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Unmanned Aerial Vehicle for Infrared Inspection of Photovoltaic Modules

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Abstract. Supervision and monitoring are mandatory for large PhotoVoltaic (PV) plants, because failures can cause high power loss, due to the large number of PV modules. InfraRed (IR) analysis is effective and reliable to detect anomalies or failures in PV modules, but it is time consuming and then expensive, when the infrared inspection of large PV plants is manual. The diffusion of Unmanned Aerial Vehicle (UAV) equipped by infrared camera can support the fast supervision of PV plants, but the use of UAVs is regulated by international and national rules and its utilization is limited, based on geographic areas and/or authorizations. This article discusses these critical issues, directs the reader to official, national, geographic maps for the drones, and suggests technical solutions for some specific issues not considered in the technical specification for outdoor infrared thermography of PV modules

Key words. defects detection, EASA, infrared analysis, PV modules, UAV.

1. Introduction

Nowadays, it is becoming common to utilize UAV for IR inspection of PV modules, in order to evaluate the state of health of PV modules and other constituting parts. The main attention is focused on PV modules, because they represent the energy generator. Moreover, if a power loss is due to the cells [1]-[2], it induces a temperature increase, as well known and described in Table 3 of [3]. However, the radiometric maps can support the final decision about the substitution or not of a PV module, but they are not sufficient. To extract further information from the IR images, the user must apply the image processing [4]-[5]. It is useful to specify that IR analysis is not the unique methodology used to monitor a PV plant. For example, when the user/owner is interested to evaluate the global behaviour of the PV system, statistics [6-9] and/or supervision of the electrical variables [10]-[12] are often used. In any case, the use of an UAV for the IR inspection of PV plants [13] is not trivial, because the flight of an UAV must be compliant with the rules fixed by the National and International Authorities. European Aviation Safety Agency (EASA) defines most of the procedures and constraints for the UAV flight in Europe, and it also delegates some decisions to each one of the 27 member states of EU (Fig. 1). Consequently, each member state defines these parts of the European rule in its own way and the results are inhomogeneous. One of the decisions that every country must make is the definition and limitations of the geographical areas, i.e., the spaces where UAVs can flight. The constraints valid for Italy are usually different from those valid Spain, or in Germany or in France, and so on. The difference is not only referred to the size of the geographical areas, but also to their definitions. Section 2 of this paper introduces the criticalities due to the national and international rules. Section 3 describes a typical system for the IR inspection of PV modules by means of an UAV. Section 4 introduces some specific criticalities of the jointed systems and suggests solution. Conclusions end the paper.

Fig. 1. EU member states. Picture from https://commons.wikimedia.org/ under Creative Commons Attribution-Share Alike 4.0 International license.

2. National and International rules

IR inspection of PV modules by means UAV and, in general, any activity with UAV is possible are not always possible, or the use is limited. In fact, the Regulation EU 2019/947 [14] classifies the activities by UAV as *open, specific, and certified,* considering the impact on the human safety and the risk levels. For this reason, the geographical areas of each country are subdivided to guarantee a safe use of UAV; usually, the limitations are available on official documents and/or on website applications that can be used by the UAV pilots during the activity. In Italy, for example, it is available a web-based application [15], which reports the critical infrastructures (airport, military zone, helicopter rescue runway, natural parks, etc.) where the flight is prohibited or restricted. Fig. 2 reports the Italy map from the d-flight website, which is the Italian tool that classifies the geographical areas based on possible activities. Particularly, red zones are prohibited areas, orange zones are allowed areas until 25m of height, yellow zones are allowed areas until 45m of hight, and light blue zones are allowed areas until 60m of height. Some restrictions are permanent (e.g., airport, natural parks, and military areas), whereas other restrictions are temporary or valid only in fixed time windows. Moreover, these limitations can be limited to the activities in open category or extended also to the specific and certified category.

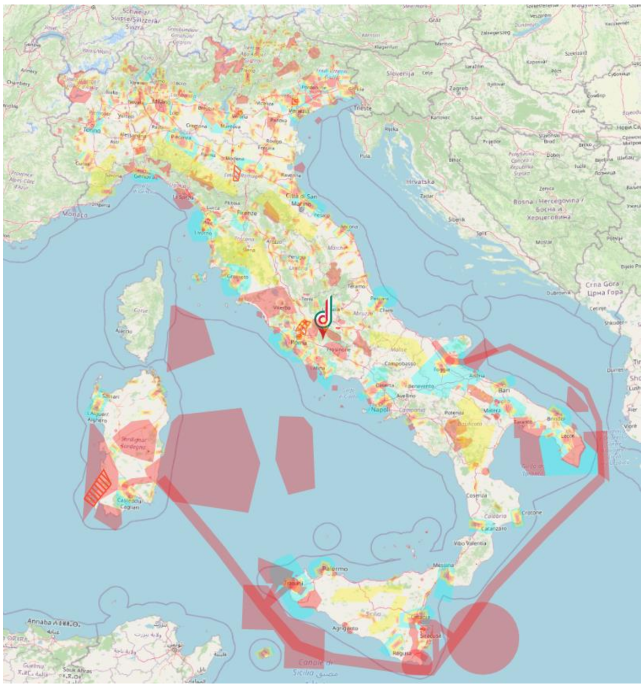

Fig. 2. Italy map from d-flight website. Colored restricted areas.

Therefore, Figs. 3-4-5 report the main limitations applied for each category.

OPEN*
(No authorization is needed)

- Maximum take-off mass: 25 kg.
- UAS belongs to one of the classes set out in Delegated Regulation (EU) 2019/945 or in article 12;
- Remote pilot keeps the unmanned aircraft in VLOS;
- UAS is maintained within 120 meters from the closest point of the surface of the earth;
- drone does not carry dangerous goods and does not drop any material.

* Open category is subdivided in A1, A2, A3.

Fig. 3. Limitation for activities in open category.

SPECIFIC
(Authorization is mandatory*)

- One of the requirements for OPEN category is not met;
- the competent authority shall issue an operational authorization if the operational risks are adequately mitigated;
- competent authority specifies operational authorization concerns;

* If UAS operator submit a declaration that operation is compliant with a fixed standard scenario, authorization is not required.

Fig. 4. Limitation for activities in specific category.

CERTIFIED
(Certification is mandatory)

Operation is conducted in one of the following conditions:

- it is over assemblies of people;
- it involves the transport of people;
- it involves the carriage of dangerous goods, that may result in high risk for third parties in case of accident.

Fig. 5. Limitation for activities in certified category.

3. Description of the hardware-software systems

Fig. 6 represents a logic scheme that describes the operation of a complete system for inspection of PV modules by means of UAV and IR camera. The main part is the hub that allows to share data among all the devices. In fact, hub receives IR images from UAV and environment parameters from the meteorological station. To automatize the calculations of some parameters of different areas of the radiometric map, a cloud-based software is necessary. In this paper we consider the software DISS that downloads IR image from hub (3), processes the image, extracts detailed information, and uploads the results (4) on hub. The data are stored into a database (5) to track the thermal history of each PV module. After DISS calculated the main parameters of the PV module, a certified technician can assume the final decision about it. As already said, this paper proposes DISS to process the infrared images, but other software with similar characteristics can be used.

Particularly, it needs that it is a cloud-based software to guarantee a fast procedure.

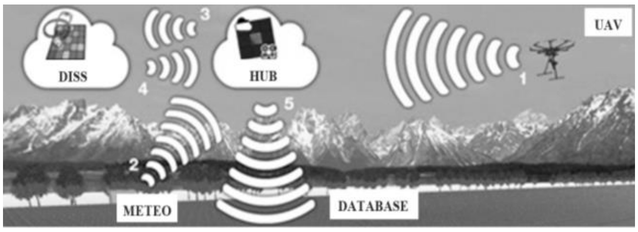

Fig. 6. Logic scheme of a jointed system: UAV and IR camera (1), meteorological station (2), cloud-based software (DISS) (3-4) and database (5).

4. Criticalities and suggestions

Defects in PV cells, and dust on PV modules reduce the energy produced by a PV plant. Focusing attention only on the defects in PV cells, it results that they appear as overtemperature, i.e., a temperature higher than the temperature of a correct operation. This parameter is specific for any module and is called Nominal Operating Cell Temperature (NOCT). This value depends on the environmental conditions; therefore, it is defined in these conditions: solar irradiation, G, equal to 800 W/m^2, air temperature, Ta, equal to 20 °C, wind speed equal to 1 m/s. It is worth noting that these conditions are different from the Standard Test Conditions (STC), i.e., G = 1000 W/m^2 and cell temperature Tc = 25 °C, which are used to specify all the other parameters in the manufacturer datasheets [16].

When a laboratory test is performed, it is possible to set the desired values of solar radiation and air temperature, and to the cell temperature with the NOCT value. Instead, when an outdoor IR analysis is performed, the values of solar radiation and air temperature are different from the NOCT conditions. Therefore, it needs to normalize the NOCT to the equivalent value in the actual conditions. In new PV module, the NOCT is substituted by the Nominal Module Operating Temperature (NMOT). In any case, the equivalent value, for example *eNMOT*, can be calculated as [17]:

$$eNMOT = T_a + \frac{NMOT-20}{G} \cdot 800 \qquad (1)$$

Table I resumes a quantitative evaluation of the overheating (light, medium, or strong hot spot), based on the amount of the power loss, based on the over-temperature with respect to the reference temperature [18].

TABLE I
AMOUNT OF POWER LOSS AS A FUNCTION OF OVER-TEMPERATURE.

Over-temperature	Power loss	Hot spot
10°C	4%	Light
10°C - 20°C	4% - 10%	Medium
>20°C	>10%	Strong

In different environment conditions, the same module is characterized by different values of eNMOT. This means that the overheating in the two cases, if any, can impact differently on the power loss. Thus, any IR inspection must be done with clear sky [19] because the thermal image is not influenced by the sky's reflection, even if the uncertainty of the reflected temperature can yield errors of up to 15 °C in the temperature estimation. This is the optimal case because it is the performance of the PV module in conditions of almost nominal power. Nevertheless, the reflected temperature, which can produce great errors, is difficult to set, because it depends on each object around the PV module. To reduce its effect, the IR analyses are usually performed with solar irradiation of up to 700 W/m^2 and wind speed below 3 m/s [19].

Moreover, when an IR inspection is based on a UAV with a thermal camera, other attention points must be considered: typology of thermocamera (mid-wave or long-wave IR camera), correct emissivity value, maximum distance between UAV and the PV module, angle view.

When a UAV-based acquisition is used, the distance between the IR camera and the PV module can be over 10 m and this volume is occupied by air [18]. The air volume has effects only on IR inspection based on mid-wave cameras. For a limited distance, e.g., 10 m, the error is limited because the attenuation due to the air transmittance is never lower than 0.85. For distance greater than 10 m, a correction should be considered for reliable evaluation of the overtemperature. Moreover, the air humidity should be low enough to avoid condensation in the air, on the measuring object, on the glass or on the lens of the IR camera.

The correct emissivity depends on the used IR camera. If a long-wave IR camera is used, the glass is opaque, and its emissivity must be set. Otherwise, if a mid-wave IR camera is used, the glass is transparent and the emissivity of the material under the glass must be set. The correct setting of the emissivity is crucial when the difference between the temperature of the PV module and the air temperature is large because an incorrect value returns a false output, that influences the final decision of the certified technician.

The distance between the drone and the PV modules under investigations also affects the emissivity and the lateral resolution. International rules do not fix this distance. Therefore, the user must decide the flight height of the UAV, based on the technical specifications of the IR camera. There is a large difference if the technician uses an IR camera with a resolution of 640 x 512 pixels or an IR camera with 160 x 128 pixels. To preserve the same level of detail, the maximum distance must be very different. On the contrary, IR inspections based on the same distance return IR images with very different details. Each pixel of an IR camera with 640 x 512 pixels can cover, based on the optical lens, a square of 1.3 cm x 1.3 cm from 10 m. For a standard square PV cell of 10 cm x 10 cm, this means that the measured temperature of each PV cell is based on several pixels, and therefore is accurate. For this reason, the maximum distance must be calculated before starting the flight, since it depends on the minimum number of pixels for a single cell that will be used to evaluate the status of the PV module. For accurate IR analysis, almost 5x5 pixels per PV cell are necessary [20]. Therefore, the height must be fixed, based on the resolution of the IR sensor.

5. Conclusion

UAV with IR camera can fast the IR inspection of large PV plants, but there are different rules in using them from country to country, even if there is a unique body in Europe with the responsibility for defining the applicability rules, that is EASA. This occurs because each country can apply different rules for critical infrastructures (military areas, airports, railway, etc.) and sensitive areas as parks. The solution to these criticalities is not sufficient to guarantee better and useful IR images acquired by UAV, because no standard rule exists about the correct procedure of the acquisition. There are some suggestions about the meteorological conditions, but no constraints are fixed about the spatial resolution, the setting of emissivity, the angle view between the thermocamera onboard and the perpendicular direction of the PV module. The paper suggested some possible solutions based on numerous applications of the jointed UAV-thermocamera system in IR inspection, but other issues are still open. Future works will focus to investigate the other open issues.

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