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Detecção de poeira em painel solar usando técnicas de processamento de imagem: Uma revisão

Dust detection in solar panel using image processing techniques: A review

Detección de polvo en el panel solar utilizando técnicas de procesamiento por imágenes: Una revisión

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Resumo

O desempenho de um painel fotovoltaico é afetado por sua orientação e inclinação angular com o plano horizontal. Isso ocorre porque esses dois parâmetros alteram a quantidade de energia solar recebida pela superfície do painel fotovoltaico. Existem também fatores ambientais que afetam a produção de energia, um exemplo é a poeira. Partículas de poeira acumuladas na superfície do painel reduzem a chegada de luz aos módulos solares, reduzindo a quantidade de energia gerada. A limpeza ou mitigação dos módulos é importante e, para otimizar esses processos, monitoramento e avaliação constantes devem ser realizados. Com o intuito de aumentar a eficiência de painéis fotovoltaicos, pode-se considerar a utilização de métodos de processamento de imagem para a detecção de poeira. Sendo assim, a criação de um documento que reúne e analisa os resultados de diferentes trabalhos desenvolvidos para solucionar esse problema facilita o acesso a informação, permitindo um melhor entendimento do que já foi feito e como pode ser melhorado. O objetivo desse artigo é fazer uma revisão sobre pesquisas que utilizam técnicas de processamento de imagens para detecção de poeira em painéis solares, a fim de compilar informações para auxiliar a pesquisa na área e proporcionar inspiração para futuros estudos.

Palavras-chave: Processamento de imagem; Detecção de poeira; Painel Fotovoltaico.

Abstract

The performance of a photovoltaic panel is affected by its orientation and angular inclination with the horizontal plane. This occurs because these two parameters alter the amount of solar energy received by the surface of the photovoltaic panel. There are also environmental factors that affect energy production, one example is the dust. Dust particles accumulated on the surface of the panel reduce the arrival of light to the solar modules, reducing the amount of generated energy. The cleaning or mitigation of the modules is important and, to optimize these processes, constant monitoring and evaluation must be carried out. In order to increase the efficiency of photovoltaic panels, the use of image processing methods can be considered for the detection of dust. Therefore, the creation of a document that gathers and analyzes the results of different works developed to solve this problem facilitates access to information, allowing a better understanding of what has already been done and how it can be improved. The objective of this article is to review researches that uses image processing techniques to detect dust on solar panels, in order to compile information to assist research in the area and provide inspiration for future studies.

Keywords: Image processing; Dust detection; Photovoltaic panel.

Resumen

El rendimiento de un panel fotovoltaico se ve afectado por su orientación y inclinación angular con el plano horizontal. Esto ocurre porque estos dos parámetros alteran la cantidad de energía solar recibida por la superficie del panel fotovoltaico. También hay factores ambientales que afectan la producción de energía, un ejemplo es el polvo. Las partículas de polvo acumuladas en la superficie del panel reducen la llegada de luz a los módulos solares, reduciendo la cantidad de energía generada. La limpieza o mitigación de los módulos es importante y, para optimizar estos procesos, se debe llevar a cabo un monitoreo y evaluación

constantes. Para aumentar la eficiencia de los paneles fotovoltaicos, se puede considerar el uso de métodos de procesamiento de imágenes para la detección de polvo. Por lo tanto, la creación de un documento que reúna y analice los resultados de diferentes trabajos desarrollados para resolver este problema facilita el acceso a la información, permitiendo una mejor comprensión de lo que ya se ha hecho y cómo se puede mejorar. El objetivo de este artículo es revisar las investigaciones que utilizan técnicas de procesamiento de imágenes para detectar el polvo en los paneles solares, con el fin de recopilar información para ayudar a la investigación en el área y proporcionar inspiración para futuros estudios.
Palabras clave: Procesamiento de imágenes; Detección de polvo; Panel fotovoltaico.

1. Introduction

Currently, there is a variety of solar panels on the market for energy production. Depending on the manufacturer and the architecture to which they are installed, their dimensions and their potential for energy production may vary. Some geographical factors influence a panel's energy production: time, seasonal cycle and weather conditions at a certain time of day (Yfantis & Fayed, 2014). Physical characteristics of the system, such as tilt angle, arrangement and organization of the panels, and the amount of sunlight incidence in each cell, also affect energy production (Pawluk, Chen & She, 2019).

The dust accumulated on the photovoltaic panel comes mainly from compounds of sand, soil and rocks; construction debris; particles from car traffic; bird droppings; and also pollens produced by flowers. Dust tends to accumulate on the surface of the photovoltaic panel (Cai *et al*., 2019). As dust accumulates on the glass in the panels, energy production decreases, as there is an impediment that part of the light incident on the glass enters and reaches the energy generating cells. The energy loss depends on the amount of dust, the size of the particles, and the chemical composition of the powder (Jiang *et al*., 2018).

Cleaning and reducing the accumulation of dust in the solar modules are important procedures. In the case of large-scale photovoltaic plants, cleaning is a high-cost process and can be carried out sporadically. To improve efficiency in energy production, cleaning and monitoring of the module must be carried out on a regular way. In general, the inspection of photovoltaic modules is typically carried out by visual verification, standard electrical tests or the use of infrared or thermal cameras (Alnaser *et al*., 2018).

To improve the performance of solar panels, researchers seek to develop methods for detecting surface dust. This can make maintenance work cheaper and simpler, reducing the use of resources and personnel, allowing energy generation with the minimum possible loss.

Therefore, this article aims to evaluate research related to image processing applied to the detection of dust in solar panels. This work evaluates, in a condensed form, the literature already produced, reinforcing that these techniques help to improve the performance and useful life of solar panels. Despite the existence of existing research indicating the negative impacts caused by dust in the production of solar energy, with presentation of techniques to mitigate this problem, there is no research presenting the results of image processing techniques in the detection of dust.

The work is organized as follows: section 2 is the theoretical background of the solar energy generation, the effects of dust and a brief introduction on image processing. Section 3 presents the research methodology in this review. Section 4 analyzes the results and techniques used by the selected works. In section 5, discusses the advantages and disadvantages of these image processing applications. In addition, the authors presents some possible improvement solutions for future works. Section 6 is the conclusion, pointing out the knowledge that can be obtained through this review.

2. Theoretical Background

2.1 Solar panel

Photovoltaic technology uses solar cells built with semiconductors to absorb sun's radiation, converting it into energy. Currently, solar energy plays a prominent role in the production of clean and sustainable energy. However, research focused on the use of semiconductors showed limitations in the efficiency of photovoltaic systems of 15 to 20%. Thus, research was conducted to improve the efficiency of photovoltaic systems, which resulted in improvements with the application of solar trackers and algorithms for both tracking (Maximum Power Point Tracker - MPPT) and estimation (Maximum Power Point Estimation - MPPE) of the maximum power point in the installation of the photovoltaic system, evidently reducing forecasting errors and improving efficiency (Ma *et al.*, 2019; Maghami *et al.*, 2016).

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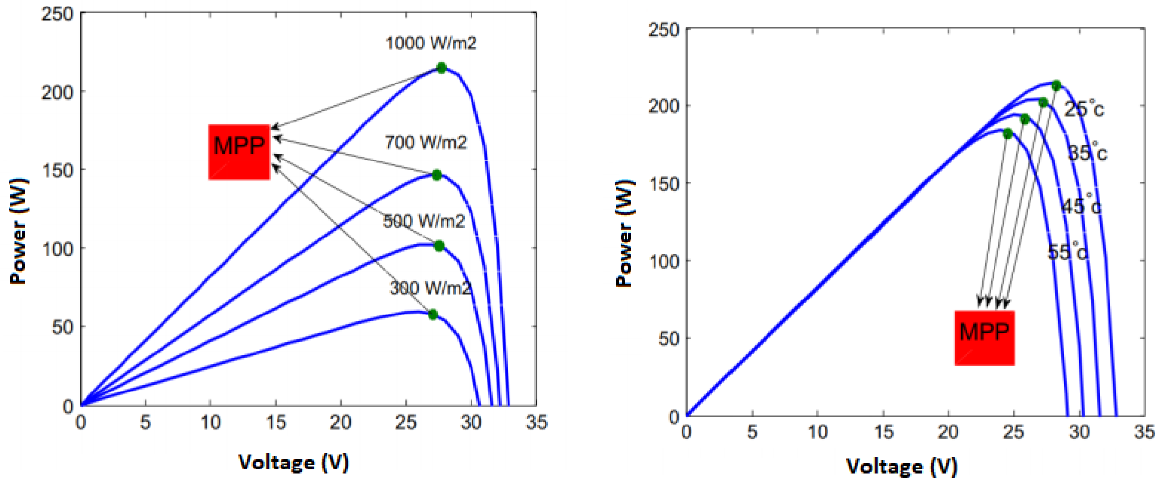
The characteristics of a photovoltaic module can be demonstrated by power-voltage curves. Figure 1 shows the power-voltage curve of a photovoltaic module for different conditions of irradiance and cell temperature.

Figure 1: Power-Voltage curve characteristics of a photovoltaic panel and location of the MPP for (a) different irradiations at 77 °F, and (b) different temperatures at an irradiation of 1000 W/m².



(a) (b)

Source: Adapted from Maghami *et al*. (2016).

The effect of increasing temperature results in a decreasing output voltage with a subsequent decreasing output power. The effect of increasing the level of irradiation results in an increasing output current which consequently increases the output power (Amr *et al*., 2019). In addition, for each curve of the photovoltaic module, there is a point on the curve where the module offers maximum power for the load. This point is known as the maximum power point (MPP) (Salas *et al*., 2006; Hemza *et al*., 2019).

Solar irradiance and cell temperature are two factors that affect the performance of a photovoltaic module, in addition to the shading caused by buildings, clouds, trees and the alignment of the solar panels. Gosumbonggot & Fujita (2019) reported a case study of photovoltaic systems installed on roofs in Germany, where 41% of the installed panels are affected by shading, resulting in energy losses of up to 10%. Another study of them showed that in a configuration of 13 solar panels that operated under shading conditions, about 70% of the energy was lost due to the failure of the panel system to identify the actual maximum power. In addition to these, the amount of energy supplied by a photovoltaic module depends on other factors, such as the reliability of other system components and other environmental conditions (Mehmood, Al-Sulaiman & Yilbas, 2017).

Solar panels are designed to produce energy with the best possible yield. There are factors that influence performance, and some of them cannot be controlled, such as weather, movement of clouds and air pollution. These factors affect the amount of solar radiation that hits the panel. For this reason, the design, installation and operation configurations of a solar panel vary in order to adapt to the conditions of the site, ensuring a greater capacity for generating solar energy from the panels. However, as more photovoltaic power plants are developed at high powers (MW and GW), it is necessary to mitigate effects that hinder energy generation, because higher are the losses (Maghami *et al.*, 2016; Amir *et al.*, 2019).

There are factors that can be mitigated, such as dust, for example. However, climatic factors preclude any intervention in a completely satisfactory manner. The technology advances to mitigate problems related to dust, with automatic supervision of solar panels through computer vision and cleaning them if necessary using robots. In addition, for climate problems, only partial solutions exist. An example is an automated system that track solar movement, but it can do nothing about a totally cloudy day.

2.2 Dust effect

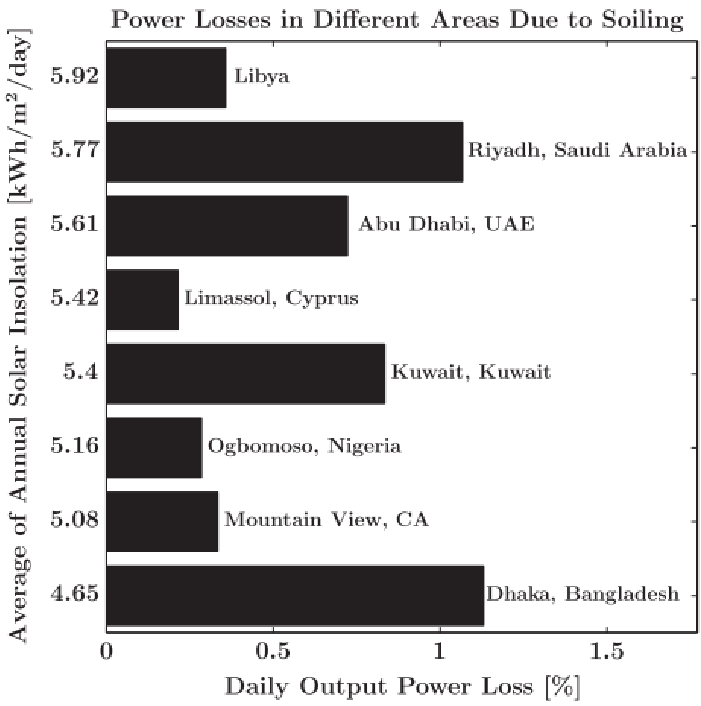
A variable that can negatively affect the production of energy in a solar panel is the accumulation of dust on it. Dust alters the energy production of photovoltaic modules in two ways. First, the dust particles suspended in the atmosphere, which are longer than the wavelength of the beam of sunlight, scatter the light, reducing the amount of radiation reaching the surface of the module, even more if combined with the effect of pollutants atmospheric. The second effect is the formation of a thick layer of dust on the photovoltaic module. This layer can change the optical properties of the panel to promote reflection and absorption of light, decreasing the energy production. This relationship is not exactly linear due to the nature of the distribution of dust particles in the photovoltaic cell (Said *et al.*, 2018).

The nature of the dirt varies from place to place. Urban areas in a more northerly climate usually have dirt dominated by pollutants found in these environments. For example, airborne coal particles, construction debris and particles from car traffic. Likewise, agrarian sites have fertilizer particles, soil lifted by the wind and vegetation residues. Organic material found in these regions increases the adhesion of dust on the surface of the modules. Desert regions of the world have significantly different dust particles, dominated by quartz, feldspar and other sand components (Guan *et al*., 2017).

Dust particles are characterized to better understand the effect of dust on the performance of the photovoltaic module and to facilitate the creation of effective mitigation techniques. Methods for characterizing dust particles include particle sizing, analysis of morphology and chemical composition (Sayyah, Horenstein & Mazumder, 2014; Styszko *et al*., 2019; Jaszczur, 2019).

The negative effect on energy production due to the accumulation of dust on the surface of solar panels in some parts of the world is shown in Figure 2. Removing the accumulation of dust on solar modules is, therefore, an important procedure. Visual inspection can be applied on photovoltaic plants to identify degradation or any other problem related to performance. However, these tests are time-consuming and are not feasible for inspection on a daily analysis especially in the case of large plants. Image processing techniques can be used, making comparisons between images of clean and dusty panels to indicate when to clean them (Qasem, Mnatsakanyan & Banda, 2016; Lee *et al*., 2018).

Figure 2: Daily loss of energy from solar plants in different parts of the world.



Source: Adapted from Sayyah *et al*. (2014).

2.3 Image processing

An algorithm interprets image through attempts to find relationships between the input image and the model initially generated from the observed world. In order to understand the input image, sometimes it is needed processing techniques to enhance its quality and extract attributes. This process is generally divided into some stages, where the lowest levels contain raw image data and the highest levels interpret this data. Computer Vision (CV) is used to process the necessary task in images in order to acquire the results for a particular approach (Sonka, Hlavac & Boyle, 2014; Yao & Hu, 2017).

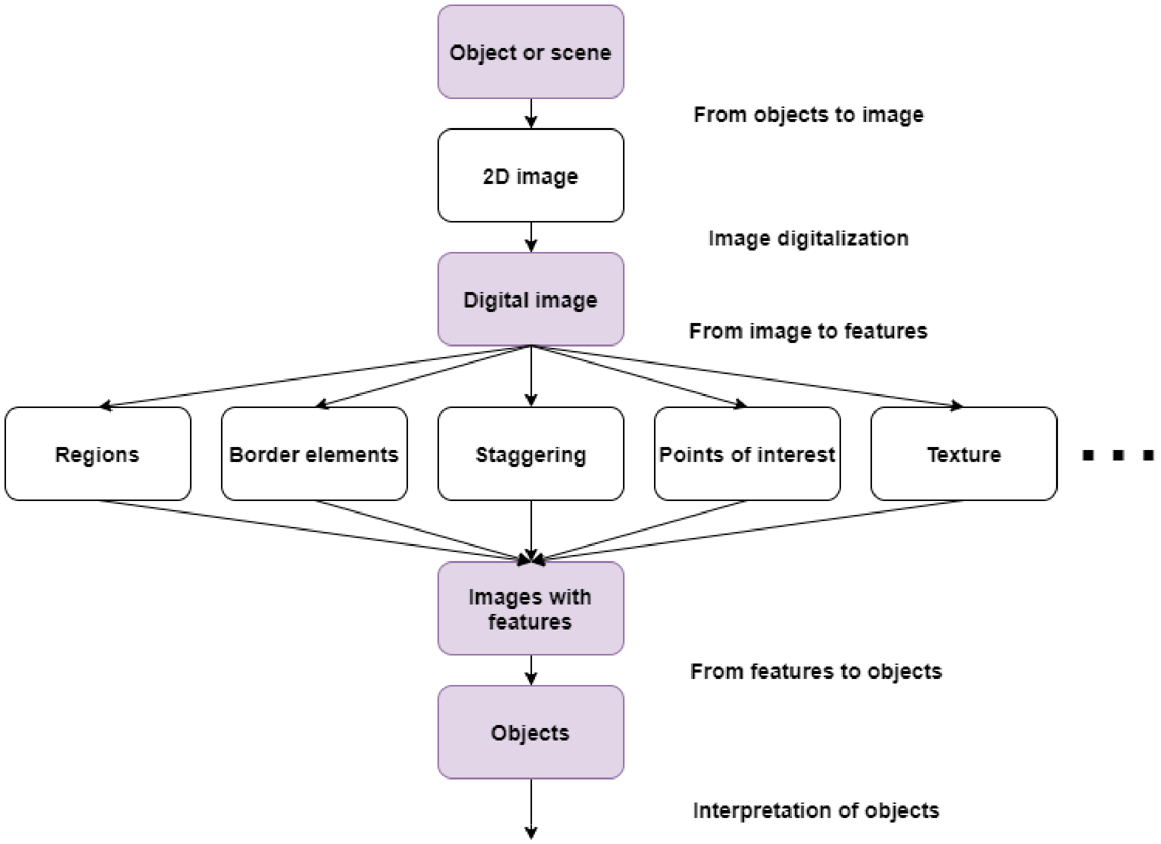
Low-level processing techniques generally use just a few knowledge about the content of the images. These methods can include image compression, pre-processing techniques for noise filtering, edge extraction and image sharpness. High-level processing is defined using objective-oriented knowledge and artificial intelligence is widely applicable. The high-level computer vision tries to imitate human cognition and the ability to make decisions according to the information contained in the image (Gonzales & Woods, 2007).

Image processing techniques allow to obtain the necessary information from the image and to generate a response. First, the image is captured. Depending on the process, image compression techniques may be used to make the process faster. Then, the captured image pass along preprocessing techniques in order to remove noise and enhance quality. A segmentation process is then defined. Its objective is to separate the desired object from the rest of the image, which is called background. The next step is the acquisition of characteristics of the object to be observed. These characteristics can be perimeter, distance, temperature etc. After recognizing the object and its attributes, it is possible to use artificial intelligence to obtain the results of the desired approach (Albuquerque & Albuquerque, 2000; Chen, Lin & Liu, 2018). The image representation can be divided into four levels indicated by Figure 3. The limits between these levels are not well defined.

Figure 3 suggests an approach with almost no abstraction to the highly abstract description needed to understand the image. The hierarchy of image representation is often processed in a simpler way, low-level, and high-level processing image.

There are some advantages of using digital image processing techniques over other techniques to monitor the accumulation of dust on a solar panel. As there is no contact with the panel, the monitoring system is more flexible and cheaper than other systems. Besides that, it can be operated remotely, being useful for the unmanned monitoring system (Dutta *et al.*, 2013).

Figure 3: Four levels of image representation suitable for image analysis problems in which objects must be detected and classified.



Source: Adapted from Sonka *et al*. (2014).

Computer vision is fundamental for dust detection systems in solar panels. It allows an effective and constant inspection without the need for people performing the task. However, the approach must be robust and know how to differentiate dust from other sources of inhibition of solar radiation, such as cloud shadows. For this, research on computer vision and its applications that adapt to this type of approach is necessary.

3. Methodology

The methodology of this work is a literary review on the use of image processing techniques for the detection of dust in solar panels. The research took into account works carried out in this field of study between the years 2012 to 2020. The bases used were IEEE, Web of Science, Science Direct, Research Gate, Society for Science and Education (SSE) and Charles Darwin University (CDU). The technologies used were analyzed, such as: the type of camera, if it contains infrared, the method of assembling the equipment for capturing images from the panel, the software used for image processing and, finally, the accuracy in the detection of dust. The review is of a qualitative nature according to the guidelines of Pereira *et al*. (2018), as it analyzes the methodology used by each researcher and the information attributed tends to follow an inductive process. The methodology used to carry out this systematic analysis is based on the following steps:

1. Selection of keywords to search. For example: solar panel, dirt problems, dirt detection.

2. Execution of research in databases of renowned conferences and journals: IEEE, Web of Science, Science Direct, Research Gate, Society for Science and Education (SSE) and Charles Darwin University (CDU).

4. Removal of repetitions and ambiguities from the articles found.

5. Evaluate the articles obtained, according to selected comparison parameters.

To perform this research, it was used the following search algorithm: (“dust” OR “soil”) AND (“deposition” OR “accumulation”) AND (“detection” OR “inspection”) AND (“solar” OR “photovoltaic” OR “pv”) AND (“panel*” OR “farm*” OR “plant*”) AND (“image processing”). The logical expression was adapted for each database searched. The research was made on multiple bases due to the scarcity of literature focused on the subject of this review. The bases are: IEEE, Web of Science, Science Direct, Research Gate, SSE and CDU. The search resulted in 14 papers found, Research Gate (4), SSE (3), IEEE (6) and CDU (1). After removing the duplicates, the final amount was reduced to 12 papers that were explored for the production of this review.

4. Literature Review

In this section, the methods and image processing used in each researched work will be discussed. Two different forms of dust detection in solar panels are addressed: infrared cameras able to identify points of heat concentration in photovoltaic modules, and digital cameras that detect the state of the panel, if clean or dirty. Infrared images are able to identify hot spots on the surface of the panels.

Phoolwani *et al*. (2020) analyzed at normal and some faulty condition the solar power meter using thermal camera to compare performances. Results were obtained at normal, partial shading and dust accumulated conditions using PV analyzer. Comparisons were made under no-load, on load, partial shading and dust accumulation conditions. The obtained data can be periodically uploaded to the cloud using NodeMcu.

Abuqaaud & Ferrah (2020) developed a computer vision based approach to detect soil and dust on PV surface. The method is based on features extraction using Gray Level Co-occurrence Matrix. Classification was achieved using a linear classifier.

Tribak & Zaz (2019) proposed a system that allows the measure of dust soiling particles concentration deposited on the outer surface of solar panels. This estimation is achieved through the use of a well-distinguished telltalle, a small plasticized paper, characterized with a distinctive texture. Calculating the image Entropy of the evoked telltale, the concentration of dust particles deposited was precisely calculated.

Unluturk, Kulaksiz & Unluturk (2019) used artificial light source in laboratory environment to compare power outputs for three different densities of dust accumulation on the module surface. From the PV module images obtained by a camera for different levels of dust accumulation, new features were obtained based on Gray Level Co-occurrence Matrix. The obtained data with new features are classified on the basis of Artificial Neural Networks to determine dust level and its effect on PV module performance.

Tsanakas & Botsaris (2012) experimentally investigated the potential and applicability of a non-destructive thermographic approach for the detection of hot spots and performance evaluation of photovoltaic modules. The data processing of the acquired thermal images was made through Regions of Interest (ROI), image histogram and line profile analysis. This system detected hot spots between 5 to 10% in the cells of the panels studied. It was concluded that infrared imaging capture thermography is proven as a reliable method for monitoring conditions and evaluating the performance of photovoltaic systems.

Yfantis et al. (2014) developed a classifier based on the multivariate probability distribution function of the image color channel modes, that are: red, green and blue. It is also included their marginal distribution function. In clean panels, the three-dimensional vector of the mean vector of modes has relatively low values, while in dirty panels, with dust particles and bird droppings, the mean of the mode vectors of the color channels increases. In this work, the Mahalanobis distance (relative statistical measure of the distance from the data point of a common point) was used for panels in the “clean” and “dirty” categories. The probability of generating correct results is quite high.

In the work of Aghaei *et al*. (2015), infrared images were captured from panels for image processing. First, some preprocessing steps were performed: gray scale mode application, noise remotion, binarization and Laplace model approach. The next step was the identification of heat concentrations in the panel, represented by a degree of "board degradation". The algorithm is accurate and demonstrates robustness for performing image processing. Even so, future improvements can help to specify different types of defects that may occur, providing better maintenance of the panels.

Yap, Galet & Yeo (2015) presented a non-invasive methodology for the quantification of dust and the level of dirt in solar panels, using five different image processing techniques. This study analyzes color histograms and statistical properties of images captured from photovoltaic panels. An image processing toolbox for Matlab was developed in this study, adopting the following techniques: binarization, histogram model, statistical model, image matching and texture matching. The tests revealed the need for some adjustments and the best method for quantifying dust was image matching.

Gao *et al*. (2015) inspected panels by maintenance groups, transporting infrared cameras, from one site to another on a solar farm. The image processing algorithm segments the solar panels in real time. To count the number of panels within a matrix, the association of each frame is established using the optical flow. Local anomalies on a single panel, such as hot spots and cracks, are immediately detected and labeled as soon as the panel is recognized in the camera's field of view. The system demonstrated good performance, including high defect detection rates, near zero false alarm rates and robustness against motion blur.

Qasem *et al*. (2016) suggested an indicator of the thickness of the dust layer deposited on the solar panel. A camera system feeds a computer with real time image. The comparison between the acquired image and the indicator allows monitoring the dust level in the panel. In dust detection, two image processing methods were used: the first was based on the average relationship between the gray scale level pixels of the calibrated sample, while the other method was based on the calibration factor regression analysis. The first method is more effective for identifying non-uniform distribution of groups of pixels compared to uniform. The second method, based on regression, tends to identify the losses caused by dirt better in uniform distribution.

Ramos, Ho & Yfantis (2016) proposed an algorithm to detect dirty solar panels. It is based on the spectral decomposition of the scattered light reflected on the surface of the panels, analyzing color images of the surface. Statistical classification methods were applied. The results of experiments indicate that the algorithm can efficiently classify dirty solar panels with an accuracy above 90%.

Ramos *et al*. (2016a) developed a terrestrial robot capable of approaching and, if necessary, cleaning the panels. This robot is equipped with 4 cameras mounted in a cross shape and it has software capable of detecting the state of the panel as clean or dirty, using the algorithm based on spectral decomposition developed in the previous article (Ramos *et al*., 2016), registering that panel.

The literature review allows to make comparisons about the methodologies. These comparisons are organized in Table 1. Some works do not specify certain details of the development, which may make it more difficult to reproduce. However, they explain parts of development of the method that can help and give inspiration for future research.

Table 1: Comparison of tools used in each paper.

Authors	Camera	Infrared	Capture	Software	Accuracy
Phoolwani *et al*. (2020)	FLIR C2	Yes	Parallel the panel	Matlab	-
Abuqaaud & Ferrah (2020)	Comercial	No	Parallel the panel	-	82%
Tribak & Zaz (2019)	HD camera	No	Above the panel	Rasp Pi3	-
Unluturk *et al*. (2019)	-	No	Current sensor	-	96.86%
Tsanakas & Botsaris (2012)	IVN 780-P	Yes	2 m from panel	Matlab	-
Yfantis & Fayed (2014)	Comercial	Not	-	-	-
Aghaei *et al*. (2015)	FLIR A35	Yes	Drone PLP-610	Matlab	-
Yap *et al*. (2015)	-	Not	-	Matlab	-
Gao *et al*. (2015)	FLIR A325sc	Yes	Motorized car	Python	97.9%
Qasem *et al*. (2016)	Sony 8 MP	Not	Above the panel	Matlab	-
Ramos *et al*. (2016)	-	Not	Above the panel	-	90%
Ramos *et al*. (2016)	-	Not	Terrain robot	-	90%

Source: Authors.

The Table 1 is important, as it shows parameters to be considered when is required to start a work in this field of study. First, it is observed that new techniques continue to be performed every year. The cameras used can be either commercial or more specialized cameras, such as HD and those that capture infrared images. There are some ways to capture images of solar panels, ranging from capture above or parallel to the panel to the use of robots, drones and current sensors. The software varies, but the trend is to use Matlab. Not all studies assess the accuracy of detection, but this is an important metric for knowing whether the result of the work is satisfactory.

5. Discussions

These works reveal results that favor the maintenance of equipment for the production of solar energy as well as the energy efficiency of the equipment. The use of image processing guarantees advantages in monitoring the modules, automating the inspection, revealing the state of the surfaces of the panels and facilitating the cleaning schedule.

However, the use of these systems does not bring perfect results. The algorithms in each specific case generate results with a fraction of errors, such as false positives, the system indicates the need for cleaning when there is not need, and false negative, when there is the need for cleaning and the algorithm did not indicated. Important mention that a poorly scheduled cleaning can generate unnecessary costs. Another disadvantage of some image processing techniques is the inability to specify the cause of a failure. The points of heat concentration can occur due to the accumulation of dust, as well as internal defects in the module or even cracks.

These systems can be improved, either by creating more robust algorithms capable of generating more accurate results (infrared capture systems capable of identifying the cause of the heat concentration points), as well as allowing to calculate the reduction in the efficiency of the modules together with the amount of dust on its surface. These improvements can enable schedule cleaning more consciously while aiming for the greatest possible energy production.

6. Conclusions

This article presents a review of image processing techniques for detecting solar panel dust. This research includes articles published in IEEE, Web of Science, Science Direct, Research Gate, Society for Science and Education (SSE) and Charles Darwin University (CDU). The high efficiency and low cost of implementing these techniques guarantee a better performance in the generation of energy in solar panels. However, this area of research has just a few studies.

The review shows that the automatic detection of dust on solar panels helps in managing the maintenance of the equipment. Computer vision benefits the energy production and reduces the costs with products and personnel for maintenance. Despite the low cost of implementation, there is still few dissemination of these techniques among farms of photovoltaic panels. It is practically absent in systems with low energy production. For this reason, the differential of this article is to reveal the advantages of detection and monitoring systems using image processing to encourage its use and inspire more research in the area.

The study of the keywords allowed obtain effective results and evidence improvements in energy production and maintenance of photovoltaic equipment. This review is useful for researchers working with photovoltaic panels and for the own solar energy industry.

Further researches are necessary to find out new approaches or improve the existing ones. A closer relationship between the photovoltaic plants community and the researchers strengthens the subject. Future prospects can allow the total use of image processing to detect dust in solar panel in daily photovoltaic plants practices, they are: computer vision systems with a better accuracy and robustness to noises; development of techniques that can automatically measure dust and classify it according with their level; creation of a publicly database of solar panel dust images containing feature information to help researchers on their works.

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