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Design and Implementation of Unmanned Aerial Vehicle for Solar PV Maintenance

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A B S T R A C T :

The maintenance of solar photovoltaic (PV) systems is essential for ensuring consistent power generation and system longevity. Traditional inspection methods are often inefficient and unable to provide real-time fault detection. To address this, an Unmanned Aerial Vehicle (UAV) equipped with high-resolution RGB and thermal cameras has been designed and implemented to perform automated solar panel inspection. The captured imagery is analysed using the YOLOv8 (You Only Look Once, version 8) deep learning algorithm, which performs rapid and accurate detection of multiple fault types, including bird droppings, snow-covered panels, physical damage, dust accumulation and electrical faults, while also identifying clean panels for performance benchmarking. The system enables precise localization and classification of defects through GPS-tagged data and real-time processing, reducing the need for manual inspection. Automated reporting and maintenance recommendations, such as cleaning, repairing or replacing affected panels, further streamline the maintenance workflow. This intelligent UAV-based monitoring system significantly enhances efficiency, accuracy and reliability in solar PV maintenance, ensuring optimized energy output and sustainable operation.

Keywords: UAV, YOLOv8, Solar Photovoltaic (PV) System, Deep Learning, Fault Detection, Thermal Imaging, Object Detection, Renewable Energy.

1.Introduction

The increasing global emphasis on renewable energy has led to the rapid growth of solar photovoltaic (PV) systems as a clean and sustainable source of power generation. Solar PV installations require regular inspection and maintenance to ensure optimal performance and efficiency. However, traditional manual inspection methods are time-consuming, labor-intensive, and prone to human error, particularly when dealing with large-scale solar farms spread over Wide areas Environmental factors such as dust accumulation, shading, cracks and loose connections can significantly affect panel performance, leading to reduced power output and higher operational costs if not addressed promptly. To overcome these challenges, the project “Design and Operation of a Drone for Solar PV Maintenance” introduces an automated and technologically advanced approach using unmanned aerial vehicles (UAVs), commonly known as drones. The designed drone is equipped with high-resolution visual and thermal cameras to monitor panel conditions and identify faults such as hotspots, surface defects, and dust deposition. The integration of a flight controller, GPS module and onboard sensors ensures stable, autonomous flight and precise navigation across the solar array. The operation of the drone involves capturing real-time data through aerial imaging, which is then processed to detect temperature variations or physical abnormalities in the panels. This information enables maintenance teams to identify faulty modules quickly and plan necessary corrective actions. In addition to inspection, the system can be enhanced with lightweight cleaning mechanisms to remove dust or Dust particles from panel surfaces, further improving efficiency. By combining automation, precision and intelligent monitoring, the drone-based maintenance system offers significant advantages over conventional techniques. It reduces inspection time, minimizes labor requirements, enhances safety by eliminating manual intervention in hazardous conditions and ensures consistent data accuracy. Ultimately, the implementation of drone technology contributes to optimized energy production, reduced downtime and improved reliability of solar PV installations. It demonstrates how modern engineering innovations, when integrated with renewable energy systems, can transform maintenance operations into faster, safer and more sustainable practices. The design and operation of drones for solar PV maintenance not only streamline maintenance activities but also support the global shift toward smarter, technology-driven energy management solutions.

1.1. COMPONENTS USED IN DRONE

F450 Frame

Lightweight glass-fibre and nylon quadcopter frame designed for strength and easy assembly, with integrated PCB for ESC power distribution. Color-coded arms (red/white) improve flight orientation and support standard 50 mm controller boards.

1400 KV BLDC Motors

Brushless DC motors that spin at 1400 RPM per volt, offering high efficiency and thrust for quadcopters. Ideal for stable and responsive drone propulsion with minimal maintenance.

ESC (Electronic Speed Controller)

Controls motor speed and direction while providing smooth throttle response to each BLDC motor. Includes a 5 V / 2 A BEC to power the flight controller and receiver without an extra battery.

Li-Po Battery (3300 mAh)

High-capacity 3S 35C lithium-polymer battery delivering reliable current for extended flight times. Features low resistance, gold-plated connectors, and IR-matched cells for safe high-load performance.

Pixhawk 2.4.8 Flight Controller

Acts as the drone's brain, stabilizing flight and processing pilot commands via sensors and software. Runs on ArduPilot firmware to manage autonomous and manual flight operations.

Power Module

Regulates and supplies stable 5.3 V power to the flight controller from a 2S–6S Li-Po battery. Monitors battery voltage and current up to 90 A for safe and efficient power management.

Safety Switch and Buzzer

Provides audio alerts for different flight modes and safety status. Allows quick arming/disarming of the flight controller to prevent accidental motor start.

Propeller Set (CW/CCW)

Lightweight propellers that convert motor torque into lift for stable or fast flight. Offer efficient performance across different motor KV ratings for various flight styles.

Fly Sky FS-i6 Transmitter and FS-iA6B Receiver

2.4 GHz 6-channel radio system transmitting pilot inputs to the drone wirelessly. Features dual-antenna receiver and unique ID binding for reliable control and minimal interference.

1.2. Different Types of Faults Occurs in Solar Panels

Bird Dropping

Bird droppings block sunlight and cause partial shading, leading to reduced power generation. They can create hot spots and corrode the panel surface, shortening the system's lifespan.

Dusty

Dust accumulation reduces sunlight absorption and efficiency by creating uneven shading. Over time, it can scratch or damage the surface, permanently lowering energy output.

Electrical Damage

Faulty wiring, overcurrent, or voltage surges can overheat components and disrupt power flow. Such damage can lead to fires or permanent failure of panels and inverters if unchecked.

Physical Damage

External impacts or mishandling can crack glass, bend frames, or damage cells. These defects reduce efficiency and may allow moisture or dust to enter, worsening faults.

Snow Covered

Snow buildup blocks sunlight and halts electricity generation completely. It can also cause uneven melting or add weight stress, risking panel or frame damage.

Fig 1: a) Bird Dropping; b) Dusty; c) Electrical Damage; d) Physical Damage; e) Snow Covered

2. Methodology

2.1. Construction of Drone

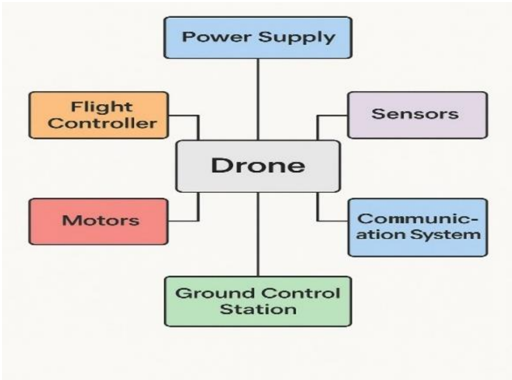

Fig 2: Construction of Drone

Power Supply

The 3300mAh Li-Po battery powers all drone components efficiently due to its lightweight and high energy density.
The Pixhawk Power Module regulates voltage, protects against over-voltage, and monitors battery status in flight.

Flight Controller

Pixhawk 2.4.8 processes sensor data and remote commands to stabilize and control the drone's flight.
It runs ArduPilot firmware, calibrated via Mission Planner for accurate navigation and motor control.

Motors

Four 1400KV BLDC motors generate lift and thrust, spinning at 1400 RPM per volt supplied.
Two motors rotate clockwise and two counterclockwise to maintain balance and prevent torque-induced rotation.

Sensors

Sensor's like gyroscope, accelerometer, barometer, magnetometer and GPS provide stability, altitude and position data.
They continuously update the flight controller to ensure safe, accurate, and balanced flight performance.

Communication System

The FlySky FS-i6 transmitter and FS-iA6B receiver enable real-time wireless control between pilot and drone.
Telemetry links with the Ground Control Station provide live updates on GPS, altitude, and system health.

Ground Control Station (GCS)

Mission Planner software serves as the control hub for mission setup, telemetry monitoring, and flight management.
It allows calibration, firmware updates, and autonomous mission planning for complete operational control.

Drone Ratings Explanation

The drone uses a 3300mAh Li-Po battery weighing 270g, giving 20–25 minutes of flight time for a 950g drone.
Required total thrust is twice the drone's weight (≈1900g), giving about 4659.75 N total or ~1164.9 N per motor for stable lift.

2.2. Stepwise Process of Drone Operation For Solar Panel Inspection

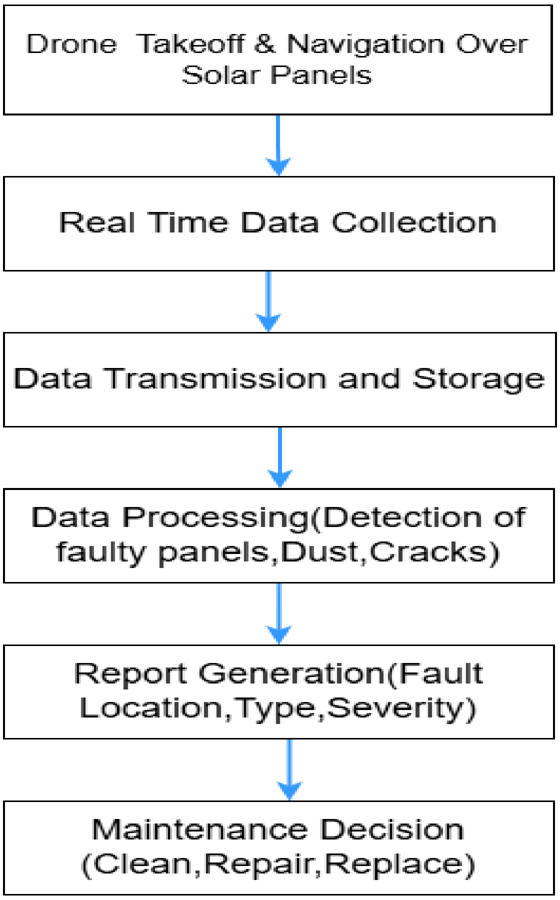

Fig 3: Stepwise Process Of Drone Operation For Solar Panel Inspection

Drone Take off & Navigation Over Solar Panels

The drone performs safe take off after pre-flight checks like battery, GPS, and sensor calibration. It flies along a pre-planned grid path over the solar panels at an optimal height (5–20 m).GPS-based navigation and safety features ensure stable flight and accurate image capture.

Real-Time Data Collection

During flight, the drone's RGB camera captures visual data while the thermal sensor detects hotspots. GPS modules record precise location and altitude for each image. This results in synchronized, high-resolution visual and thermal datasets for accurate inspection.

Data Transmission and Storage

Collected data is stored onboard or transmitted via 4G/5G to the ground station or cloud server. Each file includes GPS coordinates and timestamps for precise mapping. Encryption ensures secure transfer, while onboard AI performs preliminary fault analysis.

Data Processing (Detection of Faulty Panels, Dust, Cracks)

Raw images are pre-processed with corrections and calibrations to improve accuracy. Deep learning models segment panels and extract visual and thermal features. The system detects dust, cracks, or hotspots and classifies fault severity for maintenance insights.

Report Generation (Fault Location, Type, Severity)

An automated report compiles inspection details including fault type, severity, and GPS location. It includes annotated images and maintenance recommendations. Reports are exported in CSV or other formats for integration with maintenance databases.

Maintenance Decision (Clean, Repair, Replace)

Based on fault type and severity, the system recommends cleaning, repairing, or replacing panels. Mild soiling triggers cleaning, minor defects prompt repair, and severe damage leads to replacement. Automated work orders guide maintenance teams for efficient on-site action.

2.3. Software Used (Mission Planner)

Mission Planner is the Ground Control Station software used to configure, monitor, and plan missions for ArduPilot based flight controllers. It provides firmware flashing, sensor/motor calibration, real-time telemetry display, and mission waypoint uploading.

Connect the Pixhawk Controller to Software
Plug the Pixhawk into your laptop via Micro-USB, confirm the assigned COM port in Device Manager, and select that port in Mission Planner. Once connected, Mission Planner establishes a telemetry link to view live parameters and start configuration.

Firmware Flashing
Download the correct ArduPilot (Quad) firmware for Pixhawk 2.4.8 and use Mission Planner's "Install Firmware" tool to upload it to the board. Flashing replaces the controller's flight code and ensures the Pixhawk runs the proper firmware for your quadcopter configuration.

Mandatory Hardware Setup (overview)
Mission Planner guides you through essential hardware setup: motor layout, receiver mapping, ESC calibration, and sensor calibration to match your airframe. Correct hardware setup ensures signals, motor directions, and sensor readings are accurate for safe, stable flight.

Accel Calibration
Accel calibration records the vehicle's orientation at multiple known positions so the flight controller learns what "level" is for each axis. Accurate accelerometer calibration is critical for stable hovering, altitude control, and correct attitude estimation.

Radio Calibration
Radio calibration maps your transmitter stick movements to the correct channel values in the flight controller and defines endpoints and trims. This ensures throttle, yaw, pitch, and roll inputs from the pilot translate precisely to the drone's controls.

ESC Calibration
ESC calibration teaches each ESC the minimum and maximum PWM/servo values from the flight controller so motors spin proportionally to throttle input. Proper ESC calibration prevents uneven motor response and is required for symmetric thrust and safe take off.

Flight Mode Setup
Configure and assign flight modes (e.g., Stabilize, Loiter, RTL, Auto) to transmitter switches so you can change behaviour in flight. Tuning mode parameters lets you control responsiveness, altitude hold, and autonomous behaviours for safe and mission-appropriate flying.

3. YOLO Algorithm

Image Input
The drone's camera captures an image that is resized and normalized for consistent processing. This ensures the neural network handles all input images uniformly for accurate detection.

Image Division
The image is divided into a grid of equal cells, each responsible for detecting objects within its area. This division helps YOLO localize multiple objects simultaneously in different regions.

Feature Extraction
A Convolutional Neural Network (CNN) analyses the image to extract essential visual features. These features include shapes, textures, and edges that help identify object patterns.

Prediction of Bounding Boxes
Each grid cell predicts several bounding boxes that outline potential objects. These boxes contain coordinates for position (x, y) and dimensions (width, height).

Object Classification
YOLO assigns a class label (like person, car, or panel) to each bounding box. It calculates probabilities for each object type based on learned patterns.

Confidence Score Calculation
The confidence score combines the probability of object presence and its classification accuracy. Higher scores indicate greater certainty that an object is correctly identified.

Non-Maximum Suppression (NMS)

When multiple boxes overlap for the same object, only the one with the highest confidence is kept. This removes duplicate detections and ensures clean, precise output.

Output

The algorithm outputs final bounding boxes, labels, and confidence values for each detected object.

4. Confusion Matrix

A confusion matrix is a table used to evaluate the performance of a classification model by comparing predicted classes with actual classes, providing a deeper understanding beyond simple accuracy. It offers a detailed performance assessment by showing the counts of true positives, true negatives, false positives, and false negatives, which helps in identifying the model's strengths and weaknesses. From this matrix, important metrics such as precision, recall, F1-score, and specificity can be derived to measure different aspects of performance. Additionally, it supports error analysis by highlighting where the model makes incorrect predictions, such as confusing one class with another, allowing for targeted improvements. The confusion matrix also facilitates model comparison by assessing not just overall accuracy but also how effectively each model handles individual classes, especially in cases of class imbalance.

Table : Structure of a Confusion Matrix:

	Predicted Positive	Predicted Negative
Actual Positive	True Positive (TP)	False Negative (FN)
Actual Negative	False Positive (FP)	True Negative (TN)

Key Terms:

- True Positive (TP): Correctly predicted positive instances.
- True Negative (TN): Correctly predicted negative instances.
- False Positive (FP): Incorrectly predicted positive instances (Type I error).
- False Negative (FN): Incorrectly predicted negative instances (Type II error).

Metrics Derived from the Confusion Matrix:

- Accuracy = (TP+TN) / (TP+TN+FP+FN
- Precision = TP / (TP+FP)
- Recall (Sensitivity) = TP / (TP+FN)
- Specificity = TN / (TN+FP)
- F1-Score: Harmonic mean of precision and recall, balancing both metrics.

5. Design Flow

We have constructed the drone with following ratings:

- Battery Type = Li-po
- Battery weight = 270g
- Battery capacity = 3300 mAh
- Operating time = 20-25 minutes
- Weight = 950grams
- Total Thrust Needed = 2*Total weight of the drone = 2*950 = 1900grams
- Thrust per motor = (2*w*g)/n (in newtons)

  = (2*950*9.81)/4

  = 4659.75 newtons

6. Results

Fig 4: Construction Of Drone

	precision	recall	f1-score	support
Bird-drop	0.0000	0.0000	0.0000	4.0000
Clean	0.0000	0.0000	0.0000	4.0000
Dusty	0.0000	0.0000	0.0000	4.0000
Electrical-damage	0.0000	0.0000	0.0000	4.0000
Physical-Damage	0.1667	1.0000	0.2857	4.0000
Snow-Covered	0.0000	0.0000	0.0000	4.0000
accuracy	0.1667	0.1667	0.1667	0.1667
macro avg	0.0278	0.1667	0.0476	24.0000
weighted avg	0.0278	0.1667	0.0476	24.0000

Fig 5: Classification of Different Faults

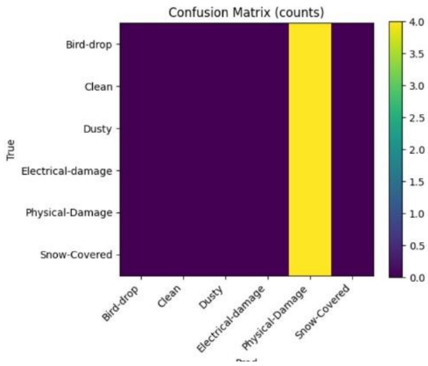

Fig 6: Confusion Matrix

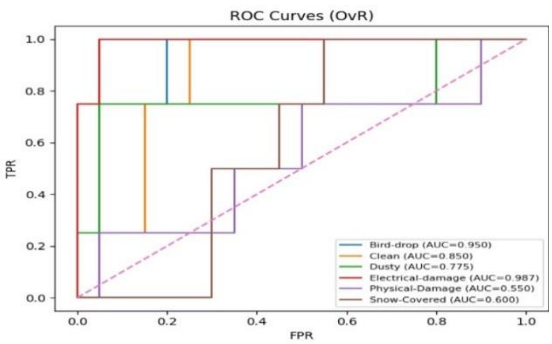

Fig 7: ROC Curves (O v R)

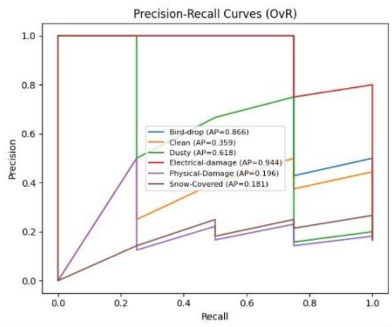

Fig 8: Precision-Recall Curves (O v R)

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