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Unmanned Aerial Vehicle for Infrared Inspection of Photovoltaic Modules

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Fig. 1. EU member states

Table 1. Constraints and limitations for geographical areas in most of the EU member

Country	Website	Limits
Austria	https://map.dronespace.at/	5.5 km from ARP
Belgium	https://apps.geocortex.com/web-viewer/?app=1062438763fd493699b4857b9872c6c4	3 km from ARP and 1 km from heliport
Czechia	https://dronview.rlp.cz/	5.5 km from ARP
Denmark	https://www.droneluftrum.dk/app/map	5 km from ARP and 8 km from military
France	https://www.geoportail.gouv.fr/carte	Variable until 10 km from ARP
Germany	https://maptool-dpul-prod.dfs.de/	1.5 km from airport
Greece	https://dagr.hcaa.gr/#map_page	8 km from ARP
Ireland	https://www.iaa.ie/general-aviation/drones/drone-regulations-guidance	8 km from ARP and 3 km from heliport
Italy	https://www.d-flight.it/portal/	Figures 8–11
Latvia	https://www.airspace.lv/drones	10 km from ARP

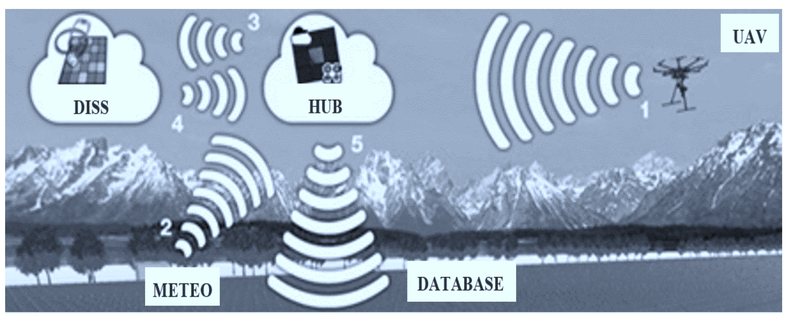

Fig. 6. Logic scheme of a jointed system: UAV and IR camera (1), meteorological station (2), cloud-based software (DISS) (3-4) and database (5).

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 specific category

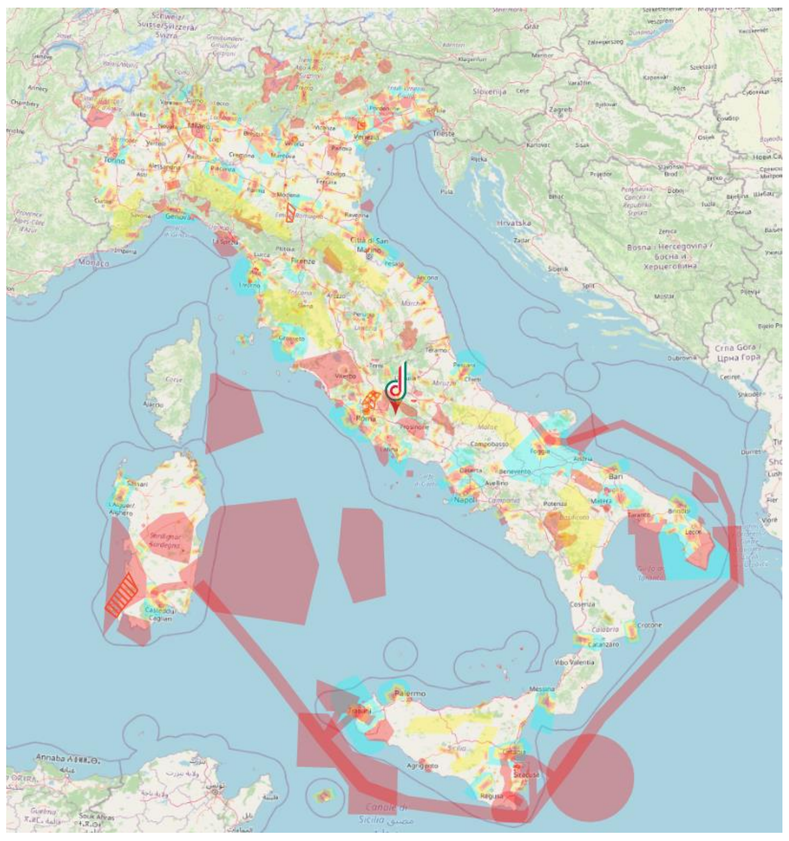

Fig. 2. Italy map from d-flight website. Colored restricted areas

- IR inspection of PV modules by means UAV and any activity with UAV is not always possible, or the use is limited.
- Regulation EU 2019/947 classifies the activities by UAV as **open, specific, and certified**, considering the impact on the human safety and the risk levels.
- Geographical areas of each country are subdivided to guarantee a safe use of UAV,
- In Italy, it is available **d-flight.com**, a web-based application, 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: 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), other restrictions are temporary or valid only in fixed time windows.

Hardware-software system

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.
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.
We suggest 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.

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]:

a) irradiance, $G \geq 600\ W/m^2$;
b) wind speed, $w \leq 28\ km/h$;
c) cloud coverage, $c \leq 2\ oktas$;
d) soil, no or very low.

$$eNMOT = T_a + \frac{NMOT-20}{G} \cdot 800$$

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

References

[1] O. Breitenstein, J. P. Rakotoniaina, M. H. Al Rifai, and M. Werner, "Shunt type in crystalline solar cells", Prog. Photovoltaics Res. Appl., 2004, vol. 12, pp. 529–538.
[2] J. P. Rakotoniaina, S. Neve, M. Werner, and O. Breitenstein, "Material induced shunts in multicrystalline silicon solar cells", in Proc. Conf. Photovoltaics Eur., 2002, Rome, Italy, pp. 24–27.
[3] E. Skoplaki, and J.A. Palyvos, "On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations", Solar Energy, 2009, Vol. 83, pp. 614–624.
[4] S. Vergura, F. Marino, "Quantitative and computer aided thermography-based diagnostics for PV devices: part I – framework", IEEE Journal of Photovoltaics, 2017, Vol. 7, Issue 3, pp 822-827.
[5] S. Vergura, M. Colaprico, M. F. de Ruvo, F. Marino, "A quantitative and computer aided thermography-based diagnostics for PV devices: part II – platform and results", IEEE Journal of Photovoltaics, 2017, Vol. 7, Issue 1, pp 237-243.
[6] F. Harrou, Y. Sun, K. Kara, A. Chouder, S. Silvestre, E. Garoudja, "Statistical fault detection in photovoltaic systems", Solar Energy, 2017, Vol. 150:485–99.
[7] S. Vergura, "Hypothesis Tests-Based Analysis for Anomaly Detection in Photovoltaic Systems in the Absence of Environmental Parameters, Energies", 2018.
[8] F. Hafiz, M. A. Awal, A. R. d. Queiroz and I. Husain, "Real-Time Stochastic Optimization of Energy Storage Management Using Deep Learning-Based Forecasts for Residential PV Applications," in IEEE Transactions on Industry Applications, vol. 56, no. 3, pp. 2216-2226, May-June 2020.
[9] S. Vergura, Bollinger bands based on exponential moving average for statistical monitoring of multi-array photovoltaic systems, Energies, 2020, 13, 3992.
[10] S. Silvestre, S. Kichou, A. Chouder, G. Nofuentes, E. Karatepe, "Analysis of current and voltage indicators in grid connected PV (photovoltaic) systems working in faulty and partial shading conditions", Energy, 2015, Volume 86, Issue, 15, pp. 42-50.
[11] V. Puliafito, S. Vergura, M. Carpentieri, "Fourier, Wavelet and Hilbert-Huang Transforms for Studying Electrical Users in the Time and Frequency Domain", Energies, 2017, 10, 188, pp. 1-14.
[12] R. Zivieri, S. Vergura, M. Carpentieri, Analytical and numerical solution to the nonlinear cubic Duffing equation: an application to electrical signal analysis of distribution lines, Applied Mathematical Modelling, Elsevier, Volume 40, Issues 21–22, November 2016, Pages 9152–9164.
[13] Report IEA-PVPS T13-01:2014, Review of Failures of Photovoltaic Modules, Photovoltaic Power Systems Programme, 2014.
[14] https://www.easa.europa.eu/document-library/easy-access-rules/easy-access-rules-unmanned-aircraft-systems-regulation-eu, accessed on 09/03/2022.
[15] https://www.d-flight.it/new_portal/, accessed on 09/03/2022.
[16] S. Vergura, Correct Settings of a Joint Unmanned Aerial Vehicle and Thermocamera System for the Detection of Faulty Photovoltaic Modules, IEEE Journal of Photovoltaics, Vol. 11, Issue 1, January 2021, pp 124-130.
[17] E. Skoplaki, and J.A. Palyvos, "Operating temperature of photovoltaic modules: A survey of pertinent correlations", Renewable Energy, 2009, Vol. 34, pp. 23-29.
[18] A. Krenzinger, A.C. de Andrade, "Accurate outdoor glass thermographic thermometry applied to solar energy devices", Solar Energy, 2007, Vol. 81,
[19] Report IEA-PVPS T13-01:2014, Review of Failures of Photovoltaic Modules, Photovoltaic Power Systems Programme, 2014.
[20] Photovoltaic (PV) systems—Requirements for testing, documentation and maintenance—Part 3: Photovoltaic modules and plants—Outdoor infrared thermography, IEC TS 62446-3:2017, Jun. 2017.

S. Vergura, "Criticalities of Outdoor Infrared Inspection of Photovoltaic Modules by means of Drones", Energies 2022, 15, 5086. DOI: 10.3390/en15145086.