Challenges and Opportunities for Autonomous UAV Inspection in Solar Photovoltaics

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Abstract. This work focuses on identifying the applications, critical challenges and future opportunities of autonomous unmanned aerial vehicles (UAV) in solar photovoltaics (PV) inspection. This paper places emphasis on aspects that require more research attention and depth that are mostly overlooked in most published research works. It therefore presents a state-of-the-art overview on the current use of autonomous UAV systems in solar photovoltaics, highlighting its major challenges and untapped potentials requiring more research. Major challenges and opportunities are identified within recent non-conventional large rooftop systems, floating and vertical solar PV systems where autonomous inspection applications are required starting from the pre-construction stage and where the requirements vary from standard ground mount systems. This is largely because autonomous systems are found to be more impactful in demanding environments. Aside from the technical aspects related to autonomous navigation, the types of sensors required and solar PV monitoring, beyond visual line of sight (BVLOS) and safe autonomy are also examined by using on-board backup/monitoring systems to assist with navigation and emergency landing. This is essential due to the nature of the application within complex-urban environments. It is considered that the "open research" areas will deepen regional impact, efficiency, accessibility and use of autonomous UAV inspection for solar PV and inspection activities in other sectors. Thus, enabling enormous transformation for both manned and autonomous inspection landscapes. This work therefore provides technical input on the current procedures applied, identifies the challenges, and provides recommendations on aspects where significant future progress would be most advantageous.

1 Introduction

Advances in recent technological approaches have resulted in massive global adoption of large-scale solar photovoltaics (SPV) installations. While the sun irradiance may be highly intermittent, advances in short-term yield predictability using overall weather condition, associated utility grid resilience and storage technologies (such as batteries or pumped hydro energy storage) have greatly improved the reliability of large scale solar PV deployment. Asides the small scale (<50kWp) SPV systems that are popular with residential or small-businesses, there has been rapid increase in the number of medium-scale ($\leqslant$ 1MWac) to large scale (>1MWac) systems. These systems are installed in various forms such as commonly seen ground mount systems, rooftop, and less popular systems such as floating systems [1]. Note that the ground mount could be stand-alone and vertical systems or hybrid such as found in Agrivoltaics [2]. As may be expected, the larger the system size or more complex the installation environment, the more challenging maintenance and management of the system becomes. SPV system management is required for a variety of reasons including monitoring degradation rates, faulty solar panels, mounting structure monitoring probably after adverse weather events, soiling, hotspots, delamination, microcracks and more. Most habitually visual inspection is a vital inspection tool for assessing the quantity of damage. Oftentimes, visual inspection is coupled with other traditional techniques such as I-V curve measurement [3], infrared imaging [4], electroluminescence [5] or signal injection measurement techniques [6]. Thus, large SPV systems using conventional and established techniques become tedious, expensive and have a limited safety assurance for workers within complex terrain or water bodies [1]. Overcoming these challenges are essential to sustainable shift towards "Clean-Energy" generation and achieving the global climate goals.

One of the innovative technologies currently applied for robust and efficient SPV management is the use of Unmanned Aerial Vehicles (UAVs). UAVs have emerged as a promising solution which simultaneously have proven viable in overcoming limitations of traditional inspection approaches. UAVs present a compelling solution, offering the ability to navigate vast solar arrays with high precision and efficiency. The UAVs can be loaded with different imaging sensors such as visual RGB, Infrared (IR), electroluminescence (EL) imaging cameras and more. The images or video frames are then further analyzed with intelligent platforms

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designed specially for such. This provides a seamless, efficient, time and cost-effective process while ensuring the safety of involved personnels. Recent advances in UAV technology provides capability for automated flight systems which are partly or fully monitored by a remote pilot. Partly monitored flights are considered automated flights/missions as navigation is usually automated. While automated flights are now being performed on various monitoring missions, integration of autonomous capabilities further enhance the UAV management system potential. Autonomous implementation [7] allows for systematic and thorough inspections, enabling timely identification of issues without the constraints of human-operated vehicles.

This paper explores the challenges and opportunities associated with the integration of autonomous UAVs in the inspection of solar photovoltaic installations. This is done with the aim of contributing valuable insights not only to SPV management but also to other renewable energy systems maintenance and management.

2 Role of UAVs in solar photovoltaics

2.1. Traditional inspection vs UAVs in Solar PV management

As previously described, advances in UAV technology are being applied to gradually phase-out time consuming and costly traditional inspection methods for medium-large scale SPV systems. For example, consider the manual ground-based inspection of a 20MWp solar installation. This site would have approximately 52,630 solar panels when installed with a medium sized 380Wp rated panel. The time required for ground-based infrared image collection is averagely 15sec per module and 220hours for the whole site under non-stop operation. The land area covered by solar panels with this same system size is about 26 acres. This same land area can be covered within 4 hours non-stop operation which translates to 1-2days (with optimal weather conditions and rest sessions) and at very high resolution using M300 DJI drones (H20 + XT sensors). This can vary based on the UAV's flight altitude as more panels would be captured. However, when the altitude is too high, it may result in losing detailed cell-level information. A similar estimate is provided in [8–10]. The above example conceptualizes the comparison of time management between conventional methods and the use of UAVs. Note that UAVs do not only assist with time management, but also with complex or hazardous terrain like desert regions, high rooftops and floating water systems where solar panels are installed. This in turn results in huge cost savings, higher efficiency and profitability.

2.2 Evolution of UAVs in Solar PV management

The use of UAVs in SPV management was initially focused on fault diagnostics for large-scale SPV installation due to the issues of time management and cost effectiveness as previously described. An overview of the procedure is described in [11]. The review from this work provides a very good description of the UAV inspection for fault detection. However, it is gradually becoming the popular choice for a variety of reasons beyond fault detection. UAVs are now being used for pre-construction and construction phases of SPV installation to monitor construction progress. This is a critical aspect that is yet to receive adequate attention as it helps with early capture of construction issues.

2.2.1 Fault detection and SPV management

Various faults such as hot spots, micro-cracks, glass breakage, soiling, encapsulation delamination, by-pass diode failures, solder joint failures, cell corrosion and snail trails (Figure 1) can now be detected with early inspection and analysis using appropriate artificial intelligence platforms/softare [12,13].

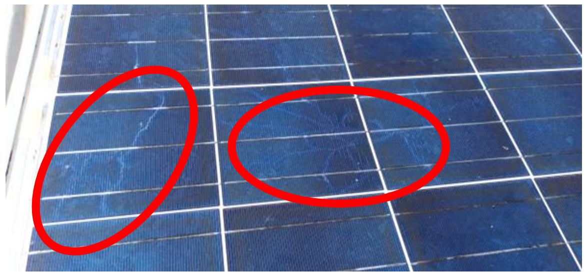

Fig. 1: Snail track effect on solar module

For example in [14], a UAV equipped with an IR sensor was used to detect defects in PV panels such as hot spots, fault cells, and open circuits that are then analyzed through an online IoT (Internet of Things) platform for detection and diagnosis. A CNN-based model combined with SVMs was developed in [13] to detect some common defects and visible faults in PV modules. An automatic algorithm was proposed in [15] that recognises defective PV panels using statistical analysis on thermal camera images captured from a UAV system. In [16], a UAV system was used with computer vision and GNSS positioning to quickly detect thermal anomalies and defective panels in a PV plant. A hot spot is an overheated area on the PV panel. It can appear on a module due to external factors such as dirt or due to internal defects e.g., cell mismatching. The early detection of hot spots is very important in order to prevent further damage to the overall PV system. For example, [17] developed a method to accurately detect hot spots using infrared and visible light onboard a UAV system. Similarly, [18] proposed a method based on a U-Net model and HSV space to detect hot spots in PV modules. A dataset collected using a DJI Matrice 100 drone is proposed in [19] for the detection and recognition of snail trails and hot spots. In most PV defects' detection approaches, the first task often consists in detecting panels that need inspection. For example, [19] proposed a stitching algorithm for the detection of PV panels using a DJI M210 drone equipped with thermal and video cameras. In [20], the authors developed an approach that enables the localization of individual solar panels from video frames using localization patterns.

2.2.2 Automated and Autonomous applications

For the purpose of this work, we make some clarification on the concept of automated systems and autonomous systems. While the two terms are often interchangeably used, this work focuses on the concepts applicable to autonomous systems. According to [21], autonomous systems are "emerging AI technology that operate without human intervention underpinned by the latest advances in intelligence, cognition, computer, and system sciences". While this may be considered as an acceptable definition, there have been several definitions mostly influenced by the body of systems applied or specific application that deviate from this perspective. [22] provided a range of definition for the word autonomy ranging from "the ability to perform given tasks based on the system's perception without human intervention" [23] to "a system that makes independent decisions and adapts to new conditions in order to achieve a predetermined goal, acts autonomous" [7]. While there are variations of the definition, the term autonomy across different academic disciplines and it is generally accepted that the underlying interpretation refers to self-decision making and operation. This is consistent with the origins of the word autonomy "auto" and "nomos", which are Greek words implying "self-governing" [22]. Here we will adopt the definition of autonomous systems described in Table I as systems that have cognitive functions and are capable of self-learning or evolution [22] without real-time human interface [24]. Thus, they can act based on their perception of the environment or by their learning process.

Table 1. Automated vs Autonomous Systems.

	Automated	**Autonomous**
Input type	Predefined input	Range of input
Response type	Determinable response every time it is actioned	Mostly probabilistic response (this may later be converted to finite response as a post process)
Evolution	Cannot evolve/learn	Can evolve/learn
Type of actions	Mostly for simplistic actions	For more complex actions
ML/AI integration	May include ML/AI integration	Must include ML/AL integration

The development of fully autonomous UAV systems for PV inspection is still in its early phases. For instance, [25] was one of the early works that proposed a control system to remotely monitor and inspect PV panels using a drone. Some works such as [26] developed a proof-of-concept that shows the operation of a UAV system able to detect and localize defective panels autonomously. [27] developed an autonomous UAV system that acquire video frames in real time, control its direction and speed in order to track and inspect PV panels autonomously. [28] proposed a model-based approach for panel detection and a new algorithm for local hot spot detection. Their approach works in real-time on board a UAV system equipped with a video camera. [29] proposed a UAV system connected to an IoT-based cloud system to autonomously detect defects. A similar work, that looks at communication issues in [30], proposed a real-time inspection of a PV station using a UAV system and a 4G private network.

2.3 UAV Technologies Enabling Solar PV Inspection

Different technologies are used in autonomous UAV systems in order to augment their sensing, navigation and control capabilities during their real-time operations in PV stations.

2.3.1 Sensing Technologies

The most common sensing technologies used for image capture in PV aerial inspection include visual, infrared, thermal and electroluminescence cameras. For example, [31] proposed a recent review of inspection and condition monitoring of PV plants using imaging techniques. A more detailed review of infrared based PV defects detection techniques using remotely controlled UAVs is provided in [32], including a detailed SWOT analysis. Infrared enables the real-time monitoring of the health of SPV modules in a non-destructive way. Similarly, [33] proposed a review of aerial thermographic inspection techniques in PV plants. Some works such as [34] have now started to combine thermographic sensor data with point clouds from a RGB sensor to perform the automatic detection of defects in PV stations.

2.3.2 Navigation and Control Systems

An autonomous system needs to be able to perceive, localize and plan its path without any human intervention. In this regard, several approaches have been proposed for both single and multiple UAV systems, we here review a few of these works. [35] proposed a path planning algorithm based on spatial clustering for a single UAV system operating in a PV environment with a complex topography. [36] developed a control algorithm that optimizes the positioning of the UAV system in order to efficiently cover the inspection area, reduce the time and the energy consumption. In [37], the authors proposed a cost-effective approach for UAV inspection based on two stages (1) get a rapid coverage of the entire scene from a high-altitude flight (2) use an optimized flight path to revisit detected areas for the classification of defects from a lower altitude. [38] described the potential geo-referencing issues with a UAV system used for the detection and identification of defects in PV inspection. [39] developed an optimal path planning approach for UAV inspection in a largescale PV plant based on a Bezier curve and particle swarm optimization. The effectiveness of the approach is shown through simulation results. [40] evaluated different UAV systems with regard to their reliability, cost-effectiveness and time-saving benefits for the detection of PV plant modules.

In [41], a spiral-coverage path planning and task assignment methods are proposed for multiple UAVs involved in PV inspection. [42] applied the ROS-MAGNA [43] framework to the control of a fleet of UAV systems used for the inspection of PV plants. In [44], the authors considered the automated inspection of a PV plant using a fleet of UAVs and unmanned ground vehicles (UGVs). Their work focuses more specifically on task allocation to the UAVs/UGVs and the overall energy consumption optimization. Similarly, [45] developed a cooperative path-planning for a ground-air system used for autonomous inspection of photovoltaics.

3 Challenges in autonomous UAV inspection

A few of the significant challenges to UAV inspection for SPV installations are highlighted as follows.

3.1 SPV array navigation and imaging limitations

Currently, the industry standard is automated inspection flight path over the SPV area to be inspected. Most often, a grid-patterned flight path is utilized. However, this is riddled with a couple of limitations such as poor coverage of hidden areas below solar array, limited intelligence to back-track to any area not properly covered (the poor coverage here could be due to reflections from the solar array glass covering or wind drift), and navigation of arrays at non-optimal angle or direction for best coverage. The constraints mentioned here are more closely related to navigation intelligence and limited capability of imaging sensors. While the navigation aspect is beginning to receive significant attention [46,47], the imaging of hidden areas beneath the solar array is not recieving corresponding attention. Rather, ground robots are being applied for under panel inspection, thus increasing the overall cost of purchase and maintenance of monitoring equipment.

Furthermore, inspection or monitoring mission using a UAV relies on high resolution images or video frames being collected or utilised. Capturing high resolution images is however not only a function of inbuilt/attached camera quality but also of UAV stability, control and inspection altitude [50]. Processing the images collected over a range of real-time imaging conditions has therefore led to a variety of algorithms in a bid to maximize the system efficiency. With several of the algorithms being sigle data source data [23,51–53] there is need to look into more data fusion algorithms for higher accuracy in processing and predictions.

3.2 Energy management and connectivity in remote installations

Another major challenge for autonomus UAV inspection for SPV system is the energy management and connectivity due to SPV instllations being built far away from urban areas or over large water bodies (Floating PV). For instances where the UAV to perform the autonmous inspection is located far away from the SPV instllation, the battery flight time would have been reduced by the amount needed to reach and return from the installation. While if the UAV is located close to the site adequate connectivity must be ensure to possibly include some real-time processing, data transmission, autonomous navigation in GPS denied environments, precision and accuracy in sensor data or other situational awareness on-board processing. All these processes are energy consuming and significcantly reduce the availble lifeting for the actual SPV inspection.

Autonomous UAVs are designed with more sensors and on-board computing processes to ensure safety and accurate data collection. However, in large SPV installations, there is a demand for extended flight times to cover larger areas or conduct more thorough inspections, thus requiring longer battery life. Currently, the concept of swappable batteries are employed, where the UAV returns-to-home for battery swap and continues from the stopping point. While this serves as an excellent solution, longer battery lifetime optimizes the workflow. Addressing this challenge requires a multifaceted approach, involving advancements in individual component robustness and optimization of on-board resources required for the autonomous navigation and inspection.

Another solution that have been applied in the industry is the drone-in-a-box concept [52], where, the UAV can be charged in a IP65 rated landing box, against its next mission. While this ia another excellent solution, it increases the overall capital and maintenance cost of the monitoring system making it less assessible to low-income regions of the world.

3.3 Weather and inspection scheduling constraints

While UAV inspection significantly reduces the challenge of monitoring large scale solar installation, it is slightly more challenging to schedule inspection details in advance. This is mostly due to complexities of long-term weather predictions most suitable for the imaging inspection to be carried out. There are two aspects to weather and environmental constraints (WECs) for autonomous UAV inspection in SPVs. First, we consider how autonomous inspection can be carried out in the presence of unpredictable weather conditions such as "thermal turbulence" or other wind gust effects which may occur during inspection. Thermal turbulence can occur when air from the evenly spaced solar array surface is heated to a higher temperature than the surrounding air and then ascends as thermals.

Secondly, we consider the accuracy of short-term weather prediction which serves as advisory to fully autonomous UAV inspection. For different types of inspection, there are prescribed weather conditions to obtain accurate results. The conditions are prescribed in International Standards such as IEC TS 62446-3 [53]. Operation outside this range is likely to yield unreliable results. Also, various UAVs have specific weather conditions under which they can operate. Thus, for a fully autonomous system, there is the need for accurate short-term weather prediction which on its own is non-trivial, and in addition to this, UAVs with robust weather conditions operating range are required. If the autonomous UAV is managed by a different operation and maintenance company (which is the current norm in SPV industry), there is an added complexity of matching the right weather and environmental conditions with the availability of the SPV inspection company. If the UAV is stationed close to the SPV installation, then remote connectivity, asset security and cyber-security challenges must be solved to ensure safe operation.

Furthermore, harsh weather conditions such as rain showers, wind, fog, and extreme temperatures can all impede flight stability and compromise data collection accuracy. Strong winds can destabilize UAVs, making it difficult to maintain a steady flight path, cause blurry images and risk potential damage to both the vehicle and the assets being inspected [40]. Harsh weather conditions described above are popular occurrences in SPV farms located in remote or inhospitable areas like deserts and rivers (for floating systems). Dust and debris can accumulate on sensors and obstruct lenses, diminishing the quality of data collected and potentially causing equipment malfunctions. Moreover, the reflective surfaces of solar panels can pose challenges for navigation and obstacle avoidance algorithms, complicating flight planning and increasing the risk of collisions.

3.4 Regulatory and Legal Issues

While regulatory and legal issues [54] may appear non-technical issues, the regulatory framework has been designed around certain conditions such as maximum-take-off-weight, maximum wind speed/gust, sensor capabilities and more. This is to ensure safety of both uninvolved and involved participants of an inspection mission. Since autonomous UAV inspections are expected to be conducted with minimum human interference, they require more strict regulations to ensure safety. However, this is not expected to become a barrier to autonomous application, rather, it opens doors for more innovation in specific areas. For example, SPV inspection in residential areas (large rooftop installations) is currently significantly restricted in most countries due to privacy concerns considering that UAVs are fitted with very high resolution cameras [55]. Rather than lose out on the immense potential of rapid inspection with UAVs, technological advancements such as UAVs with real-time human feature identification and anonymization could be an option. Also, the possibility of small weight drones with desired sensors such as LiDAR or thermal cameras to reduce 'minimum separation distance' rule in UAV operations would be immensely advantageous. Privacy concern regulations are major constraints to autonomous UAVs usage for SPV inspection in urban/residential areas. For a fully remote piloted UAV mission, when an individual privacy is perceived to be interfered with, the remote pilot can quickly alter the mission plan, return-to-home or shut down operations. However, for autonomous systems, this will require additional onboard intelligenceand processing for situational awareness.

Addressing these regulatory and legal hurdles are important for the widespread adoption of autonomous UAV inspection.

4 Opportunities and Innovations

As highlighted in previous sections, there is a need for further optimization of developed UAV models' commercial capabilities to optimize their use for SPV inspection. A few of the aspects are highlighted below.

4.1 Advancement from automated to autonomous UAV systems

Autonomous UAV systems are a good choice to overcome the challenge associated with limited accuracy in long term weather prediction and time-mismatch that occurs in booking and scheduling maintenance inspection with a UAV inspection company. Since inspection weather conditions are vital to the quality of the inspection, scheduling a suitable time may not be easily predicted on a long term as weather changes are inevitable, this may also not match-up with the available time for the UAV inspection team, which is usually from a different company. Thus, an autonomous UAV system that can be integrated into the weather monitoring station relevant to the inspection site may provide a useful solution such that it can perform the inspection within the desired inspection window.

In addition, autonomous inspection implies the UAV is able to appropriate navigate the complex array/terrain environment posed by the installation, while ensuring reliable data (image) collection.

4.2 Integration of Artificial Intelligence to identify operations in urban areas for safety

Asides the autonomous capability obtainable with AI in UAVs, it could also assist with combating privacy limitations while improving safety via situational awareness. This is more important for SPV inspection mission in urban/residential areas. Installation of medium to large-scale rooftop SPV systems pose a huge conflict between safety regulation and benefits of UAVs in SPV inspection. However, these challenges can be significantly limited with highly intelligent UAVs with fast onboard processing to identify human features for anonymization or to provide quick response (detect and avoid) to any life-forms (human, birds and animals). These systems may possess remote kill-switch and start-up depending on the situation encountered. The can be very vital for efficient Beyond-Visual-Line-Of-Sight (BVLOS) operations in urban areas.

4.3 Inspection of hidden regions such as cabling behind panels and other structures

This is crucial to optimizing autonomous UAV inspection for the construction stage of the SPV installation cabling and mounting structure or portions hidden under the solar panels. While it may not always be feasible to scan the installation to view hidden portions at the conventional flight heights currently being used in the industry, inspection schemes or scanning accessories to visualize these hidden portions are considered viable research areas. For example very low altitude terrain-following flight path in between solar arrays with light weith drone to avoid crash hazard. These will provide a means to easily monitor and prevent poor installation and structure failure from the construction stage. A direct comparison to this is the recent development of Antecursor II robot by Arborea Intellbird. The robot was optimized to position its thermal cameras for both below panel and above panel inspections. This is a significant improvement to the conventional use of ground robots for under panel inspections alone. The system was tested by Iberdola at the Villarino solar plant in Salamanca [56].

In addition to the above, [57] highlighted use of visual cameras for backsheet investigation with UAVs. This emphasizes the need for such capability starting from construction phase to routine inspection phase of SPV installation lifetime.

4.4 Development of Specialized UAVs for PV Inspection

This is another possible route for resolving several issues associated with using UAVs for SPV inspection. Some of the issues highlighted here are inspections in remote regions (deserts, floating systems on water bodies, vertical systems on hydro-dam walls, or highways) where there may be poor communications or GPS service. Another instance is the possibility of equipping smaller drones with quality thermal infrared cameras for quick inspection in urban areas due to regulations on safety on larger UAV sizes. Also, there is the need for the use of protective coatings and sealed enclosures for sensitive components protection from dust and moisture, when applied for inspection in harsh environments. This aspect could as well be extended to dedicated UAVs with a robust range of weather resilience capability and sensors [58] for system inspections.

4.5 Cost-Benefit Analysis

Similar to all commercial products, the cost-benefits analysis of the advancements has to be considered. In this case, proper consideration will ease the penetration of clean technologies in developing nations where huge financial disparity exists even for established SPV installation companies. This could include the design of drones with longer lifetime or battery life via the design of solar-powered drones [59,60]. Remotely controlled UAVs have been found to have 10-15 fold lower inspection times than conventional manual inspection techniques [32]. Fully autonomous UAV systems will have even lower inspection times, thus providing major financial gains to SPV operators.

5 Conclusion

In this work we have reviewed the state-of-art application of UAVs in solar photovoltaics. This is aimed at identifying areas of commercial application in SPV development and monitoring that may benefit from targeted advancements. Note that the technological improvements identified are not only viable for SPV systems. They can be extended and fully utilized in broader energy systems particularly other renewable energy systems. The identified opportunities are expected to significantly enhance the penetration and performance of clean energy as we continue to intensify efforts towards global net-zero carbon offsets.

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