How aerial inspections can improve O&M in a cost-effective manner

O&M | The use of unmanned aerial vehicles in solar operations and maintenance can reduce costs and save hours of painstaking labour, but only if applied correctly. Aline Kirsten Vidal de Oliveira, Mohammadreza Aghaei and Ricardo Rüther explore the optimal use of aerial inspections and emerging methods for analysing the data they gather to identify faults

As photovoltaic (PV) installations increase in number and scale worldwide, the need for reliability and optimum performance of PV power plants grows as well. Thus, it is essential to develop fast and efficient inspection techniques, to perform operation and maintenance (O&M) measures cost-effectively.

With the advent of commercially available unnamed aerial vehicles (UAVs), aerial inspections were developed to be one of the novel methods for O&M which seems to be a promising approach to this challenge. This article aims to discuss the advantages and challenges related to aerial inspections in large-scale PV power plants, discussing the association of UAVs with consolidated inspection methods such as visual inspection, infrared thermography (IRT) and electroluminescence (EL).

Aerial inspections

UAVs are typically small-scale aircrafts capable of remote or autonomous operation. They were originally designed for military purposes. However, recent advances and cost reductions in the field of UAV have made such technology applicable for civil operations such as disaster relief, energy and power line inspections, and environmental, forest and mine monitoring, among others [1]. The technology has become increasingly popular, especially in the energy and agriculture sectors.

The use of UAVs to inspect large PV plants has grown significantly over the years, thanks to their superiority in field coverage, reliable imaging, quick detection, high durability, lightweight, low cost and high robustness to operate in hostile environments. They are used with RGB cameras or with cameras for infrared thermography (IRT) or electroluminescence (EL).

Drone-enabled inspections of PV power plants are increasingly popular in solar O&M

The widespread adoption of such devices also increased the availability of controlling and route planning software. The prior path definition of the flights enables a more stable, safe and effective inspection, mostly when precise GPS data of the site is available. Nonetheless, it does not detract from having a trained workforce for conducting the flight. The routes can vary in terms of height, direction and velocity, which depends on the quality of the UAV and the camera, the shape of the power plant, wind speeds during flight, and the goal of the inspection. The direction of the route, for example, can be parallel to the module rows or orthogonal to them, as shown in Figure 1. None of the two methods

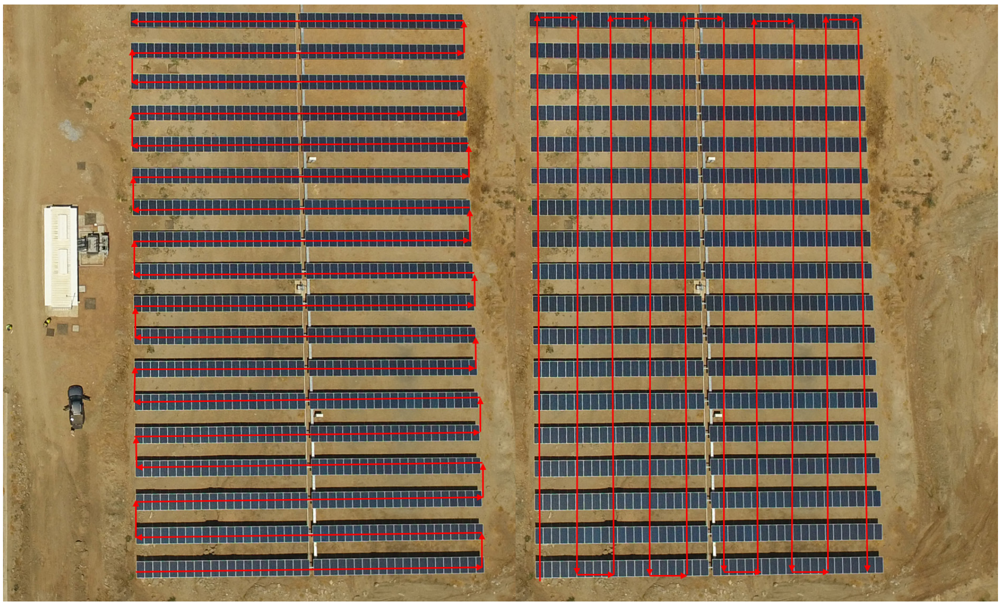

Figure 1. Different route types for aerial inspections of PV plants, marked in red. Parallel to the PV module rows on the left and orthogonal to the rows on the right

is superior to the other, but distancing between rows and power plant design factors can make one of them faster than the other. The parallel route has the advantage of facilitating the geolocation of faults, while the orthogonal route is normally more effective when flying at higher altitudes, since it covers more modules at once [2,3].

There are also attempts to determine the optimal path planning for the UAV autonomously in the literature, as in [4], developing a concept of autonomous monitoring. This is a novel concept to integrate various techniques, devices, systems, and platforms to enhance the accuracy of PV monitoring, consequently improving the performance, reliability and service life of PV systems. By this approach, the entire services of PV monitoring will be provided by a single integrated system.

For this method to be implemented, first the boundary of PV plants is determined by a neural network [5,6]. For this purpose, the neural network is trained by various orthophotos of PV plants. Subsequently, a static path planning algorithm is designed in order to create an optimal path for PV plant inspection. Moreover, dynamic path planning is created based on the flight situation and checks the UAV's abilities after any specific manoeuvre, which means if the UAV cannot complete the initial path, dynamic path planning enters in the loop to create a new optimum path according to the UAV's position and endurance [4].

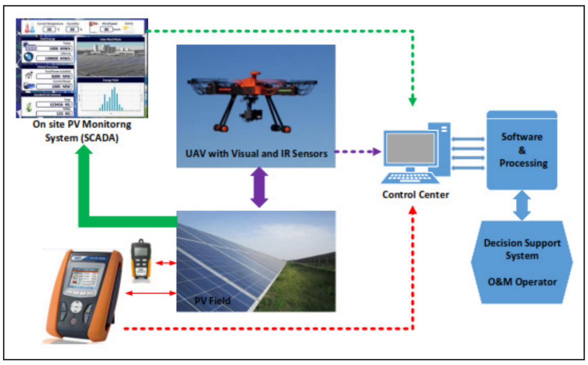

Figure 2. Schematic of the concept of autonomous monitoring system for PV plants [25,26]

Aerial visual inspection

Several defects on PV modules can be detected by a simple visual inspection. The method consists of a specialist that walks around the site and looks for any faults or failures visible by the bare eye, such as yellowing, misalignment, delaminations, bubbles, snail trails and burnt cells. For the aerial case, an RGB camera is attached to an UAV and can detect almost all of these faults in a much shorter time [7]. The great advantage of the method is the simplicity and low cost because most consumer-available UAVs are suitable for the task, with no modifications, and any operator can perform quick aerial visual inspections periodically. The inspections can be carried out from high altitudes, in order to monitor the plant and check for soiling, broken modules, vegetation over the modules and other easily spotted faults rapidly. Depending on the results, further inspections and actions can be taken. Professional UAVs, on the other hand, are more prepared for inspecting large power plants, since they provide better image quality, flight autonomy, stability and insulation against interferences from electromagnetic waves.

Aerial infrared thermography

The method of aerial infrared thermography (aIRT) has already proven to be a fast and effective method for detecting and classifying faults and there is already some commercially available equipment that offer IRT cameras mounted on UAVs. The integrated solution is ideal because it normally already contains built-in image processing software.

aIRT has been successfully employed for monitoring and commissioning of utility-scale power plants [8,9]. It provides fast identification of problems caused by environmental events such as hailstorms, windstorm, lightning, etc as the example described in [10]. Its major advantage is to evaluate a significant number of modules in a short time with no system shutdown (only trackers to be in stow mode).

The measurements are conducted outdoors, under stable conditions of irradiance above 600W/m2. Other environmental variables should also be measured (e.g. wind speed, ambient temperature). The diagnosis of faults occurs by evaluating the module's thermal pattern, which is uniform for healthy modules and reveals faults by variations in the image profile (shades of grey or colours). Examples of detectable failures include cracks and hot spots, corrosion, disconnected strings, shading, dirt, etc. The classification of detected faults is performed based on IEC TS 62446-3: 2017 [11].

The most common problems found in aIRT inspections are hot spots caused by cracks or soiling and vegetation because of the shading of cells which are not always distinguishable from actual hot spots through aerial visual inspections. When a hot spot is found in a soiled module, often there is the need to clean the module in order to re-evaluate the thermal pattern to know whether the hot spot was caused by soiling or actual damage. They are not considered failures of the system but problems that cause loss of power and present fire hazard risks. A good practice is to use aIRT equipment that also provides RGB images of the modules. The combination of aIRT with aerial visual inspections can help discard "false hot spots" and accelerate the diagnosis step.

In the case of inspections carried out during the commissioning phase of the power plant, it is common to find several disconnected strings. These are the failures that cause the most loss to a PV power plant's energy production, since they affect many modules at once. It also slows down the inspection process, since it disguises other faults, as the only problems that can be detected in a disconnected string are short-circuited modules or substrings. Therefore, the string needs to be reconnected and the thermal pattern of the PV modules re-evaluated. The causes for string disconnections vary for different equipment defects: trackers, inverters and fuses and diodes due to extreme over-irradiance events [12], on top of scheduled disconnections for maintenance or power restrictions. Disconnected strings can be detected more easily through the power plant supervisory system when current monitoring is conducted at a string or stringbox level (depending on topology and PV module technology). As the supervisory system is quite often not fully functional during the commissioning phase, the aIRT is still a fast method to perform this inspection.

Disconnected substrings are also commonly detected and are usually a PV module manufacturing defect. The substring might become disconnected in the junction box due to thermal stress during transport, installation and operation, causing the bypass diode to take on the full current of the string. This fault might cause the loss of one-third of the PV module peak power (because typical PV modules present six rows of cells, and one bypass diode for each two rows of cells), besides causing unnecessary stress to the bypass diode.

Faults that result in hot spots are more commonly detected in PV systems that have been installed for some years or that suffered from extreme meteorological events. They appear in broken glass modules, severe cracks or soldering problems, among others. The hot spots normally do not produce a significant loss of PV performance at early stages, so they are not usually detected by the supervisory systems. However, they are a potential source of fire hazards in the power plant and should be detected and removed.

Because of its flexibility, aIRT can be applied in many ways and levels of detail. The operator of a PV plant must decide how detailed and expensive the fault inspection should be and choose the flight altitude accordingly to this decision. For example, an inspection carried out at an altitude of 50 metres can detect open strings, disconnected substrings and broken cells on individual PV modules. These faults represent the biggest part of the power losses in a PV power plant. To detect the rest of the faults, which only cause a small part of the power losses, an inspection at 20 m flight altitude would be necessary. This inspection would take about double the time to be carried out and about two to four times more time for analysing the footage, and would, therefore, be much more expensive. The more detailed the inspection is, the more faults are detected, but the costs grow exponentially with detail. In large-scale PV plants, an aIRT inspection from a higher altitude will not reveal all the faults in the plant, but it will reveal the vast majority, including open strings responsible for the largest fraction of power losses. If a plant has a monitoring system detailed enough to detect all the open strings, the aIRT inspection can only provide an additional benefit if carried out at lower altitudes, which will result in higher costs. For small-scale PV plants such as roof-mounted systems, it is recommended to do the inspection at lower altitudes to get easy access to the system and obtain a detailed diagnosis of all the detectable faults [3].

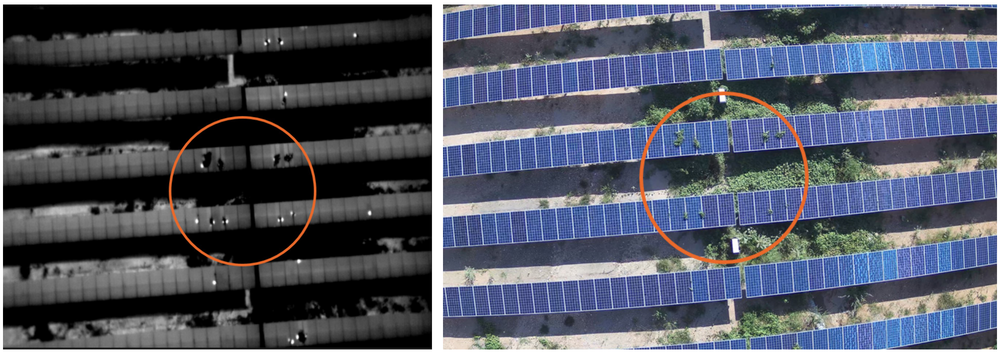

Figure 3. Vegetation over the modules detected with aerial inspections applying two different techniques: aIRT (left) and aerial visual inspection (right)

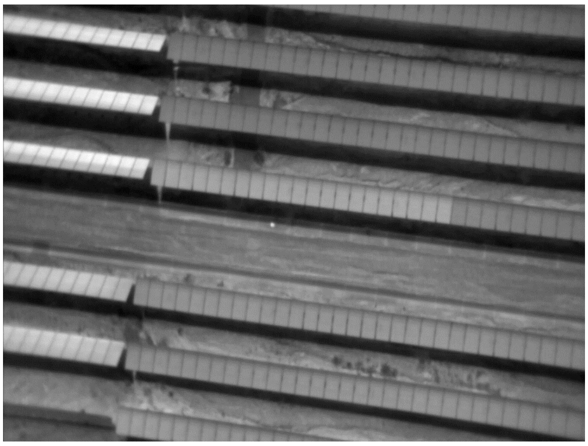

Figure 4. Disconnected string detected with aIRT on a single-axis tracking, utility-scale PV power plant

Aerial electroluminescence

EL is an effective technique for detecting faults in PV modules and requires specific EL radiation-sensitive range cameras that capture the photons emitted by the radiative recombination of charge carriers excited under forwarding bias. However, EL measurements are very time-consuming and inconvenient, since they are normally performed at night, require a mobile power source, take considerable time and are expensive to be carried out in large PV plants. For these reasons, the approach can be associated with aerial technology, such as UAVs, to employ EL for large-scale PV plants. The literature proposes different approaches for aerial electroluminescence (aEL) inspections [13,14], but most of these technologies are still costly and not broadly available.

The method simplifies the task of inspecting rooftop PV systems and allows taking images at different altitudes, so many modules can be analysed at once. In addition, during night-time, trackers in utility-scale PV power plants are set in stow mode, at a 0° angle. Taking EL images with tripods in this situation is a difficult and potentially hazardous operation, because of the necessity of placing the tripod on top of the module. Using a UAV allows the angle of the camera to be adjusted and the image can be taken at the right angle (90°).

For any EL measurement, the polarisa-

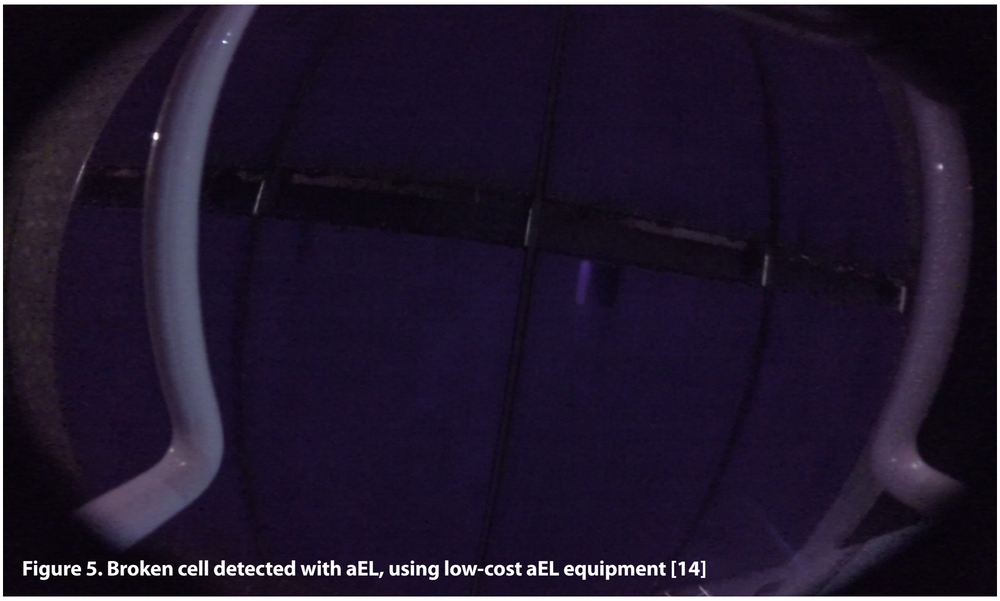

Figure 5. Broken cell detected with aEL, using low-cost aEL equipment [14]

tion of the modules through a voltage source is required. Also, for most of the cameras used, a dark room is necessary, therefore inspections in PV systems are performed during the night. For the case of using aerial equipment, when the number of modules that can be polarised at once is larger, the procedure is considerably faster and cheaper. The determination of the number of modules that can be connected at once depends on the power of the source applied. The larger the number of modules connected in series or in parallel, the higher the power which must be delivered by the voltage source. This becomes a challenge for the case of field measurements, as the power supply for the voltage source is normally a problem in large power plants that are usually built in isolated areas. In addition, the larger the power supply, the heavier and the larger the equipment, which complicates the logistics inside the power plant. A balance between the number of modules to be tested simultaneously and the cost and complexity of the inspection must be found. Another alternative is the use of switch boxes, in order to switch between strings, energising one at a time and allowing the UAV to cover the entire area quickly.

It seems ironic, having problems with power supply amid an electricity generation complex. However, this is one of the many challenges of working at night in a power plant. Other issues include the overtime costs of security and first aid teams and venomous animals. The low visibility also increases the risks of accidents and can affect the localisation system of the UAV, causing some control problems.

Despite all those challenges, the aEL procedure is effective in detecting faults and is especially useful for detecting problems that do not necessarily cause hot spots, such as potential-induced degradation (PID) and early-stage cracks. Such faults do not cause immediate loss of performance. For this reason, offering aEL services to detect them can be quite difficult. The benefit of the service comes from avoiding future hazards or warranty problems. Some extraordinary events, however, can require more sophisticated aEL inspections such as hailstorms or other meteorological accidents, loss of power because of inadequate transport of modules or even landslides that cause falling rocks over the system. In those situations, the impact of the restoration of the full performance of the power plant will pay the costs of the service.

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Besides, there are low-cost aEL solutions with lower-quality cameras associated with consumer UAV systems that produce satisfactory results as a faster procedure that can cover extensive PV areas [14].

The challenges of data analysis

The biggest challenge of aerial inspections in utility-scale PV power plants consists of the analysis of the images. The process is very time consuming and requires expensive equipment and skilled legwork. The analysis can be performed in real-time or after all the data is collected. In real-time analysis, the UAV will manoeuvre over specific individual PV modules for a precise investigation during the flight, and the drone must be equipped with data transmission hardware, which increases payload and energy consumption, reducing range and flight time. For the post-processing option, the images are stored during the flight and then transmitted for analysis. This option is more popular, because it reduces the UAV flight time and the specialists' time in the field, therefore reducing costs. It also reduces errors for the possibility of different image adjustments that improve the fault detection.

The acquisition of data can also be obtained through still images or videos. For the case of data collected in form of pictures, thousands of images are taken, and the correct geo-referencing of each image is a complex task. The process can be made through mosaicking or creating an ortho-photo of the entire power plant [15-17] which is also computer-resource consuming.

The acquisition through videos is more convenient for the cases that a specialist will be analysing all the data manually. When observing videos, it is easier to follow the movement of the camera, detect faults and distinguish them from artificial artefacts, as the sun and object reflections. The size of the files, which can reach gigabytes per video, is an issue associated with the method, requiring suitable equipment and data handling skills. One further advantage is the avoidance of blurred or non-focused images, especially for the case of aEL.

The long hours spent on data analysis are not only a waste in resources but can also lead to false-negatives due to human error. For these reasons, the next step in the development of aerial inspections is the application of automation techniques for the analysis of IRT images. Several methods in the literature are under study, applying digital image processing and artificial intelligence [16, 18-24]. Many have shown satisfactory results and will soon be able to process the large amounts of aerial images, detect the faults and categorise them. However, the correct localisation of the defected modules and their identification in terms of string and row number is the most complicated step to automate. It requires precise geolocation, processing and correlation with each power plant design.

The automatisation of the entire process will be a huge contribution to the effectiveness and cost reduction of aerial inspections. It opens the possibility of a non-specialist pilot to perform the inspections and leave it for the software to generate an automatic report of the possible faults. The plant operator will then be able to replace defective modules, repair open strings and correct other issues quickly and with minimal effort and cost. This will reduce travel costs and PV power plant downtime and increase accuracy, performance ratios and annual energy yields. The fast recognition and repair of failures in PV components will increase the reliability and durability of PV systems.

Yet highly trained people will not lose their jobs, instead they will be used more effectively in the analysis of the most serious cases. Specialists will no longer be hired to carry out repetitive and manual labour, but to analyse more complex issues such as: Why do so many modules have their front glass broken in this power plant? Why do so many modules have disconnected substrings?

The overall performance improvement of PV power plants that cost-effective aerial inspections can bring will increase the reliability of utility-scale PV power plants, reduce their levelised cost of electricity and raise the attractiveness of PV technology as a whole.

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