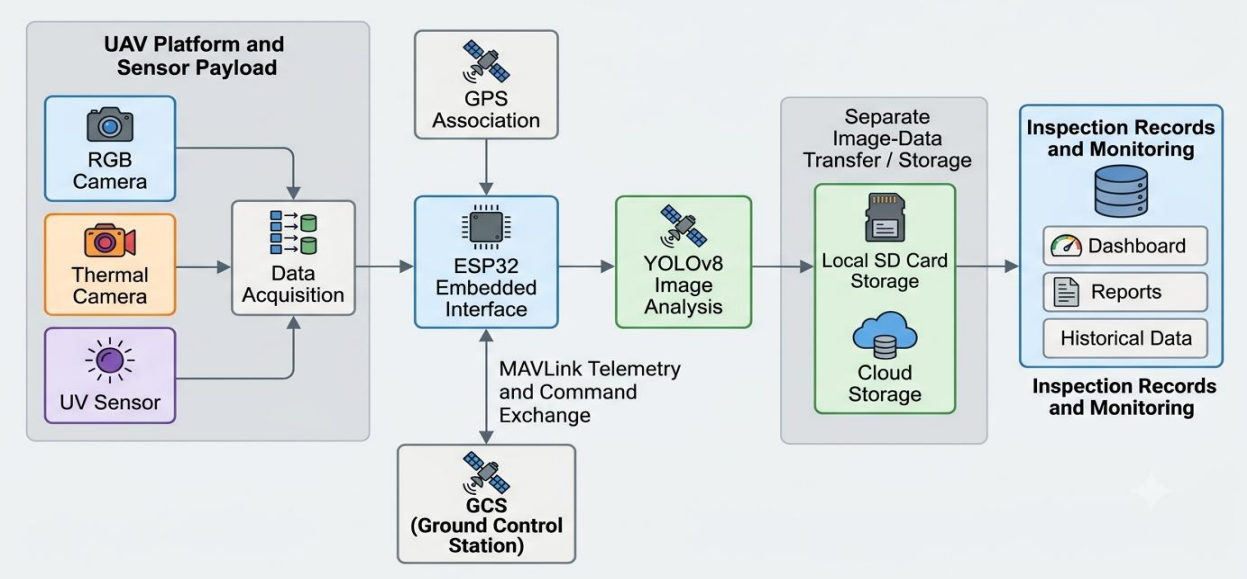
9. Solar PV hotspot inspection using UAV thermal images at an operating solar field in South India

A. K. Pruthviraj and Y. Kashyap investigated solar PV hotspot inspection using UAV thermal images at an operating solar field in South India. The study used a thermal camera mounted on a drone to inspect a large operational solar farm and generated an orthomosaic representation of the inspected area. WebODM was used for processing and digitizing the field, allowing defective panels to be geographically identified. The study reported identification of 232,934 solar panels and 2,481 defective panels, with defects associated with manufacturing problems, ageing, shading, soiling and weather-related conditions. This work is particularly relevant to the proposed project because it demonstrates the practical combination of UAV thermal imaging, large-scale PV inspection and geographic localization under Indian operating conditions.

10. YOLOv5-based defect detection using UAV thermal and RGB imagery for photovoltaic modules.

III. UNITS

Operational Workflow
UAV platform and sensor payload → RGB / thermal / UV data acquisition → ESP32 embedded interface → GPS association → MAV link telemetry and command exchange → YOLOv8 image analysis → separate image-data transfer / storage → inspection records and monitoring.



IV. METHODOLOGICAL RESEARCH AND METHODS

1. UAV-Based Solar PV Inspection

The proposed system uses a quadcopter UAV as the main platform for solar PV panel inspection. The UAV flies over the solar panels and collects inspection information during flight. This approach helps cover large solar farms more efficiently than manual inspection. The aerial platform allows repeated inspection of different sections of the solar installation. It also reduces the time and human effort required for conventional inspection methods.

2. RGB Image Acquisition

The ESP32 Hybrid Cam is used to capture RGB images of the solar PV panels. RGB imaging provides visible information about the physical and surface condition of the panels. The captured images can be used to observe cracks, glass breakage, discoloration, delamination, and snail-trail patterns. Image acquisition is performed during the UAV inspection process. The collected images are maintained separately from flight telemetry data for further inspection and storage.

3. Thermal Imaging

The MLX90640 thermal sensor is used to collect temperature-related information from the solar panels. Thermal imaging is particularly useful for identifying hotspots and abnormal temperature distributions. These abnormalities may not always be clearly visible through normal RGB images.

Thermal observations are collected along with the other inspection data during UAV operation. The thermal information provides a complementary sensing method for identifying potential PV panel faults.

4. UV Sensing

A custom UV sensor is incorporated into the proposed multisensory inspection system. The UV sensor provides an additional sensing channel for electrical-discharge-related indications. This information complements the visible and thermal observations collected from the solar panels. UV observations are organized along with the other inspection data during the inspection process. The inclusion of UV sensing allows the system to consider different types of abnormal conditions rather than depending on a single sensing technology.

5. GPS-Based Localization

A GPS module is used to obtain the geographical position of the UAV during inspection. GPS coordinates are associated with the inspection observations collected by the different sensors. This allows a suspected abnormal panel or inspection observation to be linked with its physical location. Location information is therefore an important part of the inspection record. It can also support future monitoring and repeated inspection of the same solar-panel area.

6. MAVLink Communication

MAVLink is used as the structured communication protocol for UAV telemetry and command exchange. It can carry information such as GPS data, flight status, system status, and control-related messages between compatible components.

The protocol provides a structured communication layer for the UAV system. MAVLink is not used as an image-processing algorithm or as an image-storage method. Keeping telemetry separate from image data helps maintain reliable communication for flight-related information.

7. Image and Data Transfer

The system separates image-data handling from UAV telemetry communication. RGB images are acquired through the ESP32 Hybrid Cam and are transferred or stored using an appropriate image-data mechanism. MAVLink is reserved for structured telemetry, flight status, GPS information, and commands. This separation prevents large image files from interfering with time-sensitive flight messages. The approach provides a clearer communication structure between inspection data and UAV control information.

8. Flight Control and Stabilization

The KK2.1.5 flight controller is used for UAV flight stabilization and control. The radio controller and receiver provide manual pilot commands to the flight-control system. ESCs control the speed of the 1000KV brushless motors according to the flight-control requirements. The four motors provide the propulsion required for the quadcopter platform. This combination provides the basic flight-control and propulsion system required to carry the inspection sensors.

9. Multisensor Data Integration

The proposed system integrates RGB, thermal, UV, and GPS information into a common inspection architecture. RGB sensing provides visible information about surface conditions, while thermal sensing provides temperature-related information. UV sensing adds information related to electrical-discharge indications. GPS provides the geographical position associated with the collected observations. Combining these sensing channels provides a more comprehensive inspection record than relying on a single sensor.

10. Experimental Validation and Performance Evaluation

The proposed system requires experimental validation to verify its practical performance. Image quality and consistency of the collected inspection data are evaluated during testing. GPS association, MAVLink message reliability, and communication latency are also important evaluation parameters. Flight stability, image-transfer reliability, and inspection coverage are considered for overall system performance. Battery configuration, aircraft mass, propulsion parameters, and flight endurance must also be experimentally determined before reliable flight-time calculations can be reported.

Types of Defects Found in our Solar PV Panels

Hotspots

Hotspots occur when localized portions of a module operate at elevated temperature. Thermal imaging is used to identify temperature-related anomalies. Hotspots may be associated with shading, dust accumulation, overheating, manufacturing defects or bypass-diode-related problems. If left undetected, they can contribute to efficiency reduction, accelerated ageing and damage.

Cracks or Glass Breakage

Cracks or glass breakage can result from mechanical stress, installation or transportation, thermal expansion cycles and environmental impacts. Such damage can reduce current flow and produce mismatch in power generation.

Visual imaging is used to identify visible crack or glass-breakage patterns.

Discoloration and Delamination

Discoloration and delamination can affect the encapsulant layer. UV degradation, thermal stress, poor lamination and moisture ingress can contribute to discoloration and separation between layers. These conditions can be observed using visual imaging.

Snail Trails

Snail trails can appear as irregular dark streaks across a panel surface. The condition can be associated with moisture-related effects or chemical reactions in the encapsulant layer. RGB imaging can be used to identify the visible streaking pattern.

V. FUTURE RESEARCH DIRECTIONS

The proposed architecture presents several practical challenges. Image quality can be affected by motion blur, camera angle, lighting and environmental conditions. Multisensor synchronization and calibration are required so that RGB, thermal, UV and GPS observations can be correctly associated. MAV link integration with the selected KK2.1.5 flight controller also requires experimental validation or a compatible interface/gateway.

Communication reliability is another consideration, particularly when cellular connectivity is used for remote monitoring. The image-data channel should be designed separately from MAV link telemetry to prevent large image transfers from interfering with time-sensitive flight messages. Battery configuration, payload mass and propulsion parameters must also be finalized before a reliable flight-time and power-budget calculation can be reported.

Future work should focus on MAV link-compatible integration, robust autonomous navigation, synchronized multisensor acquisition, reliable image transmission, improved GPS tagging, remote monitoring, battery optimization and systematic field validation. Automated image-analysis methods may be added as a separate future layer if suitable onboard or remote processing hardware is selected.

VI. CONCLUSION

This paper presents an updated autonomous UAV-based solar PV inspection architecture aligned with the supplied EPJ-style reference format while adapting the system to the specified hardware. The system combines RGB imaging through an ESP32 Hybrid Cam, MLX90640 thermal sensing, custom UV sensing, GPS localization, 1000KV brushless motors, ESCs, a KK2.1.5 flight controller, SIM connectivity, buck conversion, servo actuation, radio controller and receiver, and three 1200mAh lithium batteries.

MAV link is introduced as the structured communication protocol for telemetry, status and command exchange. It is deliberately separated from image processing and image storage: the protocol carries UAV communication messages, while image data requires an appropriate separate transfer mechanism. YOLOv8 and the associated deep-learning and LSTM content have been removed from the updated architecture. Therefore, the proposed work does not claim trained-model accuracy or defect-classification metrics.

The architecture provides a basis for cost-conscious solar PV inspection in which sensor observations can be associated with location and UAV status. Further experimental validation is required for MAV link integration with the KK2.1.5 controller, multisensor synchronization, cellular communication, image-transfer reliability, propulsion performance and battery endurance.

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