Renewable and Sustainable Energy Reviews 93 (2018) 566–579

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Technological review of the instrumentation used in aerial thermographic inspection of photovoltaic plants

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ARTICLE INFO

Keywords:
Aerial thermography
Photovoltaic inspection
Thermographic inspection
Photovoltaic thermographic inspection
Thermographic camera
Unmanned Aerial Vehicle

ABSTRACT

Photogrammetric studies performed with Unmanned Aerial Vehicles (UAV) have recently become more popular as they present an interesting low-cost alternative. A novel application of thermography with UAVs has been validated during the last years: aerial thermography for inspection of photovoltaic plants as a useful diagnostic technique to assess performance of photovoltaic modules, superseding time-consuming traditional manual methods. This paper describes the current state of thermographic cameras and UAV technology, with the aim of examining the general principles of aerial thermographic measurement and required instrumentation, detailing the most important system aspects, discussing new developments and future trends in aerial thermography sensors and instrumentation, and evaluating them for specific application of aerial thermographic inspection of photovoltaic plants.

1. Introduction

Photogrammetric studies performed with Unmanned Aerial Vehicles (UAVs) have recently become more popular as they present an interesting low-cost alternative. Evolution and development of electronic sensors and instrumentation involved in aerial photogrammetry and the possibilities of implementing these sensors on board UAVs have vastly increased potential of this technique.

Nowadays, photogrammetry and thermography using UAVs are used in a huge number of applications, for instance, topographic and cartographic products [1,2], surveying, mapping and documentation of different surfaces as ore mines [3], or parabolic concentrators [4], roads [5], monitoring of wildlife species [6], surveillance or small target detection [7] or detecting energy faults in buildings [8–10].

A new application of thermography with UAVs has appeared in recent years: aerial thermography for inspection of photovoltaic (PV) plants, which is one of the most promising markets in the field of the generation of renewable and sustainable energy [11]. Fig. 1 shows a photovoltaic plant in Spain with fixed 2 vertical (portrait) layout structure where aerial thermography is being carried out in order to detect under-producing modules using thermographic and visual cameras. Some authors suggest that roughly 6% of expected output power is lost as a result of undetected faults in PV modules [12]. Infrared thermography is a useful diagnostic technique to assess performance of PV modules [13].

Traditionally, faulty modules or cells within a PV plant have been located by applying electrical tests to the modules like the I-V curve test and/or manual thermography, which is a costly and time-consuming technique [14]. Furthermore, rapid growth of photovoltaic power capacity, which exceeded 300 GW worldwide in 2016 with a 50% of growth in relation to the previous year [15], and the trend of constructing bigger PV sites with a higher capacity, have motivated research into maintenance of PV plants. Operation and Maintenance (O&M) activities prevent energy losses of PV sites; nonetheless, O&M is one of the most significant costs of PV plants. Additionally, the huge size of newer PV plants makes development of innovative techniques necessary, such as the aerial thermography, to enable or optimize maintenance activities. Several researchers have shown its real feasibility for detection of faults in PV modules [16,17] and, in relation to this issue, time reduction with regard to manual thermographic inspections, with an approximate inspection time of 5–8 min for a 1000 kWp site using UAVs [12]. As analyzed within the review, there is an intense research effort to automate data capture and post-processing steps in aerial thermography, which suggest a trend towards a fully automatic system.

In order to invest in this equipment, it is absolutely necessary to know the equipment that it is going to be used and its characteristics perfectly, with the aim of obtaining accurate and usable results. Image quality will have a great impact on accuracy of the photogrammetric

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https://doi.org/10.1016/j.rser.2018.05.027
Received 6 May 2017; Received in revised form 7 April 2018; Accepted 13 May 2018
1364-0321/

Fig. 1. Photovoltaic plant in Spain with fixed 2 V layout structure where aerial thermography is being carried out using a quadcopter equipped with a thermographic camera and a visual camera.

end product [18,19]. Although there are several researchers developing this novel technique, there are no clear guidelines for selection of involved instrumentation meeting the needs of photovoltaic inspections. This makes it necessary to investigate needs and aspects involved in this issue, regarding key characteristics of sensors and platforms and current instrumentation technologies available on the market.

The paper is divided into six sections. First of all, aerial thermographic inspection and its importance in O&M activities of photovoltaic plants are presented in the introduction. Sections two and three describe the current state of thermographic cameras and UAVs technology, respectively; with the aim of examining the general principles of aerial thermographic measurement and instrumentation required, detailing the most important system aspects. Later on, section four reports related work published so far, highlighting equipment used in each research exercise. Then, in section five the pros and cons of this inspection are discussed compared to traditional methods, and new developments in aerial thermography sensors and instrumentation are evaluated for specific application of measurement and instrumentation for aerial thermographic inspection of photovoltaic plants. In the final section some conclusions about the present work are presented as well as future trends and work.

2. Thermographic cameras for PV inspection

One of the first points to consider for carrying out an accurate flight in which the final results are clear is the characteristics of the tools used to perform the flight. The main components that have to be considered are the thermographic camera (payload) and the UAV (platform), whilst not undervaluing the importance of other necessary components, such as batteries for the drone flight, professional charger for these batteries, screens to display thermal and visual images and gimbal to support the sensors.

This section reviews thermographic camera technology for aerial inspection of PV plants. It is divided into three different subsections. It starts with a historical overview that shows advances in thermographic camera technology since their creation, followed by technology guidelines in which camera operation is described, and then a technological review that summarizes the current features of available thermographic cameras adapted to the requirements and conditions of aerial thermography of PV plants.

2.1. History

Temperature was first estimated by means of a subjective evaluation, for instance, in metallurgy, the metal's temperature was estimated by workers monitoring the colors of hot metals [20].

During the sixteenth century, the discovery of the first device that showed temperature changes, the thermoscope [21], was a milestone in this area. The thermometer evolved from the thermoscope during the seventeenth century. The jump from contact to contactless methods dates from the final decades of the 19th century, when the first heat radiation experiments were performed. The bolometer was discovered in 1878, allowing measurement of heat emitted from body surfaces from a distance of 400 m. In 1888 the relationship between electromagnetism and light was established [20].

The first camera, commercially launched in the mid-nineteen sixties, could take 20 pictures in one second. Gradually, during the last decades of the twentieth century, the introduction of computing information technology was responsible for huge progress in this field. Since 1990, when the first camera with a 320 × 240 pixel resolution was launched, the technology and possibilities of thermographic cameras have evolved dramatically, just like the number of applications in which they are commonly used. Thermographic analysis is used in almost all the sciences, most significantly in medical and technical fields, in industry, military applications, telecommunications, research, ecology, aviation, energy and buildings.

2.2. Technology guidelines

Thermography is a technique that detects heat distribution in an evaluated area. This method measures the characteristics of radiative heat in order to set areas or points with higher or lower heat emissivity, areas that could indicate the presence of a fault [20]. Based on Planck's black body radiation law [22], it is known that all bodies with a higher temperature than absolute zero (−273 °C) emit infrared radiation, which the human eye cannot detect. The infrared radiation wavelength is between 0.7 µm and 1000 µm. Thermal cameras work in a narrower spectral sensitivity range, approximately from 3 µm to 14 µm, commonly known as thermal infrared range, which contains the most typical temperatures of the Earth, approximately − 20–350 °C. Nevertheless, each thermal camera indicates the wavelength range in which it works.

Optical lenses of the thermal camera converge the infrared energy coming from an object into the infrared radiance detector. This detector sends the information to the electronic sensor that processes the image. The resulting image is viewed on a luminescent monitor screen, where temperature is displayed.

The key benefit of thermographic inspection is the absence of contact between instrument and the measured object, so avoiding the thermal contact resistance effect [23].

2.3. Technological review

Thermal cameras are designed for simple and valuable integration into higher level assemblies and platforms, developing low-weight, small-size cameras that can be used in many applications. Especially during the twentieth-first century many thermal camera manufacturers have been adapting their camera designs for flying with drones. The technology is improving and developing and prices of these devices are lower than in the past. There is a huge range of these products on the market, and therefore it is important to be aware of the most significant requirements of thermal cameras. Only a few guidelines about the existing thermal cameras are given in recent publications. The Journal of Photogrammetry and Remote Sensing considers the two most common or representative thermal cameras for UAVs in 2014 to be FLIR and Thermoteknix Systems [24]. As a result of the need to complete and extend this study with cameras developed during recent years (or even months), this paper presents a study of the most important characteristics and developments in thermographic cameras.

One of the most important characteristics that differentiates a thermal camera is the resolution of its detector. This resolution is expressed as the number of horizontal pixels in the detector multiplied by the vertical number. A higher resolution allows detection of smaller objects from greater distances with clearer and more precise images. If

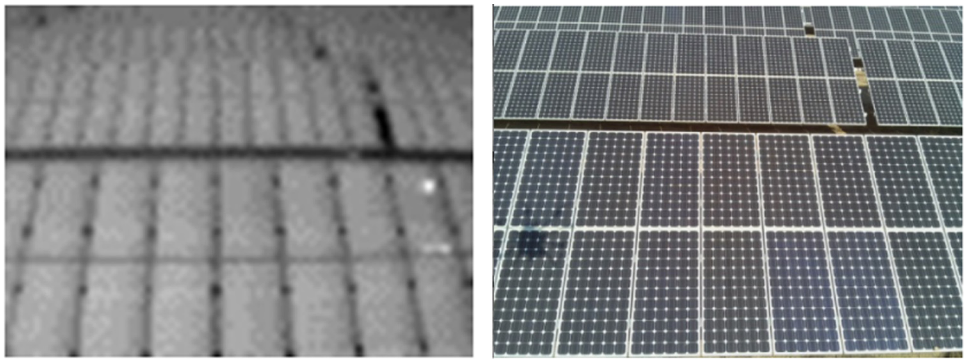

Fig. 2. a) Thermographic image captured at a 10 MW PV site in Spain with 80 × 60 pixel resolution. b) RGB image captured at the same time as the image shown in Fig. 2.a.

Table 1
Commercial thermographic cameras for aerial platforms and their main characteristics: thermographic camera manufacturer, model, resolution, thermal sensitivity and accuracy.

Manufacturer	Model	Resolution (pixel x pixel)	Thermal sensitivity/Temperature resolution (NETD)	Accuracy
Flir	VUE PRO R 640	640 × 512	< 0.05 K	± 5 °C or ± 5%
	VUE PRO R 336	336 × 256		
	TAU 2 640	640 × 512		
	TAU 2 336	336 × 256		
	ZENMUSE XT 640	640 × 512		
	ZENMUSE XT 336	336 × 256		
Workswell	WIRIS 640	640 × 512	0.03 K	± 2 °C or ± 2%
	WIRIS 336	336 × 256		
Optris	PI 640 Lightweight	640 × 480	0.075 K	± 2 °C or ± 2%
	PI 400 Lightweight	382 × 288	0.08 K	

this resolution is not enough, flight height will have to be reduced, slowing down the process considerably as the examined area will decrease significantly. Nowadays, the range of available technology in infrared cameras varies from resolutions lower than 80 × 60 pixels (4.8 kpixels) to 640 × 512 pixels (0.327 Mpixels) or similar, depending on the sensor size. In order to achieve acceptable professional results, the resolution of the detector should be at least 320 × 240 pixels. It is important not to confuse the detector resolution with the LCD screen resolution, which is much higher than the detector's resolution.

Fig. 2 shows thermographic (Fig. 2.a) and visual (Fig. 2.b) images captured in a thermographic inspection test in a 10 MW PV plant in Spain, with 80 × 60 pixel sensor resolution.

Another key factor is thermal sensitivity or Noise-Equivalent Temperature Difference (NETD), meaning the minimum temperature difference the thermal camera can measure in the presence of electronic circuit noise. Low thermal sensitivity allows detection of thermal contrast more accurately. At the present time, professional thermal cameras offer a thermal sensitivity below 50 mK.

Accuracy is another feature that is important to consider. This attribute measures the difference between the temperature the camera detects in a body and its actual temperature. Leading brands offer accuracies of ± 2%. In addition to the inherent accuracy of the thermographic camera, it is necessary, and the responsibility of the user, to identify and calculate the characteristics of the measured object and to understand its effects on measurements. The greatest cause of measurement error is setting an incorrect emissivity value [25]. Most of the cameras include the option to add and adjust emissivity and reflection temperature values easily, providing more accurate results. There are different options available to calculate these values, using emissivity tables or, in the field, by calibrating the thermal camera reading by means of a contact thermometer [26].

Accuracy and thermal sensitivity of the camera largely depends on the type of infrared detector, whether it is a cooled or an uncooled infrared thermal imager. In uncooled thermographic cameras, the sensor operates at ambient temperature while cooled detectors are contained in a vacuum-sealed case and cryogenically cooled, preventing the detector from influencing the measured temperature. In recent years, much research has been carried out in order to improve temperature measurement accuracy of uncooled infrared thermal imagers [27], with development of cameras with acceptable accuracies (up to 2% in thermographic cameras for aerial inspections), that are affordable and smaller than cooled ones. Thermal sensitivity of uncooled cameras is about 0.05 K compared to 0.01 K of cooled ones [28]. The price of cooled infrared cameras is approximately ten times higher than uncooled ones, and cooled infrared cameras are more time-consuming, as the camera may need several minutes to cool down before it can begin working. Consequently, uncooled detectors are generally used in aerial thermographic inspection. Where a detector influences temperature change, measurement results cannot meet the requirements of high accuracy temperature measurement.

Table 1 shows a summary of the most widely used commercial thermographic cameras for aerial platforms, illustrating features that have been introduced in the previous above descriptions. As opposed to the other cameras in Table 1, the Zenmuse XT is a special ready-to-fly product that consists of a thermographic camera mounted on a gimbal. Most of the cameras in Table 1 work in a spectral range of 3–13.5 µm.

There are many other features that have to be considered while selecting a thermographic camera.

It is especially important when choosing a thermal camera for PV field inspection with a drone to consider camera weight. The lifespan of the drone's batteries will decrease the heavier the camera, and therefore, it will be necessary to change the batteries more frequently, which increases downtime, decreasing daily inspection rate. Manufacturers have taken this into consideration in their camera designs for flying with drones, reducing their weight from approximately 500 to 1000 g for manual thermal cameras to 1–400 g for drone thermal cameras. The weight of the camera is highly dependent on lenses used. The dimensions of these cameras are around 4.5 × 5.5 cm. Depth is lens-

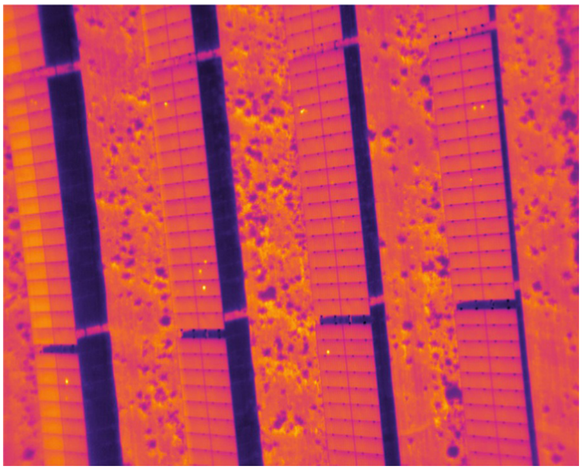

Fig. 3. Thermographic image captured at a 10 MW PV site in Spain using a Flir TAU 2 336 aerial thermographic camera with 336 × 256 pixel resolution flying at 30 m from the ground.

dependent.

Choosing the right camera lens increases flight efficiency. The lenses, together with the flying altitude and the camera's sensor, determine the size of the field the images will cover, also known as Field of View (FOV). FOV can be defined as the largest area an imager can see at a set distance [29]. It can also be described as the area the camera captures in an instant. FOV is typically defined by means of three angles: horizontal, vertical and diagonal, determined by the lens and the sensor's dimensions. Instantaneous Field of View (IFOV) or Spatial Resolution is the smallest detail within the FOV that can be detected or seen at a set distance, and Instantaneous Field of View Measurement (IFOV Measurement) establishes the smallest measurable area from which an accurate temperature measurement from set distance can be obtained [29]. The IFOV Measurement is calculated as three to five times more than IFOV, because in order to get an accurate measurement, the smallest object to be analyzed must be three to five times bigger than the smallest detail that can be detected (IFOV).

Currently, cameras offer many different lenses, which provide a huge range of FOV angles. Some of these lenses and their horizontal angles are fisheye (up to 180°), wide-angle (between 100° and 60°), standard (between 50° and 25°), telephoto (between 15° and 10°) and super-telephoto (between 8° and less than 1°). Although apparently lenses on all cameras are similar, infrared lenses are made of materials that transmit infrared radiation, typically germanium. This material has excellent mechanical characteristics and durability, because of its hardness. Nevertheless, this also means that it is difficult to manufacture the lenses, as germanium has to be cut with a diamond, which increases its price.

Aside from that, selection of a radiometric or a non-radiometric thermal camera is a crucial factor to consider depending on the intended kind of inspection of PV plants. A non-radiometric camera provides an image with temperature difference represented by different colors, but it does not provide information about the temperature at each point. Therefore, it is impossible to obtain the exact temperature of faults, such as hot spot temperatures. All the cameras in Table 1 add radiometric functionality, like most of today's cameras.

Some of the most modern equipment includes, in addition to a thermal sensor, a Red, Green, Blue (RGB) sensor, which takes visible-light images that facilitate subsequent interpretation of images and identification of the exact location of the fault in the PV field. Of the cameras in Table 1, the ones that include an RGB sensor are the WIRIS 640 and 336. RGB cameras that are added to the gimbal in addition to thermographic sensors have a high resolution, such as the 24.3 Mpixel SONY ILCE600 or 8.29 Mpixel 4 GoPro 4 K, with a price tag of around 530 €.

Furthermore, quality of camera software to process and study the images and image format is also crucial. Thermal camera software is one factor manufacturers are improving constantly, offering algorithms with more functionality and easier to use. Some of the post-processing software includes: a broad palette to facilitate interpretation of images, option to combine some images to create a panoramic image or to combine the thermal image with its corresponding visible-light image (Picture-in-Picture, PiP), different temperature analysis options (points, areas, differences, etc.) and option to create reports with the thermal images, among many other functionalities. If images are in a standard format, for example JPEG, BMP or TIFF or videos MPEG 4, MP4 or standard HDMI, instead of patented ones, transfer of images between the different players involved in the process will be easier, as they can be analyzed with most off-the-shelf imaging software. Some examples of software applied to cameras in Table 1 are Flir Tools, Workswell Core Player and PI Connect.

Another significant parameter of the cameras, especially in the case of aerial thermography where the camera is in motion or capturing moving objects, is the frame rate. Frame rate is the number of frames taken by the camera per second. Typical frame rates are 50 Hz, which means 50 frames per second.

A final parameter to be considered for thermographic cameras is the temperature range, defined as maximum and minimum temperature values that the camera can measure. Typical values are between − 20 °C and + 500 °C and can be extended up to 1700 °C using different filters [28]. For instance, in the Optris PI640 Lightweight camera, temperature ranges offered are − 20 °C to + 100 °C, 0 °C to + 250 °C and 150 °C to + 900 °C. On the other hand, FLIR defines different measurement accuracies depending on temperature range, as in the case of the VUE Pro R thermographic camera, which has ± 5 °C or ± 5% of reading in − 25 °C to + 135 °C and ± 20 °C or ± 20% of reading in − 40 °C to + 550 °C.

Fig. 3 shows a thermographic image captured during inspection of a 10 MW PV plant in Spain with a Flir TAU 2 336 aerial thermographic camera with a resolution of 336 × 256 pixels flying at 30 m from the ground. Fig. 4 shows a thermographic image captured with a PI 400 Lightweight with a resolution of 382 × 288 pixels flying at 28 m from the ground at the same PV plant. The image is presented in two different color palettes offered by the camera software.

To take advantage of all these technical characteristics, it is essential to understand every single feature of the thermographic camera. Carefully reading and considering all documentation and manuals provided by the camera manufacturer is extremely important. There is a considerable amount of information on how to perform thermographic inspections correctly, aspects to consider before starting and calculation of the inputs to the camera. A clear and easy example can be found in Testo Guide [26].

3. Unmanned Aerial Vehicles for PV inspection

This section reviews platforms for aerial inspection of PV plants. As in Section 2, it is structured into three different subsections, starting with a historical overview, followed by technology guidelines discussing the classification of different platforms and ending with a technological review, where the most important aspects of the system and new developments in UAVs are discussed.

3.1. History

Balloons and kites are considered the first UAVs by many scientific publications, since there is an aerodynamic lift and a primal control. Balloons have been used since at least 1783, and it was almost seventy years later when a powered flight was achieved by a dirigible balloon [30]. Subsequently, cameras were attached to balloons in France in 1858 and the first aerial pictures of Paris were taken that same year

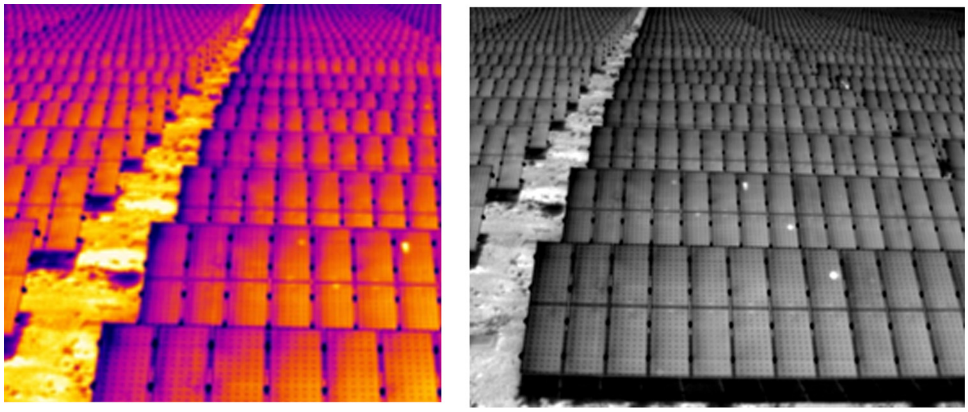

Fig. 4. Thermographic image presented in two different color palettes offered by the camera software. It has been captured in a 10 MW PV site in Spain with a PI 400 Lightweight aerial thermographic camera with 382 × 288 pixels resolution flying at 28 m from the ground.

Table 2
UAS classification following based on prevailing military descriptions [31,37].

MAV	**(Micro (or Miniature) or NAV (Nano) Air Vehicles)**
	Operation at very low altitudes (< 330 m)
	Compact size (can be carried in a backpack)
VTOL	**(Vertical Take-Off & Landing)**
	Short endurance (up to 1 h)
	No take-off/landing run required
	Operation at varying altitudes (although preferably at low altitudes)
	Hovering capabilities with image/video capturing
LASE	**(Low Altitude, Short-Endurance)**
	Small size
	No take-off/landing run required
	Weight: 2–5 kg
LASE Close	Take-off/landing run required
	Larger and heavier than LASE
	Operation at medium altitudes (< 1500 m)
LALE	**(Low Altitude, Long Endurance)**
	Very long endurance (> 30 h)
	Designed to carry payloads of several kg for long periods
	Operation at medium altitudes
MALE	**(Medium Altitude, Long Endurance)**
	Long endurance (> 20 h)
	Operation at high altitudes (< 9000 m)
	An example is the MQ− 1 Predator
HALE	**(High Altitude, Long Endurance)**
	The largest and the most complex group
	Very long endurance (> 30 h)
	Operation at very high altitudes (20,000 m or more)
	An example is the RQ− 4 Global Hawk

[30]. The first technological experiment with kites was carried out by Mr. Douglas Archibald in 1883, who attached an anemometer to a kite to measure wind speed [31]. Later, Mr. Archibald added cameras to the kites in 1887 [31].

These experiments paved the way for military and combat applications, which some authors consider to be the birth of UAV [24]. During the early stages, these devices were used during the Spanish-American War, where many pictures were taken with them. During World War I, the army used them to drop explosives over targets [31]. In 1937, a series of target UAVs was developed and two years later many target drones were manufactured during World War II [31]. Germany also used lethal UAVs during the final years of the War [31]. During the Vietnam War, UAVs were used extensively in combat, but only for reconnaissance missions, which resulted in a widespread interest in these devices at the end of the War [31]. During the final decades of the twentieth century, UAVs were used in military applications by the army and marines, especially for surveillance and reconnaissance. Mapping sensors for navigation and radio-control were understood and applied to UAV platforms during the nineteen-seventies [24]. Over the years, countless visionary organizations have worked on developing UAVs. The number of UAV systems referenced in the annual inventory of UVS International has tripled in the last decade, and the trend suggest that this number will continue to increase [24]. Further information on progress and development of new technologies can be found in [32].

3.2. Technology guidelines

A controversial topic that should be mentioned is terminology used among the people involved in this field.

A drone can be defined as an unmanned aircraft that can fly semi or fully autonomously [33]. Drone is originally the English word for a male bee [34]. Many authors believe that the term drone does not take into account the high level of skill needed in flight operations. Commonly, a drone is considered to be aircraft without an on board pilot, which is an excessive simplification that fails to recognize the vast number of different types of unmanned aircrafts available. Nevertheless, the term drone is sometimes used to simplify the issue.

The terms UAV or UAS (Unmanned Aerial System) are the favored ones in America, while the term RPA (Remotely Piloted Aircraft) is more widely used in Europe [35]. The term UAS includes the whole system: platform, communications and ground station while UAV only includes the platform or aerial vehicle. The difference between these two terms and RPA is that UAV or UAS can include or exclude the autonomous drones while an RPA always excludes them. UAV can be thought of as a generic title, as an RPA can always be designed as a UAV but, on the other hand, a UAV is not always an RPA.

There is no standard procedure for classification of UASs [36].

The first classification method used in civil science categorizes UAVs following prevailing military descriptions at different levels, dividing existing platforms into the seven groups summarized in Table 2 [31,37].

It is very common to classify UAVs by size or type. By size they are classified as very small UAVs, small UAVs (micro or mini UAVs), medium UAVs and large UAVs [31], and by type they are classified as fixed-wing systems or multirotor systems. The first type uses fixed static wings combined with forward airspeed to generate lift [34], while multirotors use rotary wings to generate lift.

In the USA, a recent classification refers to UAVs missions, classifying them into four general classes; small, tactical, theatre and combat [31].

A different way to classify UAVs is whether they are being used as non-expendable or expendable UAVs after completing their mission. Expendable UAVs are sometimes used in combat missions, as a weapon to attack a target.

As it already noted, there is no standard classification of UAVs, and

Table 3
Main characteristics of the three general drone classes: close range, short range and endurance [38].

Characteristic	Close range	Short Range	Endurance
Range [km]	≃ 50	≃ 200	> 200
Flight time	30 min to 2 h	8–10 h	> 24 h
Weight	< 5 kg	< 5000 kg	< 105 t
Speed [km/h]	≃ 60	< 485	< 730
Altitude [km]	< 6	< 16	< 20
Cost [USD]	500–70,000	< 8 million	< 123 million

other authors classify UAVs by range and endurance. Nevertheless, this method has been replaced by the newer procedures detailed above. However, it is useful to be aware of it, as it is mentioned in many types of research. Following this method [38], Table 3 summarizes the characteristics of these three different classes of drones: close range, short range and endurance.

Each kind of UAV has its advantages and disadvantages for different applications. For example, if it is needed to perform a fast flight over a large distance, a fixed wing UAV is the most appropriate. In contrast, if great stability to capture details from low altitude is needed, the best option is a multicopter, which is able to hover. In a multicopter, the rotor and rotorcraft are responsible for all flight aspects, generating lift, forward propulsion and the means to steer the craft, generating forces that move the vehicle [39]. Further information about UAV classification can be found in reference [40].

3.3. Technological review

Huge development and propagation of use of UAVs during recent years have resulted in an extensive range of platform alternatives. As already noted, there is abundance of information on applications and regulations of UAVs among scientific publications, nevertheless there is a lack of formal knowledge divulged about the most important techno-economical characteristics of UAVs for their application in the PV inspection field.

Among the wide range of UAV options, the most appropriate ones to perform thermographic inspections are multicopter systems, also known as multirotor systems, which consist of a rotorcraft with more than two rotors. These are the most stable ones, although they have shorter flying times, since they are power-hungry platforms. As multicopters are the most appropriate option for the application under study, other UAVs will not be analyzed further in this section. These platforms are the easiest to control, which makes them attractive to hobbyists [39]. Nevertheless, UAVs should not be considered to be toys, considering the risk that comes from using them. Although some authors consider that politicians and regulators have been very slow to establish guidelines to ensure public safety [41], most countries have already addressed these aspects. Many organizations are working to guarantee reliable integration of UAVs in the workplace because of their rapid development [42]. Before planning any flights, it is essential to study the applicable regulatory framework governing use of UAVs in public areas in the country concerned. For example, in Spain, UAVs are not allowed to fly over populated areas, in controlled air space or less than 8 km from an airport or airfield [43]. Additionally, in Spain, licenses required to pilot UAVs, compulsory aviation liability insurance and accreditation by the State Aviation Safety Agency are a legal requirement [44]. The list of all accredited operators is public and is available on the Agency's web site. As of today, the number of operators registered in Spain is 1938 [45].

The term rotorcraft is defined in aviation as an aircraft that uses rotary wings to generate lift [34]. Multicopters are usually classified by the number of motors they have [46], such as tricopter, quadcopter, hexacopter and octocopter with three, four, six and eight motors, respectively. Deciding the kind of multicopter in terms of the number of rotors will dictate the payload that the UAV is able to deliver. This is especially important in this application as it has to deliver a thermographic and a visual camera as well as other telemetry sensors. Also it affects the flight height (which can hugely reduce inspection time), safety of landing and stability during flight. For this reason, the different available alternatives will be extensively analyzed.

Commonly, these platforms use at least four rotors to keep them flying [34], so tricopters are not used as much. In general, the most popular multicopters on the market are quadcopters [47] as they have more power to lift and thrust than tricopters, allowing delivery of heavier payloads without significantly increasing manufacturing cost, and they are extremely maneuverable. Nonetheless, quadcopters are not as powerful as hexacopters or octocopters, which allow transportation of heavier and more complex cameras, other accessories or sensors and have a greater speed and elevation. Hexacopters are safer than quadcopters, allowing a safe landing even in the event of a damaged or dead motor and octocopters allow a safe landing even if they lose two or three rotors. As a result of increasing the amount of motors and propellers, there is a better control and stability of the aircraft and less influence from wind and rain. However, this increment means a larger device that is more expensive and has a shorter battery life.

Table 4 presents some of the UAVs used worldwide to perform thermographic inspections, such as DJI or Yuneec platforms and others which are customized to meet the needs of the purchaser.

Fig. 5 shows a hexacopter DJI S900 equipped with a Flir TAU 2 thermographic camera and a Hero 4 GoPro visual camera. The UAV's frame is the structure that holds together all the components of the drone. The drone landing gear is anchored to the lower part of the frame, as can be seen in Fig. 5. The equipment shown is ready to perform aerial thermographic inspections of PV plants. In Fig. 6, it is shown as a diagram with the different components of the drone and the connections between them. The main parts of this equipment are described below.

Starting with the ground site, the pilot commonly has two remote hand controllers (E1 and E2) and two screens (P1 and P2). P1 receives and displays the signal from the visual camera and from the telemetry systems (OSD) and E1 manages the drone (to move it forward, backwards, up, down, turning…), sending signals to receiver R1. The second screen (P2) receives and displays the signals from the auxiliary sensor, in this case from the thermographic camera, and E2 manages the gimbal (allowing the pilot or the gimbal operator to focus or position the camera as desired), sending signals to receiver R2. On the left side of the drone in Fig. 5, a remote hand control and screen can be seen.

In the air, the drone is equipped with numerous components with different functions. The GPS is composed of an antenna unit which receives satellite signals and an internal unit that sends telemetry data, such as flight altitude or speed, to the telemetry system OSD. The

Table 4
Different commercial UAV platforms used to perform PV thermographic inspections worldwide. All platforms are classified by manufacturer, model and number of motors.

Manufacturer	Model	Motors
DJI	S900	Hexacopter
	S1000	Octocopter
	Matrice 100	Quadcopter
	Matrice200	Quadcopter
	Matrice 600	Hexacopter
	Inspire 1	Quadcopter
	Inspire 2	Quadcopter
YUNEEC	Typhoon H	Hexacopter
Atyges	FV8	Octocopter
	FV6	Hexacopter
Multirotor	MULTIROTOR G4 Surveying	Hexacopter
	MULTIROTOR G4 Eagle	Octocopter
Drone Tools	Drone Octo XL	Octocopter

Fig. 5. Hexacopter DJI S900 equipped with a Flir TAU 2 thermographic and a Hero 4 GoPro visual camera. On the left side of the figure is the handheld remote control to pilot the drone and the screen that receives and displays sensor signals.

controller (A2) receives all the signals from R1, R2 and OSD, manages the drone and gimbal and sends telemetry signals to transmitter EMI1 and to the gimbal. The receivers are connected to the controller. R1 receives the signal from E1 for drone management while R2 receives the signal from E2 for gimbal management. The gimbal is the image stabilizer and minimizes unwanted drone movements. There are two transmitters. The first transmitter, EMI1, receives the signal from the controller (A2), from the telemetry unit (OSD) and from the visual camera and sends it to screen P1. With this information, the pilot knows where and how the drone is at all times, with visual images and telemetric information. The second transmitter, EMI2, receives the signal from the thermographic camera and sends it to screen P2, so that the pilot can see the thermal image. The visual and the thermographic cameras, which have been extensively described in the previous section, send their signals to EMI1 and EMI2, respectively.

Although not shown in Fig. 6, all the components are connected (directly or through controller A2) to a power source or battery. Sometimes two batteries are installed, one for the engines and drone components, such as the controller, GPS and OSD, and the other for the cameras and other components such as the transmitters.

One critical aspect of aerial thermography is the duration of batteries and flight time. The more the battery lasts, the more efficient the inspection. There are different power source options, such as batteries, solar power or hydrogen fuel, but drones for aerial thermographic inspection typically use batteries as they are the safest. A battery recharge cycle can take approximately one and half hours [43]. UAVs with Lithium Polymer (Li-Po) batteries can fly for approximately 10–40 min, which slows down the inspection, as batteries have to be recharged several times [48]. This kind of battery has a high energy density and can sustain high current loads, however they are too heavy [49]. The capacity of batteries is measured in milliamp hours (mAh) [50], which expresses how much charge the battery can store, ranging from 350 mAh for toy drones, 2000–3000 mAh for racing drones, 4500–6000 mAh for bigger multirotors (Phantom style) to 20,000 mAh for high capacity multirotors [51]. The need to increase flight time is driving research and development of newer battery technologies for drones. Graphene batteries, which are being implemented for drones during the last year, offer higher energy density and reduce charging times (they can be charged in 5 min), weight and volume (20–30% less than a lithium battery) [52].

4. Aerial thermographic inspection of PV plant related work

Photovoltaic modules present different faults generated at different stages of their life cycle: manufacturing, transportation, installation and operation. These faults are responsible for energy dissipation in photovoltaic modules, reducing electrical output and generating an abnormal temperature distribution and high stress. Tsanakas et al. [14] summarize the available work concerning thermographic diagnosis of crystalline silicon photovoltaic modules and PV module faults, classifying them into three different groups. First of all, optical degradation, which involves delamination, bubbles, encapsulate discoloration and glass breakage. Secondly, electrical mismatch and degradation, comprising cell fractures, snail trails, broken interconnection ribbons, poorly soldered shunts and short-circuited cells and shading. The third group corresponds to unclassified faults, such as Potential Induced

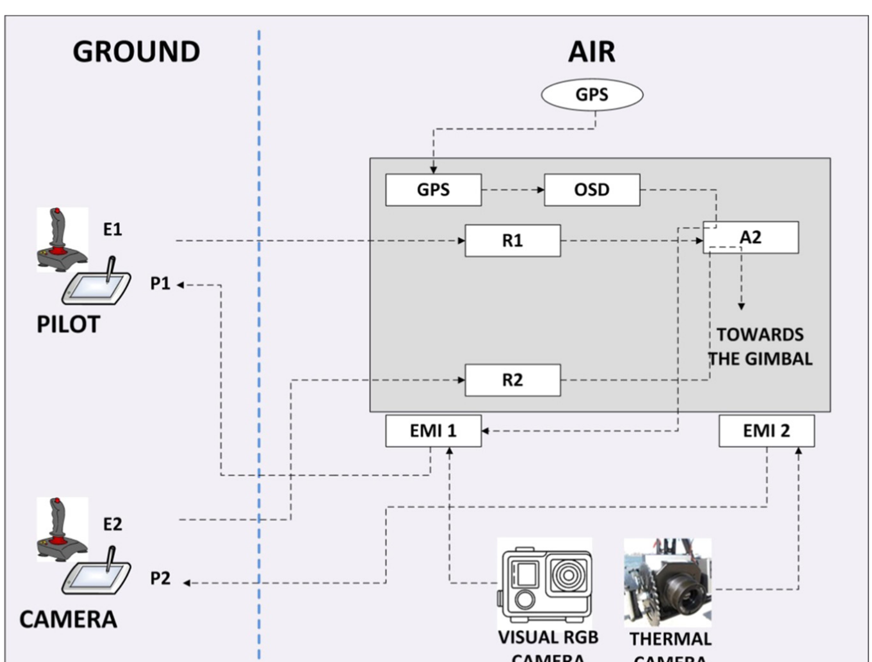

Fig. 6. Block diagram showing connections between the different components of a drone equipped with visual and thermographic cameras.

Degradation (PID).

The progress that instrumentation involved in aerial thermography has experienced during recent years has led aerial thermographic inspection to be the most suitable technique to identify underperforming PV cells at a PV site. Numerous researchers have started to probe its feasibility and suitability in this specific application during recent years, and major advances in the field have already been made.

From the beginning of the second decade of the twenty-first century some authors started to study the use of UAVs combined with thermographic cameras to monitor PV plants from the air. Denio [53] proposes the use of aerial thermography as a solution to easily reach photovoltaic arrays on rooftops and excessively large areas, concluding that it is a reliable technique to find solar arrays with problems at large scale sites but it needs to be coupled with confirmation on the ground of faults detected in flight. The equipment used in this research is not mentioned.

Later on, Buerhop et al. [12] used a remote controlled helicopter with an onboard bolometer-camera MIDAS with a spectral range from 8 µm up to 14 µm in order to inspect 60 photovoltaic plants of up to 1 MWp using aerial thermography. For the experiments, flight height was calculated to approximately achieve a spatial resolution of 7 cm/pixel in the resultant images. It was concluded that numerous faults can be viewed and distinguished with this technique, such as disconnected strings, substrings, shunted cells, faulty soldering and cell fracturing. Additionally, the impact of different faults is further studied by means of electrical simulations using an Ltspice simulator. The inspection ratio reported in this research is 5–8 min to inspect a PV plant up to 1 MWp.

Subsequently, Aghaei et al. [54,55], Bellezza et al. [16] and Grimaccia et al. [17] conducted research to prove the feasibility of UAV inspections of photovoltaic plants. The experiments of these researchers were performed on 37 independent photovoltaic modules of different technologies (15 poly-crystalline, 6 mono-crystalline, 8 micro-crystalline and amorphous silicon type, 2 flexible without glass and 6 PV-thermal) at the SolarTech lab set up on the roof of the Department of Energy at Politecnico di Milano University [17,54,55] and at actual photovoltaic plants: a PV plant in the Piedmont region with a capacity of 200 kW [16,55] and in a PV plant with about 12,600 polycrystalline photovoltaic modules (3 MW capacity) located in the north of Italy (48°50′ N and 11°07′ N) [17]. The main equipment used comprised three different Nimbus UAV platforms (PPL-610 [17,54,55], EosXi [16] and PLP6 [16]), which required use of ad hoc sensors onboard as inspection tools and different kinds of sensors onboard (thermal camera MicroCAM 640 by Thermoteknix Systems Ltd accompanied by a GoPro Hero3+ Black Edition and BRAUN Master [55] and an HD photo-camera Nikon1-v1 [16]). The sensors used in [17,54] are not specified in the paper, although it is noted that both visual and thermographic cameras were used. Results show that this novel method is an effective, powerful procedure for thermographic fault monitoring at photovoltaic sites, and more reliable, faster and cost-effective compared to traditional methods.

With the aim of validating this novel technique in comparison to traditional ground-based scanning, Kauppinen et al. [56] performed different measurements both from the ground and with a drone at two PV sites in Western Greece of 0.9 MW and 2 MW, respectively. The equipment involved in this research was: UAVs Jupiter Walkera QR-X800 (TL 16381, 60254) and Venus Walkera QR-X350 (TL 16309, 60255), FLIR Tau2 IR camera, Raspberry Pi visual camera, GoPro Hero 3+ HD video camera and FLIR E300 handheld IR camera. The authors concluded that the measurement system was successful and indicated that the product to be developed should allow automatic analysis of the images. Muntwyler et al. [57] developed its own remote-controlled system based on the commercial UAV platform DJI S1000 and a full radiometric thermographic camera Optris PI LightWeight PI400 and a GoPro Hero 3+ full HD with a resolution of 1920 × 1080. The aim of this project was to economically optimize quality control of predicted energy yields from photovoltaic plants, and it was tested on the PV LAB at Bern University of Applied Sciences BFH in Burgdorf, Switzerland, on the football stadium Stade de Suisse of 1.3 MWp and on the open-field Mont Soleil in the Jura Mountains of 554.5 kWp. The results confirmed the economic benefits of aerial thermography inspection compared to traditional manual thermography.

Aghaei et al. [58,59] follow the research proposing a promising automatic inspection and prognostic procedure by means of designing a control system able to perform photovoltaic system monitoring, diagnosis, fault and failure reconnaissance, data processing and to propose remedial actions. In this case, thermographic assessment is performed at the SolarTech Lab of the Department of Energy at Politecnico di Milano University previously detailed using a Flir A35 thermographic camera mounted on a PLP610 Nimbus platform. The main features of this camera are: resolution 320 × 256 pixels, available lenses 9 mm 48° (H) x 39°(V) or 19 mm 25° (H) x 39°(V), non-interchangeable and thermal sensibility < 0.05 °C. On the subject of image processing, Aghaei et al. [60] propose a digital image processing technique based on thermography assessment to provide Image Mosaicing for a better description of the plant by integrating many infrared images, making it easier to pinpoint the exact location of a fault within a PV plant and the total degraded area. Tests performed in [60] employed the same equipment as in [58], a light UAV PLP-610 Nimbus platform with a thermographic camera Flir A35 onboard. The results suggested that the algorithm was very efficient and reliable for analyzing the images, providing an advantageous perspective of photovoltaic plants during inspection. Following on with the automatic detection, Dotenco et al. [61] proposed automatic detection and analysis of aerial infrared images throughout the image processing pipeline. It was shown that significant temperature abnormalities such as hot spots and hot areas can be identified using their processing pipeline. The process used to identify such faults is composed of two different steps. First, the individual modules within infrared images are detected, and then statistical tests are used to identify the faulty modules. The approach is validated by means of its application to detection and analysis of faults on real-world infrared images. The inspection was performed at two different photovoltaic plants in Germany with a total power of 7MWp, and the equipment used was an unspecified remote-controlled octocopter equipped with GPS DaVinci Copters ScaraBot X8 and two light weight cameras; an Optris PI450 infrared camera and a GoPro Hero3+ RGB camera.

Later on, the same research group, Aghaei et al. [62], studied the correlation between flight altitude and detection of visual faults at photovoltaic plants with a digital camera, concluding that fault identification can be classified according to UAV flight altitude. The experiments were performed at the SolarTechLab laboratory where previous research had been undertaken, and the equipment used was a Nimbus PLP-610 UAV with a Nikon 1-V1 digital camera onboard with the following main characteristics: resolution 3906 × 2606, weight 294 g, 13.2 mm x 8.8 mm image sensor and mirror-less interchangeable lens. Grimaccia et al. [63] also studied the most observed faults during aerial thermographic inspections and their frequency, using a Nimbus PPL612-PV UAV hexacopter and two different synchronized cameras (Panasonic Lumix GM1 HD (4592 × 3448) and FLIR A35 (640 × 512) thermal imager). The results suggested that the most frequent faults in ascending order are discoloration/browning, snail trails, hot spots, by-pass/disconnect, dirty, shading, cracked cells and oxidation/corrosion.

Dalsass et al. [64] studied the correlation between radiometric infrared results obtained by means of aerial thermography and monitoring data from inverters (SMA STO 17000 TL-10), as thermographic images do not provide a quantitative estimation of power generated at a photovoltaic plant. The experiments were performed at three photovoltaic plants with a total power of 9.4 MWp. For generation of results an octocopter DaVinci Copters Scarabot X8 and two lightweight cameras were used, Optris PI450 IR camera and GoPro Hero3+ RGB camera. Conclusions suggested that there was a strong correlation between faulty modules and power of the associated string.

Tsanakas et al. [65], on the subject of automatic detection of faults and its application at large-scale installations, proposed two different techniques for advanced inspection mapping of photovoltaic plants; aerial triangulation, which uses data from images obtained with a UAV to generate orthophoto mosaics, and terrestrial georeferencing, which associates terrestrial images taken at different positions of the photovoltaic plant with geographic data. The aerial data was captured with a Condor AY-704 hexacopter with a 12 min flight autonomy equipped with an Optris PI450 thermal camera, along with a miniature lightweight PC on two grid-connected PV systems, installed within the campus of the Institut National de l'Ènergie Solaire (INES), at Le Bourget-du-Lac, in south-eastern France. This thermal camera has an uncooled focal plane array (UFPA) detector that provides images within a temperature range of -20–900 °C with a thermal sensitivity of 0.04 K, accuracy of ± 2% or ± 2 °C and full radiometric images with a resolution of 382 × 288 pixels.

Recent publications tend to focus on a computer vision approach in order to automate fault detection. Addabbo et al. [66] propose a fusion of computer vision algorithms and high accuracy Global Navigation Satellite System (GNSS) positioning techniques to detect and tag anomalies in faulty modules. This integration allows panel identification by assigning an identifier to each module that remains constant throughout different flight sessions. Different Commercial Off-The-Shelf (COTS) equipment available on the market is used in this research, such as the DJI Matrice 100 UAV platform and different sensors such as the Thermal camera Flir Vue Pro, Flir TAU2 640 × 512 and DJI Zenmuse X3 optical camera and gimbal. The inspection was performed at a test site in Lo Uttaro, a location in the Province of Caserta, Italy. Abdin et al. [67] proposed the use of a fuzzy logic algorithm to make fault diagnostics of Photovoltaic modules smart and automatic with the aim of proposing and planning the required actions to be taken at the plant and to improve plant reliability. Fault classification is done by a fuzzy rule while fault analysis is obtained by heuristic knowledge. More than 120 thermographic images of healthy and faulty modules have been used in this analysis, taken with a Flir T165, which is a handheld camera for taking images from the ground, not on board a UAV platform.

The equipment reported in the related literature is summarized in Table 5.

5. Discussion

The application of UAVs in thermographic inspection of photovoltaic modules is a major advancement in O&M activities of PV plants.

Thermography presents many advantages compared to traditional tests applied to the modules, such as electrical tests. Electrical tests allow detection of abnormal underperforming situations but do not recognize the cause or the location of the faulty module or cell. Besides not providing complete information about the defect, it is necessary to shut down the plant during the electrical inspection, which means reducing energy production significantly. For that reason, thermographic inspection is the most common method to detect faults at photovoltaics plants, being fast and simple to implement and obtaining results in real time, with no need to shut down the plant during the inspection. It is non-destructive, contactless and allows identification of faults and their exact location with great accuracy, providing a temperature map of the surface of the modules which reveals the faults. Nevertheless, despite being a trustworthy method, manual thermography presents some significant drawbacks. It is a costly and time-consuming technique and there are some situations in which it is hard to detect the faulty cells. One of these cases is PV plants in which inclination of the modules is very low (the modules are nearly horizontal), such as the one shown in Fig. 7. This layout has some advantages; for example, shading between rows is decreased, path widths can be reduced and there is more production during the summer months, when the sun is higher in the sky. On the other hand, it has some drawbacks; for instance, modules accumulate surface snow or dirt easily and it is difficult to reach some modules in order to undertake their inspection. This last drawback

Fig. 7. Photovoltaic plant located in Japan with very low inclination of modules. This module layout complicates the performance of manual thermography as it is difficult to reach the tops of the modules with the necessary angle.

Table 5
Summary of the thermographic cameras and UAVs used by the aerial thermographic research reported in the analyzed literature.

Reference	Thermographic Camera	UAV
Denio [53]	Not specified	Not specified
Buerhop et al. [12]	Bolometer-camera MIDAS	Helicopter
Aghaei et al. [54]	Not specified	NimbusPPL – 610
Aghaei et al. [55]	MicroCAM 640 by Thermoteknix Systems Ltd	NimbusPPL – 610
Bellezza et al. [16]	MicroCAM 640 by Thermoteknix Systems Ltd	NimbusEosXi and NimbusPLP6
Grimaccia et al. [17]	Not specified	NimbusPPL – 610
Kauppinen et al. [56]	FLIR Tau2	Jupiter: Walkera QR-X800 (TL 16381, 60254) and Venus: Walkera QR-X350 (TL 16309, 60255)
Muntwyler et al. [57]	Optris PI Lightweight PI400	DJI S1000
Aghaei et al. [58]	Flir A35	NimbusPPL – 610
Aghaei et al. [59]	Flir A35	NimbusPPL – 610
Aghaei et al. [60]	Flir A35	NimbusPPL – 610
Dotenco et al. [61]	Optris PI450	Remote-controlled octocopter – Model not specified
Aghaei et al. [62]	Not used	NimbusPPL – 610
Grimaccia et al. [63]	FLIR A35	HexacopterNimbus PPL612-PV
Dalsass et al. [64]	Optris PI450	OctoperDaVinci Copters Scarabot X8
Tsanakas et al. [65]	Optris PI450	Hexacopter Condor AY – 704
Addabbo et al. [66]	FlirVue Pro and Flir TAU2	DJI Matrice 100
Abdin et al. [67]	Flir T165	Not used

makes it almost impossible to perform manual thermography at these kinds of PV plants. However, it would be easier to inspect the site using aerial thermography. A similar case is the PV plants that use trackers instead of fixed structures. Trackers point the modules towards the sun and consequently the inclination angle of modules during the early afternoon is too low, complicating manual thermographic inspection during that period. In addition, this coincides with hours of higher temperatures and irradiance which are the most effective time to perform a thermography. Therefore, in these situations aerial thermography is a suitable alternative for identifying under-producing modules.

Additionally, rapid growth of photovoltaic power capacity and the tendency to construct bigger PV sites with higher capacity make development of innovative techniques necessary, such as aerial thermography, so that performing thermography or optimizing maintenance activities is possible.

Therefore, application of aerial thermography at photovoltaic plants needs to be understood not just as an innovative technique to save time and money, but as a necessary technique to be able to assess production in these highlighted situations where applying manual thermography is not possible.

However, this technique also presents some disadvantages. Although aerial thermography is cost-saving compared to manual thermography due to reduction of time and manpower, equipment used in aerial thermography is nearly ten times more expensive than equipment used in manual thermography. Additionally, the enormous propagation in the use of UAVs and thermography and extensive research on this subject involve continuous development and advancement of equipment, which means that the equipment can quickly become obsolete. Therefore, in order to invest in this equipment, it is absolutely necessary to perfectly understand the equipment and its characteristics, with the aim of obtaining accurate and usable results.

Regarding thermal cameras designed for integration in UAVs and considering the vast number of applications in which aerial thermography is used, technology is improving and developing and the cost of these devices is now lower than in the past. As shown in Table 1, some equipment already available on the market has a resolution of up to 640 × 512 pixels, thermal sensitivity of 0.03 K and accuracy of ± 2% or ± 2 °C.

As shown in Fig. 2, a resolution of 80 × 60 pixels is not enough in this application, as it does not allow detection and quantification of faults. On the contrary, clearly resolutions of images presented in Fig. 3 and Fig. 4, which have been captured with a 336 × 256 and 382 × 288 pixel sensor, respectively, are suitable for detecting module faults.

The minimum temperature difference (ΔT) between the faulty cell and the healthy area of a module is considered a malfunction if it is 5 °C or higher [14], so thermal sensitivity of 0.03 K is acceptable for accurate detection of malfunctions in PV modules.

In terms of accuracy value, which is generally around ± 2% or ± 2 °C or ± 5% or ± 5 °C, it is important to understand that, in this application, it is necessary to measure temperature difference (ΔT), so the accuracy of this difference will be twice that of the accuracy of each single temperature point. As differences of 5 °C are already reported in the literature, accuracy of available commercial cameras is not yet enough to report precise results, and therefore, it is especially important to use a camera with high accuracy. Additionally, the specific characteristics of the measured object, such as emissivity and reflection temperature values, have to be measured and inputted into the camera settings for each inspection in order to obtain accurate results.

A key aspect of the camera is its lens. In most cases, lenses are not interchangeable and need to be specified when ordered. Therefore, before acquiring any thermographic camera or lens it is essential to calculate FOV, IFOV and IFOV Measurement.

The object under analysis, in this case, PV rows covered in each flight pass, has to be completely covered by the FOV of the camera at each moment. The terrain size covered in each flight pass depends on layout or distribution of the modules, width of the path between rows, module inclination, angle at which the images are taken and number of PV rows that have to be captured in each flight pass. In order to prevent reflections from the sky or other objects and to suitably detect the module's anomalies, images should be taken as perpendicular to the modules as possible [12,58,68], always considering the time of day, day of the year and location of the PV plant to avoid sun reflections. Considering a PV plant in which the modules are fixed towards the south at 30° angle, a perpendicular image and a path width of 3.5 m for three different module layouts (1 V, 3 H and 2 V), the resultant FOVs to cover two and three rows per flight pass are shown in Table 6. As it has been assumed that the platform is flying facing the PV rows, the vertical FOV determines how many rows can be inspected.

Table 6
Resultant Vertical FOV for different module layouts (1V, 3H, 2V/4H). The calculation considers a path width of 3.5 m and 30° module inclination. The table shows resultant FOV for capturing 2 and 3 rows per flight pass for each of the three layout configurations.

	Module Layout		
	1V	**3H**	**2V or 4H**
Vertical Row Size [m]	2	3	4
Path Width [m]	3.5	3.5	3.5
Module inclination [°]	30	30	30
Path Width from drone [m]	2.5	2.3	2.0
Vertical FOV 2 rows per flight pass [m]	**6.5**	**8.3**	**10.0**
Vertical FOV 3 rows per flight pass [m]	**11.1**	**13.6**	**16.1**

Therefore, as shown in Table 6, a vertical FOV from 6.5 m to 10 m, depending on the layout of modules, is required to capture two PV rows per flight pass (considering the above assumptions) and a vertical FOV from 11.1 m to 16.1 m is required to capture three rows.

The specification of the smallest object to be measured establishes the required pixel size according to flight height and camera sensor. Applying these factors to aerial thermography for inspection of PV plants, if the smallest area to be measured is a PV cell of approximately 15 cm each side, IFOV Measurement is $15 \times 15\,cm^2$ while IFOV is $5 \times 5\,cm^2$. Therefore, pixel size at the determined flight height and with the selected camera and sensor has to be smaller than $5 \times 5\,cm^2$. Most thermographic camera manufacturers offer the option to do these calculations using their website or even using their applications on smartphones, selecting the camera model (to factor in the sensor), lens (to factor in the focal length) and distance from camera to object (for this case study, the flight height). Some examples of these tools are those offered by manufacturers Optris [69] and Testo [70]. The different possibilities in terms of commercially available lenses for thermographic cameras shown in Table 1 have been analyzed with the aim of selecting the appropriate lens, which fulfils the requirements of FOV shown in Table 6 and IFOV or pixel size of 5 cm each side. The results of this analysis are summarized in Table 7.

Table 7 shows that, with lenses selected for the cameras from the first and third group, which have the higher resolution, all proposed cases in Table 6 can be fulfilled, as the Vertical FOV is higher than 16.1 m and they have an IFOV considerably less than 5 cm each side, increasing the accuracy of measurements. On the other hand, it cameras with lower resolutions can meet the requirements for capturing two rows per flight pass, as they have a vertical FOV higher than 10.0 m, but not for capturing three rows per flight pass in all cases. With a 336 × 256 resolution, cameras with a 25° x 19° lens, it will not be possible to cover three rows per flight pass in the cases of 3 horizontal (landscape) and 2 vertical (portrait) module layouts. In the case of 382 × 288 resolution cameras with a 29° x 22° lens, it will not be possible only in cases of 2 vertical (portrait) layouts. All these calculations have to be completed before acquiring any camera or lens, adapted to each case study. In relation to the radiometric functionality,

Table 7
Resultant IFOV and FOV for different manufacturer off-the-shelf lenses, thermographic cameras models and flight heights.

LENS: FOV [°]		Camera manufacturer	Camera Model	Resolution	Flight Height [m]	FOV [m]		IFOV Pixel side [cm]
Horiz.	Vert.					Horiz.	Vert.	
45	**37**	Flir	VUE PRO R 640	640 × 512	25	20.7	**16.7**	**3.3**
			TAU 2 640					
			ZENMUSE XT 640					
		Workswell	WIRIS 640					
25	**19**	Flir	VUE PRO R 336	336 × 256	34	15.1	**11.4**	**4.5**
			TAU 2 336					
			ZENMUSE XT 336					
		Workswell	WIRIS 336					
33	**25**	Optris	PI 640 Lightweight	640 × 480	34	22.5	**16.8**	**3.5**
29	**22**		PI 400 Lightweight	382 × 288	36	18.6	**14.0**	**4.9**

there are some thermographic cameras that do not include this functionality. This kind of camera can be used along with a drone flight in order to detect where the malfunctions are, but a subsequent inspection of these points with a radiometric thermal camera is required to determine their severity. On the other hand, radiometric cameras give a value of absolute temperature in every pixel of the image. For that reason, the more pixels the camera has the more details are detected. In other applications, such as in security systems, it is not necessary to obtain the temperature at each point, they only require differences in temperatures to identify intrusions. In these cases, unlike PV described, a radiometric camera is not required.

Additionally, another important point is availability of an RGB image together with the thermal image, which can be helpful during the post-processing stage. Visual images can avoid identification of false faults, commonly known as false alarms or false positives, as a cell could appear hotter than the average module temperature in a thermographic image as a result of a bird dropping or other temporary shadows [13], which are not hot-spots. This is an important point to consider when selecting equipment as not all platforms support implementation of more than one sensor. The temperature range of thermographic cameras is between 20 °C and + 500 °C. For the specific case of photovoltaic inspection, module temperatures should be between ambient temperature and a maximum of approximately 100 °C in the case of a significant fault. Therefore, this parameter should not be an issue, although it has to be considered.

The price of thermographic cameras varies considerably depending on the technology and functionalities included. For instance, given that prices can change significantly with newer developments, prices of thermographic cameras in Table 1 range from roughly 2,500-6000 € for cameras with lower resolution up to around 4500 € – 9500 € for cameras with higher resolution. The Zenmuse XT, which is a special ready-to-fly product directly integrated in DJI products, ranges from 7500 to 12,500 € depending on resolutions and lenses. All prices can be checked on manufacturer or approved reseller websites.

With respect to UAV platforms, selecting an appropriate one to carry a thermal camera is just as important as having the latest camera with excellent characteristics. If the platform cannot provide stability for the camera, the resultant images or videos will not be accurate enough. Consequently, the system's stability is one of the most significant factors to consider when choosing a drone for thermal inspection of PV plants. That is why multicopter systems are the most appropriate platforms for this specific application.

Considering the advantages and disadvantages of the different kinds of UAV in relation to number of rotors discussed in previous sections, for aerial thermal inspections of PV plants where it is necessary to carry gear (like a gimbal) and a stable and reliable platform, the hexacopter is a good compromise between performance and price [46,47], yet this does not mean that quadcopters or octocopters cannot be used for this application.

Prices of the commercial platforms are highly heterogeneous depending on the different characteristics and functionalities. UAVs shown in Table 4 have a wide range of prices, starting from around 2000 € for the most basic commercial quadcopter to more than 28,000 € for advanced customized platforms.

Weight, model and energy source of the UAV will determine maximum altitude, flight duration and maximum payload. Before choosing a UAV, it is crucial to define all these aspects. Therefore, altitude range at which the inspections should be performed as well as thermographic and visual cameras (the payload) should be known before acquiring an UAV. There is no standard detailed methodology for flight parameters in aerial thermographic inspections; however it is known that some authors have performed their experimental measurements from 20 m [71] to 40 m [43], depending on the thermographic camera and lens. In addition, full compatibility with platform and payload must be guaranteed. On the one hand, there are some UAVs that are not powerful enough to carry two different sensors at the same time. For example, the quadcopter DJI Inspire 1 is only prepared for carrying one gimbal and its maximum take-off weight, which is specified in the data sheet, is 3500 g. Considering that the platform itself weighs 2845 g (including propellers and battery, without gimbal and camera) the payload should not exceed the difference between the above-mentioned values [72]. As a result, if the requirement is to acquire both RGB and thermographic frames or video with this specific UAV, it is necessary to perform two different flights, each with the corresponding sensor, increasing flight time and reducing efficiency of the process. On the other hand, not all sensors fit all gimbals and, furthermore, not all gimbals are suitable for all platforms. Some UAV and thermographic camera manufacturers are making some specific arrangements in order to offer full compatibility between their products, as is the case of DJI and Flir, which offer ready-to-fly products with integration of a DJI Zenmuse XT stabilized camera featuring Flir's thermal imaging technology with DJI's Inspire 1 and Matrice platforms [73], avoiding in this way integration efforts between different products.

In relation to UAV batteries, it is necessary to consider how many batteries will be needed in a day to perform the complete flight and where they can be charged on-site (availability of grid connection, autonomous generator, etc.). Proper battery handling is a key point, as they can be hazardous if exposed to high temperatures.

Improvements in the new generation of UAVs are going in different directions. First of all, with regard to configuration, the trend is to be smaller, more autonomous, cheaper and with a more rugged and sturdy structure, by using new materials, new technologies and fabrication methods, such as additive manufacturing [74] and more efficient batteries [34]. Furthermore, regarding stability of the platform, efforts are being directed towards creation of UAVs capable of ensuring stable flights in rough conditions, such as strong winds or extreme temperatures, by using high-performance motors, dual-battery systems or water resistant materials and encapsulation, with the aim of being able to fly in a wider range of environments [75]. Finally, with regard to compatibility and adaptability, the trend is towards increasing these features in commercial drones, ability to mount different payload configurations, such as dual-gimbal, incorporating additional connectivity and power ports to support third-party sensors and accessories, and improving and customizing the controlling software.

Based on information about equipment used in the reported literature, summarized in Table 5, some conclusions can be extracted. First of all, as it is a novel technique, there is not much literature available and most of it corresponds to the same research groups. As shown in Table 5, in all research multicomputer systems have been used for performing the inspections, because in this application stability is a key factor, with the exception of one of the early research projects [12], in which a helicopter was used. Additionally, a clear trend can be seen in equipment used; from customized platforms to commercial multicopters and thermographic cameras. This is because enormous development and propagation in the use of UAVs and thermographic cameras during recent years have resulted in specialized manufacturers that offer off-the-shelf ready-to-fly products at a cheaper price than the customized platforms that were being used some years ago. This development has improved so much that the actual characteristics of available thermographic cameras are better than some of those used in the analyzed literature. For instance, it is noted that for the thermal camera Flir A35 there were only two different lenses available, while current cameras support at least four or five different lenses. Finally, much of the equipment reported in Table 5 is used in different research projects, but this is mainly because they have been performed by the same research group.

6. Conclusions and future perspectives

It is clearly essential to fully understand the current possibilities of equipment in terms of techno-economical characteristics before investing in this instrumentation and to ensure accurate and usable results. In this paper, the current state of thermographic cameras and UAVs technology has been reviewed in six sections, examining and discussing general principles of aerial thermographic measurement, the most important system aspects of required instrumentation, research done by others and advancements in the field.

Image quality has a significant impact on the accuracy of photogrammetric end products and depends on many aspects of the thermographic camera, such as resolution, thermal sensitivity, accuracy, lens and the corresponding FOV, radiometric functionality, visual or RGB images, frame rate or temperature range, as well as UAV characteristics, such as stability of the system, maximum altitude, flight duration and maximum payload, full compatibility between instruments and duration of batteries.

All of these aspects have been evaluated for the specific application of aerial thermographic inspection of photovoltaic plants to assess the performance of the modules. This paper aims to present a clear review and discussion of available equipment and its main characteristics applied to photovoltaic plants, as well as review equipment already used in this application as reported in the related bibliography.

New generations of thermographic cameras and UAV are going in different directions. Regarding their configuration, the trend is to be smaller, more autonomous, cheaper and with a more rugged and sturdy structure, by using new materials, new technologies and fabrication methods. Additionally, regarding stability of the platform, efforts are being directed towards creation of UAVs capable of ensuring stable flights in rough conditions, such as strong winds or extreme temperatures, by using high-performance motors, dual-battery systems or water resistant materials and encapsulation, with the aim of being able to fly in a wider range of environments. Finally, with regard to compatibility and adaptability, the trend is towards making commercial drones more adaptable, ability to mount different payload configurations, such as dual-gimbal, incorporating additional connectivity and power ports to support third-party sensors and accessories and improving and customizing the controlling software. The improvements in the latest models of thermographic cameras for UAVs are mainly going in the same directions instead of improving some specific characteristics of these thermographic cameras, such as resolution, which are already acceptable for most applications. This is primarily because the trend of offering cheaper products, in order to generate higher market demand, is not yet compatible with the improvement of these features.

Although the evolution these devices so far has been reviewed and the actual available technologies have been shown, the vast propagation of use of UAVs and thermography and extensive research on this subject suggests continuous development and progress. Therefore, equipment features should be updated continuously.

Acknowledgements

The authors would like to acknowledge the countless equipment manufacturers, resellers and professional operators who have contributed to this review showing the latest trends and key points for the specific case study. The authors would like to extend special thanks to Solarig, global operator of photovoltaic plants and to Skydron, a specialized drone operator.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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