

Inspection of pathological manifestations in buildings by using a thermal imaging camera integrated with an Unmanned Aerial Vehicle (UAV): a documental research

W. P. A. Silva^{1*} , A. C. Lordsleem Júnior¹ , R. D. B. Ruiz¹ , J. H. A. Rocha² 

*Contact author: wpas@poli.br

DOI: <https://doi.org/10.21041/ra.v11i1.447>

Reception: 14/11/2019 | Acceptance: 30/10/2020 | Publication: 01/01/2021

ABSTRACT

This paper is intended to present the usage of an UAV integrated thermographic camera in building inspection processes. This study was based on a systematic review of related articles and technical documents, in order to investigate features and basic operations of thermographic cameras, UAVs usage and influencing factors on detection of pathological manifestations. The results enabled identification of advantages and limitations for camera and UAV integration, thus demonstrating their feasibility and effectiveness when employed together. As a contribution, this study developed a flight protocol including steps and procedures required to perform an inspection when using a thermal camera together with an UAV.

Keywords: UAV; thermal camera; building inspection.

Cite as: Silva, W. P. A., Lordsleem Júnior, A. C., Ruiz, R. D. B., Rocha, J. H. A. (2021), "Inspection of pathological manifestations in buildings by using a thermal imaging camera integrated with an Unmanned Aerial Vehicle (UAV): a documental research", Revista ALCONPAT, 11 (1), pp. 123 – 139, DOI: <https://doi.org/10.21041/ra.v11i1.447>

¹ Grupo de Tecnologia e Gestão da Construção de Edifícios (POLITECH), Universidade de Pernambuco, Recife.

² Universidad Privada del Valle, Cochabamba, Bolivia.

Contribution of each author

In this work, author W.P.A. Silva contributed the original idea, data collection, writing of the paper, and discussion of results, author A.C. Lordsleem Júnior contributed with the writing of the paper and discussion of results, author R.D.B Ruiz contributed with the writing of the paper and discussion of results, and author J.H.A. Rocha contributed with the data collection, review of the paper and discussion of results.

Creative Commons License

This work is published under the terms of an International Creative Commons Attribution 4.0 International License ([CC BY 4.0](https://creativecommons.org/licenses/by/4.0/)).

Discussions and subsequent corrections to the publication

Any dispute, including the replies of the authors, will be published in the third issue of 2021 provided that the information is received before the closing of the second issue of 2021.

Inspección de manifestaciones patológicas en edificios con cámara térmica integrada en Vehículo Aéreo No Tripulado (VANT): una investigación documental

RESUMEN

Este artículo tiene como objetivo presentar el uso de la cámara termográfica integrada en VANT en los procesos de inspección de edificios. El desarrollo de este trabajo se basó en una revisión sistemática de artículos y trabajos relacionados al tema, investigando las características y el funcionamiento de las cámaras termográficas, el uso de VANTS y los factores que influyen en la detección de manifestaciones patológicas. Los resultados permitieron identificar las ventajas y limitaciones de la integración de cámaras y VANT, demostrando la viabilidad y efectividad del uso conjunto. Como contribución, este trabajo proporcionó el desarrollo de un protocolo de vuelo que ordena los pasos y procedimientos necesarios para realizar una inspección utilizando la cámara térmica integrada en VANT.

Palabras clave: VANT; Cámara térmica; Inspección de edificios.

Inspeção de manifestações patológicas em edifícios utilizando câmera termográfica integrada ao Veículo Aéreo Não Tripulado (VANT): uma pesquisa documental

RESUMO

Presente artigo tem como objetivo apresentar o emprego da câmera termográfica integrada ao VANT nos processos de inspeção de edifícios. O desenvolvimento do trabalho foi baseado em revisão sistemática de artigos e trabalhos da área de conhecimento, investigando as características e o funcionamento das câmeras termográficas, o emprego dos VANTS e os fatores que influenciam na detecção de manifestações patológicas. Os resultados permitiram identificar as vantagens e limitações da integração câmera e VANT, demonstrando a viabilidade e eficácia do uso conjunto. Como contribuição este trabalho proporcionou o desenvolvimento de um protocolo de voo ordenando as etapas e os procedimentos necessários para a realização de uma inspeção utilizando a câmera termográfica integrada ao VANT.

Palavras-chave: VANT; Câmera Térmica; Inspeção Predial.

Legal Information

Revista ALCONPAT is a quarterly publication by the Asociación Latinoamericana de Control de Calidad, Patología y Recuperación de la Construcción, Internacional, A.C., Km. 6 antigua carretera a Progreso, Mérida, Yucatán, 97310, Tel.5219997385893, alconpat.int@gmail.com, Website: www.alconpat.org

Responsible editor: Pedro Castro Borges, Ph.D. Reservation of rights for exclusive use No.04-2013-011717330300-203, and ISSN 2007-6835, both granted by the Instituto Nacional de Derecho de Autor. Responsible for the last update of this issue, Informatics Unit ALCONPAT, Elizabeth Sabido Maldonado, Km. 6, antigua carretera a Progreso, Mérida, Yucatán, C.P. 97310.

The views of the authors do not necessarily reflect the position of the editor.

The total or partial reproduction of the contents and images of the publication is carried out in accordance with the COPE code and the CC BY 4.0 license of the Revista ALCONPAT.

1. INTRODUCTION

Pathological manifestations are present in most buildings to a greater or lesser extent, varying their appearance period and requiring diagnosis and repair, or sometimes in a more complex way, requiring a personalized analysis (Ferreira & Lobão, 2018). However, even when they directly interfere in a building useful life and performance, -generating discomfort and risk both for people who directly use the building and passers-by in surroundings-, analysis and treatment of pathological manifestations is not a priority (Bauer et al., 2011; Viégas, 2015). Many times this structure does not obtain required attention regarding design, execution and maintenance. This is a fact that increases susceptibility about development and aggravation of pathological manifestations (Silva, 2007).

Considering this, investigation and monitoring process for buildings is essential because such procedures enable monitoring their behavior throughout their use in an enterprise, thus gathering information that enable monitoring and detecting failures when sent to obtain analysis and decision models (Agostinho, 2012). In that sense, destructive tests applied to materials, components or building systems become undesirable when it comes to problem diagnosis in the context of in-use buildings. In fact, development of non-destructive techniques intended to diagnose building deterioration, has generally been study subject for many researches (Freitas et al., 2014). Since then, using infrared thermography and Unmanned Aerial Vehicles (UAVs) in building inspection processes has been explored and spread out in society (Nascimento, 2014; Ellenberg et al., 2016; Entrop & Vasenev, 2017).

Thus, infrared thermography is a non-destructive technique involving remote sensing images used to detect flaws in electrical equipment, as well as changes in different parts of a building such as roof, structural systems, masonry sealing systems and coatings. One of these changes refers to detection of excessive humidity and temperature, responsible for damaging materials, with consequences on human health (Cortizo, 2007; Lerma et al., 2011; Freitas et al., 2014). Despite infrared thermography technique has been widely spread in European countries, thanks to historical collection, in Brazil its use is relatively incipient, either due to analysis equipment cost or difficulty on practical application (Cortizo et al., 2008).

Simultaneously, UAV usage has been subject to studies regarding building inspection to verify performance conditions and determine preventive and corrective measures that might be required, due to inherent complexity (height, size, access difficulties and exposure conditions) (Witczuk et al., 2017). UAVs may reduce time in these monitoring operations, and also assist in other inspection processes involving human life risk (Álvarez et al., 2016). In this context, the current article presents application of an infrared camera integrated with Unmanned Aerial Vehicles (UAV) as a tool for building inspection and monitoring to define procedural factors (influencing factors to achieve accurate thermograms used to identify pathological manifestations), in addition to advantages and limitations of this technology.

2. BIBLIOGRAPHICAL REVIEW

2.1 Infrared Thermography

Infrared thermography is a predictive tool used in early diagnosis of failures and other problems (performance analysis study to predict and specify possible anomalies, assisting in preventive maintenance). Results are presented instantly, during inspection, in form of thermal images or thermograms, which represent surface temperature distribution for an observed object and, as such, recorded for subsequent action purposes by interested parties and archiving (ITC, 2014).

Infrared thermography systems capture thermal radiation, represented in an electromagnetic spectrum, -by the fact that all bodies are at a temperature above absolute zero and emit radiation that is converted into a thermogram which has a polychromatic (color) or monochromatic (gray) scale. Infrared radiation (IR) was first discovered by William Herschel in 1800, and thermoelectric effect was discovered by Thomas Johann Seebeck in 1821. This effect is a direct conversion between temperature difference and electrical voltage and vice versa, being this effect the basis for thermal camera operation (Mistry, 2009; Viégas, 2015). Thermal radiation emitted by an object and captured by a thermal camera is given by Stefan-Boltzmann's law (1).

$$E = \frac{q}{A} = \varepsilon \times \sigma \times T^4 \quad (1)$$

Where E is the radiation emitted by the object (W/m^2), q is the degree of energy emission (W), A is the area of an emitting surface (m^2), T is the absolute temperature (K), σ is the Stefan-Boltzmann constant of $5.676 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$, and ε is the emissivity of an emitting surface, whose value is between 0 and 1, and indicates how close a surface is to the behavior of a black body, which would be an ideal surface where radiation rate would be maximum, so $\varepsilon=1$. (Çengel and Ghajar, 2012). Additionally, this technique may be classified as active or passive according to thermal overload being used. In active thermography, an external stimulus is required to generate relevant temperature differences. Different techniques may be employed to cause a heat flow in the study subject, each with its own characteristics and limitations. The choice on the type of thermal stimulus depends on characteristics of the object to be tested and the type of information to be researched (Batista, 2019).

On the other hand, using passive thermography where no artificial stimulation is used, involves a natural temperature difference that must be present between the study subject and the medium where it is inserted, which is frequently at a higher temperature. A passive method analysis relies on natural conditions for a studied structure and its surroundings, sun heat being a determining factor (Cortizo, 2007). Therefore, as shown in Figure 1, thermographic cameras capture infrared energy emitted by objects to convert this energy into an electrical signal and, finally, into a visible image, in which each level of energy is represented in a color scale (Meola & Carlomagno, 2004).

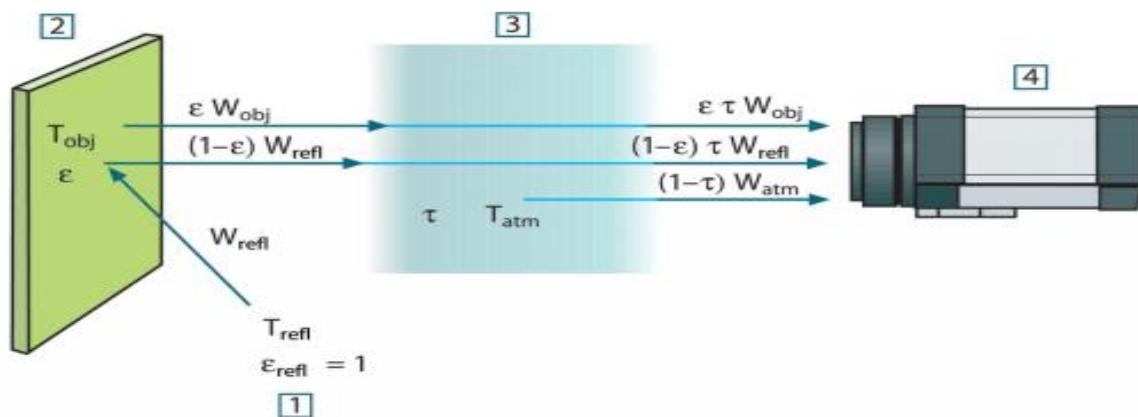


Figure 1. Schematic representation of general thermographic measurement location. 1) adjacent environment, 2) object, 3) atmosphere, 4) camera. T_{obj} : object temperature, T_{refl} : reflected temperature, T_{atm} : atmospheric temperature. W_{obj} : radiation power emitted by the object, W_{refl} : radiation power emitted by surrounding environment, W_{atm} : radiation power emitted by atmosphere (Caldeira & Padaratz, 2015).

Thus, this technique implemented in buildings may be used to evaluate comfort on floor covering (Barreira et al., 2013), detect insulation defects, air leaks (Ocaña et al., 2004) moisture problems (roof damage, moisture on walls), thermal bridges (Asdrubali et al, 2012), and inspect HVAC systems (Heating, Ventilating and Air Conditioning), construction details (Cerdeira et al., 2011; Barreira et al., 2013) and also in building inspection (Brique, 2016), as shown in Figure 2.

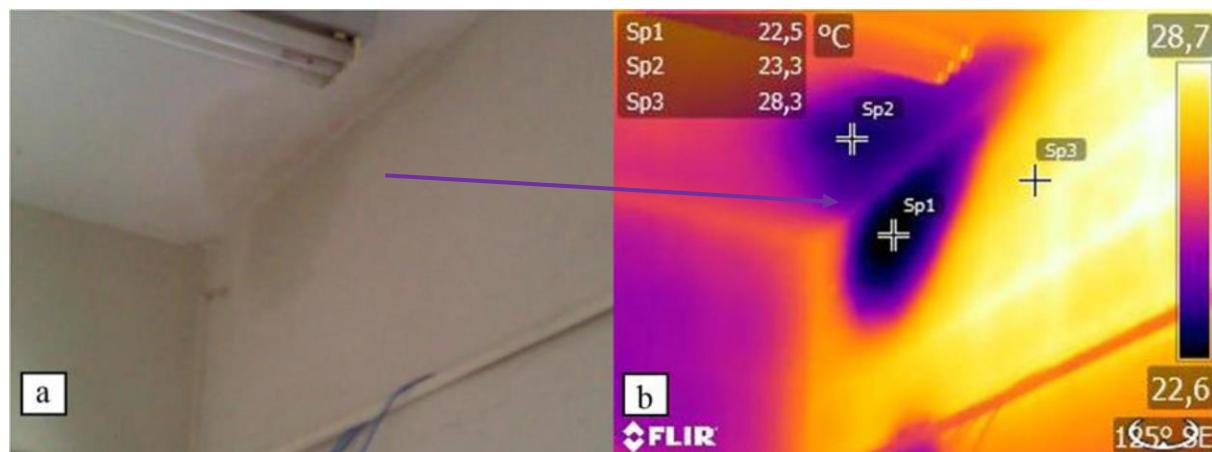


Figure 2. Pluvial water penetration: (a) digital image and (b) thermogram (Rocha et al., 2018).

According to variables highlighted in Table 1, the higher the thermal resolution (pixels) in a camera, the more likely to inspect larger areas with greater precision. Therefore, when using thermal cameras integrated with UAV, they must have the best resolution possible. Furthermore, the IFOV (Instantaneous Field of View) value and the lens opening angle are one of the main limitations in studies involving the analysis of buildings. The higher these parameters, the lower thermogram resolutions and study accuracy will be (Andrade et al., 2019). In addition, it should be noted that the inspection is limited only to a passive application of infrared thermography, which would mean that inspection to the structure would not be possible every day, or that it would be restricted to locally determined schedules.

Table 1. Key variables related to a thermographic camera (Andrade et al., 2019)

PIXEL CAMERA RESOLUTION	IFOV (<i>Instantaneus Field of View</i>)	LENS OPENING ANGLE
60 x 60, 120 x 120, 240 x 380, 320 x 240, 640 x 480.	The value varies between 0.6 and 3.7 mRad, using the equipment lens.	The most common lenses are 15 and 25 degrees but can vary between 7 and 80 degrees.

2.2 UAVs

According to ANAC (National Civil Aviation Agency, 2017), unmanned aerial vehicles (UAVs) are any unmanned aircraft that can be remotely or automatically driven. These aircrafts are remotely or automatically flown using predefined coordinates. It is a technology on the rise that is being used in several areas every day (Nascimento, 2014). UAVs were first developed in the 1950s and were exclusively intended for military purposes. Different projects started in several countries with the purpose of producing vehicles capable of performing missions without a pilot on board in order to avoid further losses (Agostinho, 2012). Over time, technology began to get disclosed, and its first use for a non-military purpose took place in 1986, when forest fires were monitored in Montana, United States (Agostinho, 2012). In this sense, increasing UAV usage is due to its low cost, agile processing collection, easy aircraft maneuvering, and efficient image capture system (Seibert & Teizer, 2014).

Besides, UAVs are effective tools to perform remote sensing procedures, including its capability for reaching places that are difficult to access as the main reason to be used, as well as a range of applicable sensors that can be incorporated such as an infrared camera, light detection and distance sensors (LIDAR, Light Detection And Ranging) (Freimuth & König, 2018).

Currently, two types of UAVs, whose basic difference is their aerodynamic system such as a rotation or fixed wing, are available in the market. The first aircrafts are similar to a helicopter or multirotor, a compact aircraft involving easy operation and low cost. On the other hand, fixed-winged aircrafts include different sizes according to functionality (Jorge & Inamasu, 2014; Melo & Costa, 2015).

Table 2. UAV Classification (Bento, 2008).

CATEGORY	ACRONYM	RANGE [km]	FLIGHT ALTITUDE [m]	BATTERY AUTONOMY [h]	WEIGHT [kg]
<i>Micro</i>	μ (micro)	< 10	250	1	<5
<i>Mini</i>	Mini	< 10	150 – 3000	< 2	150
<i>Close Range</i>	CR	10 – 30	3000	2 – 4	150
<i>Short Range</i>	SR	30 – 70	3000	3 – 6	200
<i>Medium Range</i>	MR	70 – 200	5000	6 – 10	1250
<i>Medium Range Endurance</i>	MRE	>500	8000	10 – 18	1250
<i>Low Altitude Deep Penetration</i>	LADP	>250	50 – 9000	0,5 – 1	350
<i>Low Altitude Long Endurance</i>	LALE	>500	3000	>24	<30
<i>Medium Altitude Long Endurance</i>	MALE	>500	14000	24 – 48	1500

Table 2 shows that UAVs used in building inspection process in general have a weight below 150 kg. The flight range, a dominant factor for flight protocol development and efficiency in building monitoring, is below two hours.

2.3 Thermography integrated with UAV

Although thermography and UAVs are subject to different recent investigations, an integrated study of both is still incipient. Analyzing benefits related to these two topics motivates a combination of their functionalities to obtain mutual benefits (Entrop & Vasenev, 2017). A thermal camera integrated with an UAV is an important tool to evaluate large areas in an automated way and in reduced runtime (Viana et al., 2018). Main challenges for this technology are low resolution of some thermographic cameras, regulations that limit operations involving UAV on a visual line and high dependence on climate (Witczuk et al., 2017).

In addition, heat sensors are a payload option for high resolution aerial thermal imaging. This technology enables quick and safe survey of thermal areas, often present in inaccessible or dangerous terrain (Harvey et al., 2016). These images collected by UAV are potentially critical tools in geothermal science, including geological, geochemical and geophysical surveys, study and environmental monitoring baselines, geotechnical and civil works, and as in the case of this research, an outstanding support for building inspection. Such technology may be used for mapping heat loss, and be able to gather thermal information such as heat leaks, by using an infrared camera and then processing any image obtained. Despite performing inspections, it is a less difficult process for small buildings, collecting thermal data with increasing height, especially on skyscrapers and roofs, and is a much more complex and dangerous process (Kayan et al., 2018). Aerial thermography is a technology that has been used in recent times to record thermal images without requiring access to buildings, and it is capable of reaching any difficult-access area such as a roof, while carrying an infrared camera and any other sensor (Chu et al., 2016).

Therefore, combining infrared thermography and UAVs enables optimization of maintenance tasks (Muñoz et. al., 2017), and consequently, bringing significant economic advantages (Ramírez et al., 2018). Such aspects are due to the fact that UAVs may be equipped with high-resolution cameras allowing users to obtain data in real-time. Furthermore, aerial images previously captured from another light aircraft or helicopter and their fuel cost are disadvantages that make UAVs more viable, since power source for their flight can be easily recharged (Lavars, 2015). Therefore, being equipped with a high-resolution thermographic camera, an UAV becomes an excellent tool to collect thermal information from buildings (Zhang et al., 2015). In that sense, Figure 3 shows an UAV model that is already integrated with a digital camera as well as a thermographic camera, different from other models. Removing the first camera to install the second camera is required.



Figure 3. UAV with a thermographic camera attached to a digital camera (Topdrone, 2020).

3. BUILDING INSPECTION

Thermography implementation in inspection processes is based on existing anomalies or defects that impact thermal properties in the structure. Figure 4 shows defects interrupting heat transfer from concrete, since existing voids are filled with air or water, and due to different thermal conductivity in materials, temperature variation along the structure is verified (Rocha & Póvoas, 2017).

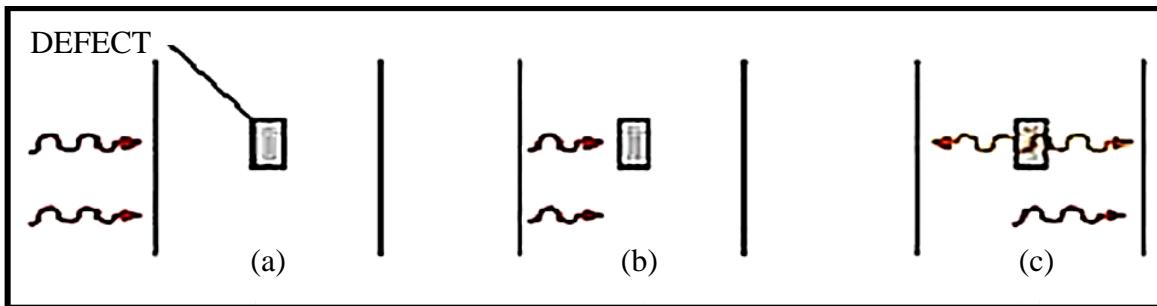


Figure 4. Modeled propagation of a single heat pulse in a material: (a) An energy pulse applied to the surface; (b) A heat pulse travels inside the material and finds a defect; (c) This defect partially reflects and partially transmits the pulse (Cortizo, 2007).

Additionally, infrared thermography produces a thermal image, where each color represents a surface temperature level in objects. By analyzing any image obtained by the equipment, it is possible to identify foci of humidity, anomalies, hidden elements, and other defects present (Grinzato et al., 2011). Consequently, infrared thermography enables detecting only anomalies associated with measurable modifications of thermal characteristics such as heat flow and resulting temperatures, and pathological manifestations with limited depths, i.e., near the surface (Bauer & Pavón, 2015). In civil construction, therefore, a temperature range from 1 °C to 2 °C is generally an indication of potential issues. From 4 °C on, existing body abnormality may be ascertained (Maldague & Marinetti, 1996; Cortizo et al., 2008).

Therefore, this technology enables identification of adhesion failure or absent mortar (Bauer et al., 2015), and confined moisture present in ceramic tiles (Edis et al., 2014; Bauer & Pavón, 2015), as well as existing cracks, detachment problems, and infiltrations, considering the thermal gradient verified in the thermogram (Freitas et al., 2014; Viégas, 2015; Rocha & Póvoas, 2017; Takeda & Mazer, 2018; Batista, 2019).



Figure 5. Inspection using an UAV integrated with a thermal camera (Nascimento, 2014)

In the case shown in Figure 5, according to Nascimento (2014), images were obtained in the early morning, making it possible to recognize areas including cracks and infiltrations, as the weather was mild and allowed a greater difference in temperature gradient, with lighter regions being those that have a higher temperature than those that are represented in darker tones.

3.1 Advantages and disadvantages

Table 3 shows the main advantages and limitations of using a thermographic camera integrated with an UAV according to literature (Yehia et al., 2007; Agostinho, 2012; Sham et al., 2012; Jorge & Inamasu, 2014; Mavromatidis et al., 2014; Seibert and Teizer, 2014; Domingues, 2015; Melo and Costa, 2015; Pajares, 2015; Watase et al., 2015; Zhang et al., 2015; Ariwoola, 2016; Ellenberg et al., 2016; Hiasa et al., 2016; Rehman et al., 2016; Entrop & Vasenev, 2017; Muñoz et al., 2017; Witczuk et al., 2017; Freimuth & König, 2018; Ramírez et al., 2018; Andrade et al., 2019).

Table 3 shows that main advantages of using this technology are linked to optimizing inspection procedures, obtaining data in real time and in a shorter interval of time. On the other hand, limitations are related to requirements to obtain an accurate thermogram, considering favorable climatic conditions and readings made from angles and distances unable to interfere with the results.

Table 3. Advantages and limitations of using a thermal camera integrated with an UAV.

VANTAGENS	LIMITAÇÕES
<ul style="list-style-type: none"> • Capability of reaching difficult access areas; • Getting real-time data; • Reducing operational risks • Increasing operator and employee safety; • Reduced inspection time that generates savings and speeding up recovery planning for a structure; • Greater reliability compared to conventional methods; • Fast, non-invasive, non-destructive and contactless technology; • Applicable at a considerable distance to analyze and inspect large areas at short intervals of time. 	<ul style="list-style-type: none"> • Flight autonomy from 30 min to 2 h, using < 150 Kg models; • Favorable weather conditions, implying both flight and surface heat emissivity; • Subject to local regulations and restrictions for flight performances, unable to be performed in any location; • Interference in results due to reflections if used in a facility surrounded by buildings including mirrored facades; • Changes in scanning obtained at distances > 10 meters between the camera and the target object; • Unable to measure thickness and depth of any pathological manifestation.

Finally, one of the most critical factors when using aerial thermography is related to operation and equipment cost; however, when comparing benefits of this tool related to conventional methods, its potentialities considering its speed in data collection and safety for people performing an inspection are verified (Mavromatidis et al., 2014; Ariwoola, 2016).

3.2 Processing factors regarding thermal imaging

Thermographic analysis is a procedure where an inspector operates a thermal imager pointing at an object under inspection and detecting a defect by an analysis of thermogram obtained. Despite the technique is apparently simple, the result analysis might be complicated and would even lead to wrong conclusions if certain precautions are not taken before and during the test (Brique, 2016). Therefore, the operator himself must be aware of strong influence posed by solar radiation, wind and rain, and how these factors impact thermal distribution of any object analyzed in an open environment (Batista, 2019).

Considering this, in order to guarantee image quality, sensitivity and thermal contrast, awareness regarding some factors such as material emissivity (a function of surface temperature and observation angle) surface reflectivity, purpose of direct incident radiation and existing external sources (shadows, reflections), distance and measurement angle is required (Barreira, 2004; Cortizo, 2007; Bauer, 2015; Viégas, 2015; Batista, 2019). Besides, sun heat radiation may affect thermographic measurement, as it modifies normal heat flow from inside out. Distance from the equipment to the object may also modify surface temperature reading, as it reduces thermogram resolutions and influences atmospheric attenuation (Labat et al., 2011).

Regarding inspection time, it was found that differences between authors are present, but this parameter depends on environmental conditions found where a studied object is located (Rocha & Póvoas, 2017). In that sense, different behaviors were verified regarding measurement periods (dry and rainy), at 8 a.m., 3 and 9 p.m. (Freitas et al., 2014). In other cases, measurements were taken at different times during the morning and the afternoon (Nascimento, 2014), as emissivity by non-metal materials decreases with increasing temperature (Barreira, 2004). There were also cases where checking measurements throughout the day (6-18h), in order to evaluate the best measurement times, both in the morning and in the afternoon was decided (Viégas, 2015).

Finally, some authors (Uemoto, 2000; Watase et al., 2015; Hiasa et al., 2016) recommend an inspection at night in order to eliminate solar radiation effect, and have a better view between the defect and the intact regions, thus avoiding false detections (Rocha & Póvoas, 2017).

In addition, thermal gradients and turbulence modify air refractive index thus causing a reduction in image quality. Meanwhile, atmosphere present between the emission source and the receiver may cause disturbances in measurement. Therefore, a 10-meter distance between the emission source and the receiver must be maintained and measurements made at greater distances must be corrected (Barreira, 2004; Comitti, 2012; Viégas, 2015). Moreover, during days including winds above 7 m/s, measurements should not be made with infrared thermography, because data obtained will induce error in thermal analysis of the object (ITC, 2014).

According to Standard NBR 15572 (ABNT, 2013), an angle between the thermal imager and the inspected point must be as perpendicular as possible, so that no emissivity reduction due to inadequate observation angles (greater than 60°) is present. For this reason, Viégas (2015) states that nobody should remain directly facing the target so thermographer heat is not reflected. Therefore, positioning at an angulation of about 5°, in relation to object horizontal line to be thermally analyzed is recommended, as shown in Figure 6.

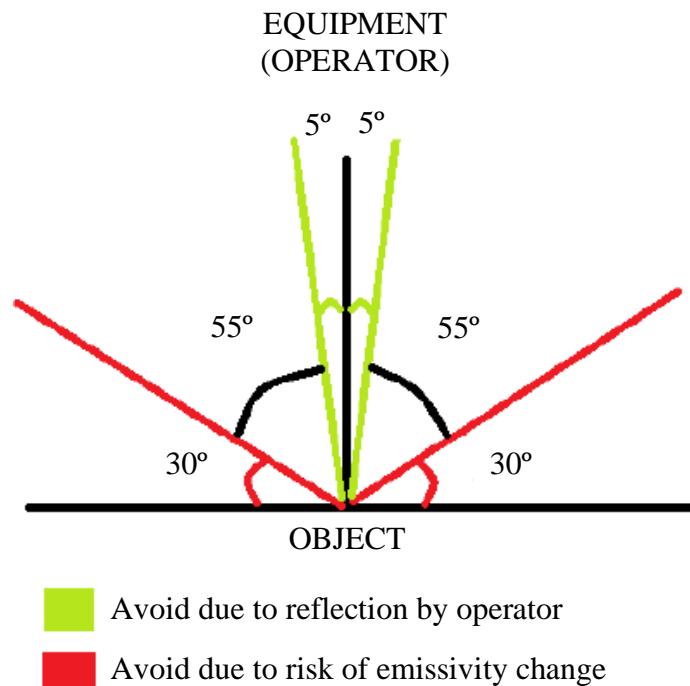


Figure 6. Measurement angles: precautions (Viégas, 2015)

3.3 Flight Protocol

Project planning and development may vary according to flight capacity, being influenced by their accuracy and course (Agostinho, 2012). However, it is perceived that commercially available flight preparation tools, in some cases are still insufficient to perform certain inspections, and it is up to an operator to create their own tools and protocols (Seibert & Teizer, 2014). As a result, the protocol shown below in Figure 7 and Table 4, was developed according to studies by several authors (Agostinho, 2012; Siebert & Teizer, 2014; Ariwoola, 2016; Ellenberg et al., 2016; Entrop & Vasenv, 2017; Freimuth & König, 2018).

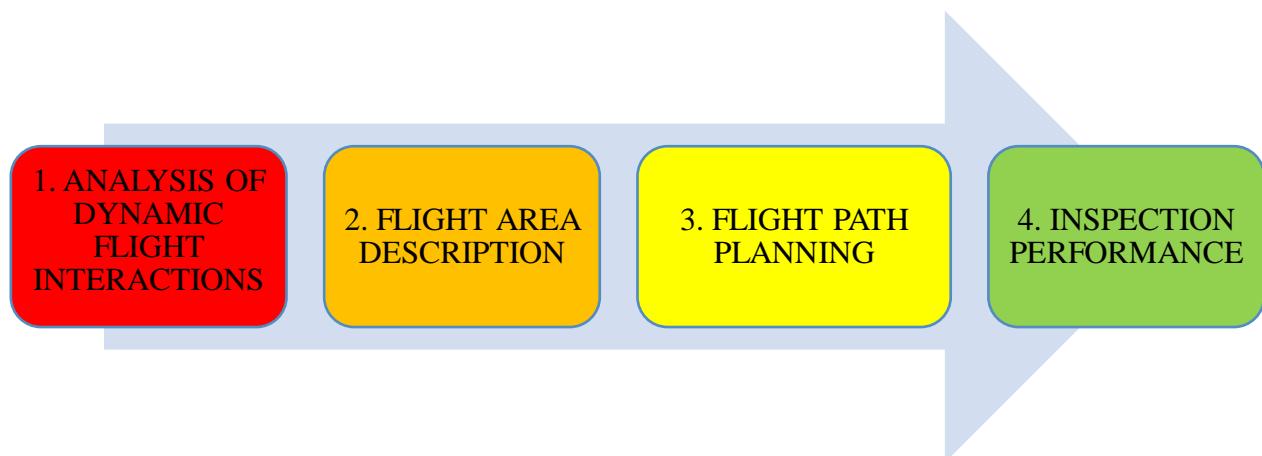


Figure 7. Flight protocol steps.

Table 4. Flight protocol.

STEPS	PROCEDURES
1. Analysis of dynamic flight interactions	At this stage, checking UAV use regulations where inspection will be performed is required. Additionally, a study on weather conditions for inspection day, and characteristics of object studied (area, number of floors, maximum level) must be obtained and then proceed with choosing an equipment.
2. Flight Area Description	On the second stage, performing a test flight to identify risk areas and establishing reading angles and distances is required.
3. Flight Path Planning	Once risk areas have been determined, a flight path must be developed so that 75% of UAV load for flight autonomy is guaranteed.
4. Inspection Performance	After completing previous steps, inspection may be performed in such a way that reading data safely and accurately is possible.

By analyzing Table 4, it is verifiable that an initial stage is related to previous requirements for the inspection using a thermographic camera integrated with an UAV, including verifying any regulation for such equipment where the procedure will be performed, weather conditions, being necessary winds of less than 7 m/s and not during cloudy days, having knowledge of the object to be studied, such as dimensions and location, and finally choosing an equipment that guarantees a flight autonomy for such procedure. Afterwards, inspection area where the UAV will be moving along the inspection must be determined, paying attention to risk areas such as places where people, animals and obstacles are present, and establishing angles and distances where readings will be taken, at distances < 10 meters and at angles according to Section 3.1, ensuring the accuracy of the data obtained. From there, a path to be traveled by the UAV must be planned in such a way that risk area displacement is avoided and the device has sufficient flying autonomy to finish a flight with 75% of charge in the battery, including energy consumed during landing and take-off procedures. Finally, once previous steps have been completed, the inspection may be performed.

3.4 Data Analysis provided by Literature

It was verified that despite simplicity in using a thermal imager to obtain thermograms during inspections, interferences and environmental conditions under which images were obtained should not be taken into account, thermogram analysis and interpretation might lead to erroneous conclusions (Takeda & Mazer, 2018). In addition, it was found that the larger and the more superficial a defect area is, the easier detection is (Rocha & Póvoas, 2017). In that sense, it was found that if R/d ratio (R: short defect dimension and d: defect depth from the surface) is greater than 1, defects are found; if this R/d ratio is equal to 0.45, they are detectable up to a depth of 10 centimeters (Farrag et al., 2016). Moreover, in thermal profiles presented in the thermograms for masonry a clear variation in surface temperature was present. This thermal difference denotes different materials present inside the masonry, due to quite distinct physical and chemical properties (Cortizo, 2007).

In addition, during inspection of a structure including ceramic coating it was verified that the best measurements were obtained after the facade was heated (passive technique), and that the thermogram in the afternoon had better clarity compared to morning thermogram (Viégas, 2015). Afterwards, when studying a building covered with mortar, it was found that the best times for measurement were from 11 a.m. to 12 p.m. and 5-6 p.m., and a "more vibrant" yellow coloration in the region including coating detachment was verified. In this region temperature increases unlike the rest of mortar-coated facade absent of pathological manifestations. Finally, when monitoring a structure covered with tile, the best times for measurement were between 9-10 a.m. and 2-3 p.m. (Viégas, 2015), thus confirming measurement times stated in 3.1.

A slight tendency in greater temperature differences (between areas with and without fissures) in the hottest areas, as well as greater dispersion of these variations measured in warmer areas were also observed (Freitas et al., 2014). Besides, at least a 5-meter distance between the UAV and the research objects to be safe was at first considered. While during the tests, this distance was increased to 10 meters, thus guaranteeing both reliable data obtained and aircraft safety (Entrop & Vasenev, 2017). Furthermore, simulation and flight model preparation comprises a more accurate inspection and better UAV performance, considering speed characteristics and battery recharge required (Freimuth & König, 2018).

4. CONCLUSIONS

Based on previous discussion and presented data, confirming thermography integrated with UAV is a capable tool to identify thermal anomalies associated to pathological manifestations is possible. Additionally, this mechanism optimizes building inspection process, enabling characterization of difficult-access areas without risking human safety. Besides, it provides fast and precise data which helps during inspection procedures and structure recovery tests.

However, few limitations are described fourfold: charging capacity is rather vulnerable, weather variations during flight, data obtained in the thermogram and object reflections in the surroundings may interfere in the results. Main contributions of this study include a specific flight protocol to use a thermographic camera integrated with a UAV and a review on principles and techniques involved in this procedure. The latter being a basis for future studies and research on development and expansion of monitoring models that tend to overcome disadvantages and guarantee effectiveness of this tool.

5. REFERENCES

Agência nacional de aviação civil. (2017). *Requisitos gerais para aeronaves não tripuladas de uso civil - RBAC-E nº 94. Resolução n. 419*. Brasília.

Agostinho, S. L. (2012), “*Inspeção e Monitorização de Estruturas em Engenharia Civil – Utilização de UAV na Inspeção e Monitorização*”, Dissertação de Mestrado, Universidade da Madeira, p. 105.

Álvares, J., Costa, D. B., Melo, R. R. S., Bello, A. (2016), “*Estudo exploratório de mapeamento 3D de canteiros de obras utilizando veículos aéreos não tripulados*”, In: XVI Encontro Nacional de Tecnologia do Ambiente Construído, São Paulo, Brasil, pp. 5067-5080.

Andrade, R. P., Resende, M. M., Maranhão, F. L., Portella, F., Bulzico, B. (2019), “*Estado da arte da utilização da técnica de termografia embarcada em drones para inspeção de revestimentos de fachadas*”, In: 2º Workshop de Tecnologia de Processos e Sistemas Construtivos, São Paulo, Brasil, p.5, disponível em: <https://antaceventos.net.br/index.php/tecsic/tecsic2019/paper/view/304/139>

Ariwoola, R. T. (2016), “*Use of Drone and Infrared Camera for a Campus Building Envelope Study*”, Master Thesis, East Tennessee State University, p. 83. <https://dc.etsu.edu/etd/3018>

Asdrubali, F., Baldinelli, G., Bianchi, F. (2012), *A quantitative methodology to evaluate thermal bridges in buildings*. Applied Energy. 97(1):365–373. <https://doi.org/10.1016/j.apenergy.2011.12.054>

Associação Brasileira de Normas Técnicas. (2013). *NBR 15572: Ensaios não destrutivos — Termografia — Guia para inspeção de equipamentos elétricos e mecânicos*. Rio de Janeiro.

Barreira, E. (2004), “*Aplicação da Termografia ao Estudo do Comportamento Higrotérmico dos Edifícios*”, Dissertação de Mestrado, Universidade do Porto, p. 198.

Barreira, E., de Freitas, S. S., de Freitas, V. P., Delgado, J. M. P. Q. (2013), *Infrared thermography application in buildings diagnosis: a proposal for test procedures, industrial and technological applications of transport in porous materials*. Advanced Structured Materials. 36. https://doi.org/10.1007/978-3-642-37469-2_4

Batista, T. S. (2019), “*Avaliação do desempenho da termografia infravermelha em diferentes espessuras e profundidades de trincas em edificações*”, Dissertação de Mestrado, Universidade de Pernambuco, p. 109.

Bauer, E., Castro, E. K., Antunes, G. R., Leal, F. E. (2011), “*Identification and Quantification of Pathologies in Facades of New Buildings in Brasília*” in: XII DBMC International Conference on Durability of Building Materials and Components, Porto, Portugal.

Bauer, E., Freitas, V. P., Mustelier, N., Barreira, E., Freitas, S. (2015), *Infrared Termography – Evaluation of the results reproducibility*. Structural Survey. 33(1): 82-86. <https://doi.org/10.1108/ss-05-2014-0021>

Bauer, E., Pavón, E., (2015), *Termografia de infravermelho na identificação e avaliação de manifestações patológicas em edifícios*. Revista Concreto e Construções.79:93-98. ISSN:1809-7197.

Bento, M. F. (2008), “*Unmanned aerial vehicles: an overview*”, Inside GNSS, pp. 54-61.

Brique, S. K. (2016), “*Emprego da termografia infravermelha no diagnóstico de falhas de aderência de peças cerâmicas utilizadas em fachadas de edifícios*”, Dissertação de Mestrado, Universidade Federal de Santa Catarina, p. 180

Caldeira, M. M., Padaratz, I. J. (2015), *Potentialities of infrared thermography to assess damage in bonding between concrete and GFRP*. Ibracon Structures and Materials Journal. 8:296-322. <http://dx.doi.org/10.1590/S1983-41952015000300004>

Cengel, Y. A., Ghajar, A. J. (2012), “*Transferência de Calor e Massa - Uma Abordagem Prática*” (Porto Alegre, Brasil: Amgh Editora), p. 906.

Cerdeira, F., Vázquez, M., Collazo, J., Granada, E. (2011), *Applicability of infrared thermography to the study of the behaviour of stone panels as building envelopes*. Energy Build. 43:1845–1851. <https://doi.org/10.1016/j.enbuild.2011.03.029>

Chu, A-M., Westerhoff1, L., Sheppard1, S., Storey, S., Goodhew, J., Fox, M., Goodhew, S., Pahl, S., Higgins, C. (2016), “*Exploring the Use of Thermal Imagery for the Promotion of Residential Energy Efficiency. Report prepared for the City of Vancouver*”, available at: <http://calp2016.sites.olt.ubc.ca/files/2016/05/Thermal-Imaging-Report.pdf>

Comitti, A. (2012), “*Engenharia de manutenção: Uso da Termografia*”, Revista Saber Eletrônica, 47(459):14-19.

Cortizo, E. C. (2007), “*Avaliação da técnica de termografia infravermelha para identificação de estruturas ocultas e diagnóstico de anomalias em edificações: ênfase em edificações do patrimônio histórico*”, Tese de Doutorado, Universidade Federal de Minas Gerais, p. 178.

Cortizo, E. C., Barbosa, M. P., Souza, L. A. C. (2008), *Estado da Arte da Termografia*. Ambiente Construído e Patrimônio Sustentável. 2(2):158-193.

Domingues, A. D. (2015), “Identificação de manifestações patológicas em fachadas prediais com revestimento cerâmico, utilizando a técnica de termografia de infravermelho”, Monografia de Graduação, Universidade Católica de Brasília, p. 29.

Edis, E., Flores-Colen, I., de Brito, J. (2014), *Passive thermographic detection of moisture problems in façades with adhered ceramic cladding*. Construction and Building Materials. 51(1):187-197. <http://dx.doi.org/10.1016/j.conbuildmat.2013.10.085>

Ellenberg, A., Kontsos, A., Moon, F., Bartoli, I. (2016), *Bridge deck delamination identification from unmanned aerial vehicle infrared imagery*. Automation in Construction. 72(1):155-165. <https://doi.org/10.1016/j.autcon.2016.08.024>

Entrop, A. G., Vasenev, A. (2017), *Infrared drones in the construction industry: designing a protocol for building thermography procedures*. Energy Procedia. 132(1):63-68. <https://doi.org/10.1016/j.egypro.2017.09.636>

Farrag, S., Yehia, S., Qaddoumi, N. (2016), *Investigation of Mix-Variation Effect on Defect-Detection Ability Using Infrared Thermography as a Nondestructive Evaluation Technique*, J. Bridge Eng. 21(3):1-15. [http://dx.doi.org/10.1061/\(ASCE\)BE.1943-5592.0000779](http://dx.doi.org/10.1061/(ASCE)BE.1943-5592.0000779)

Ferreira, J. B., Lobão, V. W. N. (2018). *Manifestações patológicas na construção civil*. Caderno De Graduação - Ciências Exatas E Tecnológicas. 5(1):71-80. Disponível em: <https://periodicos.set.edu.br/cadernoexatas/article/view/5853>

Freimuth, H., König, M. (2018), *Planning and executing construction inspections with unmanned aerial vehicles*. Automation in Construction. 96(2):540–553. <https://doi.org/10.1016/j.autcon.2016.08.024>

Freitas, J. G., Carasek, H., Cascudo, O. (2014), *Utilização de termografia infravermelha para avaliação de fissuras em fachadas com revestimento de argamassa e pintura*. Ambiente Construído. 14(1):57-73. <https://doi.org/10.1590/S1678-86212014000100006>

Freitas, S. S., Freitas, V. P., Barreira, E. (2014), *Detection of façade plaster detachments using infrared thermography – A nondestructive technique*. Construction and Building Materials. 70(1):80-87. <https://doi.org/10.1016/j.conbuildmat.2014.07.094>

Grinzato, E. (2011), “*State of the art and perspective of infrared thermography applied to building science*” in: Meola C, editor. Infrared thermography recent advances and future trends. Bentham Books. ISBN: 978-1-60805-521-0, <http://dx.doi.org/10.2174/97816080514341120101>

Grinzato, E., Ludwig, N., Cadelano, G., Bertucci, M., Gargano, M., Bison, P. (2011), *Infrared Thermography For Moisture Detection: a laboratory study and in-situ test*. Materials Evaluation. 69(1):97-104.

Harvey, M. C., Rowland, J. V., Luketina, K. M. (2016), *Drone with thermal infrared camera provides high resolution georeferenced imagery of the Waikite geothermal area, New Zealand*. Journal of Volcanology and Geothermal Research. 325(1):61-69. <https://doi.org/10.1016/j.jvolgeores.2016.06.014>

Hiasa, S., Catbas, F., Matsumoto, M., Mitani, K. (2016), *Monitoring concrete bridge decks using infrared thermography with high speed vehicles*. Structural Monitoring and Maintenance, 3(3): 277-296. <https://doi.org/10.12989/smm.2016.3.3.277>

Infrared Training Center – ITC. (2014). *Manual do usuário – Certificação Nível 1*. Sorocaba.

Jorge, L. A. C., Inamasu, R. Y., “*Uso de veículos aéreos não tripulados (VANT) em agricultura de precisão*” in: A. Bernadi, J. Naime, A. Resende, L. Bassoi, Y. Inamasu (Ed.) (2014), Agricultura de precisão: resultados de um novo olhar. Brasília, DF: Embrapa, pp. 109-134.

Kayan, H., Eslampanah, R., Yeganli, F., Askar, M. (2018), “*Heat leakage detection and surveillance using aerial thermography drone*” in: 26th Signal Processing and Communications Applications Conference (SIU), Izmir, Turkey, pp. 1-4. <https://doi.org/10.1109/SIU.2018.8404366>

Labat, M., Garnier, G., Woloszyn, M., Roux, J. J. (2011), “*Infrared measurements on ventilated cladding for assessing its surface temperature and insulated part of the envelope using a simulation tool*” in: NBS 2011 – 9th Nordic Symposium on Building Physics, Tampere, Finland, pp. 315-322.

Lavars, N. (2015), “*How drones are poised to help build the cities of tomorrow*”, acesso em 1 de julho de 2019, disponível em: <http://www.gizmag.com/drones-building-constructionindustry/36306/>

Lerma, J. L., Cabrelles, M., Portalés, C. (2011), *Multitemporal thermal analysis to detect moisture on a building façade*. Construction and Building Materials. 25(1):2190-2197. <https://doi.org/10.1016/j.conbuildmat.2010.10.007>

Mal dague, X., Marinetti, S. (1996), *Pulse phase infrared thermography*. Journal Applied Physics. 79(1):2694-2698. <https://doi.org/10.1063/1.362662>

Mavromatidis, L. E., Dauvergne, J. L., Saleri, R., Batsale, J. C. (2014), *First experiments for the diagnosis and thermophysical sampling using impulse IR thermography from Unmanned Aerial Vehicle (UAV)*. Quantitative InfraRed Thermography. <http://dx.doi.org/10.21611/qirt.2014.213>

Melo, R. R. S., Costa, D. B. (2015), “*Uso de veículo aéreo não tripulado (VANT) para inspeção de logística em canteiros de obra*”. in: SIBRAGEC-ELAGEC, São Carlos, pp. 674-681.

Meola, C., Carlomagno, G. (2004), *Recent advances in the use of infrared thermography*. Measurement Science and Technology. 15(9):27-58. <http://dx.doi.org/10.1088/0957-0233/15/9/R01>

Mistry, B. D. (2009), “*A Handbook of Spectroscopic Data*” (Oxford, England: Oxford Book Company), p. 247.

Muñoz, C. Q. G., Marquez, F. P. G., Lev, B., Arcos, A. (2017), *New pipe notch detection and location method for short distances employing ultrasonic guided waves*. Acta Acustica united with Acustica. 103(5):772-781. <https://doi.org/10.3813/AAA.919106>

Nascimento, M. L. M. (2014), “*Utilização de drone e termografia na detecção de manifestações patológicas em edificações*”, Monografia de Graduação, Universidade Católica de Brasília, p. 21.

O. T. Takeda, W. Mazer (2018), *Potencial da análise termográfica para avaliar manifestações patológicas em sistemas de revestimentos de fachadas*. Revista ALCONPAT. 8(1):38-50 <http://dx.doi.org/10.21041/ra.v8i1.181>

Ocaña, S., Guerrero, I., Requena, I. (2004), *Thermographic survey of two rural buildings in Spain*. Energy Build, 36(6):515-523. <https://doi.org/10.1016/j.enbuild.2003.12.012>

Pajares, G. (2015), *Overview and current status of remote sensing applications based on unmanned aerial vehicles (UAVs)*. Photogrammetric Engineering & Remote Sensing. 81(1):281-329. <https://doi.org/10.14358/PERS.81.4.281>

Ramírez, I. S., Marugán, A. P., Márquez, F. P. G. (2018), “*Remotely Piloted Aircraft System and Engineering Management: A Real Case Study*” in: Xu J., Cooke F., Gen M., Ahmed S. (eds) Proceedings of the Twelfth International Conference on Management Science and Engineering Management. Springer, Cham. pp. 1173-1185. https://doi.org/10.1007/978-3-319-93351-1_92

Rehman, S., Ibrahim, Z., Memon, S., Jameel, M. (2016), *Nondestructive test methods for concrete bridges: A review*. Construction and Building Materials. 107(15):58-86. <http://dx.doi.org/10.1016/j.conbuildmat.2015.12.011>

Rocha, J. H. A., Póvoas Y. V. (2017), *Infrared thermography as a non-destructive test for the inspection of reinforced concrete bridges: A review of the state of the art*. Revista ALCONPAT. 7(3):200-214. <http://dx.doi.org/10.21041/ra.v7i3.223>

Rocha, J. H. A., Santos, C. F., Oliveira, J. B., Albuquerque, L. K. S., Póvoas, Y. V. (2018), *Detecção de infiltração em áreas internas de edificações com termografia infravermelha: estudo de caso*. Ambiente Construído, 18(4): 329-340. <https://doi.org/10.1590/s1678-86212018000400308>

Sham, J., Lo, T., Memon, S. (2012), *Verification and application of continuous surface temperature monitoring technique for investigation of nocturnal sensible heat release characteristics by building fabrics.* Energy Build. 53:108–116. <https://doi.org/10.1016/j.enbuild.2012.06.018>

Siebert, S., Teizer, J. (2014), *Mobile 3D mapping for surveying earthwork projects using na Unmanned Aerial Vehicle (UAV) system.* Automation in Construction. 41:1-14. <https://doi.org/10.1016/j.autcon.2014.01.004>

Silva, A. F. (2007), “*Manifestações patológicas em fachadas com revestimento argamassado: Estudo de caso em edifícios em Florianópolis*”, Dissertação de Mestrado, Universidade Federal de Santa Catarina, p. 190.

Topdrone. (2020), “*DJI Mavic 2 Enterprise Dual*”, acesso em 25 de setembro de 2020, disponível em: <https://www.topdrone.com.br/dji-mavic-2-enterprise-dual/p>

Uemoto, T. (2000), “*Maintenance of concrete structure and application of nondestructive inspection in Japan*”, in: T. Uemoto (Ed.), Proc. Non-Destructive Testing in Civil Eng., ELSEVIER, 2000, Kidlington: OX (UK), pp. 1–11.

Viana, L. A., Zambolim, L., Sousa, T. V., Tomaz, D. C. (2018), *Potencial uso de câmera termal acoplada a VANT para monitoramento de culturas.* Brazilian Journal of Biosystems Engineering. 12(3):286-298. <http://dx.doi.org/10.18011/bioeng2018v12n3p286-298>

Viégas, D. J. A. (2015), “*Utilização da termografia infravermelha em fachadas para verificação de descolamento de revestimento*”, Dissertação de Mestrado, Universidade de Pernambuco, p. 165.

Watase, A., Birgul, R., Hiasa, S., Matsumoto, M., Mitani, K., Catbas, F. (2015), *Practical identification of favorable time windows for infrared thermography for concrete bridge evaluation.* Construction and Building Materials. 101(1):1016-1030. <https://doi.org/10.1016/j.conbuildmat.2015.10.156>

Witczuk, J., Pagacz, S., Zmarz, A., Cypel, M. (2017), *Exploring the feasibility of unmanned aerial vehicles and thermal imaging for ungulate surveys in forests - preliminary results.* International Journal of Remote Sensing. 39:5504-5521. <https://doi.org/10.1080/01431161.2017.1390621>

Yehia, S., Adudayyeh, O., Nabulsi, S., Abdelqader, I. (2007), *Detection of common defects in concrete bridge decks using nondestructive evaluation techniques.* Journal of Bridge Engineering, 12, (2):215-225. [https://doi.org/10.1061/\(ASCE\)1084-0702\(2007\)12:2\(215\)](https://doi.org/10.1061/(ASCE)1084-0702(2007)12:2(215))

Zhang, J., Jung, J., Sohn, G., Cohen, M. (2015), “*Thermal Infrared Inspection of Roof Insulation Using Unmanned Aerial Vehicles*” in: The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, International Conference on Unmanned Aerial Vehicles in Geomatics, Toronto, Canada, pp. 1-6. <https://doi.org/10.5194/isprsarchives-XL-1-W4-381-2015>