Using Matlab real-time image analysis for solar panel fault detection with UAV

K C Liao¹, ², and J H Lu¹,*

¹Department of Mechanical Engineering, National Chung Hsing University, Taichung City 402, Taiwan
²Department of Aeronautical Engineering, Chaoyang University of Technology, Taichung 413, Taiwan
*E-mail: james19831111@gmail.com

Abstract. The main purpose of this study is to evaluate the feasibility to use Unmanned Aerial Vehicle (UAV) technology for solar panel applications and to propose a reliable, economical and fast method of fault detection. In this experiment, the UAV was used to inspect the panels of a solar farm. For this purpose, a set of tools were selected including an infrared camera and a High Definition (HD) photographic lens to scan solar panel assembly. The infrared images were immediately transmitted back with backhaul HD for analysis. The infrared image display can be roughly divided into three health conditions. The first one is the normal operation of the solar panel. In the second case, the infrared image represents an abnormal situation of the solar panel. The third one is a blurred case in which the infrared image cannot be determined to be normal or abnormal. Under this kind of situation, the Matlab® image analysis was used in this study to determine the health condition of solar panels. The results show that it is effective and efficient to use UAV to capture the thermal image and to detect different faults of solar modules. Moreover, this process is fast, low cost, and can detect defects that are not noticeable by visible light. It may provide maintenance personnel with a tool to prevent solar module failure.

1. Introduction
In the last few years, the number of solar farms in Taiwan is rising year by year compared with other types of Renewable Energy Source (RES). According to the statistics of 2018, solar energy has accounted for more than 23% of green power [1]. The rapid growth of solar farms and solar roof of residential buildings have led to an increase in demand for solar modules in the global market [2]. Therefore, the maintenance and monitoring of solar modules must rely on an effective technique for predicting and evaluating future performance.

The identification of defects and faults in solar modules needs to understand the degradation characteristics of the module themselves. Accurate measurement and monitoring methods are needed to identify the failure of solar modules in outdoor applications [3]. Rapid detection of solar module failures can extend solar system life and performance [4]. It is noted that investments in solar energy are still growing globally. The productivity of the solar modules needs to be ensured in the life cycle of the entire solar farm to make profit in the market. One of the main factors that reduce the cost of solar systems is to increase the life of solar modules. As a result, detecting the state and failure of solar modules by UAV system (UAS) technology is a very novel application. The traditional monitoring process by personnel detection is labour intensive, time-consuming and easy to produce systematic errors [2]. On the contrary,
UAV can perform module defect detection in a short period of time because they have the advantages of large area coverage, light weight, high flexibility and fastness [5].

In this research, the UAV integrated infrared camera is used with the real-time image transmission function, and the MATLAB® image analysis software is used to analyze the Infrared (IR) image. When the abnormality or failure comes from the solar module, two cases may happen. First, the solar module does not produce any power. Second, the solar module produces less power than the expected value. In the second case, the result of the reduced power is that the solar module is abnormally heated. Generally speaking, the abnormal hot area in a solar module is caused by the malfunction of the cell underneath. An advanced thermal imaging technology can effectively identify typical defects in solar cells [6].

In addition, sometimes the infrared images are not clear enough to identify the cause of overheating. For these problems, the acquired IR image must be properly processed [7]. When the acquired image does not provide information about the health condition of the solar module, this paper proposes tools for preprocessing and processing infrared images. In particular, this paper proposes the application of image filtering technology, including mean, median and Gaussian filters, to effectively reduce the noise generated by IR images, and to improve the identification of defects in solar modules.

2. Typical methods for detection on PV modules

2.1. Visual Inspections
Typically, the first step of the photo-voltaic (PV) module monitoring is inspected by sight. The visual inspection is a very important and fundamental method to detect some defects or failures, such as delamination, bubbles, yellowing, browning, breakage, burning, bending, oxidation, cracked, scratching, corrosion, discoloring, looseness, brittle fracture and detachment. In fact, most of the faults are visually noticeable. Thus, a visual assessment should be performed after module installation is complete to evaluate the effects of electrical, mechanical and environmental stress on PV modules [8]. The PV module performance thereafter can be predicted according to the initial evaluation.

2.2. Thermographic Assessment
Thermal imaging inspection is a novel method that provides data on the status of PV modules. Typically, it is performed by an infrared radiation imaging sensor. Thermal vision assessment is a harmless and noncontact monitoring technology that diagnoses some of the defects and malfunctions of PV modules. In addition, the inspection procedure must be carried out at moderate environmental temperature and winds and sunny days with irradiation of at least 700 W/m² on the modules. It should be considered that, during the inspection process, the inspector must be aware of the sensor's reflections, shadows and radiation. In addition, the optimal position of the infrared imaging camera is in a vertical position relative to the target module [8,9]. It is worth mentioning that this method can detect the internal conditions of the PV system. The hot spots caused by abnormally high temperatures can be detected by IR image as shown in Figure 1 and Figure 2 that are the comparison of the visual image and IR image for the same panel.

2.3. PV Parameter Performance Assessment
Generally, the I–V curves (current–voltage curves) of a solar module are measured under Standard Test Condition (STC temperature = 25 C, Irradiance = 1000 W/m², spectral distribution of irradiance air mass = 1.5, wind speed = 0 m/s). Measurements can be performed outdoors under sunlight, or indoors using a solar simulator. Although the environmental conditions can be better controlled in indoor test, the measurement is not so valuable in practice as real environmental temperature is usually higher than STC [10-12]. They are only an ideal reference for comparing photovoltaic modules under different conditions.
3. New method and experimental setup

In this study, a new method was developed to establish a detection system for a solar farm. Such a system is capable of detecting, identifying, analysing and post-processing various defects and faults on the module in a timely manner and providing reliable and accurate information about the condition of the solar module. To this end, the experiment system monitors the PV module status by using HD and IR images mounted on the UAV to scan for defects and faults and send them back to the ground control station for analysis. In the following sections, special attention is given to IR analysis and comparison.

3.1. experimental setup

The innovative method of this research is to test the PV module by combining the UAV, the visual, and the IR detection instruments together. Figure 3 is a schematic diagram of the proposed system for monitoring PV devices using UAV (Table 1) technology. To carry out the inspection program, the UAV was employed to fly over the solar panels for aerial IR image photography by a thermo-camera (FLIR Duo R) onboard, contains visual images, thermal images, and temperature of the PV module, which is then instantly transmitted to the ground station via an integrated Radio Frequency (RF) channel for image analysis. However, the interpretation of the acquired IR image is difficult due to many reasons such as image quality, weather conditions, shadows during inspection or reflection of sunlight. Therefore, it should be beneficial to use software tools to facilitate the defect and fault detection process.

| Table 1. UAV specification and parameters. |
|-------------------------------------------|
| Parameter              | Value             |
| Type                   | S380              |
| Propeller              | 8 inch x 4        |
| Weight                 | 1.5 kg            |
| Load                   | 250 g             |
| Mission Altitude       | 5-10 m            |
| Cruise Speed           | 5-10 m/s          |
| Sensor Resolution      | 160 x 120         |
3.2. Innovative methods

In this study, an algorithm is proposed to process the infrared images of PV modules in the Matlab® environment. Image processing technology was developed to analyse the health condition of PV modules using filtering, binary images and 3 dimensions (3-D) images. Image processing is a useful technique to determine the degradation pattern of the PV module. It also helps to distinguish defective and healthy cell on PV modules. Furthermore, the technique can provide comprehensive information about the condition of the module in further detail. Usually, most infrared images are in RGB (Red, Green, Blue) scale, so the first step is to convert the image from RGB to grayscale. This is to enhance the resolution and color of the image to facilitate diagnostics. Afterwards, the image needs to be filtered to remove noise and to reduce sharpening on the image.

In fact, filtering techniques are performed as a pre-processing of image processing. Typically, Gaussian filters are used to reduce noise and other unnecessary details from the IR image. However, defects such as hot spots and cracks can also affect the temperature uniformity of the photovoltaic modules. Thus, binary transformation should be applied to the filtered image to distinguish between healthy components and defective components on the PV module. The pixels of the image are divided into black and white, which represent the cold and hot regions on the surface of the PV module, respectively. At the same time, binary images can provide wide information about the percentage of PV module degradation states [13,14]. Finally, we convert the filtered image from binary image to 3-D image to see more clearly whether the solar module is defective. The process of defect detection is shown in Figure 4.

Figure 4 is the flowchart of the image analysis procedure. This flowchart shows the process of detection on a PV module. In the proposed algorithm, the first step is to convert a color image into a grayscale image because the latter is sharper than the original image. This step is performed to determine the brightness on the surface of the PV module. In a digital color image, each pixel is characterized by 3 bytes, which is associated with the brightness of the primary basic colors (red, green, and blue). In contrast, the gray level is defined in the interval range \([0; 255]\), 0 means black, and 255 means white area. Therefore, the brightness of a pixel is usually described by 1 byte, which is equivalent to 256 levels [15].

Three filtering techniques are used in this paper for image analysis, the mean filtering, the median filtering, and the Gaussian filtering. Mean filtering is to use each of the pixels to do the averaging operation with the surrounding 8 pixels. Mean filtering is the local averaging of the signal, and the average value is used to represent the gray value of the pixel. The image can be smoothed but the noise cannot be removed. Median filtering is very effective in smoothing impulse noise, while it protects the sharp edges of the image. Weighted median filtering improves the edge signal retention of the median filter. The Gaussian function can form a low-pass filter with smooth performance in the frequency domain. Gaussian filtering can be achieved by making a product in the frequency domain.
Figure 4. Procedure for the image analysis carried out in this study.

4. Result and discussion

In this study, thermal imaging analysis of PV modules was performed by infrared cameras (FLIR Duo R) mounted on the UAV, and IR images were immediately transmitted back to the ground station for analysis. The results were divided into two cases to explain. After receiving the IR image, each case will perform grayscale processing and filtering (mean, median, Gaussian) and present in 3-D image to increase the discrimination of defects. Finally, the IR image were analysed by the image processing techniques presented in Section 3 to identify failures and defects on the PV module.

It is noted that this experiment was carried out at the condition of the standard inspection condition of moderate environment temperature and irradiation of at least 700 W/m² on the modules [7, 8]. The effect of environmental condition on the quality of IR image and the results of associated processing was not investigated in this paper.

4.1. Case 1

In this work, we only selected several samples to demonstrate the test system's ability and reliability. In order to get a good comparison, we select 3 sets of modules of the same model. The first case is that the
module has a significant fault (hot spot) in the IR image. The second case is that there is no obvious fault phenomenon in the IR image, but the output power is significantly reduced. The third case is a normal module under good condition (Figure 5a, b) as a reference for comparison. Case 1 (Figure 6a, b) shows the defects that can be easily identified using IR images. At the same time, grayscale processing (Figure 6b) and noise removal processing (Figure 6a) are performed in order to make the image look clearer.

Figure 5. Healthy PV module image:
(a) 2-D IR Origin Image, (b) 2-D Grayscale Image.

Figure 6. PV module image of defect (hot spot):
(a) 2-D IR Origin Image, (b) 2-D Grayscale Image.

In this study, three filtering methods, mean, median, and Gaussian filter, were used to eliminate noise. The results show that the hot spot can be easily identified in the IR image. The location of the defect can also be displayed in the mean, median, and Gaussian filtering, as shown in Figure 7a–c. At the same time, for further analysis, the 2 dimensions (2-D) image of Figure 7a–c is converted into a 3-D image (Figure 7d–f). It is noted that the 3-D image can more clearly identify the location of the hotspot, and can also examine the relative temperature of the hot spot in the image (as shown on the z-axis) and to
present a better visual effect. More information may be offered to the maintenance personnel to make appropriate judgments on the status of solar panel.

Figure 7. Comparison of different filters in 2-D and 3-D images for Case 1:
(a) 2-D Mean Filtered Image, (b) 2-D Median Filtered Image, (c) 2-D Gaussian Filtered Image,
(d) 3-D Mean Filtered Image, (e) 3-D Median Filtered Image, (f) 3-D Gaussian Filtered Image.

4.2. Case 2
Figure 8 shows the case that the defects cannot be easily identified in IR images, but the output power is significantly reduced. The same processing analysis was carried out in this case as that in Case 1. The results show that in the original 2-D IR image (Figure 8a), the defect location is difficult to be detected. The gray scale processing may enhance the colour difference so that defect location can be observed (Figure 8b). However, it is still not clear. In order to make the image clearer, the grey scale image was processed with three filters, the Mean filter, the Median filter, and the Gaussian filter, as shown in Figure 9 a–c. The purpose of filtering is to improve image quality and to smooth the image. We can see that the contrast between the white area (hot spot) and the rest of the image has been enhanced, and the quality of the image is improved, making the reconnaissance operation of the defect easier.

The white areas in Figure 9a–c look pretty similar. It is difficult to tell which filter may do the best job. In order to differentiate the effect of different filters, the filtered images were presented in 3-D, as shown in Figure 9d–f. The results show that the Gaussian filtered 3-D image can clearly show the location of the defect, while the mean and median filtered 3-D image are less obvious, but the defect location can also be defined. On the other hand, from the temperature axis (z-axis), the high temperature area (marked with red circle in the figure 9) of the three filtered images reaches a relatively high value. Therefore, it is clear that the 3-D image can effectively find the part of defect with abnormally high temperature that cannot be easily recognized by the IR image. Furthermore, it should be considered that
the original image of the Case 2 module is brighter than the module of Case 1, due to the high illumination of the sunlight during the inspection and the position of the sensor towards the module.

Figure 8. Unable to use IR images to identify defects in PV modules:
(a) 2-D IR Origin Image, (b) 2-D Grayscale Image.

Figure 9. Comparison of different filters in 2-D and 3-D images for Case 2:
(a) 2-D Mean Filtered Image, (b) 2-D Median Filtered Image, (c) 2-D Gaussian Filtered Image,
(d) 3-D Mean Filtered Image, (e) 3-D Median Filtered Image, (f) 3-D Gaussian Filtered Image.
5. Conclusion
This paper proposes to use the UAV integrated infrared camera with real-time image transmission function, and use MATLAB image analysis software to analyze the IR image. The results show that in addition to the instant IR image, the cell health condition can be clearly determined. According to the procedure proposed in this study, not only the detection time can be greatly shortened, but also the defect position of the IR image can be analyzed in real time. In particular, the relative temperature of the detected PV module can be seen in the 3-D image portion. It is concluded that the defects and faults that the IR image cannot be identified are solved, and the best results are obtained.

In the future work, measurements and comparisons will be made under different weather conditions. And explore the differences between the methods of this study under different weather conditions. We would like to try to find the best weather measurement conditions and increase the rigor of this detection method. Besides, in the next phase of the study, more solar panel image information of different defects will be collected to provide a database for future AI identification of solar panel defects. Combining AI technology and the UAV instant transmission technology of this study may achieve the ability of automatic identification. It is expected to effectively reduce manpower and improve maintenance efficiency.

6. References
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