An efficient optical inspection of photovoltaic modules deploying edge detectors and ancillary techniques

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ABSTRACT

With the enhanced industrial and domestic energy needs, there is a great urge for renewable energy sources because of their eco-friendly nature. Solar energy is crucial among renewable energy sources and there is a great need to optimize and enhance the performance of solar energy usage that is mainly dependent on the system components. The current work has been aimed to discuss the fault detection of photovoltaic (PV) modules by evaluating an efficient, facile inspection algorithm electrical analysis for real-time applications. The paper presents a real-time experimental model for infrared thermography using a thermal imager mounted on a tripod at a suitable distance from the PV modules to capture the images in the best possible way. A novel hybrid algorithm has been proposed and the fault detection along with the electrical parameter analysis has been accurately performed on the PV modules to analyze and process various externally induced faults in the PV systems.

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1. INTRODUCTION

Industrial revolution 4.0 has dramatized the energy demand of industrial and domestic utilities. The aim of fulfilling the demand needs to be reconsidered as the depletion of fossil fuels is more. The solution is simple and lucid to rely on renewable energy resources such as solar photovoltaic (PV), wind, and tidal. Among them, the scope of research for solar PV is more commending. PV power generation plants have attained predominant attention because of their high potential and promising aspect of exploiting renewable solar energy. The fundamental component of PV power generation is a solar cell which forces the electrons to move through light absorption and causes the current flow. The metal contacts placed at the top and bottom of the solar cell collect the current. The cell voltage and the current offer the power. Certain factors influence the amount of electricity produced i.e. module composition, type, and the installation combined effect [1]. Solar irradiance is a crucial element to maintain the PV module's heat balance, power output, convective and radiative heat exchanges [2]. The major limitations are uncertain solar irradiance that leads to fluctuation of temperatures in the PV modules [3], [4]. For instance, PV modules of crystalline kind suffer a 0.5% loss of efficiency when there is a 1 °C rise in temperature. The abnormal weather conditions lead to fluctuations in voltage and frequency creating complications in the power systems operation and maintenance. In other perspectives, the variable loads can adjust themselves based on real-time onset points [5]–[7].

Solar PV modules provide power to the utilities like buildings, homes, and many more applications. Before the enhanced demand and the world energy needs, there is a continuous need for research and development in this field. The optimum usage of renewable energy resources is a crucial point to reduce the environmental perilous effects [8]. Due to the technological advancements and ample competitors in the market reduced the production cost of the solar PV modules enabling rigorous installations by the consumers. The tremendous spread and distribution of the PV modules have not only depreciated the installation of PV plants but also providing the best return on investments for consumers [8]. Government organizations and autonomous entrepreneurs have also vested much in renewable energy resources such as solar PV for modernized technological applications [9], [10]. Hence to obtain the better performance of a PV system, optimizing energy, money and mimicking the hazardous effects through fault diagnosis is a crucial procedure to be adopted at an early stage.

The most common faults at the time of manufacturing are delamination, junction box malfunction that can lead to high resistance, abnormal heating, and the breakage of the frame. There are also certain external faults such as connectors failure, clamping, transport, and installation failures [11]. Other faults related to the PV module include hotspots due to the panel behaving abnormally like load and electrical problems in bypass diode or a shunt resistor, anti-reflective aging, bubbles in between the Tedlar and beneath the panel [12]. To identify the faults in the PV modules, infrared imaging is a technology that captures invisible infrared images and converts them into visible images. The PV modules inspection and fault detection play a major role in getting optimized and efficient power from the PV systems by reducing the maintenance costs through detection of the fault at an early stage of the damage [13]–[17]. Employing the infrared (IR) images can aid to mimic the hotspots in the PV modules that can indicate the abnormal operations causing reduced power generation or the harmful hazards caused to the humans or the plant.

Researchers in 1998, detected the hotspots in the circuits and devices employing fluorescence micro thermography (FMT) based on the temperature-relying luminescence of chelate dyes. There had been a survey on infrared imaging of the solar PV modules in 2000, the key formulations they dealt with were solar cells, solder bonds of a resistive kind, heating in reverse bias, the functionality of the by-pass diodes, and the other factors that affect the balance of the system [18]. Gao *et al.* [19] to diagnose the PV module defective cases, a proposal of infrared imagery on the moving cart was developed. The frame-to-frame association for optical flow to count the panel in an array has been implemented. They used the generalized Hough transforms and the clustering density-based spatial clustering of applications with noise (DBSCAN) strategy in relevance with the neighboring pixels [19]. Tsanakas *et al.* [20] implemented the canny edge detection algorithm using thermal imaging technology. A key investigation was held on the hotspot detection based on heating. The algorithm found the defective modules using the edge detection phenomenon [20]. An automatic surveillance and fault diagnosis method employing the PV power loss route was proposed by Chouder and Silvestre [21]. They employed the key parameters of the PV system for examining the data logger in real-time considering the temperature effects and the solar insolation [21]. Inspired by the above literature, we employed an efficient technique for fault diagnosis of the PV modules installed in the United Arab Emirates (UAE). The current work elucidates the comprehensive understanding of the PV measures employed with the consistent electrical and thermographic approach as shown in Figure 1. The novelty lies in designing the most robust and competitive algorithm aids the efficient implementation.

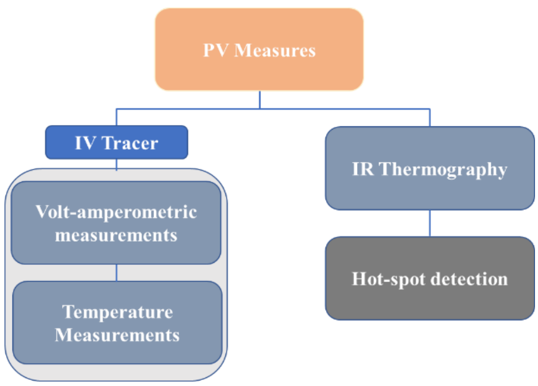


Figure 1. A systematic flow for the current experimental setup

2. MATERIALS AND RESEARCH METHODS

Figure 2 demonstrates the schematic illustration of the experimental setup. The system consists of a thermal imager to capture the PV module image instantaneously. The images obtained were processed using the MATLAB software employing fault diagnosis and detection algorithms in image processing and computer vision toolbox to detect the fault and identify the malfunctioned PV panels. The intended monitoring system is operating on the multicore CPU along with the parallel processing module using C++ programming. The crucial image processing algorithms were accommodated to find the PV module defect. The algorithm is robust with the least error and deviation in identifying the fault. The Table 1 furnishes the information about the key elements employed for the current protocol. The components were obtained from the laboratory and used under supervised inspection.

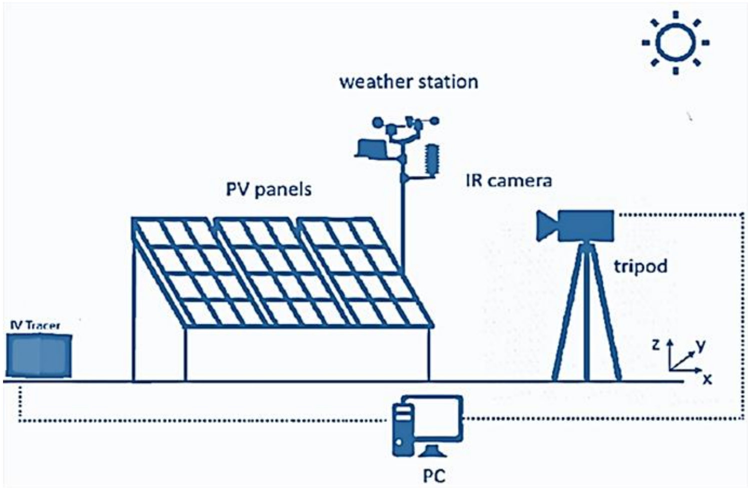


Figure 2. Schematic illustration of the experimental setup

Table 1. Components of the experiment

Components	Specifications
Solar PV Panel	Waaree WS-50 W
Battery	Eternity Technologies 12 VDC, 56 AH
Charge Controller	Morning Star SS-MPPT-15L
Thermal Imager	Fluke Ti-45
Clamp Meter	HEME Analyst 2050
Tripod	BOSCH BS280
Multimeter	Fluke 176
IR Light	250 W IR
Load	2 x 24 W DC Motors

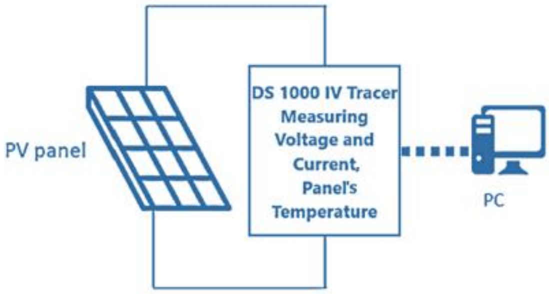
2.1. Electrical setup

All the measurements were calibrated on a sunny day, with the average solar irradiance of 1000 W/m^2 that can be measured by the pyranometer (DPA 053 and the mini data logger) along it. To elucidate the voltage and current calibrations, the typical curves can be obtained by the IV tracer that was connected to the workstation PC specifically considered as a load depending on the setup. Figure 3 demonstrates the electrical calibrations of the PV Panel associated with the IV tracer for obtaining various parameters such as IV parameters, temperatures, solar global radiation. The setup in Figure 3(a) distinguishes that the pyranometers, IV tracers, and thermocouples were properly attached to the PV panels. The global solar radiation with respect to time and temperature has been mentioned in Figure 3(b). From Figure 3(c), it is evident that the current and voltage measurements were found to have fewer amplitudes on par with the proper PV panels without the shadowing or without the polystyrene patches. ΔIV depicts the difference between actual IV and obtained IV after shadowing. Generally, identifying the shadowing and damages of the PV panel cells is a bit of a tedious process, hence there is a great need to employ the thermographic setup for depicting the shadowing or cracks on the PV panel surface which will be discussed in the following sections.

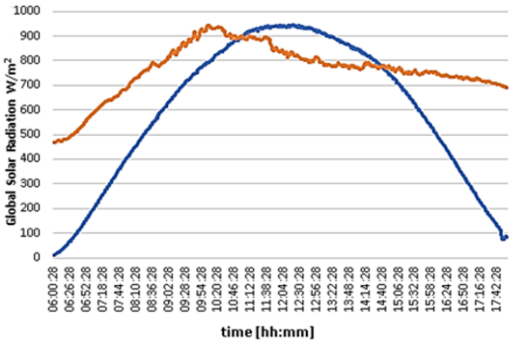
2.2. Thermographic setup

Thermal images were obtained with a photo rate of 10 seconds at the time of the panels' heating phase, which can be due to the exposure to the solar radiation and by the application of the electrical loads.

A tripod, placed at a suitable distance from the panels, enables the continuous acquisition of the images. The distance can be adopted in such a way that all the panels can be visible simultaneously avoiding the possibility of the IR camera not obstructing the image acquisition. Hence, the angle of viewing in between the IR camera lens and the object was perpendicular and was zero.



(a)



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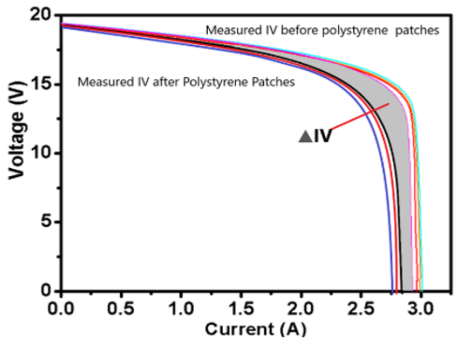


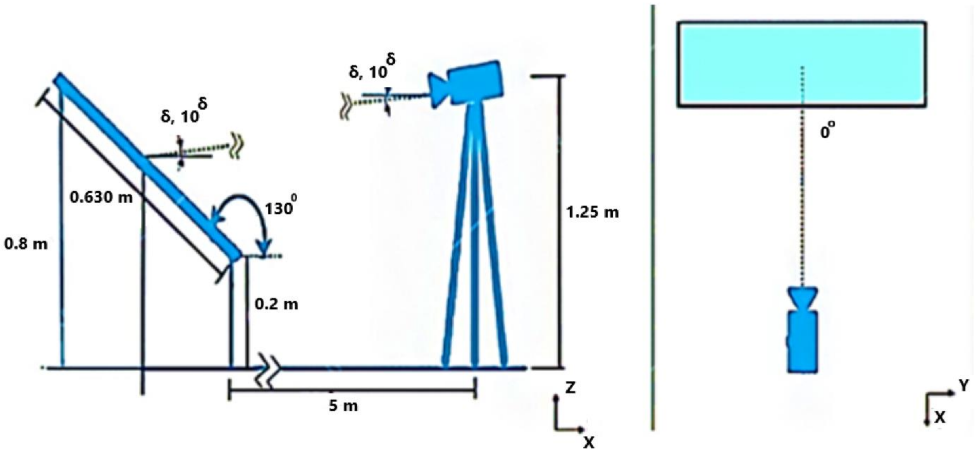
(c)

Figure 3. Demonstration of layout and electrical calibration (a) experimental setup of electrical measurements, (b) global solar radiation concerning the time and temperature, and (c) measured IV characteristics before and after the shadowing

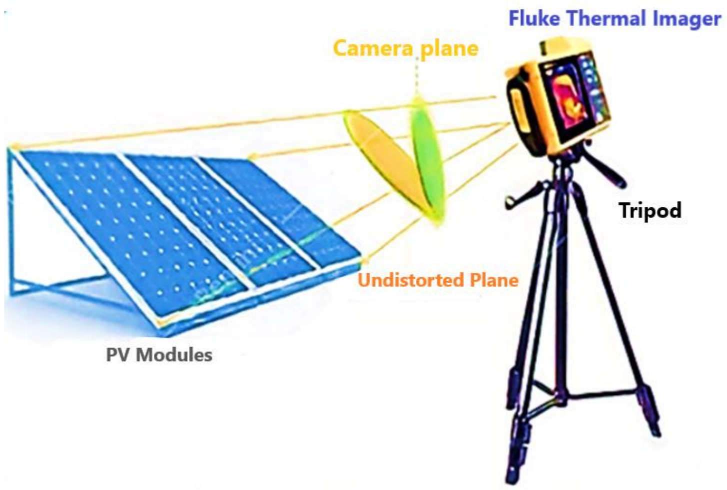
Hence, the thermal camera was employed in such a way that to acquire the images in a symmetrical phenomenon Figure 4. The IR camera was tilted in such a way to precisely frame all the panels simultaneously. It is a bit contrast in the common practice, viewing angle is not much encouraged because of the camera reflection itself. The current work employed the distance in such a way that the distance between the tripod and the PV panel along with their tilt angle about the ground does not affect the self-reflection. The design perspective of the experiment and projection of design layout prototype of the experimental setup is depicted in Figures 4(a) and 4(b) and a photograph of the setup is illustrated in Figure 4(c).

2.3. Segmentation by canny edge detection algorithm and bounding box technique

Initially, as mentioned in Figure 5, the input image is converted into grayscale where threshold values are adjusted that are held for binary image edge detection and to identify the regions of interest from the input thermal images. The solar cells of the defective kind are generally yellow or white in colors having sharp edges in thermal images, makes lucid to identify the region of interest. The threshold value, ‘Th’ is ascribed to a binary image. Convolution of the image is done by Gaussian filter coefficients. Later non-maximum suppression (NMS) is performed on the image. The hysteresis thresholding is depicted for the image followed by 8-connected components labeling. Furthermore, the morphological transformations also benefit from the kernel assignment, defining the structuring element. At first, the erosion technique is applied to the image, depending on the kernel kind, the pixels of the image are ascribed as such, else the erosion takes place in the image. Boundary pixels will be faded or discarded in the image based on the kernel size estimating the white color area reduction. The dilation is adopted later which is contradictory to the erosion, the pixel is 1 when at least any one of the pixels under the kernel is 1. This can be elaborated as the white region in the image grows or dimensions of the objects in the foreground enhances. Therefore, the faulty solar cells in the modules can be identified by the optimal Canny’s Algorithm accompanied by the region props and bounding box techniques.



(a)



(b)

(c)

Figure 4. Thermographic setup (a) design perspective of the experiment, (b) projection of design layout, and (c) experimental setup of thermographic calibrations

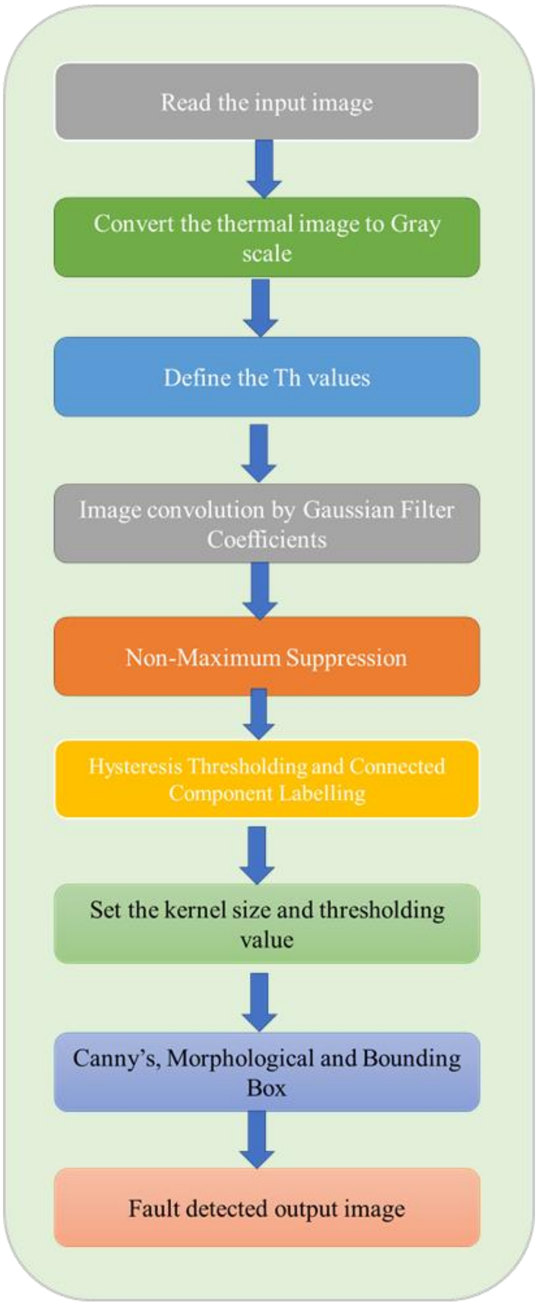


Figure 5. The flow diagram for the fault detection algorithm

3. RESULTS AND DISCUSSION

The input images were captured for our PV modules in the Ras Al Khaima Research and Innovation (RAKRIC) center at the American University of Ras Al Khaima (AURAK), UAE to substantiate our proposal (Latitude and Longitude of 27.2046° N, 77.4977° E). The experimental setup has multiple hardware components is such as depicted in the following tabular column of Table 1. The complete system was constructed in our research facility is as shown in Figure 6 considering all the elements of connectivity, calibrations, and escalations.

The Fluke Ti-45 has been used as a thermal imager and the resolution of the images is found to be accurate for processing images in the MATLAB software. The BOSCH BS 280 tripod was employed for the experiment. The thermal imager was mounted on the Tripod facing the solar PV module at an appropriate distance to capture the images. Moreover, indoor imaging is also taken into consideration for fault detection analysis. For this, the IR light sources of 250 W were employed and mounted on two more tripods. We utilized placing certain pieces of polystyrene sheets on the surface of the PV panel that can act as a minimal defect. C++ program on the MATLAB command prompt was accessed to perform operations and process the input images obtained from the thermal imager. The specifications of the workstation PC are ASUS Tek Computer.Inc, X556UB, professional, Intel (R) Core (TM) i7-6500U Processor, 2.59 GHz, 12.0 GB RAM, 64-bit operation system x 64 based processor, and a Windows 10 professional operating system is employed. MATLAB R2020b was installed on the Windows 10 platform, along with other image processing and computer vision toolbox with other extensions. Employing internet of things (IoT), which will be our future work provides the privilege for the real time monitoring of various PV panels parameters and crucial constraints include temperature, cracks and shading of PV cells. This can be achieved by the novel technologies in the AI such as Thinkspeak can avail facile access.

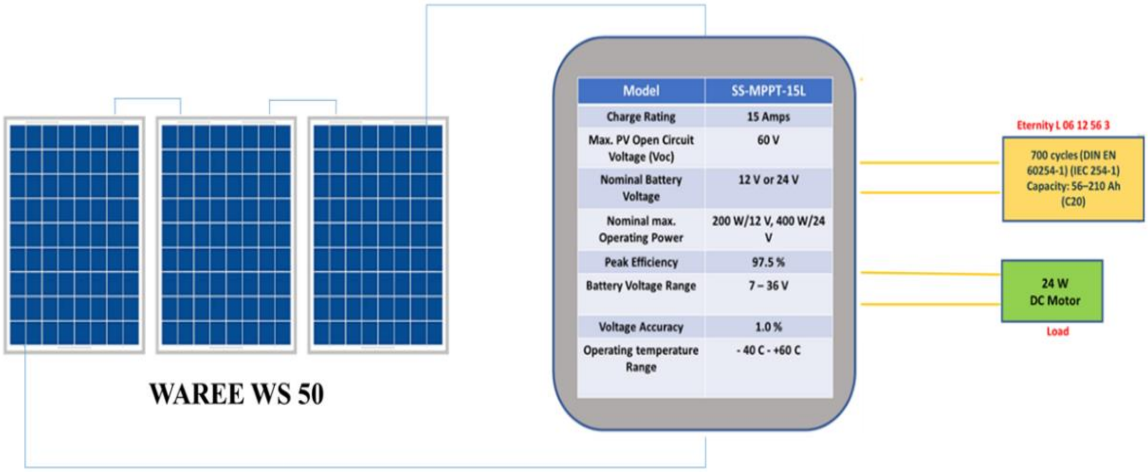


Figure 6. Scheme of PV module setup at RAKRIC

3.1. Algorithm implementation for edge detection

The morphological transformations and canny edge algorithm were used to identify the fault in the PV module as depicted in Figure 7 in both the cases of indoor and outdoor setup. In the outdoor setup, two out of the three panels of the system are made manually defective with a certain random arrangement, while the other panel is left as it is. In the indoor setup, one PV panel was used and manually made defective. The thermal image of all the panels is depicted in Figure 7(a). Now the processing of images is taken into consideration. After loading the input thermal image and converting it into the grayscale, the thresholding is foxed with Tlow as 0.075 and Thigh as 0.175 along with the Gaussian filter coefficients. Gaussian filtering is intended for the convolution of the image in both X and Y directions. It is of a linear filter, typically aimed at blurring the image or reducing the noise in the image. The considerable usage for dual purpose and subtracting makes to edge detection or unsharp masking. The filter operates to blur the image and contrast reduction. The Gaussian filter is faster since it multiplies and adds that makes it more robust than sorting.

The output image with the color scaling is elucidated in Figure 7(b). In the concatenation to this, the non-maximum suppression is performed and shown in Figure 7(c). The non-maximum suppression is intended to scan the image in the image gradient direction in case the pixels are not in line with the local maxima, they are zeros [22]. This has the overall effect of suppressing the information of the image which is not in the local maxima region. For this image, the hysteresis thresholding is evaluated and assigned suitable T values that give the outputs in Figure 7(d). The technique evaluates and compares the two images to build the intermediary image by taking the two binary images which were thresholded at different levels [23]. The more the threshold, the lower will be the pixels population. The accurate and more relevant pixels are found in the higher threshold region depicting the real edges by adding them to the hysteresis images. Now the morphological transformations with appropriate structural elements are assigned to get Figure 7(e) and bounding box techniques are applied to detect the final defect in the PV module shown in Figure 7(f). This technique is certainly an illusionary rectangle that acts as a reference point to aid object detection and draws the collision boxes for the object [24], [25]. Data annotators generally draw the rectangles over the images outlining the object of interest in each image by ascribing the X and Y coordinates. The following Table 2, evaluates the comparison of thermal imaging for PV panel inspections.

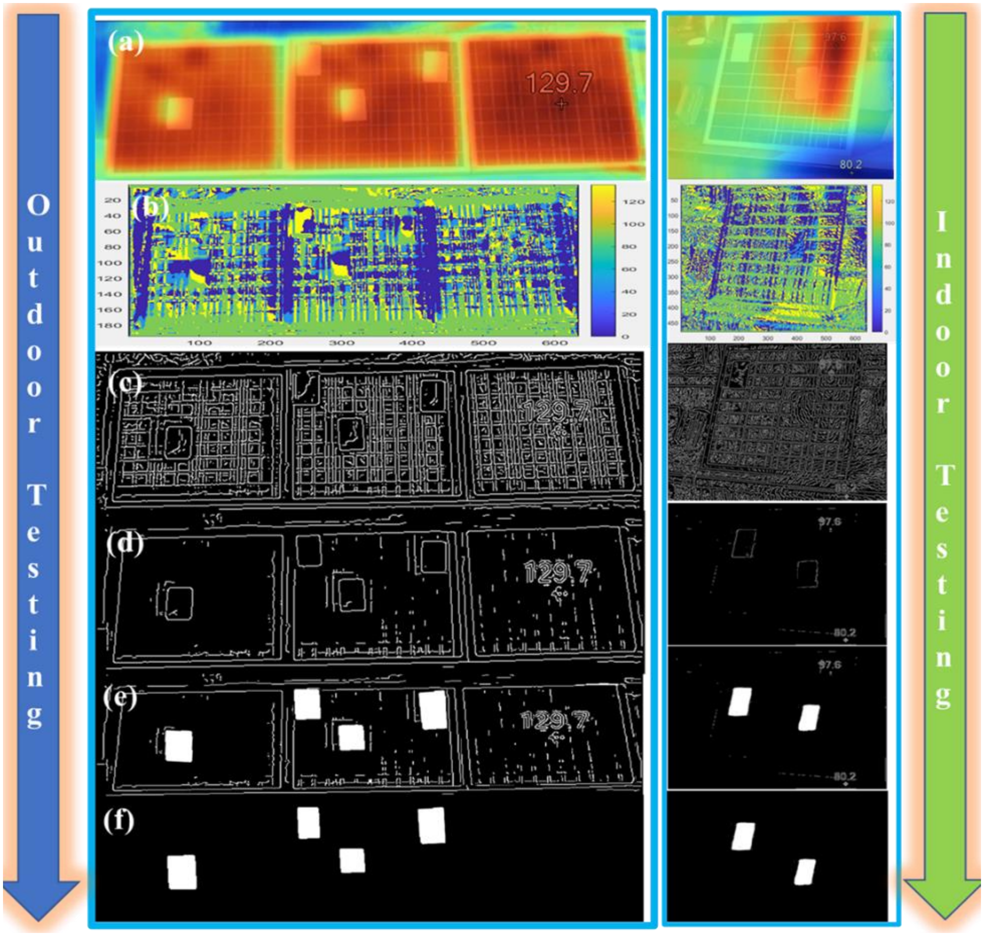


Figure 7. Various stages of the algorithm (a) input thermal image, (b) scaling colored image, (c) NMS, (d) hysteresis thresholding, (e) morphological transformations, and (f) bounding box techniques

Table 2. Comparative literature with various thermal imagers

Reference	Thermal Imager
Aghaei *et al.* [26]	MicroCAM 640 by Thermoteknix Systems Ltd
Quater *et al.* [27]	MicroCAM 640 by Thermoteknix Systems Ltd
Kauppinen *et al.* [28]	FLIR Tau2
Muntwyler *et al.* [29]	Optris PI Lightweight PI 400
Aghaei *et al.* [30]	Flir A35
Addabbo *et al.* [31]	FlirVue Pro and Flir TAU2

4. CONCLUSION

With the advent of industrialization, the quest for alternate energy resources has become more ardent. Renewable energy resources are found more feasible and optimal for this purpose. Solar PV technology playing a crucial role in satisfying the energy demands. Various factors need to consider in the design, construction, and evaluation of the PV plant setup. Performance is the key factor that needs to be addressed. To elucidate the faults and improve the performance of the system to save energy, economy and mimic the dangerous effect during the operation of the PV systems, the current work has initiated a new hybrid algorithm that can be employed for real-time monitoring. The experimental system employs an infrared thermal camera mounted on a tripod along with the electrical parameters measured with the real-time testing in our laboratory. The practical analysis on the current proposed model along with the suitable best-fit algorithm correlated to minimize the hazardous effects and enhance the performance of the PV setup and reliability through employing algorithms for fault detection. Our future work is to integrate the IoT technology with the current work to check the performance and identify the fault on a go (through mobiles) technology and dynamically monitor the electrical performance as well. The results found feasible for real-time applications and processing time is found very optimal for the PV plants.

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