UBRISTES: UAV-based building rehabilitation with visible and thermal infrared remote sensing

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Abstract. Building inspection is a critical issue for designing rehabilitation projects, which are recently gaining importance for environmental and energy efficiency reasons. Image sensors on-board unmanned aerial vehicles are a powerful tool for building inspection, given the diversity and complexity of façades and materials, and mainly, their vertical disposition. The UBRISTES (UAV-based Building Rehabilitation with vISible and ThErmal infra-red remote Sensing) system is proposed as an effective solution for façade inspection in urban areas, validating a method for the simultaneous acquisition of visible and thermal aerial imaging applied to the detection of the main types of façade anomalies/pathologies, and showcasing its possibilities using a first principles analysis. Two public buildings have been considered for evaluating the proposed system. UBRISTES is ready to use in building inspection and has been proved as a useful tool in the design of rehabilitation projects for inaccessible, complex building structures in the context of energy efficiency.

Keywords: building inspection, Computer Vision, façade pathologies, thermal loss, UAV

1 Introduction

Building rehabilitation is a promising discipline in Architecture and Civil Engineering, as many buildings are approaching the end of their life cycles while the improvement of energy efficiency in urban areas is triggering building renovation and rehabilitation, for economic and environmental reasons, and also as required by European Directives, such as EPBD (Energy Performance of Buildings Directive) 2002/91/EC [5] and EPBD 2010/31/UE [7].

Rehabilitation is a complex field of work, as there is no general solution for all buildings, but rather technical solutions that should be chosen for each building according to its specificities [4]. Energy audits in urban areas get more difficult as the architecture gets denser and more complex. Even in the same building, different energy performances may be observed in different parts of it, depending mainly on its materials and façade typologies [9].

Building inspection is a key process in the design of rehabilitation projects. In particular, building thermography is a method of indicating and representing the temperature distribution over a part of the surface of a building envelope [3]. Infra-red thermography can be used in various fields of building rehabilitation to assess construction conditions and detect anomalies (i.e. humidity, infiltrations, thermal bridges, etc.). The sensed thermal infra-red (TIR) radiation is a function of the surface temperature, the characteristics of the surface, the ambient conditions, and the sensor itself. Therefore, obtaining temperature measurements involves using the information contained in the thermal images, corresponding to a digital signal proportional to the intensity of the sensed radiation, together with a number of parameters including surface emissivity, distance between sensor and surface, air temperature, air humidity, and others. Furthermore, different effects should be considered when analysing thermal images for building inspection. For example, heat flow can lead to either warming up or cooling the building surfaces due to different mechanisms such as conductive differences, thermal bridges and air filtrations. Also surface humidity often reduces the surface temperatures due to evaporative cooling [23].

The main disadvantage when capturing thermal images of building façades, comes from the lack of accessibility and shooting angle necessary to limit the effect of reflected temperature on the captured images (recommended angle of incidence $\geq 30°$). In urban environments it is possible to collect images correctly from the first floors at street level, but in tall buildings, the effect of reflected temperature (TRFL) increases upwards as a function of the shooting angle, and it becomes difficult to account only for the thermal energy radiated by the surfaces.

Nowadays the opportunity arises to exploit the complementarity of the information provided by TIR images captured at street level and those captured from Unmanned Aerial Vehicles (UAVs). TIR cameras have been developed and have expanded rapidly in the last years due to the development of digital imaging technology and bolometers, bringing low cost, lightweight, high-quality thermal cameras into the market. Microbolometers are the dominant uncooled IR detector technology with more than 95% of the market in 2010 [19]. These recent developments in thermal image sensors widen the possibilities for UAV applications in remote sensing. Also the development of UAVs in the last decade for many different applications has powered the use of onboard TIR image sensors for building inspection purposes, proposed as a mid-term challenge by [10]. Also Eschmann et al. [6] included this kind of design in the framework of promising developments in the non-destructive testing (NDT) domain. The integration of these sensors allows for the inspection of inaccessible places, ensuring a close enough and orthogonal camera position in an inexpensive way. Similarly, it is possible to take pictures of structures or façades from above, by changing the orientation of the on-board camera(s). For these reasons, remote sensing analysis in urban areas for monitoring and management purposes presents challenging problems, mainly due to the diversity and complexity of materials and façade typologies [18].

The present paper presents the UBRISTES system, a UAV-based solution with an integrated TIR sensor for pre-rehabilitation building inspection, validating the usage of visible (VIS) and TIR UAV monitoring to detect construction pathologies in façades and demonstrating its potential.

The remainder of this paper is organized as follows. Firstly, a review of the related works is presented. Secondly, a description of the system including the selected UAV platform, the sensors and how they are integrated is provided. Thirdly, a methodology for evaluating the system is presented. Fourthly, the evaluation results are discussed. Finally, conclusions are presented.

2 Related works

Research based on performing thermographies from UAVs has been sparse in the past, but is recently gaining impetus. Martinez-de-Dios [14] proposed the use of UAVs for passive building thermography and to detect heat losses originating from windows. Later, the work by Iwaszczuk [11] focused on matching VIS and infra-red airborne imagery to an existing building 3D model. Eschmann et al [6] were able to obtain highly detailed mosaics of building façades using an octocopter UAV. Although they mentioned the possibility of using their algorithms to acquire thermal images, they only showed results using visual imagery. In this direction, but using ground-based imagery, González-Aguilera [10] applied a modern 3D reconstruction image processing pipeline to thermographies to obtain a thermographic model of a façade. Recent work by Yahyanejad [24] proposed novel image feature descriptors to match images in different spectra, and showed their performance for image mosaicing using visual and thermal imagery taken from multiple quad-rotors.

A description of the main methodologies to obtain thermographies from an area of interest including the different types of surveys, characteristics and related bibliography has been published by Fox [8].

Another field that is getting increased attention is the georeferenciation of imagery taken from UAVs. In this direction, Lagüela [12] developed a methodology for the automatic extraction of building geometry directly from aerial oblique thermographic imagery. The obtained geometric and thermal 3D models are usually inserted into a complete Geographic Information System (GIS). The geo-referenciation of imagery acquired from UAVs is an active field of research but it is often focused on visual imagery. For instance, Rumpler [21] and Maurer [15] have focused on matching point clouds with publicly available data sources. In this manner, the acquired images are geo-referenced. In more recent research, Rumpler [22] has also explored the use fiducial markers to increase the automation and the quality of the obtained 3D reconstructions.

3 UBRISTES System description

3.1 UAV platform

The proposed UAV platform is an AscTec Pelican quad-rotor [1], equipped with an AscTec Atomboard (Figure 2) as on-board computer. This quad-rotor is commonly used in research laboratories because of its high payload capacity (up to $650g$), flight performance and adequate structure design that allows to integrate a number of additional sensors. Furthermore, its small size (651 x 651 x 188 mm) makes it suitable and less dangerous for urban operations, as it can fly closer to façades and in narrow spaces.

3.2 Sensors

Thermoteknix MicroCAM 384M (Fig.1a) is a passive long-wave infrared (LWIR) sensor with a spectral range of 8 to 12 μm. 7.5 mm optical lens were used, providing a field of view (FOV) of $65° \times 51°$. The thermal sensitivity of this camera is 80mK, and it can operate at a maximum frame rate of 60 frames per second. Thermal images with a resolution of 384 x 288 pixels can be acquired, with the TIR radiation being codified into an analog video output. The MicroCAM 384M TIR image sensor has been integrated on-board the AscTec Pelican, as shown in Fig.2.

(a) Thermoteknix MicroCAM 384M.

(b) Flir B335 LWIR camera.

Fig. 1: Thermal sensors integrated

Street level images were taken with a calibrated Flir B335 LWIR camera (Fig.1b), in order to obtain accurate temperature measurements. This handheld camera has a spectral range of 7.5 to 13 μm. With a field of view (FOV) of $25° \times 19°$, it features a 320 x 240 pixel resolution and a thermal sensitivity of 50mK. The scene temperature range supported is $-20°C$ to $120°C$ while the temperature measurements have an accuracy of $\pm 2°C$.

Street level images in the VIS spectrum were captured as well using an IDS UI-3250CP USB 3.0 camera, with a sensor size of 1/1.8" and a maximum image resolution of 1600x1200 pixels. A 2.9 mm focal length camera lens was used.

3.3 UAV integration details

The sensor acquisition software was implemented using the Robot Operating System modular framework [16]. The software set-up allows to configure the camera on runtime. TIR images from the MicroCAM 384M can be acquired and saved into the on-board computer at 30 fps and the battery on-board allows a flight time of approximately 10 minutes, enough for the inspection of most building façades.

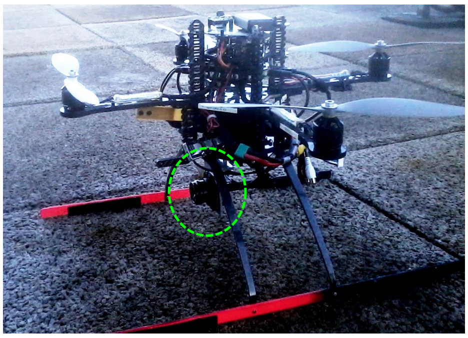


Fig. 2: AscTec Pelican quadrotor with the onboard MicroCAM 384M TIR sensor highlighted in green.

4 Evaluation methodology

Two buildings, both academic centres in the Technical University of Madrid, were selected for evaluating the UBRISTES system: ETSI Caminos (Civil Engineering) main building and ETSI Industriales (Automatic and Robotic) building. ETSI Caminos main building was built in 1963 mainly with concrete (structure and façade) and carries linear narrow lines of windows with poor insulation. ETSI Industriales Automatic and Robotic Building was a pre-existent building from the 1930's with thick brick façade. In the beginning of the XXI Century, a new insulated roof was built and new insulated windows were installed. The façades selected for monitoring were north facing (ETSI Caminos) and east facing (ETSI Industriales) to avoid noise from solar radiation.

During the evaluation, the quad-rotor was remotely piloted by a human operator. Three types of potential façade pathologies were monitored: dampness, degradation and thermal bridges. These pathologies were previously estimated via visual assessment and evaluated through image analysis by experts. Indoor and outdoor temperatures were continuously monitored during image capture.

A room was warmed up during the night in order to enhance the temperature changes related to thermal bridges, since only drastic changes in the surface temperature may allow the detection of pathologies in these areas.

4.1 Image analysis

Outgoing surface radiation is formed by the portion emitted by an object (which depends on its temperature), the portion reflected from ambient sources and the emission from the atmosphere. Only the radiation emitted by an object provides data on its temperature, and the rest of the radiation must be filtered to obtain correct temperature measurements.

Data processing techniques have been used to retrieve information from thermal data. They usually include geometric correction, radiometric correction, and a number of analyses (image enhancement, image arithmetics and statistical analysis). The choice of techniques depends on the image quality and the required output. The main function of the different processes applied to the acquired data is to produce a single perfectly co-recorded, multi-sourced file. This is aimed at undertaking a posterior analysis for the purpose of spatially correlating the elements of monitoring interest (walls, windows, structures, materials, ...) with the superficial temperature at which they were recorded.

Flir B335 images were processed with Flir's software in order to obtain the radiometric (temperature) information, including the ambient temperature and humidity during the tests. The emissivity and reflected temperature were also inputs in the image software.

MicroCAM 384M images were analyzed using the image processing package ENVI from ITT [2] (also available from other packages as ERDAS-Imagine or PCI Geomatics). No radiometric correction was applied to the MicroCAM images. For geometric correction we selected ground control points from the images captured with the Flir B335 camera. The thin plate spline method (a method for geometric correction and geo-reference of images based on a set of interpolating bi-dimensional polynomials) was applied to a number of ground control points in the original image.

5 Results and Discussion

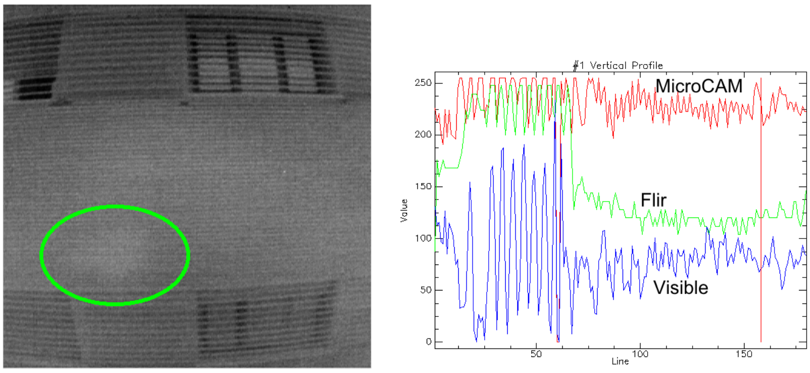
In this section the results of the proposed methodology are presented. Firstly, a description of two radiometric effects observed in the MicroCAM 384M TIR camera is presented, together with the proposed solutions. Then an example of image analysis for active humidity detection is discussed. Finally, examples of the assessment of thermal losses in different types of façades and slabs are presented.

5.1 Radiometric effects

In the MicroCAM 384M TIR camera images two radiometric effects were observed. One consists of an unusually brighter band in the edges of the image. The second one is a local defocussing in some bands. Both effects were caused by problems in the instrument during the experiments, and require specific solutions. For the brighter band, a normalization function has been computed as the mean of the ND (radiometric or digital value) for each image column in the area of study and the effects have been removed by applying a Minimum Noise Fraction (MNF) transform to the output multi-source file. The defocussing has been minimized using a standard high pass filter. The same strategy has been followed to build a single image per band, mosaicing the individual frames. No atmospheric correction was applied. As a final step, a textural analysis was applied using state-of-art filters designed for enhancing image structures (i.e. Sobel filter).

5.2 Image analysis for humidity detection

We carried out a pattern recognition analysis. With the Flir and the MicroCAM thermal channels we calculated a thermal index [17], profiting from the separability between the spectral sensitivities of both sensors. We generated image convolutions using a median filter, which were used afterwards to make a ratio between the 8 μm and 12 μm wavelengths (spectral range), weight corrected by the ratio between each channel's gain. We established thresholds on the resultant variable for highlighting detected pixels as possible anomalies, as shown in Figure 3.



(a) Aerial thermal image obtained with the UBRISTES system and enhanced with morphological operations for visualization purposes. The green ellipse indicates a humidity area in the façade.

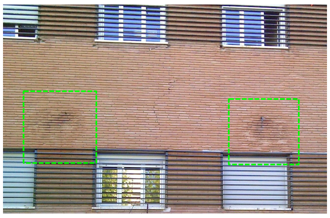
(b) Multisource vertical profile of the humidity area: red (MicroCAM), Green (Flir) and Blue (Visible).

Fig. 3: Analysis of a humidity area in a façade.

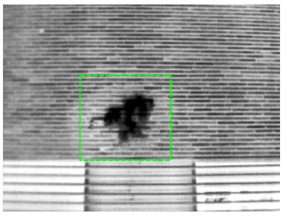
5.3 Active humidity detection using VIS-TIR imagery

The UBRISTES system allowed for acquiring both buildings' façades in the VIS and TIR spectra. Image filtering, analysis and visual assessment of the images was carried out, identifying potential pathologies in the VIS and TIR channels. These potential pathologies were validated with a second fieldwork visit to both buildings.

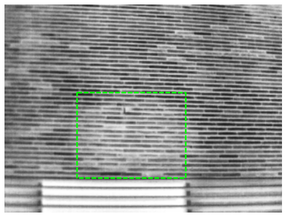
Figure 4 presents an example of combined humidity detection, using VIS and TIR images. The combined VIS and TIR monitoring allows for the identification of humidity-induced pathologies. Two zones were detected in visual inspection (Fig.4a) whereas thermal images showed that one presented a colder area (Fig.4b), probably caused by the presence of humidities, while the other did not (Fig.4c).



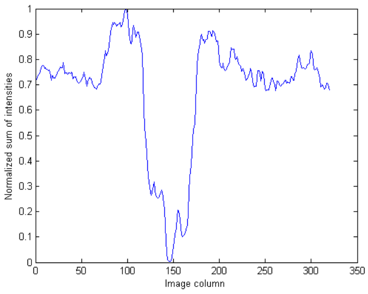
(a) Visible image indicating the presence of two possible humidity areas in the façade, highlighted in green.



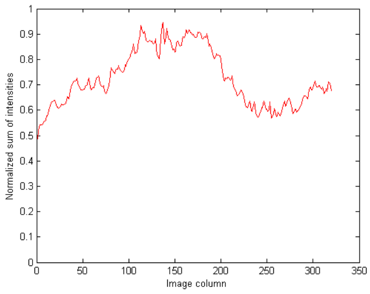
(b) Aerial thermal image captured with the MicroCAM 384M showing an active humidity, highlighted in green.



(c) Aerial thermal image captured with the MicroCAM 384M showing a non-active humidity, highlighted in green.



(d) Active humidity thermal profile.

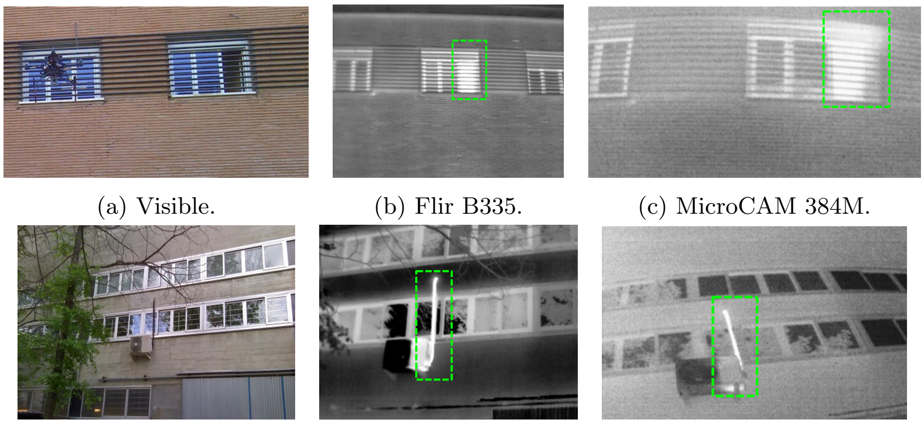


(e) Non-active humidity thermal profile.

Fig. 4: Humidity analysis in the ETSI Industriales building (UPM).

5.4 Thermal loss assessment using VIS-TIR imagery

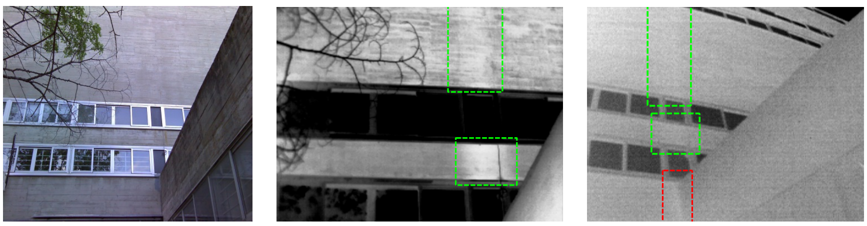
Figure 5 shows the evaluation of thermal losses in two cases, one related to a poorly-insulated window and the second related to an air-conditioned room with low external insulation. Air conditioning conductions show important thermal losses. Similar thermal losses were identified with hand-held thermography in building of the Instituto Eduardo Torroja (CSIC), built in 1953 with a brick façade and poorly-insulated windows [13].



(a) Visible. (b) Flir B335. (c) MicroCAM 384M.
(d) Visible. (e) Flir B335. (f) MicroCAM 384M.

Fig. 5: Assessment of thermal losses in different façade elements. A poorly insulated window and an air-conditioning conduction, highlighted in green.

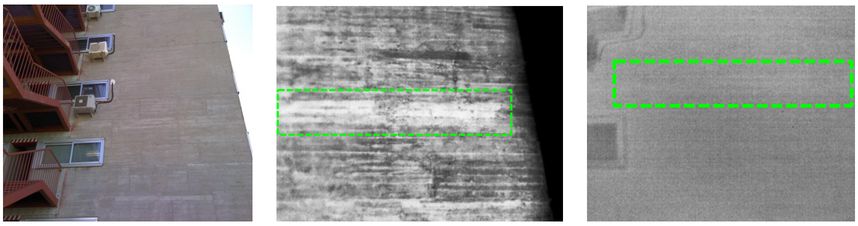
Figure 6 shows the detection of thermal losses in vertical front walls in façades. The aerial image captured by the UBRISTES system (Fig. 6c) shows a vertical loss, highlighted in red, in the junction between the front wall and the concrete façade.



(a) Visible. (b) Flir B335. (c) MicroCAM 384M.

Fig. 6: Assessment of thermal losses, highlighted in green, in a vertical front wall. A thermal loss in a vertical junction is also shown in the MicroCAM 384M image, highlighted in red.

Figures 7b and 7c show the presence of thermal anomalies related to slabs in a façade, highlighted in green. Junctions of slabs and façades are usually vulnerable to thermal losses, as façade insulation may be lost if the construction process is not accurate.



(a) Visible. (b) Flir B335. (c) MicroCAM 384M.

Fig. 7: Assessment of a thermal loss, highlighted in green, in a façade slab.

ETSI Caminos building images (concrete façade) show a constant pattern of temperature data over the whole surface, not related with thermal bridges or other pathologies, but with façade texture, conditioned by each of the concrete finishing surfaces depending on the form-work tables with which it was made and the lack of flatness. As a result, a distortion is appreciated in a continuous surface due to small changes in the orientation of each form-work table and hence small temperature changes in the reflected IR are registered by the sensor.

Analyzed buildings presented typical pathologies common to other XX century buildings in Spain, as the IETCC building [13]. Furthermore, as whole districts in our cities built in the postwar era (1945 - 1965) are approaching the end-of-life of their buildings and infrastructures, inspection for rehabilitation should be carried out at neighbourhood level [20]. This will require the combination of monitoring techniques, including satellite, airborne and UAV remote sensing.

6 Conclusions

The UBRISTES system is a useful tool for obtaining close aerial imagery buildings under inspection. The acquired imagery effectively fills the gap between high altitude imagery and ground-based imagery.

The evaluation experiments, in which ground-level VIS images, and aerial and ground-level TIR images have been compared, confirm that combined VIS-TIR UAV monitoring can enable logging and tracing façades spectral data with high spatial resolution. The exploratory data analysis, which has focused on the study of space-thermal correlation between the surfaces and materials, can help in identifying anomalies and pathologies on façades.

Multispectral UAV monitoring allows reaching inaccessible parts of the buildings, with both VIS and TIR image sensors, obtaining global homogeneous models that can be analysed off-line with enough time and detail. These global models ensure objective diagnoses even in most complex building and city environments. Measurement of areas and perimeters of the affected areas is also possible, with an accuracy that depends on the image resolution and geometric correction.

The effects of reflected temperature observed during the experiments also demonstrate that these studies are more reliable in untextured, homogeneous surfaces.

The UBRISTES system is ready to use in building inspection and has been proved as a useful tool in the design of rehabilitation projects for inaccesible, complex building structures in the context of energy efficiency.

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