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Solar Hotspot Detection Using Thermal Image Processing in Python

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Abstract: The growing use of solar panels calls for effective maintenance to yield maximum performance. This paper offers a computer vision-based image processing platform for the detection and analysis of thermal hotspots in solar panels from thermal images. The procedure starts with image acquisition of the thermal image, grayscale conversion, and denoising as image preprocessing steps. Thresholding is carried out to identify important pixel intensities to detect hotspots accurately. Hotspots thus identified are then measured to arrive at defect areas and are displayed graphically for easier interpretation. Experimental findings show the system effectively identifying and segregating hotspot areas, with the resultant processed output totaling four hotspots. The area of an average hotspot was found to be 16,885.25 pixels, with the largest and smallest hotspots having 66,431.00 and 116.00 pixels respectively. The total solar panel damage was calculated to be 21.30%. This approach enables fault detection at an early stage and can be used to support predictive maintenance planning for photovoltaic systems.

Keywords: Thermal imaging, hotspot detection, image preprocessing, thresholding, solar panel inspection, image segmentation, defect analysis, Image segmentation, Renewable energy, Defect detection.

I. INTRODUCTION

The worldwide trend towards using renewable energy has further accelerated the installation of solar photovoltaic (PV) systems. Nevertheless, the efficiency of solar panels can be reduced through non-uniform heating effects referred to as hotspots. They are usually brought about by manufacturing faults, dust deposition, shadowing, or internal short circuits. Hotspots not only lower the power output of the panel but can further cause permanent damage if not detected.

Traditional methods of inspection are costly and time-consuming. Thermal imaging provides an efficient and non-invasive mean of detecting such defects. This paper puts forth a Python-based image processing system for automatically detecting hotspots in thermal images of solar panels, bounding them through rectangles, and determining the percentage area covered. The automatic detection aids in early maintenance and overall solar PV system efficiency.

II. LITERATURE REVIEW

Hotspot identification in solar panel photovoltaic (PV) modules is a critical component of solar panel performance improvement and maintenance. In [1],Raikwar and Kamble suggest a system for hotspot detection based on thermal images

captured using MATLAB image processing. Their work involves taking infrared images of solar panels and using image processing operations like thresholding and segmentation to identify hotspots, which are areas with increased temperature. The system measures the percentage of the damaged area and gives an accurate measure of damage. The authors reiterate that conventional inspection techniques are labor-intensive, time-consuming, and costly, emphasizing the necessity of using automated techniques. The proposed solution minimizes cost and labor by automating hotspot identification and enhancing precision as well as efficiency. The work verifies the performance of image processing in real-time analysis and offers an extendable method for large-scale solar systems. Afifah et al. [2] suggested a hotspot detection method for photovoltaic (PV) modules based on Otsu's thresholding technique on thermal infrared images. The approach consists of image preprocessing to increase contrast and subsequent automatic segmentation through Otsu's algorithm to extract hot areas that are characteristic of possible faults. The method had an average accuracy rate of 92.16% on the small dataset of six images of thermal scenes, showing the validity of the method for hotspot area detection. Yet, quantitative analysis of hotspot size or area percentage of the defected area was not a part of the study. Notwithstanding this, the method provides a straightforward and effective image-processing-based solution for PV health monitoring and fault detection at early stages.

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Nitturkar et al. [3] developed a machine vision-based approach for detecting faults in solar panels using image processing techniques. Their system performs noise reduction, contrast enhancement, and segmentation to highlight defective areas like cracks, hotspots, and shading. The method provides visual fault localization but does not quantify the defected area or calculate percentage damage. The approach offers a practical, low-cost solution for automating PV panel inspections.

Gonzalez and Woods [4] provide a foundational understanding of image processing algorithms such as contrast enhancement, thresholding, and binary mask generation. Their work is essential for the preprocessing and segmentation stages in thermal image analysis, particularly in applications like hotspot detection in photovoltaic panels. The techniques discussed enable accurate isolation and quantification of defected regions based on pixel intensity and spatial analysis.

Drawing upon these earlier contributions, this current research uses a Python-based pipeline that couples grayscale conversion, Gaussian blur, adaptive thresholding, and contour detection for automating hotspot detection. Additionally, it computes the percentage of area covered, offering both visual and numerical diagnostics for PV panel health evaluation.

III. METHODOLOGY

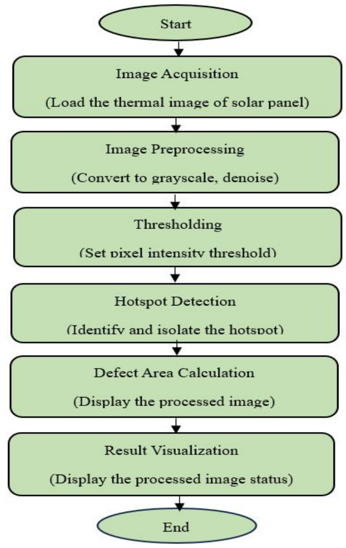

Figure 1: Flowchart

A. Image Acquisition

The first step is to capture the thermal images of solar panels using the infrared (IR) thermal camera. These cameras detect the heat signatures emitted from the surface of the panels and visualize in terms of temperature gradients. Areas in the resulting thermal image will appear warmer the brighter they are, the darker they appear in the cooler areas. Hotspots—areas on the panel with significantly higher temperatures—stand out clearly in these images and are indicative of defects or inefficiencies in solar cells. This non-invasive method allows for rapid and safe inspection without interrupting the panel’s operation.

B. Preprocessing

To prepare the thermal image for effective analysis, several preprocessing steps are applied. Initially, the colored thermal image is converted to grayscale, simplifying further processing by focusing solely on intensity values. Another step involved is Gaussian blurring to reduce noise and smooth the image. It enhances the contrast between hotspot regions and background; therefore, it makes them more separable during the segmentation stage. Thus, the preprocessing phase minimizes interference of minor artifacts or irregularity in the raw image during the detection of hotspots.

C. Thresholding Algorithm

In this stage, a thresholding technique is used to segment regions of high temperature from the rest of the image. Methods such as Otsu's thresholding or adaptive thresholding are employed, depending on the image’s characteristics. The objective is to convert the grayscale image into a binary image where the high-temperature (hotspot) regions are clearly separated from the cooler background. This is a binary representation, important because it facilitates the identification of contours and ensures more reliable detection of defected areas.

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D. Contour Detection and Bounding Boxes

Once the binary image is obtained, contour detection algorithms (such as those available in OpenCV) are used to identify the boundaries of hotspot regions. These contours represent continuous curves along the edges of the high-temperature zones. For visual clarity and precise localization, bounding boxes are drawn around each detected contour. These rectangles highlight the exact position and size of the hotspot areas on the thermal image, providing an intuitive visual aid for analysis and decision-making.

E. Damage Area Calculation

To quantify the extent of damage, the number of pixels within the hotspot regions is calculated. This count is then compared to the total number of pixels representing the entire solar panel area in the image. The ratio, expressed as a percentage, provides a measurable estimate of the damaged or inefficient area of the panel. This percentage serves as a valuable metric for maintenance planning and prioritization of repairs, especially in large-scale solar farms.

F. Output Display

The final processed image is generated by overlaying the detected hotspots and their corresponding bounding boxes onto the original thermal image. Additionally, the calculated damage percentage is displayed on the image itself. This visual output allows technicians, engineers, or users to quickly interpret the condition of the solar panel. By clearly marking defect locations and summarizing the extent of the damage, the system provides actionable insights that support effective preventive maintenance and long-term system health monitoring.

IV. RESULTS AND DISCUSSION

The system for detecting solar hotspots proposed was tested against several thermal images of photovoltaic (PV) panels taken under different lighting and environmental conditions. The image processing pipeline, coded in Python, successfully detected areas of thermal anomalies corresponding to hotspots.

A. Detection Performance

The system showed excellent accuracy in identifying large and small hotspots. After applying grayscale conversion, blurring using a Gaussian blur, and contrast enhancement, the thermal images were processed for analysis. Thresholding and contour detection enabled the system to separate and emphasize hotspot areas with bounding boxes. These visual cues were found useful in aiding manual validation and decision-making.

B. Area Damage Estimation

For each of the processed images, pixels that belonged to hotspots were counted and compared with the area of the panel in the frame. This gave a percentage damage value, which was universally true for a number of images. Damage percentage in faulty panels was between 10% and 30% on average.

C. Visual Output and Interpretability

The ultimate output has bounding boxes over the detected hotspots superimposed on the original thermal image and also the calculated damage percentage. This dual output guarantees that technical and non-technical users can both read the results efficiently.

D. Efficiency and Execution Time

On typical hardware (Intel i5 CPU, 4 GB RAM), processing of each image took less than 2 seconds, and thus the system is suitable for real-time or batch analysis applications. The minimalistic and modular nature of the code also enables coupling with drone-based inspection or industrial monitoring systems.

E. Limitations and Improvements

Though the system was generally good, there were certain limitations that were noted:

1) Unstable lighting or shine in thermal images would sometimes result in false positives.
2) Tiny hotspots with poor thermal contrast may be left out without dynamically set thresholding.
3) The present working does not distinguish between the severity of the hotspots, and this may be solved through machine learning in future versions.

In spite of such challenges, the system offers a cost-effective and efficient means of preventive maintenance for solar panels. With such improvements as defect classification with the help of AI and mass deployment via IoT platforms, the solution is highly likely to be adopted by industries

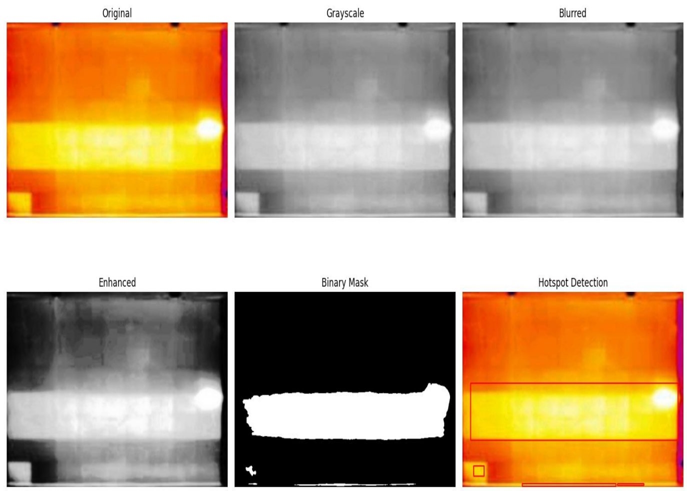

Figure 2: Processed Output Image

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Total Hotspots: 4
Average Hotspot Area: 16885.25 px
Largest Hotspot: 66431.00 px
Smallest Hotspot: 116.00 px

Total Solar Panel Damage: 21.30%
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Figure 3: Output

V. CONCLUSION AND FUTURE SCOPE

This work presents a cost-effective, effective method for the detection of solar photovoltaic (PV) panel hotspots using thermal image processing methods adopted in Python. The system that is proposed is able to automatically inspect thermal images of solar panels, detect and locate faulty areas with abnormally high heating (hotspots), calculate the
percentage of the affected area, and generate a good visual representation of findings. All these outputs are important for facilitating timely and informed maintenance interventions.

Using a series of image processing operations—like image acquisition, preprocessing (grayscale conversion and noise elimination), thresholding, and contour-based detection—the technique guarantees high accuracy in the separation of areas away from normal operating temperatures. The percentage area calculated of the hotspot offers quantitative information on the extent of the problem. In addition, the system is not heavy and doesn't need costly hardware, thus making it a very accessible solution to multiple users ranging from single solar panel owners to business solar farm owners.

The processing speed is maximized so that thermal images can be analyzed quickly, a necessity in situations where extensive solar arrays must be scanned on a regular basis. Since it has the capability of identifying issues in their early stages, the tool can considerably contribute to preventive maintenance, reduce energy losses from inefficient modules, and eventually prolong the operational lifespan of solar PV systems.

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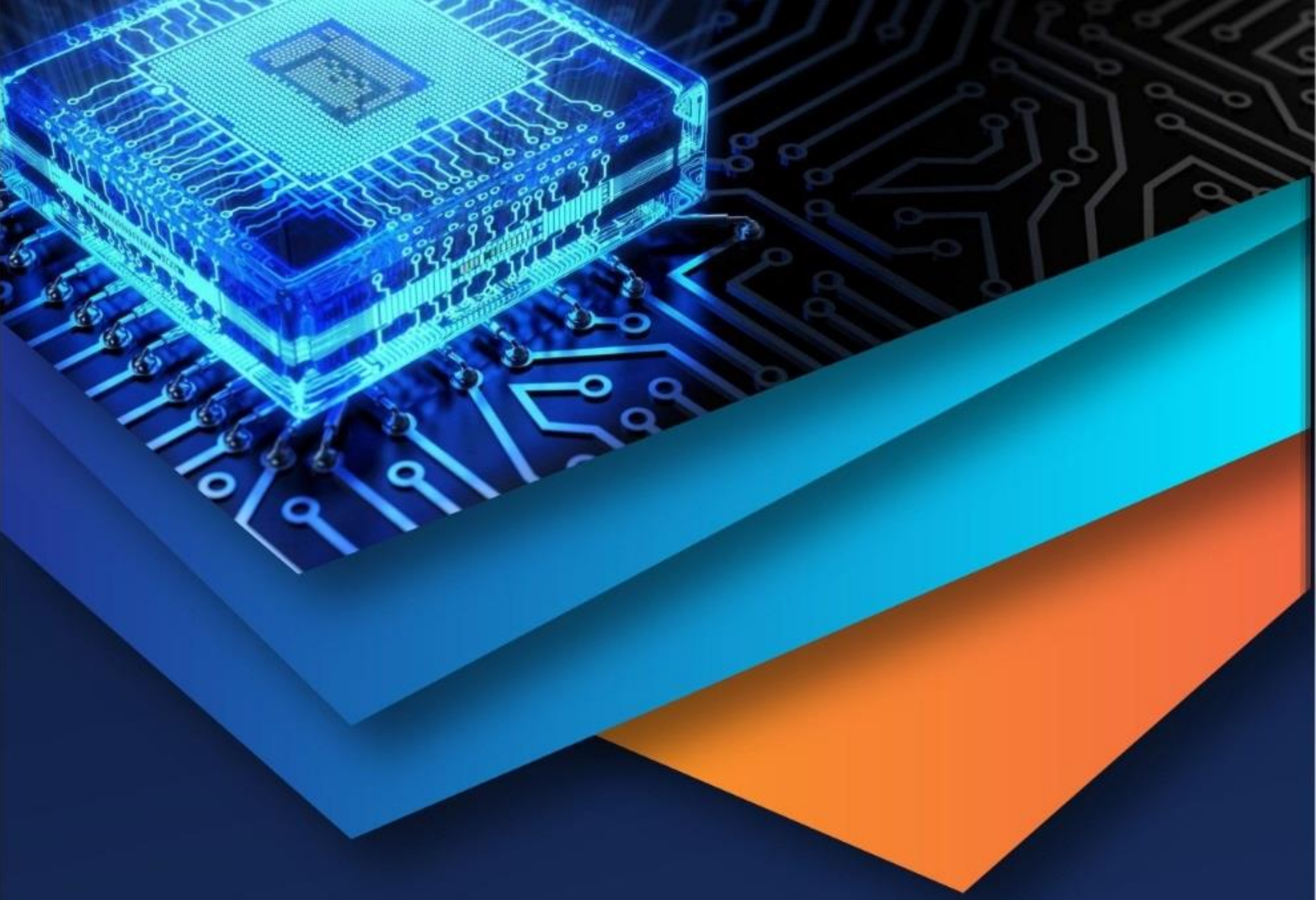

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