Remotely piloted aircraft system (RPAS) use in construction: a thermography inspection case study

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Abstract. The inspection of buildings with thermographic cameras is a powerful and non-invasive means of monitoring and diagnosing the state of buildings. In the field of energy efficiency, the use of thermography allows detecting insulation defects, humidity detection, location of water leaks, detection of air leaks, among others. The implementation of thermal devices in aircraft facilitates the recognition of the efficiency status of buildings and solves problems that compromise operator safety. However, it is a complex application that requires a step-by-step methodology where all the conditioning factors that can negatively affect the results are collected. This research presents a working methodology to perform energy inspections on roofs using a RPAS (Remotely piloted aircraft system) equipped with a radiometric thermal camera. In the methodology presented were detailed the premises to be taken into account before carrying out an operation of this type, the different stages related to the execution of the flight, the materials used for the acquisition of thermal images and the post-processing techniques to obtain the results of the energetic inspection. The results showed remarkable apparent temperature changes on the roof surface, in special, in the north-west part of the building. Weaknesses related to heat loss were identified in the flat roof borders and the sloping roof ridges. The execution of the inspection demonstrated the viability of using the aerial thermography for monitoring the performance of a building by identifying energy problems in advance, documenting and correcting them before they become worse and more costly to repair.

1. Introduction

The inspection of buildings with thermographic cameras is a powerful and non-invasive means of monitoring and diagnosing the state of buildings. In the field of energy efficiency, the use of thermography allows detecting insulation defects, humidity detection, location of water leaks, detection of air leaks, identification of thermal bridges, location of leaks in domestic hot water systems and air conditioning systems, detection of electrical faults, among others. The implementation of thermal devices in aircraft facilitates the recognition of the efficiency status of buildings and solves problems that compromise operator safety. The use of RPAS (Remotely piloted aircraft system) allows these tasks to be carried out quickly and accurately, reducing operational costs and minimizing security risks [1]. However, it is a complex application that requires a step-by-step methodology where all the conditioning factors that can negatively affect the results are collected.
Some authors have conducted literature reviews that address the identification of standard procedures for operating RPAS in energy audit missions [2]–[4]. Julian Moore et al. (2018) proposed a simple, cost-effective method for performing site inspections of water, heat, and ventilation systems in 30 buildings on a campus [5]. Juan Ortiz-Sanz et al. (2019) tested the use of aerial thermography to detect thermal bridges, air leaks and the presence of humidity in a semi-buried building [6].

In this research, it presents a working methodology to perform energy inspections and detect heat leakages on roofs using a RPAS equipped with a radiometric thermal camera. Heat leakage is the undesirable and typically uncontrolled loss or gain of energy through the building envelope. Heat leakage can occur through thermal bridging or excessive heat loss, air leakage and the lack of or damage to thermal insulation in building elements [7].

The aim of this experiment was double: firstly, to carry out a flight with a RPAS to identify the different tasks and processes involved in preparing and carrying out an inspection work; secondly, to apply infrared thermography to diagnose the energy status of a building built in 1962 that takes part of a future rehabilitation and maintenance project.

The development of the case study consists of different stages: the identification of the materials and software used to carry out the energy inspection, the planning of the RPAS mission, the execution of the flight, the post-processing task of the telemetry acquired and the analysis of the results obtained from the aerial thermography.

This research follows the next structure: The materials and methods used for the execution of the case study are detailed in section 2. The results acquired in the case study are shown in section 3 and they are discussed in section 4. Finally, the conclusions obtained throughout the development of this research are presented in section 5.

2. Materials and methods

The inspection was carried out in a 58-year-old building belonging to the University of Huelva, the Von Neumann building located near the former Higher Technical School of Engineering in La Rabida (37°12′9.2″N 6°55′15.8″O) (Figure 1). This university building is part of a future campus rehabilitation and maintenance project. Prior to the design of this project, an aerial inspection was carried out to detect and document possible energy problems in advance and include their correction in the project report. The aerial inspection carried out with the RPAS focused on the diagnosis and analysis of the building's roof.

The characteristics of the building's horizontal envelope were identified. Several types of roof were differentiated in the building:
- Tile single-sloped roof in the four perimeter blocks.
- Tile hip-roof in the central block.

![Figure 1. Von Neumann building.](image-url)
- Flat roof with different materials in the section that connects the central block with the perimeter ones. The materials identified on the flat roof were: ceramics of different colors, brick and glass (Figure 2).

Special attention was given to the materiality of the roof to be inspected by thermography because it is necessary to know its emissivity to apply this technique correctly. Thermal cameras measure the infrared radiation emitted by objects. This depends on the temperature of the body and the emissivity of the material. It does not depend on the color of the material. The color of the visual spectrum has no perceptible effect on the infrared radiation emitted by a body. It is true that colors absorb visible light, and since solar radiation is higher in the visual spectrum than in the infrared, some colors absorb more radiation than others and therefore get hotter (and radiate more to the camera), but it does not depend on the emissivity [8].

![Figure 2. Materials identified on the roof of the building.](image)

It should be noted that if the emissivity of the material is less than 0.60, an accurate temperature reading will not be obtained using infrared technology. Thermography is especially useful for materials with emissivity higher than 0.8. In these cases, the apparent body temperature is close to the real temperature. The emissivity values of the materials identified were checked using standard emissivity tables and it was confirmed that all of them had an emissivity in the range of 0.92- 0.94 (Table 1). However, glass also has high reflectivity and reflects ambient radiation rather than emitting its own, giving inaccurate temperature readings. For this reason, this area was not taken into account in the analysis of the inspection results.

| Material   | Emissivity (ε) |
|------------|----------------|
| Tile       | 0.93           |
| Brick      | 0.94           |
| Ceramic    | 0.92           |
| Glass      | 0.93           |

2.1. Materials and software tools
This section shows the materials and software used to carry out the energy inspection. The first step in flight execution is mission planning. For this, the software DJI Flight Planner™ (DJI, Nanshan, Shenzhen, China) was used [9]. For the execution of the flight, the DJI Matrice 100 quadcopter (DJI, Nanshan, Shenzhen, China) equipped with a radiometric thermal imaging camera FLIR Vue Pro R 640 (FLIR, Wilsonville, Oregon, USA) was employed [10], [11]. The flight operation was performed using the Litchi™ application and the camera parameter settings in the FLIR™ software [12], [13]. To use both, a smartphone device was connected to the RPAS’s transmitter. The post-processing phase of the collected aerial images was carried out by the Pix4Dmapper™ software (Pix4D, Lausanne, Switzerland) [14].

2.2 Planning of the RPAS mission

The planning of a flight in a wide and spacious inspection area can be easily executed by generating simple polygons, regular squares or circular trajectories using specialized software. It is necessary to perform a preview inspection to know the heights of the scene and to design a flight plan without collisions. The task becomes more complex if the RPAS’s trajectory is carried out in densely built urban areas where the surrounding environment must be considered and safety distance conditions maintained from any obstacle. This type of mission also requires manual operation by experienced pilots during the flight to ensure safety [15].

The most common method for automated aerial imaging is to use a standard flight planner such as DJI Flight Planner™ [9], PrecisionHawk™ [16] or PixHawk Ardu Planner™ [17]. In this experiment, the mission planning was carried out by the DJI Flight Planner™ software, which allows the drawing, based on a satellite image, of the waypoints that the aircraft will follow during the flight (Figure 3).

![Figure 3. Scheme of the path planning.](image)

The entire flight trajectory was automated as the building that was inspected is located far from the urban center. The heights of the elements surrounding the building were secured to avoid any type of collision and to establish an appropriate flight height. Using the software, a square shaped polygon was drawn on the roof of the building to be inspected and data such as: flight altitude above ground level (18 meters), air speed (5 km/h) and image overlap (85%) were set to automatically estimate the number of photos needed to cover the study area. With these specifications, the average flight time established was approximately 30 minutes, requiring two batteries.

2.3 Execution of the flight
In order to carry out thermography correctly, special attention was paid to several factors like the time of the flight inspection which was carried out early in the morning to avoid possible reading errors due to direct sun incidence. Weather conditions were also key: a day with light cloud cover and little wind was chosen. It was ensured that there was no rainfall in the previous days to avoid surfaces wet from rain or exposed to it for several hours as the water reduces its temperature considerably. In addition, a thermal difference of more than 10°C was guaranteed between the interior and exterior of the building, to facilitate the identification of insulation defects in the building's roof. The outside temperature was measured at 14°C. The heating systems in the building's labs were set at 26°C from the day before the inspection until the end of the flight. However, this indoor temperature was not assured in all rooms of the building due to the lack of these devices in all areas. Even so, the transfer of hot air from the laboratories to the other rooms was facilitated by opening doors prior to inspection. This limitation was taken into account in the interpretation of the results. Two flight tests were carried out prior to the one shown in this research to define and optimize the whole process carried out during the case study. The flight was made early in the morning on the 19th of November 2020, at 08:42 am with a duration of 28 minutes in La Rabida, Huelva (UTC+1). The DJI Matrice 100 quadcopter was used, which is a fully programmable multirotor platform that can be customized with different sensors for specific applications (Figure 4). This RPAS is powered by four rotors that allow its vertical take-off and landing. The dual battery components allow for a flight range of up to 40 minutes and its rigid and lightweight structure allows for the incorporation of up to 1 kg of payload. It can reach a maximum cruising speed of 22 m/s and support the wind resistance of up to 10m/s. It is controlled by a transmitter that allows a maximum transmission distance of 5 km on an operating frequency between 5725 and 5825 GHz [10].

The payload included a radiometric thermal camera FLIR Vue Pro R 640 in order to gather thermal infrared measurements. This sensor is sensitive to the mid-infrared spectral band between 7.5-13.5 µm. The resolution of the camera is 640x512 pixels equipped with a 45 degree lens providing 327,680 measuring points in the image. It has an accuracy of (+/-) 5°C and a thermal sensitivity of 0.05°C. The FLIR camera is connected to the RPAS by a single USB cable and does not require a sensor control module [11]. The mission planning was exported directly to the Litchi™ software to perform the flight [12]. This application allows the RPAS to take off, fly the mission and land safely after automatically capturing all the necessary images. Tracking through the waypoints was ensured in real time with this application (Figure 5). The radiometric thermal camera equipped on the RPAS was connected via Bluetooth to the FLIR™ software to set the camera settings and data capture [13]. The data collected did not record the GPS locations of each image during collection. The camera settings set were: range of humidity (>60%), air temperature (14°C) and emissivity of the materials to be inspected (0.93).

Figure 4. DJI Matrice 100 equipped with the thermal camera FLIR Vue Por R 640. Figure 5. Litchi™ software interface during the mission.

2.4. Post-processing of aerial images
Once the flight was finished, the 976 images captured were processed by the Pix4Dmapper™ [14]. Pix4Dmapper™ is commonly used for photogrammetry and professional mapping using RPAS. This software transforms images and allows to create and edit point clouds, digital surface models (DSMs), meshes and orthophotos. These processes are performed automatically due to its processor core based on photogrammetry techniques and artificial vision algorithms [18]. By means of a grid interpolation of the dense point cloud obtained by the sensor, a three-dimensional model of the building was obtained. All the individual images were combined into an orthomosaic thermal image to obtain an orthophoto of the entire area of interest.

3. Results
This section presents the results obtained from the thermal inspection carried out by RPAS in the case study. A qualitative analysis was carried out during this inspection. In this type of analysis, the thermal image is analyzed to reveal anomalies of varying magnitude. These are located and evaluated, but not quantified, as the work is carried out at apparent temperatures. When thermography is used qualitatively, the temperature scale is not useful. Quantitative analyses are rarely carried out, especially in interior rooms, because certain specific conditions are required and data must be obtained in situ on the real values of the material’s emissivity and the apparent temperature reflected. Differences in emissivity between materials complicate quantitative inspections that require precise temperature measurements [8]. For this reason, many specialists choose to carry out qualitative inspections to focus on the temperature difference such as follows in this section.

Once the flight was completed and the thermal images acquired were processed, a point cloud grid and a 3D model of the whole building was obtained using the Pix4Dmapper™ software (Figure 6).

![Figure 6. Point cloud grid and 3D building model.](image)

All the individual images were combined into an orthomosaic thermal image to obtain an orthophoto of the entire area of interest (Figure 7). It is shown next to a figure which includes the ground floor and the roof floor of the building to facilitate the identification of insulation defects.
The thermal image shows higher thermal radiance in the northern perimeter block (containing laboratories 5 and 6 and the installation room) than the rest of the perimeter blocks. In this same block, there is also a considerable difference in apparent temperature in the roof over the laboratory room and the installation room. The west and east perimeter blocks show similar thermal radiance patterns and there is a slight increase of apparent temperature in the upper areas near the ridge roof. The southern block shows a different color pattern between the eastern and western part, with more thermal radiance in the western part over lab 1. The central block shows a high apparent temperature in the part of the ridge roof facing south-east orientation. The flat roof shows significant thermal radiance differences in a single room that functions as a lobby. The northwestern area covered with bricks and ceramics shows large apparent temperature exchanges in the whole surface and at the borders of the roof that are in contact with the walls that form the slope of the inclined roof. However, the south-east area covered with the same materials, and especially the access area to the east façade and the toilets, is the one that shows the lowest apparent temperatures. In this part of the roof there is a slight increase of apparent temperature in the borders.

As specified in materials and methods section, the part of the window cover was not analyzed due to the high reflectivity of the material that reflects ambient radiation rather than emitting its own, giving inaccurate temperature readings.

4. Discussion
This section discussed the results obtained in the section 3. The changes in apparent temperature identified can be related to problems with the energy performance of the building:
- The north block shows higher surface apparent temperatures than the others, which is evidence of poor energy performance due to heat losses in the roof of this area of the building. The difference in roof thermal radiance between the installation and laboratory rooms may be due to: i) the difference in internal temperatures (there is no HVAC system in the installation room to ensure the ten-degree difference with the outside), ii) poorer thermal insulation in the laboratory area.
- The east and west blocks show slight increase of apparent temperature in the upper areas near the ridge roof where normally heat is accumulated due to the rise of hot air under the roof.
- The central block shows a high apparent temperature in the part of the ridge facing south-east orientation, although this is possibly due to the slight incidence of sunlight at the time of inspection.
- The flat roof shows poor energy efficiency in the northwest area. The whole flat roof shows variations in apparent temperature between the different surfaces although no radiance pattern is repeated between the same materials. The defects may be due to the execution of the roof because heat leaks are detected in the borders with walls.

These problems could be solved by adding continuous insulation panels on all roofs. In the case of sloping roofs, the ridge areas should be covered to prevent heat leakage. And in the case of flat roofs, by covering the areas between different materials and their borders in contact with the vertical wall that forms the sloping roof.
Below, they are a series of recommendations and analyses carried out by the scientific community that can complement this research in future works before defining a definitive and conclusive solution. For example, it would be useful to carry out further inspections using aerial techniques at a lower height and with a different angle of vision to obtain more precise images [19]. This task can also be complemented by the use of a variety of sensors and manual thermal cameras inside the building. Other systems such as the blower door test (EN 13829) is useful to detect infiltration/exfiltration regions and thermal bridges. Burak Kakillioglu et al. (2018) applied aerial and manual techniques of infrared technology to study the thermal performance of buildings. They concluded that ground-based thermography complemented aerial techniques by providing more accurate identification of heat loss in buildings [7]. Mohamed Larbi et al. (2020) complemented the use of infrared cameras with other devices such as thermocouples, fluxmeter and pressure and humidity sensors to diagnose the energy performance of a building. The experiment was carried out by collecting measurements every second for more than a week [20]. The measurement of the thermal transmittance value U of the building envelope can also be measured by thermography and complements the energy audit. This coefficient takes into account all the heat transfer processes that are taking place through a building envelope. The precise evaluation of energy leaks can be quantified by knowing the value of thermal transmittance [21]. However, the difference between theoretical and actual thermal transmittance obtained by infrared techniques can be considerable and can lead to an over or underestimation of energy efficiency. For this, it would be necessary to carry out a quantitative thermography that provides real temperature values [22], [23]. This energy audit can be complemented by using aerial thermography to diagnose other problems in the building related to energy efficiency such as mold growth and the presence of water condensation between the walls and the roof as carried out by David Glew et al. (2017) [24]. Wet parts of a roof lose heat more quickly than dry areas, as moisture is a better conductor of heat energy than air. Thermography allows to detect heat and to distinguish this pattern of irregular heat dissipation. The efficiency of thermal insulation in buildings has a direct impact on energy consumption for heating and ventilation. Therefore it will also be necessary to compare the results obtained in thermography with the electricity consumption data of the building. As well as checking the HVAC equipment to supervise its correct operation which can seriously affect the results obtained through thermography.

To achieve substantial energy savings by improving existing buildings is the result of accurate and reliable energy audits, followed by adaptation strategies that respond accordingly. An inaccurate energy audit may result in lower than expected energy savings, no energy savings or even an occasional increase in energy use [7]. For this reason, the energy audit shown in this case study should be complemented with other techniques derived from the literature review, in order to avoid a worse environmental impact and a waste of investment capital.

5. Conclusions
An experiment in aerial thermography was carried out in a 58-year-old building, whose progress was presented step by step in order to facilitate its understanding and offer the possibility for other researchers to carry out similar maintenance and inspection tasks. The materials and software used to carry out the energy inspection were defined. The mission planning process was also detailed, as well as the execution of the flight with the different requirements to be taken into account to perform a correct thermography and the post-processing of the 976 images obtained to finally generate a three-dimensional model of the building and a single thermal orthophoto.

The application of thermography in the building made it possible to diagnose heat leakages in the roof, documenting them in advance before they become worse and more costly to repair. The execution of the case study demonstrated the viability of using this non-invasive technique for monitoring the energy status of a building. Weaknesses related to heat loss were identified in the flat roof borders and the sloping roof ridges. The results showed remarkable apparent temperature changes on the roof surface, in special, in the north-west part of the building (both on the sloping roof and on the flat roof). These problems could be solved by adding continuous insulation panels on all roofs. However, before defining a conclusive solution it would be necessary to carry out further inspections that provide
accurate and reliable results and do not aggravate the energy performance of the building or lead to wasted economic expenditure.

For this reason, different recommendations for future work were proposed to complement the energy audit carried out and presented in this investigation. Some examples are: the repetition of the aerial inspection with RPAS changing the angle of vision, at a lower altitude and incorporating the view of the facades; the complementary use of other techniques such as manual thermal cameras or humidity sensors inside the building; the use of systems such as the blower door test (EN 13829) that allows the identification of thermal bridges and air leaks with greater accuracy; the calculation of the envelope's real thermal transmittance factor; the detection of other pathologies such as the presence of humidity and condensation; the maintenance and revision of air conditioning systems (HVAC) and the analysis of the building's electricity consumption in order to quantify the consequences generated by the envelope's pathologies on economic costs.

The proposed methodology, the results obtained and the recommendations suggested for future work based on scientific literature, can be extrapolated to other buildings and be the basis of knowledge for other researchers and building designers who are committed to the implementation of new technologies for the energy audit of buildings.

6. References

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