Conference Paper

“Online Fault Detection in Solar Plants Using a Wireless Radiometer in Unmanned Aerial Vehicles”

- Lecture Notes on Multidisciplinary Industrial Engineering -

Accepted: 29 June 2017

Carlos Quiterio Gómez Muñoz

Ingenium Research Group, Universidad de Castilla-La Mancha

CarlosQuiterio.Gomez@uclm.es

Alfredo Peinado Gonzalo

Ingenium Research Group, Universidad de Castilla-La Mancha

Isaac Segovia Ramirez

Ingenium Research Group, Universidad de Castilla-La Mancha

Isaac.Segovia@uclm.es

Fausto Pedro García Márquez

Ingenium Research Group, Universidad de Castilla-La Mancha

FaustoPedro.Garcia@uclm.es

Cite as: Muñoz, C. Q. G., Gonzalo, A. P., Ramirez, I. S., & Márquez, F. P. G. (2017, July). Online Fault Detection in Solar Plants Using a Wireless Radiometer in Unmanned Aerial Vehicles. In International Conference on Management Science and Engineering Management (pp. 1161-1174). Springer, Cham.

DOI: https://doi.org/10.1007/978-3-319-59280-0_96

Online Fault Detection in Solar Plants Using a Wireless Radiometer in Unmanned Aerial Vehicles

*Carlos Quiterio Gómez Muñoz, Alfredo Peinado Gonzalo, Isaac Segovia Ramirez,
Fausto Pedro García Marquez,*

1 Ingenium Research Group, Castilla-La Mancha University, Spain

*(CarlosQuiterio.Gomez; Alfredo.Peinado1; Isaac.segovia;
FaustoPedro.Garcia;)@uclm.es*

Abstract

A novel Non-Destructive Test (NDT) is presented in this paper. It employs a radiometric sensor that measures the infrared emissivity of the solar panel surface embedded in an unmanned aerial vehicle. The measurements provided by the sensor will determine if the panel is healthy, damaged or dirty. A thermographic camera has been used to check the temperature variations and validate the results by the sensor.

The study shows that the amount of dirt influences the temperature on the surface and the energy generated. Similarly, faults in photovoltaic cells influence the temperature of the panel.

The NDT system is less expensive than traditional thermographic sensors or cameras. Early detection of these problems, together with an optimal maintenance strategy, allows to reduce costs and increase the competitiveness of this renewable energy source.

Keywords: Infrared sensor, radiometry, solar plants, photovoltaic panels. Fault detection and diagnosis.

1. Introduction

1.1. Renewable Energies

The whole energy produced in the Earth has been obtained, directly or indirectly, from the Sun. Even fossil fuels, which come from the decomposition of plants that have previously needed the sun to perform photosynthesis. These fossil fuels are oil, coal and natural gas, and they are in limited reserves.

From the industrial revolution, fossil fuels consumption has increased without considering the environmental effects, such as global warming or climate change. However, as they are finite resources, alternative forms of fossil fuels must be sought to obtain energy and to avoid the pollution they produce. These measures are being carried out globally, led by the Intergovernmental Panel on Climate Change (IPCC).

The renewable energies are being developed and employed to use a clear production, e.g. in Spain they produce 28.6% of the energy consumed [1,2]. Renewable energies are those based on the use of virtually endless resources, e.g. the sun (Figure 1), wind or ocean currents, or resources that are renewed periodically if they are used sustainably, such as biomass or biofuels. In general, its production is more expensive than fossil fuels, but it does not generate polluting emissions during their production. These include: Wind energy [3,4], tidal, solar (Figure 1), biomass and biofuels, geothermal and hydraulic.

Figure 1: China and Pakistan project for Solar plant “Solar Quaid Azam” installed in Pakistan (<http://www.qasolar.com/>).

1.2. Non-Destructive Experimenting

Non-Destructive Experimenting (NDT) is a type of experiment that is performed on parts and pieces to verify its state and operation without interfering in the integrity of the material or its usefulness to the service [5-8]. They are carried out in recognition and preventive maintenance work in all types of industrial areas. These experiments are used to detect internal and surface defects [9-12]. Some of these experiments are: Radiography with X-ray and Gamma, magnetic particles, Eddy currents, ultrasound experimenting [13-15] and infrared thermography [16]. Infrared thermography consists in checking the state of a part or a structure from a thermal image. They are used in many industries and they can be applied in any production phase.

2. Infrared Thermography

2.1. Radiation

There are only three methods of heat transmission in physical terms: conduction, convection and radiation. In the case of radiation, a transmission medium is not necessary, the energy is transmitted due to the temperature of the emitter body.

Depending on the temperature, the radiation emitted changes. The law of Stefan-Boltzmann, Equation 1, is used to quantify it. It must be adjusted for real bodies, by adding the emitter parameter to the equation.

$$E_N(T) = \sigma \cdot T^4 \quad (1)$$

where E_N is the emittance of the body, σ is the Stefan Boltzmann constant, value $5,6710 \cdot 10^{-8} W/m^2K^4$) and T the body temperature. This emittance is for of a black body, which must be corrected for real bodies through the emissivity. The Planck law is given by equation 2.

$$E_N^\lambda(\lambda, T) = \frac{C_1}{\lambda^5 \left(e^{\frac{C_2}{\lambda T}} - 1 \right)} \quad (2)$$

where E_N is the spectral emitted, C_1 and C_2 are constants, λ the wavelength and T the body temperature. Equation 2 shows that most of the radiation emitted by bodies at low temperatures is found in the infrared region [17].

Emittance is the proportion of energy that a body can emit relative to the total. In a black body (maximum emitter) is the unit. In any other body, this magnitude is smaller and depends on the temperature. In addition, the characteristic wavelength of the bodies also depends on their temperatures, generating the electromagnetic radiation spectrum.

The thermal behaviour of a real body is different from a black body. While the black body absorbs all the energy that reaches its surface and emits throughout the radiation region equally, a real body does not absorb all the energy and does not emit in the entire electromagnetic spectrum.

A real body does not absorb all the radiation, but part of it passes through it or reflects on its surface. In addition, this behaviour also depends on the wavelength being studied, that depends the concept of emittance, given by equation 3. Emittance is the ratio of energy that a body emits with respect to the total that it can emit with a certain temperature and wavelength [17].

$$\varepsilon^{\theta,\varphi,\lambda}(\theta, \varphi, \lambda, T) = \frac{E^{\theta,\varphi,\lambda}(\theta, \varphi, \lambda, T)}{E_N^{\theta,\varphi,\lambda}(\theta, \lambda, T)} = \frac{I_E^{\theta,\varphi,\lambda}(\theta, \varphi, \lambda, T)}{I_{E,N}^{\theta,\varphi,\lambda}(\lambda, T)} \quad (3)$$

being ε the emissivity, θ and φ emission angles, E emittance and I the radiation intensity of the body.

For this research work, infrared radiation is the most relevant, since it is the dominant thermal radiation in this temperature range. Therefore, the camera and the sensor are designed to collect this type of radiation.

2.2. Applications

The main function in this paper of infrared thermography is the visualization of elements whose surface temperature variations show their state [18-20]. Among its applications include the following:

- *Electrical and mechanical systems:* It is possible to observe the hot spots of the systems and areas subjected to higher thermal stresses by comparison on the surface of the system [21].
- *Structures:* Any irregularity in the temperature of the facade can correspond to different conditions in buildings, such as poor insulation, the emittance of an area with a greater amount of bricks than concrete, or even an insect nest within the facade.
- *Welds:* Temperature variations in a pipe are usually due to areas where welds have been made. If these variations show a very irregular appearance, it is probably due to a bad union
- *Surveillance:* Control of emissions, traffic, fire prevention, etc.
- *Medicine:* Monitoring of diseases and anomalies in the human body.

The infrared thermography is done by a non-radiometric camera to check the results obtained with the sensors

3. Experimental Platform.

3.1. Radiometer

They are used to check the temperature and the radiance of the measured targets. Both sensors are used to contrast the data obtained with each one in the different case studies.

Campbell SI-111 Sensor

This sensor is connected to an Arduino board, which processes the voltage data and process that information to obtain the temperature in Celsius degrees. The system is

capable of making accurate measurements to the bodies that are within its field of vision. The SI-111 Precision Infrared Radiometer features a thermistor to measure its internal temperature, and a thermopile for the target temperature using a germanium lens.

Using Stefan-Boltzmann's law of radiation, and the voltages in the thermopile and the thermistor, the target temperature is calculated [22].

The temperature measured by the sensor is the average of the temperatures of its view range, receiving between 95 and 98% of the infrared radiation of the view range and between 2 and 5% from outside. Figure 2 shows the view range of the SI-111 sensor with half-angle of 22.5° . The view range depends of the distance to the area and the inclination with respect to this area (see Figure 2).

Figure 2: SI-111 Sensor Field of View.

This sensor has been chosen because of its high accuracy, reaction rate to changes in temperature and the large range of temperatures that can operate. Its size and weight allow a great manageability. Its installation on the unmanned aerial vehicle allows the global system to performance more efficient and flexible inspections.

Table 1: Technical characteristics of the Campbell SI-111 sensor

Input voltage	2.5V excitation for the thermistor.
Absolute accuracy	$\pm 0,2^\circ C$ between $[-10 \text{ and } 60]^\circ C$ $\pm 0,5^\circ C$ between $[-40 \text{ and } 70]^\circ C$

Response Time	Less than 1 second for changes in target temperature.
Field of View	22o of half-angle
Operating Environment	Highly water resistant Designed for continuous outdoor use Operating range -55 ° C to 80 ° C 0 to 100% relative humidity

3.2. Arduino Platform and Wi-Fi Shield

For this research, Arduino Uno G3 motherboard is used and the Shield Wi-Fi extension, which grants wireless features to the original board. This device has been chosen due to its great extension in this type of applications and its low consumption.

The Arduino Uno R3 (Figure 3.a) is a motherboard that uses the ATmega328 microcontroller and is powered by either USB cable connected to a computer or external power from a battery.

The Wi-Fi Shield component is an Arduino expansion card. It allows the transmission of data via wireless connection by Wi-Fi (Figure 3.b).

(a)

(b)

Figure 3: Arduino Uno G3 (a) and Wi-Fi Shield expansion card (b).

Data obtained by the sensor is processed and sent via Wi-Fi to the online platform Thingspeak to monitor the results.

3.3. Thermographic camera

The camera is non radiometric used to check the data obtained with the sensors and to see the temperature differences of the observed pieces. This camera consists in assigning a determined colour to each level of radiation that it receives. These levels are calculated for each resolution pixel that the camera has, creating a thermographic picture.

Figure 4: Thermographic camera Flir VUE

3.4. Photovoltaic solar panels

These panels were used in the experiments to check their temperature and voltage at the terminals. Their technical characteristics are shown in Table 2.

Figure 5: Solar panels used in the experiments.

Table 2: Technical characteristics of photovoltaic solar panels.

Manufacturer's name	TSM-170D
Max power	2.5 W
Maximum Voltage	35.8 V
Maximum Intensity	4.76 A
Open Circuit Voltage	43.6 V
Short circuit current	5.25 A
Maximum System Voltage	700 V
Work temperature	$[-40^{\circ}C, 90^{\circ}C]$
Dimensions	$1581 \times 809 \times 40mm$
Cell Type	Monocrystalline
Number and size of cell	72 pieces, $125 \times 125mm$
Type of glass and width	3.2 mm tempered
Weight	15.6 kg

3.5. Unmanned Aerial Vehicle DJI Spreading Wings S900

This unmanned aircraft operated by remote control is designed for reconnaissance, monitoring and taking of measurements and images, thanks to its control system that allows a great stability and handling.

The hexacopter can operate around 18 minutes autonomously, following pre-established routes. It is made of carbon fiber to lighten weight, which allows a maximum load capacity of 8.2 kg. The gimbal is a crucial component for this application for increasing the stability and accuracy of the measurements. This support contains the measurement equipment (sensor, camera, Arduino card and electronic components) in the drone. A schematic representation of the drone collecting data in a photovoltaic plant is shown in Figure 6.

Figure 6: Representation of the air vehicle taking a measurement with the wireless sensor mounted on the Gimbal mount.

This system allows to inspect solar plants in a totally automatic and autonomous way. It can inspect large areas, and a very large park can be inspected by sections. The system sends online all the information about the state of the plates (dirt and defects), generating alarms and reports of each module.

4. Case study.

The objective of the experiments was to detect dirt on the solar panels [23]. The experiments were carried out in three different scenarios: In the first scenario, the solar panel was clean; the second one, mud was added in half solar panel; third scenario, the solar panel was totally covered by mud. In each experiment, the temperature values collected by the radiometer and the volts generated by the solar panel were obtained.

Figure 7: Solar panel without dirt on its surface.

Figure 8: Solar panels covered in half of mud.

Figure 9: Solar panels totally covered of dirt

The incidence of the sun is crucial in the emissivity values collected by the radiometer. For this reason, they were carried out three cases of study at different hours to study the incidence of the sun in the results. The first case study was performed at 10:00 am. The second case study at 12:00 noon. The last case study was carried out with absence of direct light because of clouds.

4.1. Case study 1: Incidence of sunlight at 10:00 AM

Experiments have been performed at 10:00 am to check the temperature reached by the panels when, due to the incidence of light, the panel does not reach its maximum power generation. Table 3 shows the obtained temperature and generated voltage by the panel.

Table 3: Results obtained in the case study 1.

	Temperature (°C)	Voltage (V)
Clean panel	46.2	36.2
Partially covered panel	44.7	35.7
Fully covered panel	44.1	35.3

It is observed an evident difference of temperatures between the clean panel and the panel with dirt on the half of its surface. There are also minor differences between the half dirty panel and the panel totally covered by mud. Figure 10 shows the different temperatures obtained in the series of experiments represented by columns. The ambient temperature series has been added to contrast with those acquired by the panels in each case shown in the form of a line.

Figure 10: Comparison between the different panel temperatures in case study 1.

These relationships are proportional to the voltages generated by the solar panel. Figure 1 shows the influence of the mud in the voltage at 10:00 am [24].

Figure 11: Comparison between different panel temperatures and voltages in case study 1.

4.2. Case study 2: Incidence of sunlight at 12:00 PM

These experiments have been performed to observe the differences in temperature and energy production of the panels when the panel reach its maximum of production, i.e. when the light strikes perpendicularly on the panels.

Table 4: Results obtained in the second experiments.

	Temperature (°C)	Voltage (V)
Clean panel	61.9	37.2
Partially covered panel	57.9	34.4
Fully covered panel	51.8	33.5

The temperature variations are bigger than in the first case study, as well as the voltage. This is because of the intensity of the light is much greater and it makes more evident the cases where the panel is covered with dirt. Greater differences in temperature are observed in Figure 12, as well as higher temperatures.

Figure 12: Comparison between different panel temperatures in case 2.

A greater voltage difference is shown in Figure 13. It is due to a greater inequality of sunlight incident between the panel without dirt and completely covered.

Figure 13: Comparison between different panel temperatures and voltages in case study 2.

4.3. Case study 3: Absence of direct light (18:00 p.m.)

These experiments have been performed at 18:00 pm with clouds to study the effectiveness of the system for the detection of dirt under these conditions. The temperature results obtained are shown in Table 5.

Table 5: Measurements obtained in the case study 3.

	Temperature (°C)	Voltage (V)
Clean panel	31.4	27.3
Partially covered panel	31.2	27.3
Fully covered panel	30.9	27.3

The differences of temperatures are lower, with a large margin of error that does not allow to know exactly the condition of the panel. Figure 14 shows the low temperature variations between the different experiments.

Figure 14: Comparison between the different panel temperatures in case study 3.

The voltage in each case are similar for all case studies. In these conditions, it is concluded that the system is not effective to detect the dirt in the solar panels.

Figure 15: Comparison between different panel temperatures and voltages in case study 3.

5. Conclusions

Dirt and dust in solar panels is a common problem in photovoltaic plants, which are usually located in desert areas with lots of sand and dust. A novel non-destructive test system is proposed in this paper, based on: a radiometer; Arduino; a Wi-Fi Shield, and; a UAV for inspecting the state of the photovoltaic panels.

The low weight and cost of the system can reduce the costs in operation and maintenance of the whole solar plant. The system can be automated, reducing the inspection time and the costs.

Three different conditions of the solar panel were analysed: Clean, half covered by mud and totally covered. The infrared radiometry of the panels was read and the voltage of the panels. The experiments were performed in three different solar conditions to increase the actuary of the experiments: at 10 am, 12:00 pm and with clouds and without direct sunlight. The absence of direct light does not allow identification among the three cases.

Acknowledge

The work reported herewith has been financially by the Spanish Ministerio de Economía y Competitividad, under Research Grant Ref.: RTC-2016-5694-3.

6. References

1. Montoya, F.G.; Aguilera, M.J.; Manzano-Agugliaro, F. Renewable energy production in Spain: A review. *Renewable and Sustainable Energy Reviews* **2014**, *33*, 509-531.
2. Heras-Saizarbitoria, I.; Cilleruelo, E.; Zamanillo, I. Public acceptance of renewables and the media: An analysis of the Spanish PV solar experience. *Renewable and Sustainable Energy Reviews* **2011**, *15*, 4685-4696.
3. Pliego Marugán, A.; García Márquez, F.P.; Pinar Pérez, J.M. Optimal maintenance management of offshore wind farms. *Energies* **2016**, *9*, 46.
4. Márquez, F.P.G.; Tobias, A.M.; Pérez, J.M.P.; Papaelias, M. Condition monitoring of wind turbines: Techniques and methods. *Renewable Energy* **2012**, *46*, 169-178.
5. Ramirez, I.S.; Muñoz, C.Q.G.; Marquez, F.P.G. In *A condition monitoring system for blades of wind turbine maintenance management*, Proceedings of the Tenth International Conference on Management Science and Engineering Management, 2017; Springer: pp 3-11.
6. Muñoz, C.Q.G.; Márquez, F.P.G.; Tomás, J.M.S. Ice detection using thermal infrared radiometry on wind turbine blades. *Measurement* **2016**, *93*, 157-163.
7. Gómez Muñoz, C.Q.; Trapero Arenas, J.R.; García Márquez, F.P. In *Structural health monitoring for concentrated solar plants*, 11th International Conference on Condition Monitoring and Machinery Failure Prevention Technologie. Manchester, UK, 2014.
8. Gómez Muñoz, C.Q.; Ruiz De la Hermosa Gonzalez-Carrato, R.; Garcia Marquez, F.P. In *Acoustic emission and signal processing for fault detection and location in composite materials*, Global Cleaner Production & Sustainable Consumption Conference, 2015.
9. Papaelias, M.; Cheng, L.; Kogia, M.; Mohimi, A.; Kappatos, V.; Selcuk, C.; Constantinou, L.; Muñoz, C.Q.G.; Marquez, F.P.G.; Gan, T.-H. Inspection and structural health monitoring techniques for concentrated solar power plants. *Renewable Energy* **2016**, *85*, 1178-1191.
10. Gómez Muñoz, C.Q.; García Marquez, F.P.; Liang, C.; Maria, K.; Abbas, M.; Mayorkinos, P. A new condition monitoring approach for maintenance management in concentrate solar plants. In *Proceedings of the ninth international conference on management science and engineering management*, Springer Berlin Heidelberg: 2015; pp 999-1008.
11. Gómez Muñoz, C.Q.; García Márquez, F.P. A new fault location approach for acoustic emission techniques in wind turbines. *Energies* **2016**, *9*, 40.

12. Gómez Muñoz, C.Q.; García Marquez, F.P. In *Energy environment maintenance management*, 2015 GFEECC International Conference for Energy, Environment and Commercial Civilization. Chengdu, China., 2015.
13. Jiménez, A.A.; Muñoz, C.Q.G.; Marquez, F.P.G.; Zhang, L. In *Artificial intelligence for concentrated solar plant maintenance management*, Proceedings of the Tenth International Conference on Management Science and Engineering Management, 2017; Springer: pp 125-134.
14. Gómez Muñoz, C.Q.; Villegas, M.A.; García, F.P.; Pedregal, D.J. Big data and web intelligence for condition monitoring: A case study on wind turbines. In *Handbook of research on trends and future directions in big data and web intelligence; information science reference, igi global: Hershey, pa, USA*, 2015.
15. Gómez Muñoz, C.Q.; Ruiz de la Hermosa Gonzalez-Carrato, R.; Trapero Arenas, J.R.; Garcia Marquez, F.P. A novel approach to fault detection and diagnosis on wind turbines. *GLOBAL NEST JOURNAL* **2014**, *16*, 1029-1037.
16. Acciani, G.; Simione, G.; Vergura, S. In *Thermographic analysis of photovoltaic panels*, International Conference on Renewable Energies and Power Quality (ICREPQ'10), Granada, Spain, March, 2010; pp 23-25.
17. McAdams, W.H. *Heat transmission*; 1954.
18. Bazilian, M.D.; Kamalanathan, H.; Prasad, D. Thermographic analysis of a building integrated photovoltaic system. *Renewable Energy* **2002**, *26*, 449-461.
19. Pilla, M.; Galmiche, F.; Maldague, X.P. In *Thermographic inspection of cracked solar cells*, AeroSense 2002, 2002; International Society for Optics and Photonics: pp 699-703.
20. Ancuta, F.; Cepisca, C. In *Fault analysis possibilities for pv panels*, Energetics (IYCE), Proceedings of the 2011 3rd International Youth Conference on, 2011; IEEE: pp 1-5.
21. Maldague, X.P. Introduction to ndt by active infrared thermography. *Materials Evaluation* **2002**, *60*, 1060-1073.
22. Quinn, T.J.; Martin, J. A radiometric determination of the stefan-boltzmann constant and thermodynamic temperatures between-40 degrees c and+ 100 degrees c. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* **1985**, *316*, 85-189.
23. Dorobantu, L.; Popescu, M.; Popescu, C.; Craciunescu, A. In *The effect of surface impurities on photovoltaic panels*, International Conference on Renewable Energy and Power Quality, 2011.
24. Fares, Z.; Becherif, M.; Emziane, M.; Aboubou, A.; Azzem, S.M. Infrared thermography study of the temperature effect on the performance of photovoltaic cells and panels. In *Sustainability in energy and buildings*, Springer: 2013; pp 875-886.