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Application of Optical Remote Sensing in Photovoltaic Inspection

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Abstract. As the installed capacity of photovoltaic (PV) power plants is increasing year by year, an efficient PV inspection system is needed to gain the benefits of PV power generation. Conventional PV inspection is expensive and does not meet the demand for large-scale PV plants. Remote sensing offers wide coverage and high efficiency, meeting various PV fault-detection needs. And it has been primarily applied to PV inspection and has achieved a series of successes. This paper presents optical remote sensing technologies applied to PV power plant inspection, including visible-light cameras, infrared cameras, and light detection and ranging (LiDAR). The conclusions are as follows: visible-light and infrared remote sensing can monitor the surface condition and internal faults of PV modules, and light detection and ranging can detect terrain changes in PV plants. Secondly, novel high-performance sensors ought to be developed to identify a wider range of PV fault categories. Thirdly, multi-sensor fusion is necessary, as a single remote sensor can detect only one fault type and cannot capture all fault types, further reducing the overall efficiency of PV inspection. Finally, the existing optical remote sensing technologies need to be lighter, and the adverse effects of natural illumination need to be mitigated to improve image quality. The paper aims to summarise the applications of each optical remote sensing technology in PV inspection. It also describes the drawbacks of each remote sensing sensor, offering some insights for future work.

Keywords: optical remote sensing, PV inspection, optical sensors

1. Introduction

Recently, solar energy has become the primary component of clean energy, and PV power production leads global solar power production. As for PV plants, they have a specified operating lifetime. If faults arise during operation without timely maintenance, the power output lifetime will be shortened, and the corresponding economic benefits will be reduced. More seriously, PV module faults may lead to fires and other accident risks. In addition, the installed capacity of PV modules is nearly doubled by 2030 according to International Energy Agency (IEA) forecasts, amounting to almost 80% of all renewable energy power generation capacity worldwide [1]. To sustain the rapid growth of the PV industry, efficient fault inspection of PV power plants is essential to improve the performance of PV power stations.

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Traditional PV inspection methods, such as manual visual inspection and detecting PV inverter electrical characteristics, are no longer used. Manual inspection is generally expensive, and the missed detection rate is always above 15% [2]. PV plants in mountainous areas and on water surfaces pose a risk to manual inspection. Meanwhile, electrical characteristic detection can only detect faults in PV strings, rather than in PV modules [3]. Airborne optical remote sensing allows large-scale inspection of PV. Airborne optical remote sensing can collect high-resolution visible images, thermal infrared images with temperature information, and point cloud data of PV plants, which support accurate fault detection, fault classification, and fault cause analysis, and thus optimise the operation and maintenance of PV stations. For example, researchers used visible-light images to replace visual inspection and airborne infrared cameras to replace handheld detectors. A comparison between UAV-based remote sensing technology and traditional manual inspection shows that airborne sensors require only 4 hours. In contrast, manual inspection requires 220 hours for a 20 MW PV plant [4]. Therefore, UAV-based remote sensing offers a faster, more flexible and efficient solution.

This paper describes the applications of remote sensing in PV inspection, introduces commonly used sensors, and summarises their operating principles and related workflows for hotspot detection, surface defect inspection, and terrain deformation monitoring. The paper also discusses existing limitations in optical remote sensing technology and analyses the future development trends of optical sensors.

2. Overview of optical remote sensing technologies for PV inspection

Common optical remote sensing technologies used for PV inspection include LiDAR, visible-light cameras, infrared cameras, and dual-light cameras. Visible-light cameras can capture images of PV strings in the visible band, and surface defects can be recognised visually from these images. Infrared cameras record the thermal radiation of PV modules and capture images of PV strings in the infrared band, helping identify temperature abnormalities and invisible internal faults. Airborne LiDAR can penetrate vegetation to obtain surface information and construct 2D or 3D digital models of PV plants using point cloud data. Visible-light and infrared cameras focus on capturing surface conditions and temperature data on PV modules, whereas LiDAR is used for field deformation detection in PV plants.

2.1. Visible-light camera

Visible-light cameras operate over the range of human vision. They collect visible light reflected by the object and focus it onto the photosensitive element. Then, the optical signals will be converted into electrical signals, and through data processing, the high-resolution images will be produced. Its primary function is to detect cracks, fractures, and foreign-object blockages, including fallen leaves, vegetation shadows, sand, and bird droppings on PV modules. But it is easily influenced by natural illumination, and the reflection from PV panels would limit image clarity and cause missed or false detections.

The paper gives the flow of the visible-light image collection and data analysis, and the flowchart of specific steps is shown in Figure 1. Step 1 is the analysis of ambient light conditions. Due to the high sensitivity of visible-light cameras, higher-quality images are usually captured around noon (10:00-14:00) on clear days, when illumination is sufficient, and glare from PV panels is minimal [5]. Step 2 is the data collection based on UAV platforms. UAVs are required to hover above the PV array to capture visible images of multiple PV strings. Nevertheless, the raw images contain large amounts of data and are not conducive to computer analysis, so they need preprocessing. Perspective correction is the first step in image preprocessing. The perspective correction corrects for lens distortion and regularises the PV string to a rectangle in each image. PV string segmentation aims to segment the entire string in the image and reduce the file size for program-based analysis. To achieve precise PV fault localisation, images of the PV string must be partitioned into individual modules, each representing a small square area on the PV string. Finally, the fault identification analysis uses deep learning to analyse remote sensing images and diagnose faults on the PV panel surface.

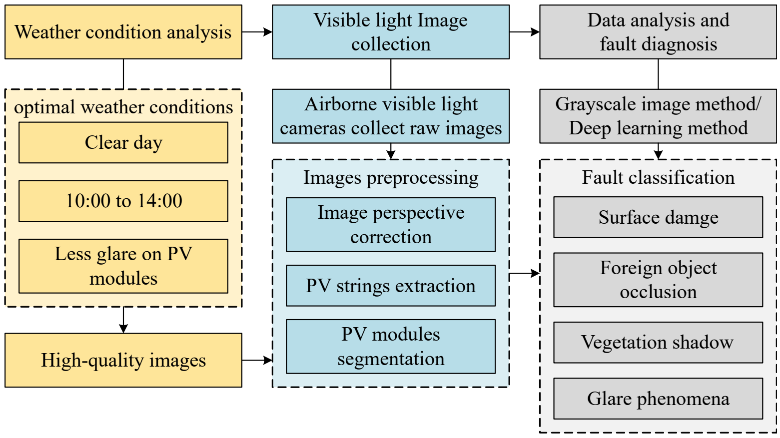

Figure 1. Workflow diagram of visible-Light camera

2.2. Infrared camera

Infrared cameras work in the near-infrared and mid-infrared regions and are less affected by weather. During the PV station inspection process, infrared cameras can capture surface temperature images by detecting infrared radiation emitted by PV panels, which helps identify internal PV faults. But infrared cameras have low resolution and cannot capture clear PV string and PV module edges, as well as the surface conditions of PV panels, so using visible-light cameras alongside infrared cameras to develop dual-light cameras has become a new trend. The dual-light camera integrates the infrared and visible-light modules; it can capture multi-wavelength images and integrate multiple information sources, including remote sensing data, by combining the advantages of the two camera types.

Acquiring infrared remote sensing data using infrared cameras and dual-light cameras involves the following steps: Firstly, the analysis of ambient conditions is still necessary. Although infrared cameras are less affected by natural light, they can still be disturbed by glare, which can be misinterpreted as high-temperature areas, leading to false detections, for example. The infrared data-acquisition process is the same as the visible-light image, and both use the UAV platform to acquire information about PV panels when the drone hovers over PV arrays. After capturing the raw images, perspective correction is required to regularise the shape of the PV string into rectangles in each frame, standardising the form of image display for a given frame and making further data processing easier. Preprocessing steps also include segmenting the string, which yields the entire image of a PV string. Since it is very hard to control the distance between drones and PV panels, there is always an unfinished part of the adjacent string that appears in the photo. To achieve higher-precision fault localisation, a computer program will detect and extract the PV modules that make up a PV string. For the dual-light camera, after separately preprocessing the visible and infrared images, pairwise

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matching should be conducted between the two bands. Owing to the different resolutions of the 2 cameras, the pairwise matching procedure is based on feature-point identification and corresponding matching. Additionally, feature-point matching methods can be used for PV module identification, since the edges of PV modules may be blurred in infrared images. The fault classification and diagnosis based on deep learning are the final steps in producing the results of PV inspection. The complete workflow of infrared band remote sensing is shown in Figure 2.

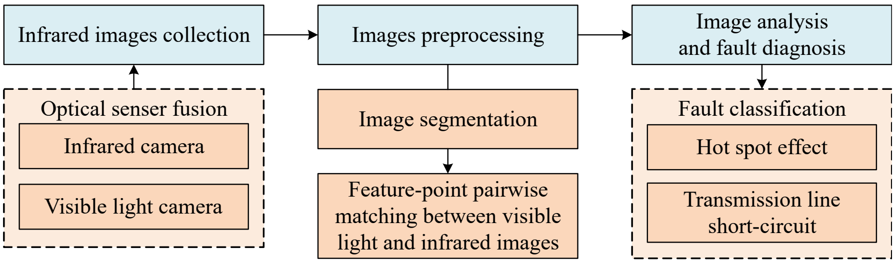

Figure 2. Workflow diagram of an infrared camera

2.3. LiDAR

LiDAR is an optical remote sensing method that can range, position, navigate, or produce point clouds. LiDAR shoots laser beams at the target and then receives the reflected beams from objects. LiDAR can calculate the distance to the target by measuring the travel time of the signal or the continuous-wave phase difference [6]. The strongest feature of LiDAR is that the laser can penetrate forests directly detecting ground-surface information, so LiDAR is suitable for searching PV stations in mountainous areas. Combined with UAV platforms and realising sensor fusion of LiDAR with GPS, RTK and IMU, which are collectively called a Position and Orientation System (POS), LiDAR can generate point clouds and form 3D models of a PV station under an absolute geographic coordinate for PV field deformation monitoring.

PV inspection using LiDAR technology includes several key steps, all of which together ensure the high accuracy of point cloud data acquisition and analysis. To begin with, open the ground GPS receiver and the UAV POS to define the UAV's position in the absolute coordinate system. Then, perform data acquisition by a UAV-borne LiDAR scanning system. To obtain higher-quality data, it is advisable to collect data on a clear day. Afterwards, clean the point cloud data to remove noise and outliers. The output scanning data are refined and can be used to generate data products. The most commonly used data products are digital elevation models (DEMs) and 3D digital models, both of which can help detect field deformation. The key nodes of the LiDAR-based PV inspection workflow are illustrated in Figure 3.

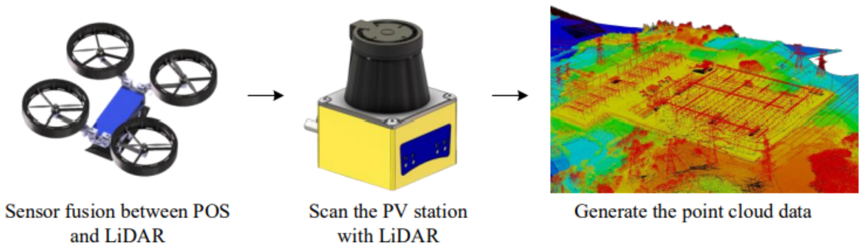

Figure 3. Workflow of LiDAR in point cloud data collection

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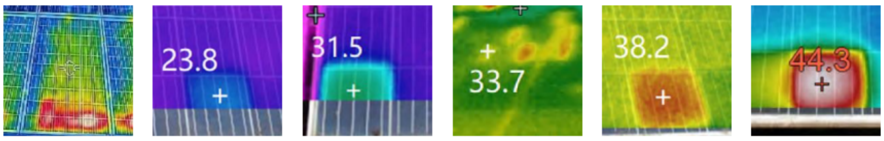
3.Applications of remote sensing technologies in PV inspection

3.1.Hot spot inspection of PV modules

The hot spot effect is defined as a localised area with high temperatures caused by interpenetration phenomena such as shading, foreign objects, and internal electrical faults. The hot spot effect causes a severe decrease in power generation from PV and fires. The hotspot effect is a fault that can be detected with temperature; infrared remote sensing is suitable for estimating severity. The onboard infrared camera of the UAV is better than that carried by the hand camera, with a lower failure rate of missing detection, and is most suitable.

Infrared cameras capture thermal images and establish a relationship among thermal radiation intensity, temperature, and defect level. The correlation between temperature and colour of the PV modules in local regions in infrared images is shown in Figure 4. Zhai built the MI-YOLO model based on YOLO v4 to analyse infrared remote sensing images of a PV plant in Jilin City, China [7]. Infrared remote sensing images of the PV plant were collected using UAV-based visible-light and infrared camera systems by Hong to obtain temperature information for 250,000 PV modules at a 65 MW PV station in Hainan. Pairwise matching between the images and modules was realised during the process of extracting images in visible-light and infrared bands. And YOLO v5 is used to detect abnormal temperature regions in a PV module [8]. Vergura also confirmed the convenience of infrared remote sensing for PV inspections and indicated the requirements for obtaining high-quality infrared images, the operating band ranges for infrared cameras, and the UAV's speed range [9], too. Infrared images can also be useful for analysing the cause of the hot spot effect. If high-temperature regions have a stripe-like distribution, there is usually a short circuit in the transmission line. If regions exhibit a spot-like distribution, it is usually due to shading, occlusion, and internal damage.



(a) panorama (b) normal (c) warning (d) light (e) moderate (f) severe

Figure 4. Hot spot effect inspection and severity level classification with infrared camera [7]

Even though the infrared camera can detect hot-spot effects and is not affected by ambient light, its deficiencies are obvious: poor resolution and a limited view of PV module edges. The solution to overcome these disadvantages is multi-sensor fusion. Using dual-light cameras or collecting visible-light and infrared images simultaneously can improve inspection efficiency and image processing.

3.2.Surface condition monitoring of PV modules

Surface condition monitoring can detect occlusion, shadow, surface damage and glare. Usually, long-time shading results in serious local heating, which reduces power generation efficiency [10]. Glare is not a fault but can be easily identified as other faults, so it needs classification. Surface faults can be detected using visible-light band remote sensing. The PV module faults detectable by visible-light cameras are shown in Figure 5.

Yang used a grayscale image and deep learning to preprocess visible-light images and classify them into three categories: surface damage, occlusion (foreign-object occlusion, shading), and glare [5]. Li used UAV-based visible-light digital single-lens reflex (DSLR) cameras to capture snail trails

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and dust occlusion on PV modules. Using the first-derivative of Gaussian (FDOG) and feature-point pairwise matching method, the results are consistent with actual practice [11]. Kabir used visible remote sensing to detect bird droppings, and by analysing the shading rate of foreign objects (such as dust and bird droppings), they further developed targeted PV cleaning plans for different seasons [12]. Visible remote sensing also detects ageing and damage to transmission lines by identifying bright spots in the grayscale image.

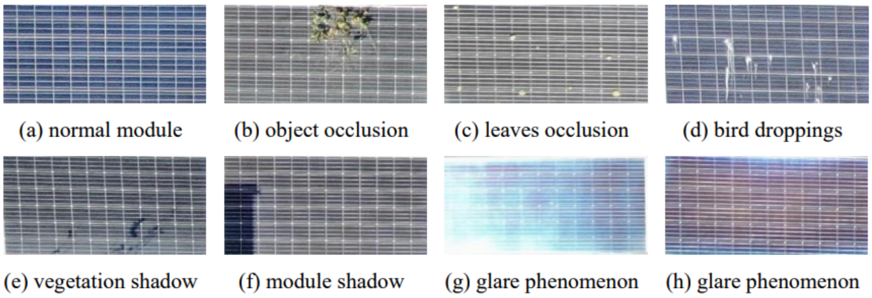

Figure 5. Surface faults classification in visible-light images [5]

Visible light remote sensing has the advantages of high resolution and easy identification. But visible-light remote sensing is affected by natural light and glare, limiting its use to surface inspection. To enhance the usability of visible-light cameras for PV inspection, visible-light remote sensing cameras are usually combined with infrared remote sensing to leverage complementary advantages.

3.3.PV station deformation monitoring

From a risk perspective, PV stations at a mountain are exposed to risks (such as landslides and damage to the PV support structures and steel frame from rain, snow, and other severe weather). Coupled with POS, LiDAR can obtain 3D digital models of PV plants in the absolute geographic coordinate system, achieving millimetre-level accuracy. By comparing models acquired at different periods, field deformation can be accurately assessed. Moreover, LiDAR point cloud data can be used to obtain a digital elevation model (DEM) to analyse the shadow regions of the PV panels, supporting potential power generation assessments and early fault warnings. Comparing the industrial camera inspection with the airborne LiDAR revealed that LiDAR achieves an accuracy of around 10mm. In comparison, the industrial camera achieves about 5mm accuracy, and airborne LiDAR is effective for PV inspection [13]. LiDAR can be used not only on centralised PV power plants but also on distributed PV plants, and it can be used to analyse the power-generation benefits of rooftop PV systems. Figure 6 shows the workflow for 3D model construction and rooftop PV panel placement optimisation analysis.

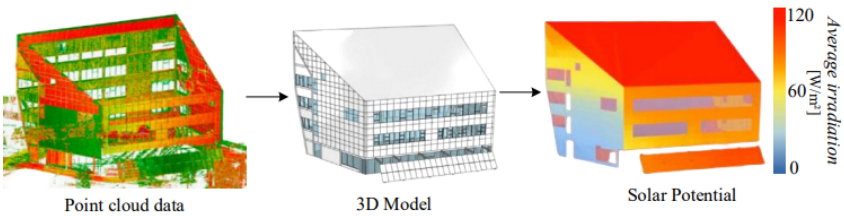

Figure 6. Workflow of rooftop PV system power generation analysis via LiDAR [14]

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3.4.Issues and recommendations

Remote sensing advantages are particularly pronounced in PV inspection and PV field deformation monitoring. However, remote sensing still has several limitations for wider application. For the visible-light camera, high sensitivity to light limits its application scope and data acquisition times. In addition, visible-light cameras can only detect surface defects. Infrared cameras can help with temperature detection, but their low resolution limits the identification of surface faults. Because the edges of the PV module in infrared images are blurry, PV module extraction is difficult. As to LiDAR, it is suitable for terrain deformation detection but cannot identify PV faults. Therefore, LiDAR is suitable only in some situations, such as PV power stations in mountainous areas and on roofs. The main issues and directions for improvement are discussed below. Firstly, optical remote sensing is sensitive to lighting conditions, which limits its application. Therefore, advanced sensors have to be developed to reduce light interference, for example, due to a lack of natural light and glare. Secondly, a single remote sensing sensor cannot inspect the fault across multiple missions. Further research should focus on the remote sensing sensor fusion to facilitate the multi-source data acquisition and fault inspection. And the range of faults that can be detected by remote sensing is very limited, so new sensors should be developed to expand it. Finally, the optical sensors should be lighter to improve the UAV's endurance. And they have to be smarter and capable of dynamic adaptation and deployment across different circumstances to meet the needs of PV inspection.

4. Conclusion

With a continuously growing installed PV capacity, PV power generation is playing a greater role in the power supply. An efficient PV inspection system should be established to protect the economic profitability of the PV plant. The traditional PV inspection, involving manual PV inspection and electrical characteristic monitoring, is no longer implemented; it is replaced by remote sensing inspection. Remote sensing integrated with UAV platforms has been applied to PV inspection, yielding a series of research and application achievements, and boasts promising development prospects in the future. This paper introduces remote sensing commonly used in PV inspection, presents several types of sensors and their applications in PV inspection, and analyses their shortcomings and directions for future improvement.

Visible-light cameras, infrared cameras, and airborne LiDAR are critical sensors in optical remote sensing. A visible-light camera captures images in the visible spectrum and performs PV fault inspection using image segmentation, perspective correction, and data analysis. An infrared camera acquires images in the near-infrared and mid-infrared bands. By performing image segmentation, pairwise matching between visible-light and infrared images, and data analysis, infrared cameras can monitor the temperature of PV panels and inspect internal faults. LiDAR integrated with POS can generate a 3D digital model of PV plants to monitor field deformation and also a digital elevation model (DEM) to analyse the power generation potential of the PV field. During PV module hotspot inspection, an infrared camera can detect thermal radiation from PV panels and establish a relationship between PV panel temperature and fault severity to issue an early fault warning. During the surface inspection of a PV module, visible cameras capture high-resolution, real-time images to enable fault identification and classification, including foreign-object occlusion, surface damage, and glare. And during PV field deformation inspection, LiDAR can generate digital modelling of a PV plant at 10 mm resolution, enabling the diagnosis of landslides and damage to the supporting structure of PV panels.

However, several limitations remain in PV inspection based on optical remote sensing: limited performance of a single sensor, constraints on applicable scenarios and data-acquisition time windows due to environmental interference, and restricted types of faults detectable via remote sensing. This paper proposes targeted improvement strategies for the aforementioned issues and outlines future development trends in remote sensing technologies for PV inspection systems.

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