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A REVIEW ON IMAGE PROCESSING TECHNIQUES FOR DAMAGE DETECTION ON PHOTOVOLTAIC PANELS

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Abstract. *The image processing topics for damage detection on Photovoltaic (PV) panels have attracted researchers worldwide. Generally, damages or defects are detected by using advanced testing equipment which is still quite varied according to the types of damages. In this respect, the types of damages of solar panels or photovoltaic modules can be classified into damage on module surface, shadows and dirt from external effects and internal problems originating from the PV system itself. These damages can be effectively detected using the image processing method-based imaging technology, namely Electroluminescence (EL) and Infrared (IR) thermal imaging. The results of measurement can be used for the application of complex computer vision techniques which are sorted into stages of image acquisition, image processing and pattern recognition. This paper would like to investigate more detailed about the damages of photovoltaic module identification and the image processing techniques for the reasons of ensuring safe and efficient utilization of photovoltaic systems.*
Keywords: Image processing, Damages classification, Computer vision, Damages detection methods

1. **Introduction.** Nowadays, solar panels are one of the renewable energy sources widely used. Solar panel, or also often called Photovoltaic (PV) system is a device that is able to convert sunlight directly into electricity. Photovoltaic system can be referred to utilizing equipment to maximize the enormous potential of the energy of sunlight reaching the earth. It has been widely implemented because of the relatively low cost and easy maintenance. It is quiet energy due to no moving parts and it is clean energy due to no liquid utilization. However, this panel cannot be protected from damage for instances cracking, failures of soldering and interconnection, potential material malfunction and hot spot problems. Therefore, early detection is highly important to ensure the continuous output energy supply of the PV panels.

Solar cells provide direct energy conversion from sunlight into electricity [1]. It is highly necessary to enhance the output energy solar cell at high efficiency without any defect problems during the implementation. Nowadays, it is very important to carry out initial checks to detect damaged solar cells. It is due to the fact that early detection of solar cell damage is highly significant in the material research, manufacturing process and utilization of solar panels [2]. In other approach, the utilization of thermal energy by means of the photovoltaic-thermal systems has been investigated regarding the efficiency energy output enhancement of photovoltaic panels [3].

It is hard to determine the faulty of solar panel without expert knowledge. The fault detection on solar panel has been proposed using drones, thermal cameras and RGB (Red, Blue, Green) cameras [4]. However, RGB images cannot provide sufficient information

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and cannot detect damaged solar panels using only one type image. In this case, a thermal image processing to detect solar panel failures which are caused by cracking, sticking with other objects and disconnecting the solar panel wire is more effectively instead of an RGB image process.

Damaging of PV cells can be caused by short-circuit condition of bypass diode [5]. In this case, it is highly important to reduce the impacts of unhealthy PV cells as the consequence of surface deterioration, such as discontinuity output, cracks and shading of PV cells [6]. The non-uniform sunlight intensity entering the panel surface yields shading operation and potential hot-spot problems which might be sequentially damaging the shaded cells [7].

The over-current due to internal faults of PV panels commonly produces an over-heat condition and defects to PV components [8]. The types of internal faults of PV panel are ground and line to line faults. A ground fault condition is the current flowing to ground through the earthing system that provides pathway between one or more conductors of array. Meanwhile, the line to line fault is the short-circuit connection of two parts of panel with different voltage levels. Another type of dangerous fault in PV array is caused by low intensity of sunlight during evening condition.

Different techniques of fault identification are concentrating on the framework design of automatic diagnostic system for damage identification of solar panel components using thermal image processing with accurate and timely response to alert the unsafe conditions [9]. This research detects accurately the hotspot from image using Simple Linear Iterative Clustering (SLIC) of super-pixel technique. SLIC is based on a spatial localization of K-means clustering version which is a very good tool for decomposing an image into small homogeneous regions. This technique saves the efficiency, power production and overhaul time for the solar panels effectively.

Some of the faulty PV modules are well-identified, such as failures in the Anti-Reflective Coating (ARC), bubbles in the solar modules, and browning and yellowing of modules [10]. Failures in the ARC are due to an oxidation of the ARC components and might affect loss of adherence between PV cell materials. Furthermore, bubble inside the solar panel occurs due to a chemical reaction where some gasses from PV cell materials are released. Other failures of browning and yellowing modules may reduce in the light transmittance entering the solar cells and thus a decrease in the energy output.

Analysis methods through images processing of solar cell performance are commonly by scanning techniques of small parts of the solar cell in order to obtain spatial information of damages. Combination of the image processing methods with more recently scanning methods is highly necessary due to the complex interpretation and analysis of images, different material and process, varied test conditions and deviation from the actual performance of the solar cell [11]. Therefore, this paper attempts to provide clear information regarding the photovoltaic damage detection based on computer vision for the reasons of ensuring safe and efficient use of solar systems.

The contribution points of this study can be divided into academic and practical perspectives. From academic, it summarizes and provides a more detailed damage classification. Several points related to the causes of damage to solar panels were also discussed that show a type of damage can be caused by several causes. The methods of image processing for identifying the damage are also presented. These findings contribute new information that can be used for future research. For practical contribution, it gives general information for the company and users of PV in order to improve the quality of production, installation, maintenance and proper monitoring of the user.

More detailed information regarding the photovoltaic damage detection and other aspects of computer vision is provided in the following section. In Section 2, the classification of damages is given. Section 3 deals with the overview of EL imaging and IR imaging. In

Section 4, the review of computer vision damage detection is presented. Finally, Section 5 shows the conclusions of this review study.

2. **Classification of Damages.** Different knowledge and experience have been elaborated over the past decade to identify the potential defects during the operation of PV panels. This section reviews the commonly reported damages problems including the damages classification focusing on the improvement of manufacturing PV cell technologies, safety and lifetime operation of installed PV system. The main damage classifications in PV system are surface defects on the PV module, external shading and soiling, and internal of PV system. A description of these classifications is presented in Table 1.

Table 1. Classification of damages on PV modules

Classification of damages	Types of damages	Causes of damages				
		Installation/ maintenance	Surrounding environment	Climate	Chemical reaction	Unintentional connection
Surface defects	Cracking	O		O		
	Delamination		O	O		
	Discoloration				O	
	Bubbles				O	
	Defects in ARC				O	
External problems	Shading		O	O		
	Soiling		O			
Internal problems	Ground faults	O				O
	Line-line faults					O

2.1. **Surface defects on the PV module.** On the PV module, surface defects lead to hot cells formally named as hot spots. A hot spot is an area of a PV module that has a very high temperature that could damage a cell or any other element of the module. A review of the types of damages on PV module surface is presented as follows.

2.1.1. *Cracking.* Cracking as shown in Figure 1 is a usual problem occurring in PV array installation. The problem might change in different phases of the module utilization. Nevertheless, it occurs in majority of cases during installation, maintenance and mostly during the transportation of PV modules to installed location. Moreover, cracking is affected by the rise temperature from the thermal stresses of cell and mechanical loads due to wind and snow (pressure and vibrations) [12]. In this respect, different color lines can be noticed in the cell, although the cracks are not seen by bare eyes. It is called micro-cracks. Once PV panels with these varied color lines are scanned by the

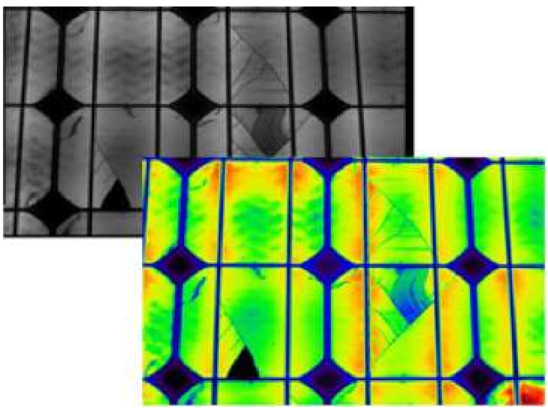


Figure 1. Cracks in the cell [10]

Electroluminescence (EL), the tiny-crack spots are darker in EL due to lower generation of light emission. The crack isolates the healthy cell to produce normal electricity current [10].

2.1.2. *Delamination.* Delamination is the damage of the binding between composing layers of module lamination. This problem causes deficiency of heat dissipation and rises the potential of reverse-bias cell heating. The main cause of delamination is the movement of cells out of the normal cell interconnection due to environmental stresses. Moreover, the operation of PV panel in surrounding high temperature environment accelerates the aging of physical cell materials that leads to delamination failures [12].

Delamination highly potentially occurrs in hot and humid temperatures. If the problem appears in the edge of panels, it will be more severe not only because of the power losses but it is dangerous due to potential electrical risks of panels and the area of installation. Figure 2 shows an image of the worse delamination that could damage the PV panel when the defect appeared. Delamination is also correlated with light transmittance loss entering the panel surface as materials do not respond optically coupled with the loss part of sunlight [10].

Figure 2. A PV module with delamination [10]

2.1.3. *Discoloration.* Discoloration (yellowing and browning) is a color changing in the PV cell materials from white to yellow and/or brown. It mainly occurs due to the reduced performance of the Ethylene Vinyl Acetate (EVA) encapsulant. The main causes of EVA performance reduction are Ultraviolet (UV) beams combined with water which has temperatures higher than 50°C. The color changes of the material produce a variation of the light transmittance entering the cells and result in decrease of energy production [12].

Figure 3 presents an image of yellowing effect that occurs only over some parts of PV panel. In some cases, yellowing appears in areas according to different polymeric encapsulant of a different origin or characteristics. It means that yellowing occurs in

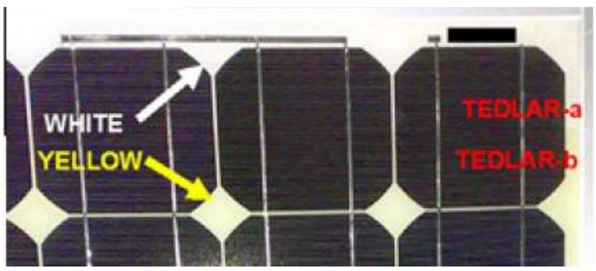
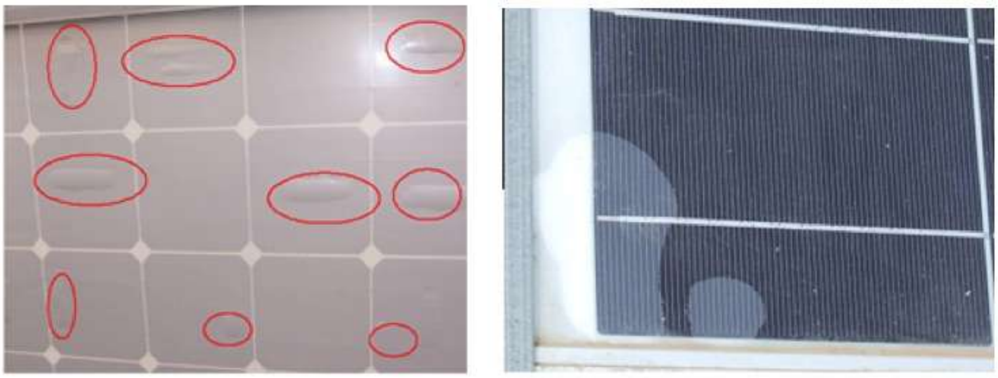


Figure 3. Discoloration of a PV module

polymeric encapsulant instead of in the adherent element (usually EVA). In this respect, EVA does not uniformly exist in overall areas of the PV panel where different polymeric encapsulant was utilized.

2.1.4. *Bubbles.* The bubbles are the type of damage that appears after some gasses are released and trapped inside the PV panel. It forms some kind of air chamber where the gas temperature is lower than that of the neighbouring cells. Moreover, the bubbles can break the panel glass and damage the back-sealing surface that allows the humid air entering the panel [12].

Once bubbles appear in the back side of the PV panel (Figure 4(a)), a bulk rise in the polymeric encapsulant or the back cover forming a bubble that prevents the heat dissipation of the cells to ambient air. The hot bubbles will subsequently decrease the cell lifespan despite the fact that the performance of the PV module is not severely reduced when this problem has just appeared. In Figure 4(b), the bubbles can also occur on the front side of a PV panel between the glass and the cells. However, this kind of problem is not very common on the front side of the panel surface. It is due to the fact that the cell material is stiffer than polymeric encapsulant material.



(a) Back side (b) Front side

Figure 4. Bubbles on PV modules

2.1.5. *Defects in the Anti-Reflective Coating (ARC).* The Anti-Reflective Coating (ARC) may experience unexpected changes as well. During the operation of the PV module, the ARC exposes to radiation that could lead to alteration in the ARC coloring (Figure 5). This defect occurs due to an oxidation of the ARC which could cause loss of adherence between the cells and the glass materials. The sunlight that enters the panel surface may be lower than expected. Nevertheless, this color alteration should not reduce in the effective wavelength radiation for the output power of cells, but rather only influence a part of the visible light [10].

2.2. **External soiling & shading.** Total or partial shading of irradiance that occurs in the PV module surface as in Figure 6 can be a critical issue in PV array operations. The shading can be from the other parts of building, trees, snow and other light blocking objects. Shading causes significant reduction of panel output power and can even make the modules with defects if not properly solved.

Meanwhile, PV panel soiling is formed of dirt on the module surface. The impacts of soiling seem nearly not significant for a moment, but become more significant for larger volume of dirts during long operation. In addition, a single dust storm can decrease the output power by 20% and a reduction of 50% if no cleaning efforts are performed on modules surface for long period.

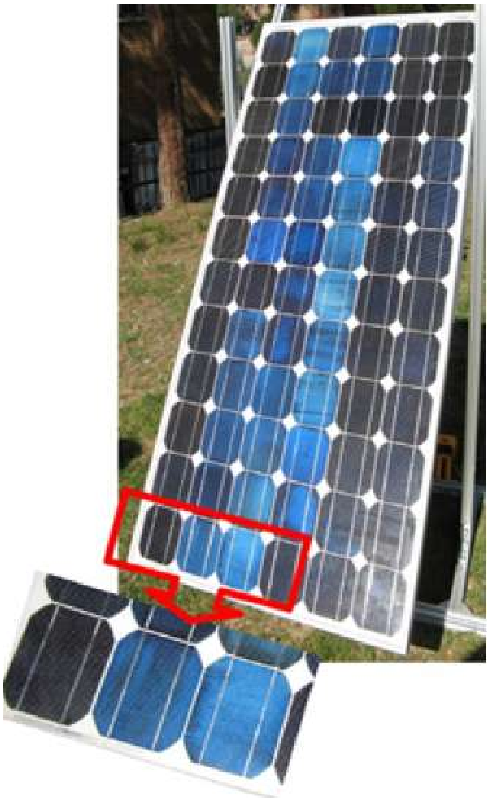


FIGURE 5. Decolouring of cells due to a change in ARC [10]

FIGURE 6. Partial shading of a PV module [7]

2.3. **Internal problems of PV system.** Ground faults and line to line faults are the most common internal fault problems in the PV system installation. Ground faults are described as a conductor having connection with the system ground unintentionally. A ground failure mechanism occurs when the circuit builds up an unexpected path to ground. This results in reduced output voltage and power, and can be dangerous if the leakage currents are flowing through a person. If a ground fault stays unidentified, it can develop a DC arc in the fault and generate a fire risk.

A-line-line fault is unexpected short-circuiting between two points in the array with different potentials. The line-line fault could be interpreted as a short circuit fault in a grounded system or a double ground fault in an ungrounded system [8]. This fault is not as common as ground fault in PV systems. It is more difficult to detect and clear by conventional protection devices. Therefore, it must be protected against for safety reasons.

3. **Damage Detection Using Imaging Techniques.** Quality control of the PV modules is a requirement for good performance and long lifespan. PV modules may develop damage during operation, which can be fixed if they are discovered early [10]. Fast and reliable methods to evaluate the performance of the photovoltaic modules are required to confirm the operation of the PV modules. Electroluminescence (EL) and Infrared thermal (IR) imaging inspections of PV are the solution to make sure the safety and great performance of the PV module. They are the imaging techniques, which recognize damage developing of PV modules [13]. The methods for damage detection of photovoltaic modules are shown in Table 2.

Table 2. Methods for damage detection of photovoltaic modules

Common process	Imaging technologies	
	Electroluminescence (EL)	Infrared (IR) thermal
Image acquisition	Sensovation digital camera SVSB-14-M [14]	FLIR C2 infrared camera [2], FLIR Vue Pro [9]
Image enhancement	Morphological smoothing process [18]	RGB to CIELAB colour space [2], RGB to grayscale [4, 17], Smoothing filter & edge-preserving [17]
Image segmentation	Partitioned into individual solar cell subimages	RGB to HSV [17], K-means and SLIC [2]
Feature extraction	Independent Component Analysis (ICA) [18]	Distribution of graytones (intensity pixel) [19]
Damage identification		Comparing mean values [4], Neural network classifier [20]

3.1. **Electroluminescence (EL) imaging.** EL imaging is a technique with high resolution that produces a map of intensities over the domain of the PV [14]. The EL technique can be profitably applied to identifying and distinguishing between different damages [13]. Damages are usually caused by surface defects, which create a localized additional resistance. Therefore, surface defects such as cracks can be visually identified (Figure 7).

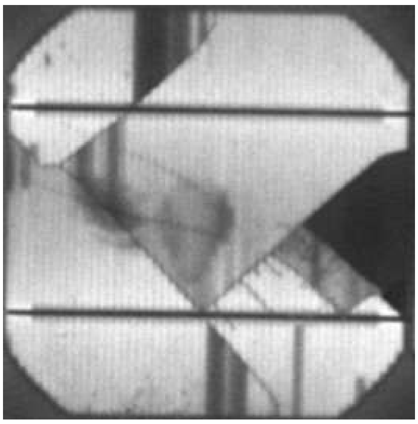


Figure 7. EL image of a solar cell with a typical crack pattern [13]

In the EL testing, PV modules perform under forward bias like a Light Emitting Diode (LED), and therefore have to be power supplied. An EL drawback is the operating condition that requires dark environments [13]. Progress researches have recently been made to perform EL images in the field, with the use of shrouds to cover the module, or using cameras able to operate also in almost dark environments at sunsets, or integrating the camera in drones for aerial inspection [14].

3.2. **Infrared (IR) thermal imaging.** IR imaging method has a noticeable record in non-destructive testing, such as in recognition of failures within building walls, faulty engines, plastic manufacturing quality control, and many other detection problems in industrial and electrical systems. Damaged PV modules that cause hot spot or heat effects can be easily identified with this technique. It eliminates the need to disconnect each solar PV module from the array for testing since they can identify damaged PV modules through the images [2].

Figure 8 shows IR patterns of overheated cells due to external shading. The IR pattern that can be observed strongly depends on the exact external shading source, which is usually divided into local shading and large-scale shading. Local shading sources are for example soiling and small plants. Large-scale shading sources are high buildings, lightning rods, masts (pylons) or trees next to the PV [13]. This pattern indicates local shading source due to the fact that the shading is caused by the small plants. The IR imaging is a time saving and inexpensive method able to locate mostly common issues related to surface defects, external partial, and internal cell problems. It can be performed in dark or illuminated surroundings [14]. Amongst existing inspection methods today, IR imaging is rated as a promising tool for fast and reliable damage detection.

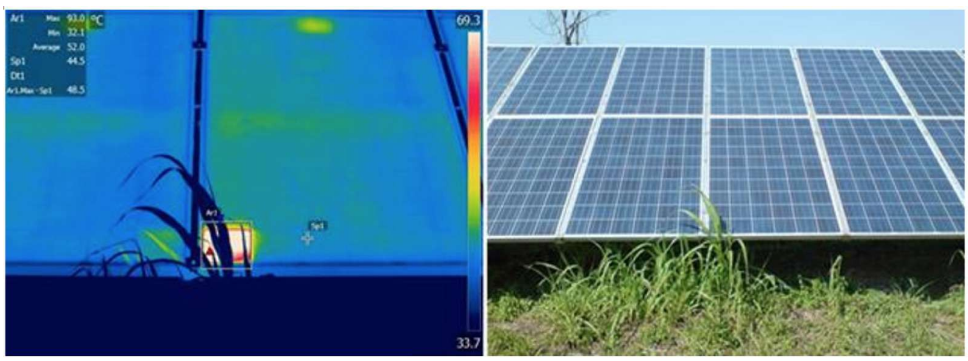


FIGURE 8. PV module shows overheated cells due to shading by plants [13].

4. **Computer Vision Techniques for Damage Detection – Common Process.** Computer vision is the method of using a computer to obtain high level information from a digital image. A computer vision system takes image and puts into the computer which will be executed using image processing and pattern recognition. Computer vision algorithms then perform to achieve a specific purpose. Figure 9 shows a common process of computer vision techniques for damage detection.

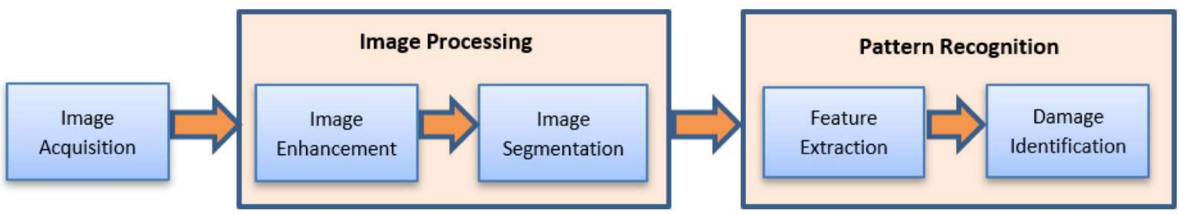


FIGURE 9. Common process of computer vision techniques for damage detection

Computer vision algorithms are already operated in solar panel damage detection. The damage detection methods usually consist of two main steps: image processing and pattern recognition. In the image processing step, image enhancement and image segmentation techniques are applied to the images so that noise is eliminated while damages are enhanced. More analysis based on features using classification or clustering algorithms is executed in the pattern recognition step to recognize the damages.

4.1. **Image acquisition.** The beginning step of every image processing is the image acquisition. Basically, an image acquisition is a process through which images are taken from various devices. The common aim of image acquisition is to convert an optical image into an array of numerical data which could be later managed on a computer. The optical image is captured by suitable camera depending on needs and converted into a manageable form.

For IR imaging, there are many IR cameras existing on the market. In [2], FLIR C2 infrared camera was operated for thermal imaging. It is a convenient infrared camera with a thermal sensitivity of $< 0.10°$C and an infrared sensor resolution of 80×60. The distance between the camera and the PV module was set at 1 m. This camera takes images at angles between 20° to 35° to avoid casting shadows on the PV module. In [9], the IR camera that is used is FLIR Vue Pro with resolution of 336×256 pixels. This resolution is quite high to display an appropriate thermal resolution from the panels. Another tool that can be utilized for image acquisition is drone [4]. Drone takes solar panel array pictures using RGB camera to recognize the position of solar panel and thermal camera to determine the error panel.

For EL imaging, images are captured with a Sensovation digital camera SVSB14-M under forward bias with exposure time of 300 s [14]. A high resolution EL camera might be necessary in order to analyze the defect of a PV module. High resolution camera also enabled PV modules to be taken from a far distance and capturing more modules per image [13]. When the images have been captured, then various processes are applied on the images.

4.2. **Image processing.** There are two important stages of image processing, i.e., image enhancement and image segmentation which will be explained as follows.

4.2.1. *Image enhancement.* Image enhancement is a pre-processing stage in image processing that aims to improve the quality of an image. In the process of image acquisition, image is often contaminated by external noise, resulting in degraded quality [15, 16]. The goal of enhancement is an improvement of the image data that overcomes the external noise or unwilling misinterpretation and strengthens some image features for further processing.

For the IR images in [2], the RGB values were transformed to CIE L*a*b*. CIELAB is a color space, stated by the International Commission on Illumination (Commission internationale de l'clairage). It has three coordinates to represent the lightness of the color, where L* = 0 yields black and L* = 100 is white, a* represent between red and green, where negative values indicate green and positive values indicate red, and b* represent between yellow and blue where negative values indicate blue and positive values indicate yellow. The conversion from RGB to CIE L*a*b* decreases the computational complexity of the algorithm since the color scale was reduced from 3 to 2 dimensions. This minimizes computation time and large variations of clusters.

Moreover, the proposed system in [4] converts the RGB to grayscale images to identify the boundary of PV array. In [17], after converting RGB into gray scale, the image is cropped to one selected panel, and removes noise by applying smoothing filter and edge-preserving. For the EL image, a particular morphological smoothing process is implemented in order to smooth the dark-region background and preserve the defect shapes, before it is used for learning and detection [18].

4.2.2. *Image segmentation.* Image segmentation is an important step in image processing that is used to find objects and boundaries. Image segmentation is a process of separating foreground from the background or clustering regions of pixels according to similarities in shape or colour in order to identify and characterize the object. In [4], thresholding method is applied to segmenting an image into a particle region, which consists of a background region and objects under inspection based on the pixel intensities within the image. This method produces the binary image. In [17], image segmentation is executed by converting image colour space from Red, Green and Blue (RGB) image into Hue, Saturation and Value (HSV) to split the colours and to enable the threshold mask to detect the hot-spot based on RGB to HSV conversion.

In [2], image segmentation applies K-means clustering. K-means is used to classify pixels that are in the same temperature range. Euclidean distance is used to group the image data points to the nearest cluster index. After the image is divided into k groups, the highest temperature range is selected. Finally, the isolated hotspot is presented including the average temperature value and relative percent area affected by the hotspot. Also in [9], the SLIC super-pixel technique is applied based on the spatial localization of the K-means clustering. SLIC is a good tool for decomposing an image into small homogeneous regions, that is to group pixels locally and thus to present a perceptual understanding of content. Superpixel minimizes the complexity of the images from hundreds of thousands of pixels to only a few hundred.

4.3. **Pattern recognition.** Pattern recognition can be explained as the distribution of data based on knowledge already gained or on statistical information extracted from patterns and/or their representation. Pattern recognition is used to extract relevant features from given image data and is used in computer vision for various applications. There are two major components for pattern recognition systems: feature extraction and classification or identification for decision making.

4.3.1. *Feature extraction.* Feature extraction is the necessary step in pattern recognition process to extract some features such as shape, texture, and color of the image data. These features compose the significant information and can be used in multiple applications. In [19], features of images are extracted as they present a higher-order information of the image and include description about the spatial distribution of gray tones. According to the value of intensity points (pixels) in each combination, statistics are classified into first-order, second-order and higher-order statistics. Pixels whose values are very similar for the objects are considered to be in the same group, while whose values are very different for the objects are placed in different groups. In the proposed study of [20], features include a relatively small set of values that can be used to represent the target in a feature space. For proposed panel recognition algorithm, lines are used as features. Although the appearance of a PV module is a continuous region that does not stand out from the background, its edges and the rectangular contour formed by the edges help to identify the panel.

4.3.2. *Damage identification.* In this process, the parameter values that represent the characteristics of the object in each class are used as input data. The data is then processed in order to obtain a formula to recognize the object. In the identification stage, generally two main processes are carried out, namely the training process and the testing process. The training process is done using a set of training data which contains feature parameters from feature extraction step that are used to differentiate between one object and another. The algorithm used is selected based on the characteristics of the object.

In [4], mean values of every solar cells were compared to identify higher or lower value than the normal solar panel. If the faulty solar panel is found, then the red colored bounding box will be drawn. For thermal image in [20], when the feature data is achieved, neural network classifier is used for generating the classification method. Scaled conjugate gradient back propagation is adapted for regulating the bias and weights of the network.

5. Conclusions.

5.1. **Review results.** A review of damage of photovoltaic and image processing techniques to identify the damage has been presented. There are various types of damage on photovoltaic modules. The damage can be classified into categories based on the location of damages. From the review study in literature, it has been shown that the most causes of damage on PV are caused by surrounding environment, climate and chemical reaction. In addition, the image processing is developed to be a promising technique for detecting damage on photovoltaic panels. The technique provides fast, quite reliable and straightforward interpretation results regarding to the condition of photovoltaic systems.

5.2. **Future research tasks.** Further interest and investigation of current research are invited to develop a complete PV module condition monitoring technique, with image processing and detection of the types of damages.

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