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Outdoor Photoluminescence Imaging from Unmanned Aerial Vehicles

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Abstract

As photovoltaic (PV) electricity generation enters the terawatt scale; solar PV power plants are getting ever bigger – some already containing a million or more solar modules. Reliable and consistent quality control of field-deployed modules is becoming increasingly important to ensure (i) minimum investment risk, and (ii) maximum reliability and longevity of operating solar power plants. In this context, outdoor photoluminescence (PL) imaging has a unique role to play as it can detect a large range of electric defects that cannot be identified with other methods with the same level of detail and throughput. Previously, we demonstrated outdoor PL imaging in bright daylight using (i) contactless switching of single modules, (ii) optical PV string modulation, and (iii) ultra-narrow bandpass filtering. We are currently developing a mobile inspection platform that integrates (i) outdoor PL imaging, (ii) thermal infrared imaging, and (iii) visual imaging. In this paper, we describe an improved method of performing outdoor PL imaging using an unmanned aerial inspection platform. Initial imaging results on single and multiple solar modules are presented and avenues for further improvement are evaluated.

Background

The systematic application of PL imaging in both R&D and for process monitoring in high volume production has played a significant role in the breath-taking development of the PV technology over the last one and a half decades. This has led PV technology to provide the cheapest electricity that humans have ever had available [1]. For continued growth, PV modules must maintain their high quality and performance throughout their intended lifespan of >25 years. With our recent work on outdoor PL imaging [2], [3], we are extending the benefits of PL imaging into field deployed solar modules in operating solar farms, thereby, extending the quality feedback loop in the PV life cycle.

Photoluminescence imaging [4] is usually performed in the lab under well controlled illumination conditions, which typically entails a high-powered monochromatic light source (laser or light emitting diode, LED) to provide strong "high-quality" sample illumination. Suitable optical filtering then provides the required wavelength selectivity needed to separate the very strong excitation light from the orders of magnitude weaker PL signal that is emitted from the illuminated wafers, cells, or modules.

Outdoor PL imaging is fundamentally much more difficult to perform than PL imaging in the lab since the sun itself is used as a broadband "low quality" high-power excitation source. A combination of using (i) a narrow bandpass filter and (ii) electrical or optical modulation have previously been demonstrated to overcome the substantial challenges of performing outdoor PL imaging of solar modules in full daylight. Electrical modulation is usually based on accessing the terminals of individual PV modules or strings of PV modules [5]. However, we previously also introduced outdoor PL imaging that does not require any modifications to the PV power plant via a method termed "contactless optical switching" [Fig. 1(a)] [2], [3], [6].

The currently used methods of outdoor PL imaging have been demonstrated to be suitable for detailed quality inspection of field-deployed solar modules. However, the deployment of outdoor PL imaging for routine inspection on solar power plants is strongly dependent on the ease of use and throughput of this method. The throughput is currently limited by the need to move the image capture unit throughout the PV power plant on a custom-built tripod. In this study, we provide a proof-of-concept for the use of outdoor PL imaging via unmanned aerial vehicles and provide initial results on capabilities and image quality of the system in use as well as steps to improve its performance further.

Outdoor PL imaging via optical PV string modulation

In previous work, we demonstrated outdoor PL imaging via optical contactless switching where an optical modulator was used on a single module [Fig. 1(a)] [2]. Two or more images of a PV module are required to be processed into a final PL image. The advantage of this method is that it can be very quickly and easily be applied at any location on a solar power plant. However, the throughput of this method is fundamentally limited to about 1-2 PV modules per minute due to the requirement to move the optical modulator from module to module.

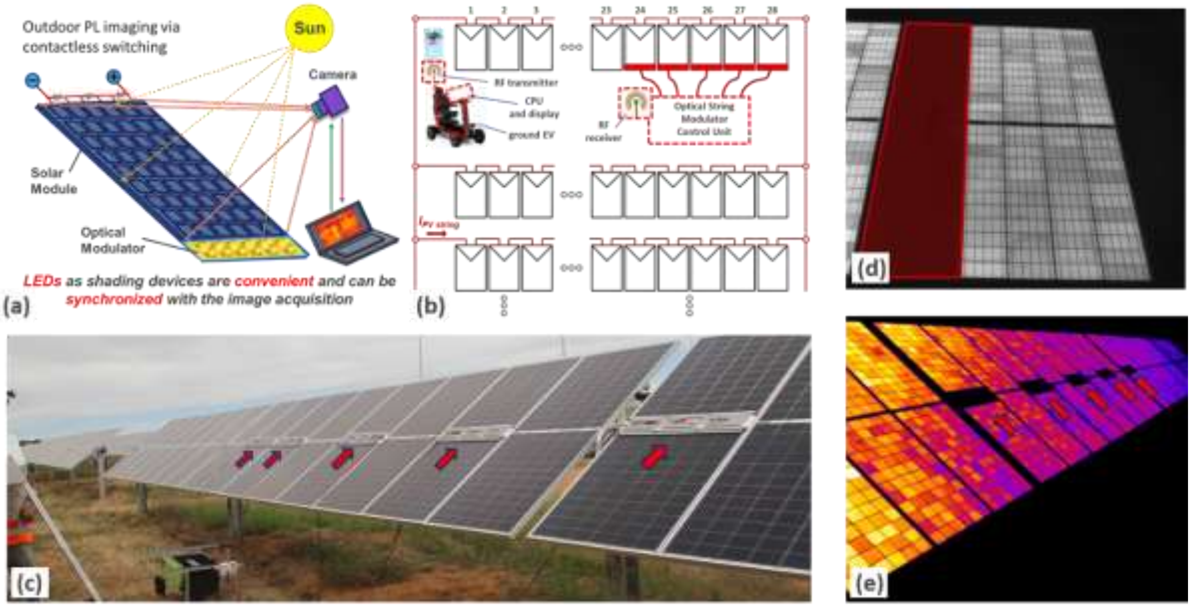


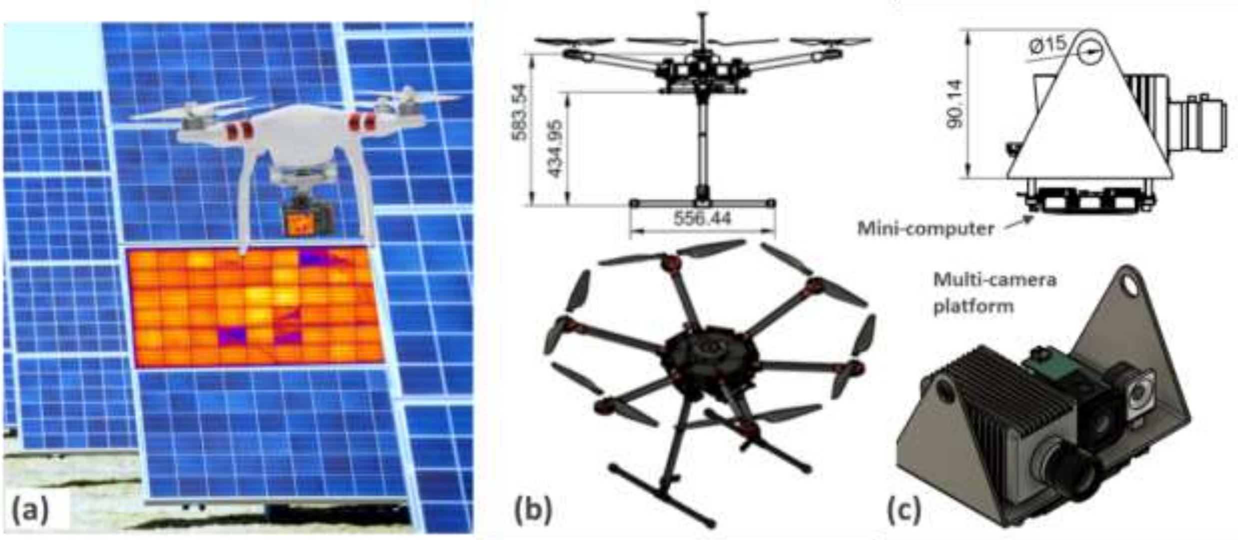
Figure 1. (a) Outdoor PL imaging of single module via contactless switching; (b) principle of outdoor PL imaging technique based on PV string modulation; (c) optical modulators (red arrows) on PV module string; (d) PL image of a full module with faulty bypass diode; and (e) outdoor PL image of several modules in a PV string.

Therefore, we recently developed outdoor PL imaging via optical PV string modulation. In this improved approach, several optical modulators are used, which in turn enables the switching of the entire string of PV modules at once [see Fig. 1(b-e)] [7]. The method is based on the principle that in a large-scale PV powerplant many tens of PV module strings (containing about 28 series connected modules each) are connected in parallel, thereby, pinning the array (and hence string) voltage to an almost constant value even when one string in the array is rapidly toggled from maximum power point to open-circuit voltage. With PV string modulation, the toggling of the operating point of an entire string of about 28 modules is achieved via up to five optical modulators that are placed on the modules connected to one PV string [Fig. 1(b, c)]. This enables rapid outdoor PL imaging of a single PV module or even the acquisition of PL images of many modules simultaneously [Fig. 1(d-e)]. The image acquisition is performed while synchronising the optical modulators and the imaging camera via low-latency wireless radio frequency (RF) transmission as schematically displayed in Fig. 1(b). Fig. 1(d) shows a PL image of a half-cell PERC module with a bypass diode that has failed in short-circuit, which manifests itself as dark substrings. The image was acquired in about 1 sec. A key advantage of this method is that it is now also possible to image two or more PV modules simultaneously as illustrated in Fig. 1(e). The optical PV string modulation method provides a viable route to further increase the throughput via taking outdoor PL images from unmanned aerial vehicles (AEVs; drones) as detailed in this paper.

Outdoor PL imaging from an aerial vehicle platform

As mentioned above, manually moving a ground-based tripod from module to module in a large-scale solar farm – often on very rough terrain – is cumbersome and fundamentally limits the throughput of outdoor PL imaging. Unmanned aerial vehicles are already routinely used for high-volume thermal infrared (IR) inspection of PV power plants [8] and electroluminescence (EL) inspection of PV modules at night [9], and have most recently been demonstrated for EL inspection in bright daylight [10]. Thus, aerial vehicles can substantially increase the throughput of outdoor PL imaging during daylight conditions [Fig. 2(a)].

Figure 2. (a) Concept of outdoor PL imaging from an aerial vehicle platform; (b) hexacopter used to carry the multi-camera inspection platform; (c) a mini-computer that is used to capture and process the image data.



We have designed an aerial vehicle platform based on a hexacopter configuration [Fig. 2(b)]. This configuration provides the necessary redundancy should a motor fail and increases the maximum payload weight compared to traditional quadcopter configurations. The custom payload includes three types of cameras (i) a visual camera (4 MP silicon chip), (ii) a thermal infrared camera (FLIR Tau 2), and (iii) outdoor PL short-wave infrared (SWIR) camera as depicted in Fig. 2 (c). The core of the platform is the SWIR camera for outdoor PL imaging which is based on a 640×512 pixels indium gallium arsenide (InGaAs) camera (Bobcat 640-GigE). The camera is wirelessly synchronised with the optical modulation of the operating point of the target PV module. Unlike thermal IR imaging, outdoor PL imaging requires multiple image pairs to capture a final PL image of the modules. It is therefore critical to have systems in place to minimise movement of the camera during image acquisition. In the conference, we will present our first outdoor PL imaging method and results based on the aerial vehicle platform that was custom designed for this purpose.

Conclusion

High volume and high-quality PV module inspection is one key element in the further rapid growth of global PV deployment. Outdoor PL imaging is a unique technology that has recently been demonstrated on field-deployed solar modules in bright daylight. This paper provides initial proof of concept results for outdoor PL inspection using an aerial vehicle platform. The technology has the potential to become the new standard for routine high-volume and high-quality inspection of PV modules on operating solar power plants.

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