Aerial thermographic inspection of photovoltaic plants: analysis and selection of the equipment

Sara Gallardo-Saavedra[1], Estefanía Alfaro-Mejia[2] Luis Hernández-Callejo[1], Óscar Duque-Pérez[3], Humberto Loaiza-Correa[2] and Edinson Franco-Mejia[2]

[1] Universidad de Valladolid (UVa), School of Forestry, Agronomic and Bioenergy Industry Engineering (EIFAB), Department of Agricultural and Forestry Engineering, Soria (Spain)

[2] Universidad del Valle, Escuela de Ingeniería Eléctrica y Electrónica, Santiago de Cali (Colombia)

[3] Universidad de Valladolid (UVa), Industrial Engineering School, Department of Electrical Engineering, Valladolid (Spain)

Abstract

In recent times, more and more countries are choosing the alternative of generating clean energy. The photovoltaic (PV) energy installed is rapidly increasing around the World. PV cells are made with semiconductor materials such as Si, GaAs, among others. Despite the quality controls in the manufacture and manipulation of the panels, damages occur during their manufacturing, installation, use or of wear due to environmental factors, doing it necessary a periodic review. Manual inspections become expensive and largely inefficient due to the big extensions of PV plants. For this reason, it is necessary to automate the inspection task. This paper presents a methodology for the selection of equipment used to make inspections of faults in solar panels using aerial thermography, based on the review of the state of the art and the latest equipment technology available.

Keywords: Aerial thermography, photovoltaic inspection, photovoltaic thermography, faults diagnosis

1. Introduction

Renewable energies are an adequate answer to the actual problems of energy deficit. The negative effects caused by fossil fuels are disheartening due to their harmful impact on climate change, marine and terrestrial ecosystems. The impact generated is so big that there have been appreciable increases in the expected extinction rates.

Nowadays, more countries are choosing the alternative of generating clean energy. An example of this is Portugal, which used solar, wind and hydroelectric energy during four days, supplying the entire country network using natural sources of energy generating zero carbon emissions.

It is therefore necessary to be aware of the current environmental situation by promoting the use of clean energy. Solar radiation is a renewable source harnessed from photovoltaic cells, which are made with semiconductor materials such as Si, GaAs, among others. Despite the quality controls in the manufacture and manipulation of the panels, damages occur during their installation, their use or of wear due to environmental factors. The environmental exposure is one of the factors that most contributes to the underproduction of the modules. Optical degradation is a common effect produced as a consequence of a prolonged sun exposure, generating a discolored appearance and favoring the increment of temperature and humidity in the module. This affects electrical characteristics of the module and produces electrical mismatches which can lead to fractured cells that generate remarkable power losses (Tsanakas et al., 2016), doing it necessary a periodic review.

Also, due to the big extensions that modules cover, manual inspections become expensive and largely inefficient as a result of the capture conditions such as solar angle, irradiance levels, among other factors, which must be taken into account. For this reason, it is necessary to automate the inspection task. An alternative technique often used today, is to perform a photogrammetric flight with Unmanned Aerial Vehicles (UAVs), considering parameters such as the area covered by each photograph, separation between flight lines, among others.

doi:10.18086/swc.2017.20.03 Available at http://proceedings.ises.org

The inspection of solar panels using aerial thermography with UAVs is a topical issue. During the years 2015, 2016 and 2017 it has had 6, 9 and 13 publications respectively in high impact magazines, which confirms that aerial thermography is a very active area of research at the present time.

Different methodologies have been explored for the detection of faults in solar panels, some of them are: the analysis of electrical measurements to classify abnormal behavior in the characteristic curve IV, infrared thermography (IRT) and electroluminescence (El). The first alternative can be impractical and costly since it requires that each module must be monitored. Alternatively, IRT and EL allow non-invasive quantification of the damage presented by the photovoltaic module.

The main objective of this paper is to study the equipment that has been used in the researched presented up to now, with the objective of proposing a methodology for the selection of equipment for fault detection with thermography applied to photovoltaic plants and considering the requirements for the protocol of image capture. To achieve that goal, a comprehensive review of the equipment used for fault inspection in solar panels using thermography is accomplished and a methodology for the selection of equipment is proposed, highlighting relevant aspects in thermographic cameras and UAVs.

2. Method

The applied methodology used to fulfil the objectives of this paper has been the research on the necessities and aspects involved in thermographic inspections of PV plants, the key characteristic of sensors and platforms and the current technologies available in the market. The results have been obtained by means of reviewing the current literature in relation with this topic; investigating the available technology in the market contacting manufacturers and distributors of this instrumentation and by the internet and collecting information about the most important aspects with the aid of professional operators. More than thirty different parties have been contacted, from which relevant information and key points have been obtained.

3. Results and discussion

Nowadays, 80% of the energy produced worldwide is produced from fossil fuels, generating therefore a negative impact on the environment and increasing the CO_2 emissions and increasing the global warming. Consequently, it is necessary to change to renewable alternatives that replace non-renewable energy sources. A clean alternative is the solar energy, which is produced from photovoltaic modules manufactured with GaAs and monocrystalline and polycrystalline Si, being more efficient in the monocrystalline configuration. Each kW produced by photovoltaic systems reduces 0.6 kg the CO_2 emissions (Elibol et al., 2017).

Photovoltaic modules present faults throughout different stages, being the environmental exposure the one that most contributes to the underproduction of the modules. Optical degradation is a common effect produced as a consequence of a prolonged sun exposure, generating a discolored appearance and favoring the increment of the modules temperature and humidity. This affects electrical characteristics of modules and produces electrical mismatches which can lead to fractured cells, generating remarkable power losses (Tsanakas et al., 2016).

Different methodologies have been explored for the detection of faults in solar panels, some of them are: the analysis of electrical measurements to classify abnormal behavior in the characteristic curve IV, IRT and El. The first alternative can be impractical and costly since it requires that each module must be monitored. Alternatively, IRT and EL allow non-invasive quantification of the damage presented by the photovoltaic module, measuring the temperature difference that the faulty modules present. Due to the large area that current photovoltaic sites take up, an adequate way to carry out the inspection is using UAV, where the photogrammetric routes are plotted, considering times to cover the total area and the amount of frames per second or overlap of images

The research on this topic has had an important impact since the year 2015, when the use of UAVs and portable thermographic cameras in aerial vehicles was integrated to the inspection and diagnosis of photovoltaic modules. This impact can be shown in Fig. 1 which has been obtained by examining the bibliography Scopus database for the last years, using the following search equation: PV AND UAV AND THERMOGRAPHY AND PUBYEAR > 2014 AND PUBYEAR < 2018 AND (LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016) OR LIMIT-TO (PUBYEAR,2015)). This figure represents the high impact of this topic, in which the number of published articles has increased from 6 articles in 2015, to 9 in 2016 and 12 articles so far this year. The research centers and universities that lead this research at to now are: Universia degli Studi di Napoli Federico II, Politecnico di Milano, Korea Institute of Civil Engineering and Building Technology.

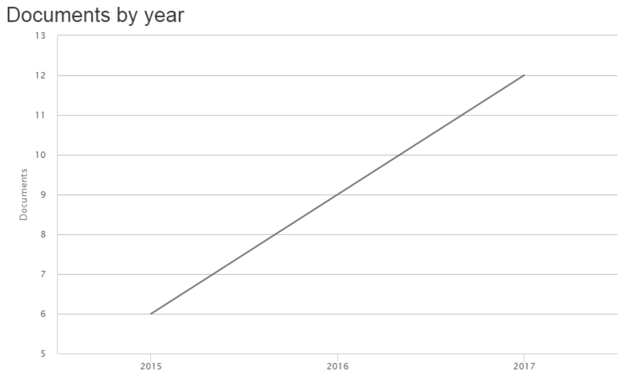

Fig. 1 EB1 impact of the theme between 2015-2017

The results obtained regarding the characteristics of the instrumentation used in the research reported so far are presented throughout the following paragraphs. Different offline processing techniques are introduced and analyzed.

There are different manufacturers which offer alternatives for the inspection and diagnosis of defects in PV plants. One example of this is the manufacturer Workswell, which proposes the use of its thermographic cameras in different applications, as the building diagnosis, roofs and high voltage lines inspections. This manufacturer has developed high spectral range thermographic cameras that combine the thermographic and visual images, as they incorporate a RGB camera. Additionally, there are some tier one brands which are starting to offer ready-to-flight products for the inspection of PV plants, as for example DJI and Workswell. These brands offer the possibility of using a DJI S900 with a Workswell thermographic camera and the software Workswell CorePlayer for the image post-processing. This software has different functionalities, as modifying the emissivity or the reflection temperature values, obtaining thermal curves, geometrical delimitation of relevant areas using dots or rectangles or generating reports. The equipment reported in (Wiris, n.d.) is summarized in Tab. 1.

Tab. 1: UAV and Thermographic camera characteristics reported in (Wiris, n.d.)

UAV	**Characteristics**		**Thermographic camera**	**Characteristics**	
DJI S900	**Flight controller**	A2	Worskswell Wiris (integrated RGB camera)	**Resolution (pixels)**	640x512 - 336x256
	Total Weight (kg)	3,3		**Temperature sensitivity (mK)**	50 to 30
	Power Battery	LiPo (6s 10000 mAh)		**Spectral range (um)**	7,5 to 13
	Max Power consumption (W)	3000		**Weight (g)**	<400
	Hover time (min)	18		**Memory**	32 GB
	Hover environment temperature (°C)	-10 to 40		**Temperature ranges (°C)**	25 to 150
	Takeoff Weight (kg)	4,7-8,2		**Accuracy**	+-2% or +- 2 °C
	Dimensions (mm)	460x450x360		**IR Color Palettes**	19 interchangeable in real time
	Type	Hexacopter		**Emissivity**	Adjustable

The main equipment used in (Addabbo et al., 2017) is an UAV Matrice 100 of DJI and a thermographic camera Flir Tau 2. Their main characteristics are summarized in Tab. 2. Additionally, it is used a RGB DJI Zenmuse X3 camera to obtain visual images. In this research, the UAV performs a defined flight plan over the modules to capture the thermographic and visual images separately.

Tab. 2: UAV and Thermographic camera characteristics reported in (Addabbo et al., 2017)

UAV	**Characteristics**		**Thermographic camera**	**Characteristics**	
DJI Matrice 100	**Flight controller**	N1	Flir Tau 2	**Resolution (pixels)**	640x512 - 336x256
	Total Weight (kg)	2,3		**Temperature sensitivity (mK)**	50 to 30
	Power Battery	LiPo (6s 10000 mAh)		**Spectral range (um)**	7,5 to 13
	Max Power consumption (W)	3000		**Weight (g)**	112
	Hover time (min)	18		**Memory**	32 GB
	Hover environment temperature (°C)	-10 to 40		**Temperature ranges (°C)**	-25 to -135, -25 to -100
	Takeoff Weight (kg)	3,6		**Accuracy**	+-5% or +- 5 °C
	Dimensions (mm)	650		**IR Color Palettes**	15 interchangeable in real time
	Type	Quadcopter		**Emissivity**	Adjustable

The data taken by the optical RGB sensor is communicated through one of the drone buses with the embedded system equipped on board the UAV, called the Intel Joule 570X quad-core, where some processes are carried out, such as management of sensor acquisition, the storage of the acquired images and the detection algorithm, in which a task of labeling and identification of the panels is executed. The input data for the tracking and geo referencing algorithms require altitude data and GPS, which are extracted from the DJI on board SDK. The SDK can be modified using programming languages such as C or C ++.

For the definition of the thermographic images capturing protocol, a video/C&C port (GPIO) of the drone is used. This port is connected with the embedded system Joule 570X, which allows the control of the Gimbal by a serial port. Subsequently, the processing of the thermographic images is done offline.

In (Kauppinen et al., 2015) it is used a quadcopter Walkera QR X800 a thermographic camera Flir Tau 2 and a RGB camera GoPro Hero 3. As embedded system it is used a Raspberry Pi on board, which is connected with the terrestrial station through WLAN connection.

In order to perform the image acquisition protocol, they consider the meteorological conditions, such as measurements of air temperature, relative humidity using a Vaisala HM34C sensor and irradiance levels on the photovoltaic system with the Ophir PD-300-3W sensor.

The captures of the thermal images are obtained by operating the UAV manually, monitoring the live image from the terrestrial web browser and taking the images, only when they have the right scene. In this way it is eliminated the possibility that the UAV shadow projection interferes with the measurement. The images are stored in the memory of the Flir Tau 2 camera. On the other hand, the acquisition of RGB images is done automatically using the APM flight controller planner2. The resultant images are stored in the Raspberry Pi. In addition, in this research it is performed manual inspection of the site with a FLIR E300 thermal camera.

Tab. 3: UAV and Thermographic camera characteristics reported in (Kauppinen et al., 2015)

UAV	Characteristics		Thermographic camera	Characteristics	
Walkera QR X800	**Flight controller**	Walkera FCS800	Flir Tau 2	**Resolution (pixels)**	640x512 - 336x256
	Total Weight (kg)	3,9		**Temperature sensitivity (mK)**	50 to 30
	Power Battery	LiPo (6s 10000 mAh)		**Spectral range (um)**	7,5 to 13
	Max Power consumption (W)	-		**Weight (g)**	112g
	Hover time (min)	40		**Memory**	32 GB
	Hover environment temperature (°C)	-15 to 65		**Temperature ranges (°C)**	-25 to 135°C, -25 to-100
	Takeoff Weight (kg)	3		**Accuracy**	+-5% or +-5 °C
	Dimensions (mm)	620x620x460		**IR Color Palettes**	15interchangeable in real time
	Type	Quadcopter		**Emissivity**	Adjustable

In (Aghaei et al., 2015) it is used a UAV PLP-610 Nimbus Platform and a Flir A35 thermographic camera, which main features are summarized in Tab. 4. Some of the most relevant issues to be considered while performing a flight plan and capturing the images are described in the paper, as reflections or shadows produced by the surrounded vegetation, clouds, other module structures or by the own drone. The geo referencing data is not considered in this study.

The thermographic image processing is done offline using Matlab. The flow diagram of the algorithm goes from the conversion of the IR image to RGB, later to grayscale to perform a Gaussian type filtering. To the resultant image is applied Laplace algorithm and a diagnosis is issued. If the panel is healthy, the post processing is finished, otherwise, in case of detecting a defect in the module, it is established the degradation percentage of the photovoltaic module.

Tab. 4: UAV and Thermographic camera characteristics reported in (Aghaei et al., 2015)

UAV	Characteristics		Thermographic camera	Characteristics	
PLP 610 Nimbus Plataform	**Cruise Speed (kts)**	0-20	Flir A35	**Resolution (pixels)**	320x256
	Operational range (km)	0.25		**Temperature sensitivity (mK)**	50 to 30
	Max Altitude (m)	150		**Spectral range (um)**	7,5 to 13
	Hover time (min)	25		**Weight (g)**	112g
	Weight (kg)	2,8		**Memory**	32 GB
	Dimensions (mm)	300x980		**IR Color Palettes**	15interchangeable in real time
	Type	Hexacopter		**Emissivity**	Adjustable

In (Tsanakas et al., 2017) it is used a hexacopter Condor AY-704 with an Optris PI450 on board and a conventional Single Les Reflex (SLR) connected to the UAV. The embedded system is not described in the paper. The image capturing conditions complied with IEC 62446-3 TS first edition standard in relation with the minimum irradiance, soft clouds and maximum wind speed. The resultant images are represented in an interactive map without connection, similar to Google Earth. The fault processing algorithm is implemented on the ortomosaic in Matlab. Additionally, when an anomaly is found in the image, a manual inspection and I-V electrical characterization curve are performed on site, as validation of results.

Tab. 5: UAV and Thermographic camera characteristics reported in (Tsanakas et al., 2017)

UAV	Characteristics		Thermographic camera	Characteristics	
Condor AY 704	**Flight controller**	-	Optris PI450+lightweight mini PC	**Resolution (pixels)**	382x288
	Total Weight (kg)	-		**Temperature sensitivity (mK)**	50 to 30
	Power Battery	LiPo (6800 mAh)		**Spectral range (um)**	7,5 to 13
	Max Power consumption (W)	-		**Weight (g)**	380
	Hover time (min)	20		**Memory**	32 GB
	Hover environment temperature (°C)	-10 to 50		**Temperature ranges (°C)**	-25 to 135, -25 to 100
	Takeoff Weight (kg)	-		**Accuracy**	+-2% or +- 2 °C
	Dimensions (mm)	1,7		**IR Color Palettes**	15 interchangeable in real time
	Type	Hexacopter		**Emissivity**	Adjustable

In (Zhang et al., 2017) it is used an octocopter DJI Spreading Wings S100 with a Flir Tau 2 on board. Additionally, it includes an image storage module that allows saving image and positioning data at the same time. The image acquisition is performed with flight speed of 2 m/s and flight height of 20 and 40 meters with respect to the module. The image capture schedule corresponds to the time period between 10:00 am and 12:00 pm, corresponding with the maximum irradiance. Image processing is offline; the flowchart of the algorithm developed includes a preprocessing stage, recognition of each individual module and detection of the anomaly.

Tab. 6: UAV and Thermographic camera characteristics reported in (Zhang et al., 2017)

UAV	Characteristics		Thermographic camera	Characteristics	
DJI S1000	**Flight controller**	A2	Flir Tau 2	**Resolution (pixels)**	640x512 - 336x256
	Total Weight (kg)	4,2		**Temperature sensitivity (mK)**	50 to 30
	Power Battery	LiPo (6s 10000 mAh, to 20000 mAh)		**Spectral range (um)**	7,5 to 13
	Max Power consumption (W)	4000		**Weight (g)**	112g
	Hover time (min)	15		**Memory**	32 GB
	Hover environment temperature (°C)	-10 to 40		**Temperature ranges (°C)**	-25 to 135°C, -25 to-100
	Takeoff Weight (kg)	6,0 to 11		**Accuracy**	+-5% or +-5 °C
	Dimensions (mm)	460x511x305		**IR Color Palettes**	15interchangeable in real time
	Type	Octocopter		**Emissivity**	Adjustable

In (Dotenco et al., 2016) it is used a Da Vinci Scara Bot X8 with a thermographic camera Optris PI450 and a RGB GoPro Hero3+. The inspection was always performed with a minimum irradiance of 600W/m^2 and a maximum of 1000W/m^2.

The processing of the thermographic images is done by means of a segmentation that allows identifying the region of interest, in this case the photovoltaic modules, from the information that does not contribute to the analysis, as the background.

The implemented algorithm is described in four stages: normalization, thresholding, orientation of photovoltaic modules estimation and correction and refinement. The first stage proposed, corresponds to thermal contrast. This procedure allows dismissing temperature values below a defined threshold. In the following stages it is done the automatic selection of thresholds in order to separate the solar panels from the background, using combinations of Gaussian models (GMMs).

Subsequent to the segmentation stage, it is proposed the extraction of information obtained from the average temperature values of each solar module and its cells. Additionally, the asymmetry measures of the histograms are used to provide information about the distribution of the temperature in the picture

Tab. 7: UAV and Thermographic camera characteristics reported in (Dotenco et al., 2016)

UAV	Characteristics		Thermographic camera	Characteristics	
Da Vinci Copters ScaraBot X8	**Flight controller**	Pixhawk	Optris PI450	**Resolution (pixels)**	382x288
	Total Weight (kg)	2,15		**Temperature sensitivity (mK)**	50 to 30
	Power Battery	6S Li-ion 15Ah		**Spectral range (um)**	7,5 to 13
	Max Power consumption (W)	4000		**Weight (g)**	380
	Hover time (min) payload 2400g	24		**Memory**	32 GB
	Hover environment temperature (°C)	-10 to 40		**Temperature ranges (°C)**	-25 to 135, -25 to 100
	Takeoff Weight (kg)	5.0		**Accuracy**	+-2% or +- 2 °C
	Dimensions (mm)	545x545x402		**IR Color Palettes**	15interchangeable in real time
	Type	Octocopter		**Emissivity**	Adjustable

In (Leva et al., 2015) it is used an UAV Nimbus PLP-610, as in (Aghaei et al., 2015), with a visible spectrum camera Nikon 1-v1.

In the article, it is developed a protocol for the acquisition of the images, which describes the characteristics and conditions of flight as altitude, and angles of capture, to detect faults and defects on the photovoltaic modules using only an RGB camera. The obtained results, allow establishing the relations on the flight height at which the acquisition of the images is done and the type of faults detected. The paper does not have a diagnosis that identifies the severity of the faults as they do not use thermographic images.

In order to properly evaluating the features of the instrumentation required in aerial thermography of PV plants it is necessary to consider some relevant aspects about the image capturing conditions that are analyzed throughout this paragraphs. These capturing conditions restrict the platform and sensors characteristics that can be used to obtain usable results. According to the review of the state of the art some of the most relevant characteristics for the selection of cameras correspond to the following items: resolution, ranges of temperature, sensitivity, precision, spectral range, calibration, memory, file transfer, interface, video resolution, weight, FOV, spatial resolution.

Tab. 8: UAV and Thermographic camera characteristics reported in (Leva et al., 2015)

UAV	Characteristics		Thermographic camera	Characteristics	
PLP 610 Nimbus Plataform	**Cruise Speed (kts)**	0-20	Flir A35	**Resolution (pixels)**	3906x2606
	Operational range (km)	0.25		**Dimensions (m)**	113x76x43.5
	Max Altitude (m)	150		**Lens focal length (mm)**	35
	Hover time (min)	25		**Weight (g)**	294g
	Weight (kg)	2,8		**Battery**	Nikon EN-El 15 Lithium-Ion
	Dimensions (mm)	300x980			
	Type	Hexacopter			

In order to obtain accurate and usable images, the camera should be on-board of a stable gimbal and the platform should be able to hover for obtaining detailed information. In this regard, the most appropriate platform to perform aerial thermography for PV plants inspections are the multirotor, also known as multirotor. There are different multirotor kinds generally classified in terms of the number of rotors that the UAVs have.

Additionally, the platform should have the capacity of carrying at least two different sensors, the thermographic and the visual camera. A visual image along with a thermographic image facilitates the identification of the defect mode, the detection of false hot spots, as bird drops or shadows and makes it easy to determine the exact location of the defect module in the PV plant.

Nowadays multirotor allow the autonomous operation mode by waypoints, which is a desirable option to avoid human errors that can be produced during the manual flight. In this case, it is necessary to have cartographic information of the site and if not, performing a flight previously to the inspection to feed the platform software.

The UAV batteries should be as long as possible to maximize the producing time and to optimize the inspection performance. There are different batteries options and several researches are being done in this respect during the last years. UAVs with Lithium Polymer (Li-Po) batteries can fly approximately from 10 to 40 minutes. A battery recharge cycle takes one hour and a half approximately. In order to perform an efficient inspection, it is convenient to have various batteries not to be recharging them during the inspection. There are several researches on innovative batteries that offer a greater energy density and reduce charge time, weight and volume, as graphene batteries.

The flight height of the UAV delimits the resolution that the sensors must have so as to acquire acceptable results. If the pixel size is higher than the cell size, the accuracy of the resultant images is not acceptable as smaller defect will not be properly identified. Therefore, the flight height restrings the sensor resolution required, considering also the lens used and the consequent field of view.

4. Conclusions

Although some authors mention the equipment used in their researches there is not a convenient study which compiles other available alternatives that meet the requisites established and their most relevant characteristics.

A procedure to indicate a review of the available equipment used in aerial inspection of photovoltaic plants was presented, in order to determinate and to analyze the key aspects that have to be considered to properly select the equipment to be used. The results are obtained by means of the examination all the information in relation to the characteristics of the instrumentation involved and the compilation of the UAVs and thermographic sensors alternatives with their available characteristics.

The necessary equipment consists mainly of a thermographic camera and an Unmanned Aerial Vehicle. In the case of UAVs, full compatibility with the camera must be guaranteed and factors such as maximum operating temperature, flight controller, and flight autonomy are necessary characteristics for the selection of the equipment. According to the review of the state of the art, some of the most relevant characteristics for the selection of cameras correspond to the following items: resolution, ranges of temperature, sensitivity, precision, spectral range, calibration, memory, file transfer, interface, video resolution, weight, FOV, spatial resolution. These respects have been analyzed with the aim of informing about the essential aspects to consider while selecting the equipment for this application and of facilitating this selection to researchers. It is important to understand that the utility of the equipment is in many cases directly linked to the available budget, as the improvement of the features is usually associated with a notable increase in the price.

5. Bibliography

Addabbo, P., Angrisano, A., Bernardi, M. L., Gagliarde, G., Mennella, A., Nisi, M., Ullo, S., 2017. A UAV infrared measurement approach for defect detection in photovoltaic plants. IEEE International Workshop on Metrology for AeroSpace 2017 (MetroAeroSpace). 345–350.

Aghaei, M., Gandelli, A., Grimaccia, F., Leva, S., Zich, R. E., 2015. IR real-time analyses for PV system monitoring by digital image processing techniques. International Conference on Event-based Control, Communication, and Signal Processing 2015 (EBCCSP). 1–6.

Dotenco, S., Dalsass, M., Winkler, L., Wurzner, T., Brabec, C., Maier, A., Gallwitz, F., 2016. Automatic detection and analysis of photovoltaic modules in aerial infrared imagery. IEEE Winter Conference on Applications of Computer Vision (WACV). 1–9.

Elibol, E., Tüzün Özmen, Ö., Tutkun, N., Köysal, O., 2017. Outdoor performance analysis of different PV panel types. Renewable and Sustainable Energy Reviews. 67, 651–661.

Kauppinen, T., Panouillot, P.-E., Siikanen, S., Athanasakou, E., Baltas, P., Nikopoulos, B., 2015. About infrared scanning of photovoltaic solar plant. THERMOSENSE: THERMAL INFRARED APPLICATIONS XXXVII. 9485, 948517 1-14.

Leva, S., Aghaei, M., Grimaccia, F., 2015. PV power plant inspection by UAS: Correlation between altitude and detection of defects on PV modules. IEEE 15th International Conference on Environment and Electrical Engineering, EEEIC 2015. 1921–1926.

Tsanakas, J. A., Ha, L., Buerhop, C., 2016. Faults and infrared thermographic diagnosis in operating c-Si photovoltaic modules: A review of research and future challenges. Renewable and Sustainable Energy Reviews. 62, 695–709.

Tsanakas, J. A., Ha, L. D., Shakarchi, F. Al., 2017. Advanced inspection of photovoltaic installations by aerial triangulation and terrestrial georeferencing of thermal/visual imagery. Renewable Energy. 102, 224–233.

Wiris, W. (n.d.). Thermo diagnosis of photovoltaic power plants. Retrieved October 2, 2017, from https://www.drone-thermal-camera.com/wp-content/uploads/Workswell-WIRIS_photovoltaic.pdf

Zhang, P., Zhang, L., Wu, T., Zhang, H., Sun, X., 2017. Detection and location of fouling on photovoltaic panels using a drone- mounted infrared thermography system. Applied Remote Sensing, 11(1), 016026 1-11.