Exploitation of Thermal Imagery for the Detection of Pathologies in Monuments

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Abstract. Documentation of monuments includes not only geometric analysis but also the detection of alterations and pathologies to define proper actions for protection and preservation. Several pathologies can be found on façades such as moisture, detachments, leaks and replacements. Multispectral techniques can help users to detect and determine these phenomena. Thermography is a non-intrusive imaging technique that allows the inspection of different materials and related issues based on their temperature. It has the advantage of reaching unapproachable areas onto and below the surface. However, there are still many issues in thermography when applied to cultural heritage surveys. Depending on the application, multitemporal images can be captured and combined with conventional images to analyse its state of conservation. This paper presents an approach based on multitemporal thermal imagery to detect alterations on building façades. Methods and tools of multispectral analysis targeting the detection of alterations and pathologies are presented and evaluated.

Keywords: Documentation, Cultural Heritage, Thermal Imagery, Multitemporal Analysis, Principal Components Analysis (PCA), Orthophotos.

1 Introduction

1.1 Thermograhpy

Thermography is a remote sensing technique that allows users to measure temperatures of the surface of various materials. Differences in temperatures may lead to conclusions about the state of conservation of the materials and structures, and consequently, assist experts to take suitable actions if necessary.

All materials with temperature above the absolute zero emit thermal energy, whose wave length varies with temperature. The emitted energy follows the Stefan-Boltzmann law

$$\Phi = \varepsilon \times s \times T^4 \ . \qquad (1)$$

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Where: Φ is the energy emitted per surface unit; ε is the emissivity of the material; s is the Stefan-Boltzmann constant; and T is the temperature of the material.

1.2 Applications of Thermography in Cultural Heritage

Infrared thermography (IRT) has been implemented for the last decades in monitoring qualitative and quantitative information on buildings [1-4]. During the recent years spectral imaging has gained ground in the field of monument conservation [5]. Based on the initial implementation of near-infrared (NIR) in the case of paintings [6], spectral imaging has broadened the possibilities of the method, especially through the use of filters. This non-invasive research method, which collects spectral and spatial information at the same time, has proven very useful for the conservation community [1,7].

As far as Cultural Heritage is concerned, IRT has been successfully implemented in four main fields: (1) study of materials for monuments of archaeological, historical and cultural value [8], (2) evaluation of conservation methods [9], (3) monitoring of the historical monuments and sites [4,7]; and (4) digital imaging for recording, documentation and archival purposes [6,7,10].

The use of non-compatible materials in cases of monument conservation leads to deterioration acceleration. Hence, evaluation of conservation interventions through IRT techniques is of utmost importance. The effective integration of IRT, near-infrared and visible imagery [7], as well as terrestrial laser scanning [10] has helped the visualization of thermal distribution and the identification of the existing problems of the monuments.

Section 2 includes a description of the historic evolution and the form of the study site. Section 3 presents the process of image acquisition and the relevant equipment. Section 4 shows and describes pre-processing steps carried out for the thermographic survey of the selected document. Section 5 continues with a discussion of the achieved results. Last section, Section 6 draws some conclusions.

2 Study Site

The study presented was implemented in the southern east façade of the Cathedral of Valencia (*Catedral de Santa Maria de Valencia*), Spain (Fig. 1). The main components of this façade are the Romanesque gate, known as *Puerta de l'Almoina* (Fig. 2), and its large Gothic window above. The Romanesque gate is dated in the 13th century and forms a prominent feature of the façade. It includes a total of six concentric semicircular arcs, which are decorated with geometric and floral patterns. The arcs are supported by thin columns with capitals, on which images from the Exodus and the Genesis are presented. The Gothic window was hidden until the last reconstruction of the Cathedral. It consists of three arches relying on columns. The geometric documentation of the Romanesque gate was the subject of a former project [11,12].

Fig. 1. Cathedral of Valencia, south east façade

Fig. 2. Close view of the *Puerta de l'Almoina*

3 Image Acquisition

Two digital cameras were used for the image data acquisition, one thermal infrared camera and one color single lens reflex (SLR) digital camera. The FLIR ThermaCAM^{TM} B4 was used to acquire the thermal images. This camera is suitable for building inspections and works in the spectral domain of 7.5 to 13 µm. The lens has a field of view of 23° x 17° and the camera's sensitivity is 0.10ºC. The resolution of the thermal images was 320 x 240 pixels.

For the visible images, a SLR digital camera Sigma SD15 was used, equipped with a 40mm lens. It processes the images with a Foveon X3 sensor, delivering three Red, Green and Blue bands without interpolation at a resolution of 2640 x 1760 pixels.

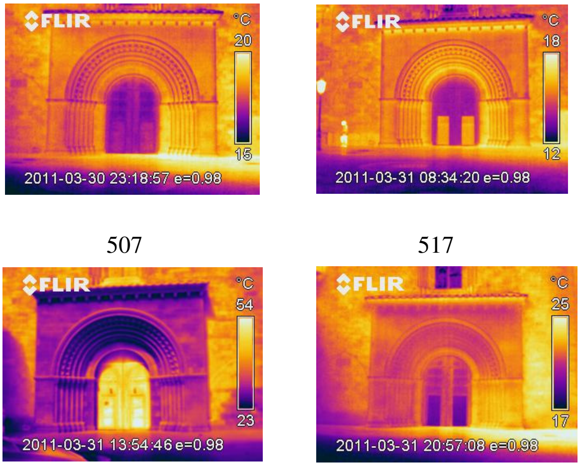
Both thermal and visible images were captured on the 31st of March 2011, on a sunny day. Thermal images were captured throughout the day and night. Therefore,

Table 1. Thermal images on-site displaying time and temperature during acquisition

Thermal Images	Time	Outside temperature (ºC)
507	23:19	17.2
517	08:34	13.4
531	13:55	21.5
546	20:57	21.5

some images contained hard shadows. Details of the capture times and environment conditions are presented in Table 1.

The set of four thermal images used in this study are displayed in Fig. 3. Worth noticing is the variation of temperature between the stone and the wood materials, as well as the decorative materials in iron. Furthermore, the variation in the thermal stress allows users to confirm different materials, identify damages, restored features, as well as occlude reinforced structures. Particularly interesting is also the difference in behavior of the Romanesque gate when shot early in the morning (in shadow at 8:34) and at moon, 12 h + 2 h in summer time (with direct sun hitting the façade).



531 546

Fig. 3. Input thermal images

4 Image Preprocessing and Analysis

4.1 Implemented Approaches – Combined Results

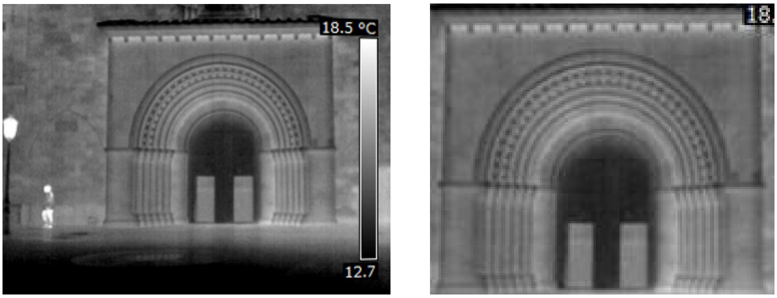
For the purpose of the presented thermal analysis, various approaches were implemented after preprocessing. These approaches include principal components analysis (PCA), supervised and unsupervised classification, creation of pseudo color images and temperature measurements. Each one of the methods applied produces distinct results which combined lead to the description of the alterations detected on the façade. These results, finally, are presented on a final plot of pathologies.

Next sections describe the steps followed for the documentation survey at the Romanesque gate of the Cathedral of Valencia.

4.2 Preprocessing

Preprocessing of images was performed to co-register the different visible and thermal images in a single multiband image. Each visible and thermal image was acquired at different times from slightly different positions and with different attitudes. Therefore, the aim of the preprocessing was to create a multiband image, consisting of both thermal and visible bands, so that all data provided could be gathered in a single image.

Preprocessing required two steps: color transformation as well as geometric transformation. Firstly, histogram equalization was individually executed inside the FLIR Quick Report software for all the thermal images in order to enhance the contrast and achieve easier recognition of small thermal variations. The output was four single band images in grey palette; image 517 is displayed in Fig. 4a. Secondly, a projective transformation, with the aid of an orthogonal grid, was performed for all thermal and visible images in Photoshop®. Fig. 4b displays the thermal image 517 after rectification. The last step was fundamental for the registration of the set of all images. Finally, after the registration, the four thermal bands and the three visible ones (R-G-B) were superimposed and merged into one multiband image with seven bands.



(a) (b)

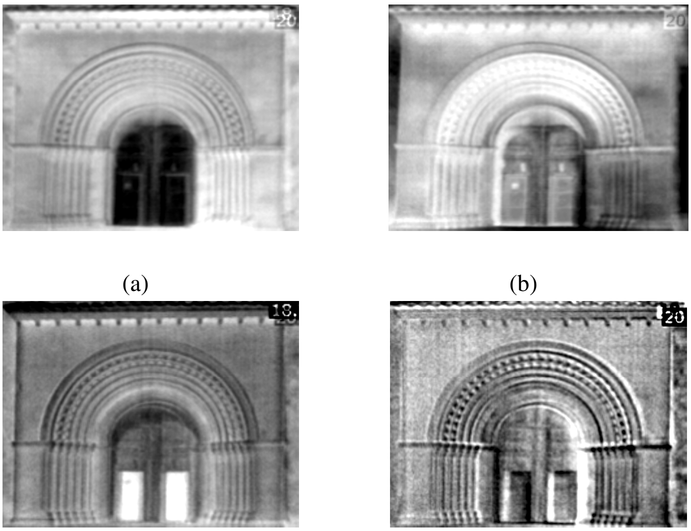
Fig. 4. Thermal image 517: a) in grey scale palette; b) rectified

4.3 Principal Components Analysis

Principal Components Analysis (PCA) allows users the reduction of the dimensionality of the data, collapsing the multiple bands down to a fewer bands [13]. These new bands are used instead of the original data.

Two PCA are presented, one with the thermal bands, and another one with the seven multiband image (three visible and four thermal). The first PCA is performed only with the four thermal bands and, as a result, the PCs computed are based only on thermal information. Hence, since the majority of the alterations of the materials are recognized through their temperature fluctuations, the first PCA is advisable for this purpose. The second PCA combines the visible and thermal bands. In this case, the visible bands provide additional information for the structure and the surface of the materials. In addition, while they have a better resolution, the final PCs are detailed images, where the appearing phenomena can be described clearly.

The outputs (components) of the first PCA are presented in Fig. 5. In the first component, PC 1, an area on the left upper side of the wall is portrayed in different tones in comparison to the total wall structure. The same phenomenon is observed above the right horizontal cornice. Furthermore, the difference among the interior and the internal part of the door is obvious. The same areas of the stone wall and the door are distinguished in the second component, PC2, with reverse colors. However, more emphasis on differences can be found regarding alterations. The third and fourth images do not produce exploitable results: the third component yields a flat image (Fig. 5c), while the fourth component yields significant noise (Fig. 5d).

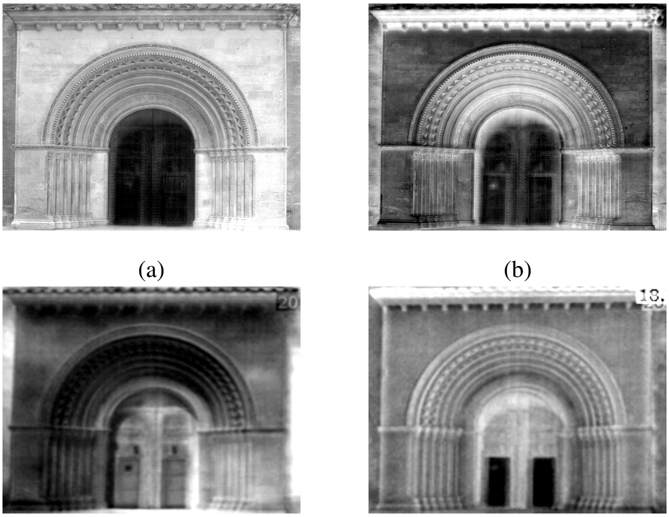


(a) (b)

(c) (d)

Fig. 5. Principal Component Analysis of the four thermal band images: a) PC1, b) PC2, c) PC3, d) PC4

A second PCA was performed considering the 7 bands image, which delivered four components (Fig. 6). Among the outputs from PCA, in PC2 stand out the variations on the stone wall, which are represented with darker tones (Fig. 6, PC2). These parts are situated on the right side of the arcs and on the upper level of the wall. A small dark area is also noticed above the horizontal cornice, in the right side. An area in the left upper side has a distinct appearance from the surrounding stones. In addition, variations are presented in the wooden door, where the parts on either side of the door opening and along their border, have arisen brighter. However, the latter is strongly affected by the shadow and shall not be taken into consideration. The same alterations of the door are also shown in the first image, PC1. PC3 presents the already noticed variations of the stone wall, in both right and left sides, with less detail. The fourth, as expected, is a noisy image due to different reasons like sensor noise or inaccuracies in registration.



(a) (b) (c) (d)

Fig. 6. First four components after PCA on the 7 band image: a) PC1, b) PC2, c) PC3, d) PC4

In general, equivalent phenomena stood out in both PCAs, whilst the second one provided more detailed information concerning the limits of the problematic areas.

4.4 Classification

A supervised classification of the multispectral image of seven bands was conducted with the use of the maximum likelihood algorithm (Fig. 7). A total of fourteen classes were considered, in order to include all the materials as well as variations that appear on the façade. It has to be noted that in areas where a material is in shadow then a second class was considered with the aim to avoid confusions in the classification process. Training sets were picked in well distributed polygons, all over the study site, to gather a full description of the material’s signature.

Supervised classification helped to distinguish stones or wider areas which are found in different status compared to the neighboring. It is characteristic that, whilst the stone wall is built with the same material in all its extent, its components are not at the same state and, for this reason, are classified in four distinct classes (light orange, dark orange, purple and violet). It has to be stated that stones in orange colors have, generally, sharper surface than the ones classified in the other two categories, which is a sign of alteration. Stones in purple color are among the ones with smooth surface and light color. The lower left area, classified in violet, represent the most deteriorated and worn stones.

The results of the classification help the interpretation of the previous and following produced images, since it compiles the various alteration areas. It is seen that classes in orange colors correspond to the spots described through the PCA.

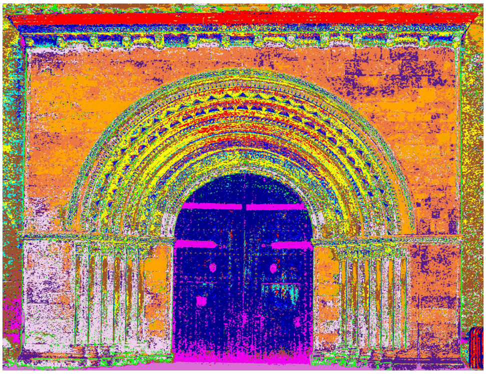
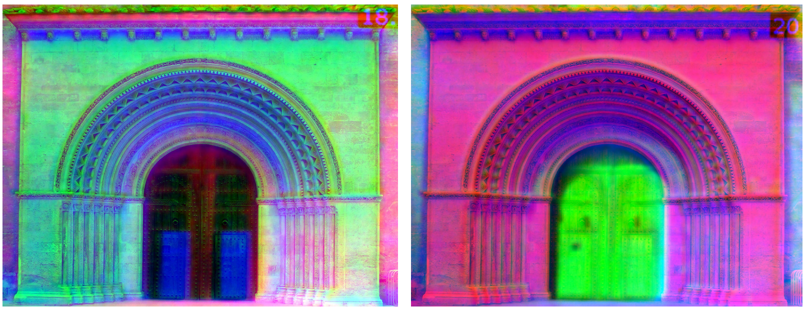


Fig. 7. Maximum likelihood classified image with fourteen classes

4.5 Pseudo Color Images

Pseudo color images were created in order to obtain various illustrations of the problematic areas. Different band combinations enhance this representation. In the following images both thermal and visible bands are introduced (Fig 8). The division of the areas of the upper side of the stone wall that were described above is apparent. At the same time, fluctuations across the surface of the door are pointed out with different colors. The zones on both sides of the door opening appear in magenta, contrary to the rest.



(a) (b)

Fig. 8. False color combinations: a) 546 - Green- 517; b) Red - 531 – 507

In Fig. 8b, the previous alterations of the wall are clearly described. Furthermore, an additional phenomenon appears in the lower part of the wall. Stones in grey tones portray deteriorated regions, whilst the occurrence on the left is significantly severe.

4.6 Temperature Measurements

Once problematic areas are detected and their limits are described, temperature was measured in sample points on the original thermal images, with the aim of depicting distinct material status. The sample points are presented in Fig. 9.

In Fig. 10, pink and blue colors represent the areas with alterations detected in the right part of the wall and above the horizontal garland. Purple corresponds to the equivalent parts on the left. Yellow stands for the average temperature of the rest of the stone wall, while cyan refers to the parts right under the molding of the roof. This figure confirms the variations all over the surface.

The last two spots described present lower temperature fluctuation, which indicates possible moisture. However, in the elements of the cyan categories, shadow effects are present. Hence, the existence of alteration is questionable. It has to be pointed out that maximum variations are noticed between images 517 and 531, which means that materials' temperature are significantly changing most from morning to afternoon.

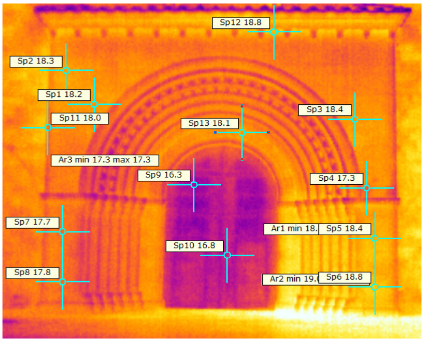


Fig. 9. Temperature measurement spots

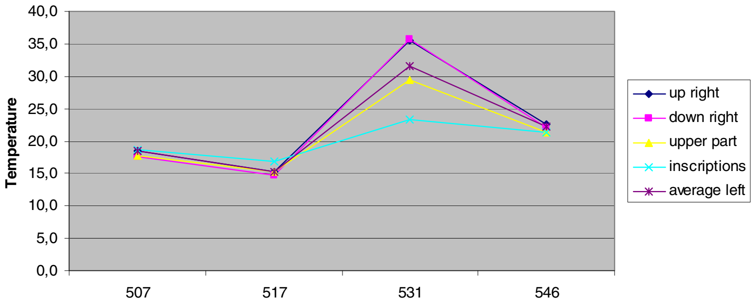


Fig. 10. Temperature values extracted from the four images

4.7 Plot of Pathologies Overlaid onto an Orthoimage

The identification of the pathologies detected is reliable and their position and shape are clearly defined after the results of all previous processing steps. In derivative images, where alterations are noticed in the display of the object, the borders of problematic areas are described either clearly or more blurred, depending on the type of processing. When one problematic area appears in more than one image, then it is more likely to represent an alteration or pathology. In the step of temperature measurements, measures in various spots of these areas either confirm or reject the possibility of an existing problem. Finally, the latter results are taken into account and the areas we are interested in are defined. The limits are digitized, each time, with the help of the derivative image (PCA, classification or pseudo color image), where they are more clearly represented. This means that, different borders may be digitized on different images. All variety of polygons with pathologies and alterations are integrated and overlaid onto a visible orthoimage (Fig. 11). Thus, the position and extension of the phenomena can be easily recognized.

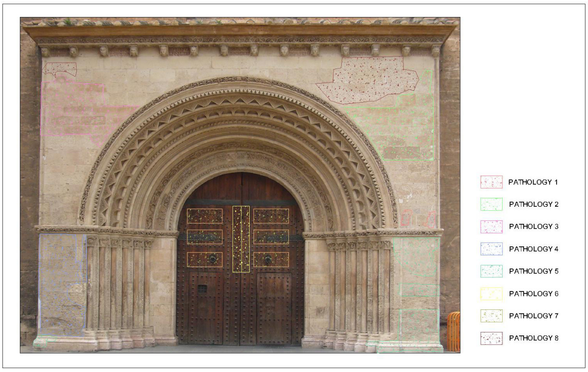


Fig. 11. Pathology information overlaid onto a visible orthoimage

5 Discussion and Conclusions

This paper presents an approach of multitemporal analysis for the detection of alterations in historical buildings. Analysis is based on temperature fluctuations of the materials and includes pathologies that are visible or not to the naked eye. It is significant for this purpose, to obtain multiple images in distinct times of day, distributed during day and night. In addition, special attention should be paid on shadow effects. These should be avoided in order to eliminate their influence on the imaging of the objects and the recording of their temperature.

Different processing methods were used, each exploiting differently all the available data. The creation of the multiband image guarantees the simultaneous processing and integrity of the data inserted in each method. The results provided by classification, PCA and pseudo color images are supplementary and their combination leads to the main understanding of the state of conservation. Classification produces an image mapping of the materials and elements of the object and can serve as a guide for the interpretation of images. PCA images reveal phenomena that may not be visible in the original images, while pseudo color images, in appropriate combinations of the bands, highlight them.

The results extracted from the analysis, and mostly image-based pathology plans, could form a useful tool for building technicians in restoration and reconstruction works, as well as in their inspection. Further work could be expanded with the addition of information concerning the materials found in the object. Elements such as thermal properties could help the interpretation of their responses.

Additional knowledge concerning thermal properties of the examined materials can help the recognition of pathologies. Emissivity values of the materials, which can be obtained from samples in the laboratory, enhance results in building diagnostics. Techniques such as mercury intrusion porosimetry and water absorption analysis for studying the stone in terms of their microstructure and isothermic behaviour respectively reinforce the detection of moisture in porous stones. IRT monitoring in the field of conservation can detect differences of texture and indicate risk areas and compatibility problems.

The presented approach can also integrate additional spectral bands, whenever available. The semi-automatic delivery of thematic information on close range imagery for cultural heritage documentation is highly requested by professional. Nevertheless, fully automatic processing of multispectral data to plot alterations and damages on historical building is desirable, despite the complexity of the mission. The inclusion of additional bands in other electromagnetic ranges will be tested in the near future.

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