

DIGITAL PRESERVATION, DOCUMENTATION AND ANALYSIS OF PAINTINGS, MONUMENTS AND LARGE CULTURAL HERITAGE WITH INFRARED TECHNOLOGY, DIGITAL CAMERAS AND RANGE SENSORS

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ABSTRACT:

The digital documentation and 3D modelling of Cultural Heritage monument and sites is receiving great attention in the last years. There is a large variety of technologies for 3D surveying purposes and generally a technique is chosen according to the project requirements, operator experience, budget and location constraints. Digital images and range sensors (laser scanner or stripe projection systems) are generally the most used technologies used to virtually reconstruct the whole geometry of the studied heritage. The combination of the two recording methods has demonstrated to be an efficient way of 3D modeling as no technique by itself is able to provide accurate 3D results in all the applications and in short time. Other data are becoming nowadays pretty common and important for a more deep documentation and investigation of heritages, i.e. image data coming from the light spectrum outside the visible range. In this work, we present how we derive geometric 3D models of heritage structures by means of close-range photogrammetry or range sensors while extra information acquired with infrared cameras are used for texture mapping purposes and other studies. Data obtained from all those instruments are registered and fused together for documentation reasons, historical studies, restoration plans and visualization purposes.

1. INTRODUCTION

Nowadays the digital documentation and 3D modelling of Cultural Heritage monument and sites is receiving much more attention. On the technology side we currently have at our disposal a vast array of relevant and efficient data acquisition tools: high-resolution satellite images, large format digital aerial cameras, hyperspectral sensors with hundreds of channels, interferometric radar, range sensors, thermal cameras, model helicopters, panoramic cameras and a large number of diverse customer still video cameras and camcorders. The correct selection, combination and integration of these techniques requires great experience and the need to combine them comes from the complexity of some heritage structures and the lack of a single method capable of providing satisfactory results in all measuring conditions.

The available technologies and methodologies for digital recording of heritage sites and objects are really promising and the whole heritage community is trying to adapt these approaches for fastest, detailed and easy 3D documentations. Indeed we have to face that our cultural heritage is constantly under threat and danger. Architectonical structures and heritage sites are threatened by pollution (air pollution, acid rain, birds, etc), tourists, wars as well as environmental disasters like earthquakes or floods or climatic changes. On the other hand hidden cultural heritage (under the earth's surface or those partially visible above ground) are affected by agriculture (vineyards, olive cultivation, erosion processes), change of agricultural regimes due to economical change, mining, gravel extraction, contraction of infrastructures (roads, railways), industrial areas and those factors lead to its constant destruction. Therefore 3D modelling could be extremely powerful to improve identification, monitoring, conservation and restoration. At the landscape scales, digital 3D modelling and data analysis allow site managers and archaeologists to

conserve and protect as well as integrate, without breaks, different archaeological features and physical context to better document the area. At the monuments/sites scale, 3D can give accurate measurements and objective documentation as well as a new view under a different point of view. At the artefact scale, 3D modelling allows to reproduce accurate digital/physical replica of every piece that can be studied, measured, showed, etc. as well as data for general public use, virtual restoration and conservation.

In this work we report about the use and integration of infrared thermography data, consumer digital camera images and range data, for the documentation of complex architectures and heritages. The goal is to explain the different techniques, their integration and the used methodology for the digital recording purpose.

The innovation in our approach consists in the combination of data coming from different measuring sources and with different resolutions (in geometry and texture) into a single textured 3D model representing the structure of interest, which can be analyzed and easily used by restorers.

2. 3D MODELLING TECHNIQUES

In this section we report the main 3D modelling techniques used in the heritage field, i.e. image-base and range-based modelling approaches, the most employed in the digital documentation and preservation of cultural heritages.

In the choice of the modelling techniques to be adopted, different factors have to be considered, as for example the required level of detail, occlusions, time and space for data acquisitions etc. It's impossible to give a general rule and decide which technique has to be used in a certain situation and with which instrument. For sure, so far, the integration of the

different techniques is leading to the best results, in terms of accuracy, time and details.

2.1 Image-Based Modelling (IBM)

Image data are probably the most complete source for digital documentation and 3D modelling. Indeed, geometry and texture information can be derived at the same time, using cheap sensors and fast procedures. Generally the image measurement phase is regarded as the most tedious part leading non-expert to consider this modelling approach as inappropriate, time consuming and, with the advent of range sensors, as out-of-date. Between IBM methods, photogrammetry is a highly accurate and flexible approach, suited for different scales and used to derive metric and reliable information of a scene from a set of images [Remondino and El-Hakim, 2006]. Images acquired in the visible domain are generally employed, even if IR or UV data could also be employed. Old images, stored in databases or archives, may be also used to document lost objects [Grün et al., 2004].

Semi-automatic image-based modelling techniques are particularly suitable for 3D reconstruction of buildings and man-made objects that contain generic geometrical shapes as for example parallel lines, planes and right angles. Generally at least two images are required, even if it is possible to calculate 3D data using a single image using geometrical constraints and image invariants. With the advent of automated procedures and fully digital products in the 90's, photogrammetry has become easier to use, cheaper and a wide range of commercial software is available. Photogrammetric packages allow, after the (manual) markerless tie point measurement and bundle adjustment phase, to obtain sensor calibration and orientation data, three-dimensional object point coordinates from multi-image networks, as well as wireframe or textured 3D models.

In order to obtain accurate and correct results, the employed cameras have to be calibrated [Remondino and Fraser, 2006]. It is generally better first to calibrate the internal camera parameters with a given setting, using the most appropriate image network, and then recover the object geometry using those calibration parameters at the same camera setting.

The latest developments, in particular related to surface measurement and reconstruction, are increasing the automation [El-Hakim, 2006; Remondino and Zhang, 2006] and the trend is to create automatic and user friendly tools that site managers, archaeologists, restorers, conservators and the whole heritage community could use instead of expensive and cumbersome range sensors.

2.1.1 IR Thermography

Infrared (IR) thermography has been recently extensively used for the documentation of cultural heritage, in particular for art work studies [Pelagotti et al., 2007] and for monitoring and conservation of historical buildings [Moropoulo et al., 2001].

IR thermography transforms the thermal energy, emitted by an object in the infrared band of the electromagnetic spectrum, into a visible image.

Thermography represents a great potentiality to be exploited in many fields, but this simple technique is still not diffuse because of a lack of adequate knowledge and its expensive equipments. By utilizing a thermal imaging system, it is possible to detect and display the normally invisible infrared radiation ('heat') emitted by an object. This infrared energy is converted to a real-time visible light image, which is displayed on a monitor. Depending upon the type of thermal imager, measurement of object temperature is also possible.

In particular, this non-destructive technique is used for the assessment of various traditional-historical materials and structures before and after they had been conserved, restored or repaired. Non-destructive testing and evaluation are performed on the materials and structures in order to assess the physico-chemical behaviour of conservation treatments such as stone cleaning, stone consolidation, as well as to disclose any substrate features, such as tesserae on plastered mosaic surfaces, to detect buried defects and inhomogeneity, to monitor hidden structure and moisture content, to analyze corrosions and to check the quality of welding and reinforcements elements. Hidden structure identification, adhesion of frescoes checking, cracks mapping and air flows studies are among the most important applications for conservators and restorers.

Modern IR imagers resolve surface temperature differences of 0.1°C or less. With this high sensitivity, they can evaluate subtle thermal phenomena, which are only revealed in the form of slight temperature gradients.

An example of painting analysis in terminal range is shown in Figure 1. In this case, the IR image is able to show the structure of the painting's frame while in other IR ranges, the preparatory drawing of the painter could also be detected [Pelagotti et al., 2007]. Figure 2 shows the materials employed for the consolidation of a textured wall. Similarly, we could detect the compositions of buildings façades or reveal stoppings and paddings.



Figure 1. The visible and the thermographic image of a painting.



Figure 2. An internal wall with frescoes in the Buonconsiglio Castle of Trento (Italy) and its appearance in IR thermography.

Infrared thermography can be used both as qualitative and quantitative tool. Some applications do not require obtaining exact surface temperatures. For example, to identify hidden structure or adhesion of frescoes, it is sufficient to acquire thermal signatures. This method of qualitative visual inspection is based on image interpretation. On the other hand, quantitative analysis requires a rectification of the thermal images to provide correct length or surface measures.

The wavelength, e.g. the distance between successive peaks in the oscillations of the electric and magnetic field, can vary over a wide range representing a different phenomenon including radio transmissions, microwaves, infrared, visible and ultraviolet light, x-rays and gamma rays (Figure 3). The IR portion of the electromagnetic spectrum includes wavelengths from ca 0.78 μm to ca 1000 μm . Therefore this radiation has wavelengths just a little longer than those of visible light and cannot be seen with the unaided eye.

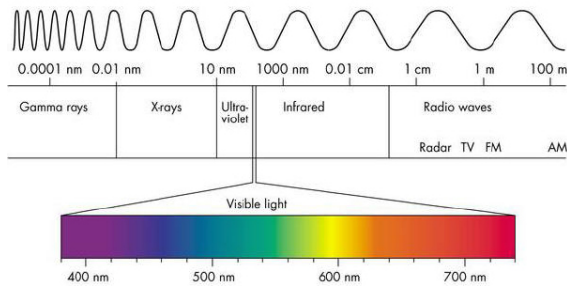


Figure 3. Electromagnetic spectrum.

The infrared spectrum has a number of technological uses including target acquisition and tracking by the military, remote temperature sensing, short-ranged wireless communication, spectroscopy, weather forecasting and astronomy.

The sensors able to record infrared radiations are usually designed only to collect radiations within a specific bandwidth. Indeed the infrared band is pretty wide and often subdivided into smaller sections that relieve different features.

Short IR wavelength, also referred as near-IR, contains wavelengths near the visible range (0.78 μm to ca 1.5 μm). Images acquired in this range are well suitable for high temperature subjects and are often used to image lasers, such as in the development of LIDAR systems. In particular, IR reflectography in the range between 0,8 and 2 μm allows the analysis of many materials which compose the pictorial layers [Fontana et al., 2005]. Most of the materials which compose the painting's layer are in fact at least partially transparent to the IR radiation, therefore IR imaging generally allows to see features underneath the layers visible by human eye and to visualize under-drawings or pentimenti of the artist (Figure 4). This is very useful information to decide whether a painting is the prime version by the original artist or a copy, and whether it has been altered by restoration work.

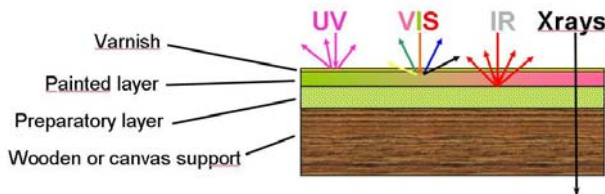


Figure 4. A typical painting cross-section, with its different layers and the wavebands that can be used to investigate them.

Longer wavelengths ($>8 \mu\text{m}$) of the IR band are instead referred as far-IR. In this part of the spectrum it is possible to see the environment with or without visible illumination. The amount of radiation emitted by an object increases with temperature, therefore thermography allows to see variations in temperature. All objects above 0 degrees Kelvin emit thermal infrared energy, so thermal imagers can passively see all objects temperatures. Infrared thermography cameras produce images of invisible infrared or heat radiation and provide precise non-contact temperature measurement capabilities. Furthermore, it is possible to check the structure of buildings and to find the defects on one or more parts of a structure.

Thermography with far-IR (up to ca 15 μm) is used to detect insulation abnormalities in walls and roofs. In addition to this, it's possible to find and to determinate air leakage through exterior walls and roofs, thermal irregularities (Figure 5), water penetration and moisture accumulation. The moisture in heritage materials can destroy structural integrity and nurture mould. An infrared camera instantly shows what is wet and what is dry.

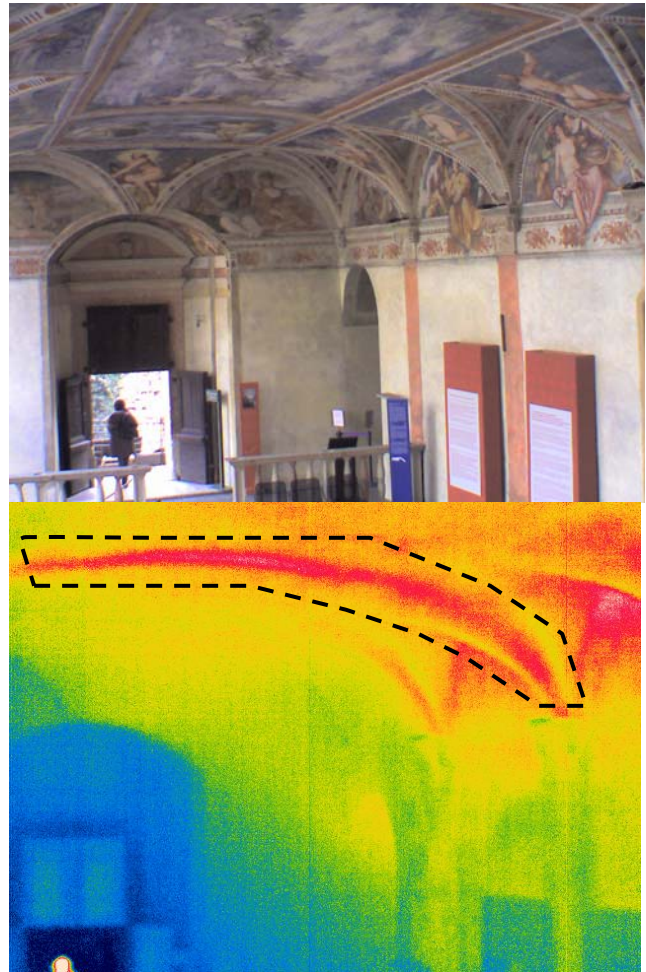


Figure 5. A visible (above) and thermography (below) image of frescoed vaults. The IR analysis shows a very hot area (probably a pipe, here highlighted by the contour) passing onto the frescos and producing damages.

Nevertheless performing correct measurements in long wave IR images presents some difficulties because the value of energy captured by the camera is affected by material's characteristics (like emissivity) and ambient conditions (presence of sunlight, ambient temperature, moisture, distance of object, etc). A conventional material that is transparent to near infrared, yet opaque to long-wave IR, is common glass.

2.1.2 UV

On the other side of visible spectrum there is UV (Ultraviolet) radiation. It is an electromagnetic radiation with a wavelength shorter than 0.4 μm but longer than soft X-rays (10-2 μm). It is possible to subdivide into near UV (0.4–0.32 μm), far UV (0.32–0.1 μm) and deep UV ($<0.1 \mu\text{m}$).

In artwork studies, near UV images are mostly used to identify different varnishes and over-paintings, in particular with induced visible fluorescence imaging systems. When UV light is shined onto an object, the result is the emission of photons in the visible region of the spectrum. This phenomenon, called fluorescence, occurs when light photons of high energy are absorbed and re-emitted in the visible wavelengths regions [Lettner et al., 2007]. Indeed, photons in the UV region of the spectrum are absorbed by the painting varnish and this effect, imaged with dedicated image systems, allow to characterize the used material, evaluate the artwork conservation state or

localize retouches and previous restorations [Fontana et al., 2005; Pelagotti et al., 2006; Pelagotti et al., 2007]. In a painting the aged varnishes have different fluorescence properties than new varnishes and some modern pigments have a different fluorescence emission than traditional pigments, even if the look alike under visible light. And fluorescence of oil paintings under ultraviolet light shows if any restoration has been done. Not only the paintings can be analyzed with UV but also other objects like porcelain, ceramic and paper art showing their hypothetical repairs and cracks.

2.2 Range-Based Modelling (RBM)

Range-based approaches are often complementary or combined to image-based ones [El-Hakim et al. 2004; Voltolini et al., 2007]. By using range sensors, we can generally perform detailed 3D models, with fast acquisition but often large editing efforts. While the recording devices are still expensive, important progress has been made in recent years towards an efficient processing and analysis of the range data.

The use of active sensors has become a very common source of documentation data in recent years, in particular for non-expert users, as they provide range data of surfaces in high resolution and generally with high accuracy.

Like photogrammetry, active sensors are suitable for different scales. Range-based systems [Blais, 2004] are mainly based on two principles: triangulation and time delay. Triangulation-based systems work on short distance (between 0.1 and 500 cm) and can reach very high accuracy and resolution. The high accuracy in the 3D measurements is essential for 3D documentation of very detailed object as sculptures, paintings, low reliefs and other complex small objects. Time delay active sensors are instead employed for large objects, as for example architectures, rooms, walls and archaeological sites. These sensors work on longer distances (i.e. 2 – 1000 m) but are less accurate than triangulation systems. Other types of active sensors are conoscopic systems that have better precision than triangulation ones (few microns) but a smaller field of view. For these reasons they are generally used for planar object, as for example paintings and small coins.

In addition to the geometric information acquired with active sensors, digital images have to be used (and generally

separately acquired) for the texture mapping purpose to get a photo-realistic 3D model [Bernardini and Rushmeier, 2002; El-Hakim et al., 2003].

3. DATA INTEGRATION

When multiple data sources are used and a unique final product must be delivered, all the information should be integrated to provide also better interpretation. The combination of the different models, generated with different data sources and techniques, is a key step in the 3D modelling process.

In this section we present the combination of data coming from the different measuring sources reported before and having different resolutions (in geometry and texture). The goal is to produce a single textured 3D model representing the structure of interest, which can be analyzed and easily used by restorers.

3.1 Integration of 3D data

Even though photogrammetry is acquiring a growing important role in the digital cultural heritage documentation and preservation fields and dense surface measurements can also be realized using images [El-Hakim, 2006; Remondino and Zhang, 2006], range sensors are nowadays the most used instruments for detailed and complex structures. But, according to our experience and as also reported in many scientific publications, in many cases, it is necessary to combine range data with data obtained by means of image-based modelling.

The models created by means of image-based modelling are assembled together and then registered into the same reference system with those generated using range sensors. The registration can be done either with common points or with surveyed control points, or both.

An example of integration between data from different sources is shown in Figure 6. This is an internal courtyard of the Buonconsiglio Castle (Trento, Italy) where the main structures (columns, arches and capitals) have been modelled through image-based modelling while the ceiling by means of a terrestrial laser scanner. The two models have been then merged by using some common control points.

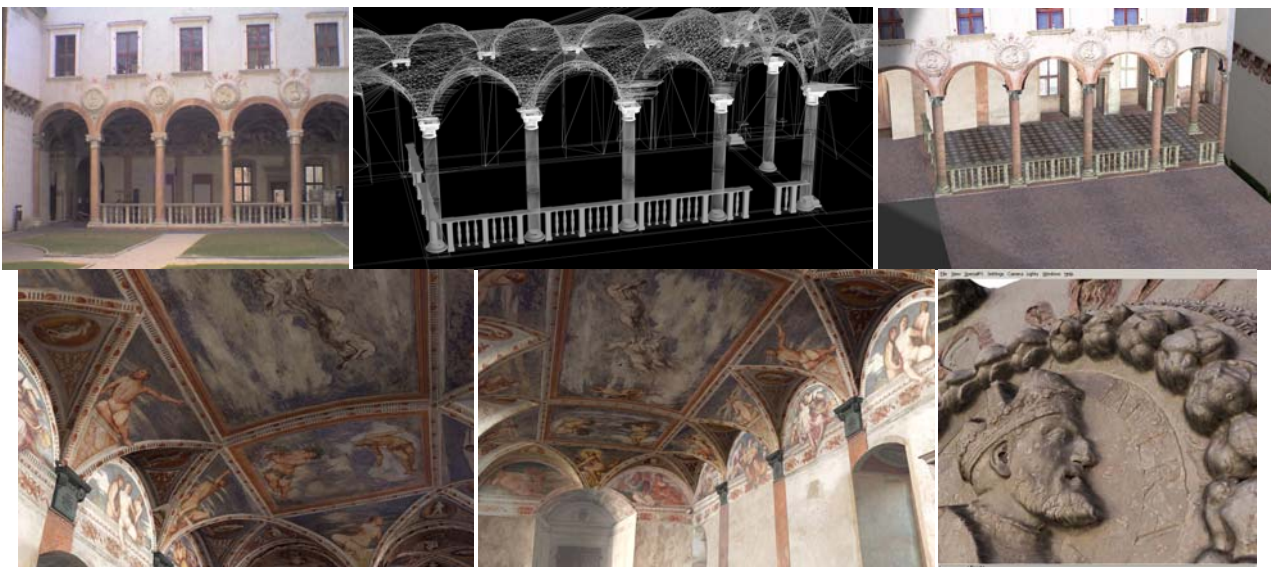


Figure 6: The internal courtyard of the Buonconsiglio castle in Trento (Italy) with the frescoed 'Romanino loggia'. The wireframe model after the integration of range and image models and different views of the final textured 3D model of the interior and exterior parts.

3.2 Integration 3D - Infrared

Multi spectral imaging techniques become a powerful tool in the scientific analysis and documentation of objects, since images in different wavelengths provide information that human eye cannot see. Applied in the spectral range from UV, visible up to IR, these techniques provide 3D model with both spatial and spectral information. Merging these data gives an additional dimension to the results and spectral information are presented together with 3D and visible ones.

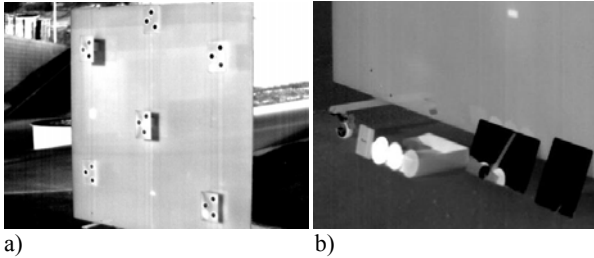


Figure 7. Testfield for infrared camera (a), Emissivity tests (b).

In our case studies, we integrated visible image coming from high resolution SRL digital camera with range data coming from TLS and infrared data acquired with a FLIR P640 thermal camera. The IR thermal camera works in the range between 7,5 and 13 μm , provide for 640x480 pixel images with a pixel of 25 μm . As for visible camera, the infrared one must be calibrated by means of photogrammetric bundle adjustment to provide for

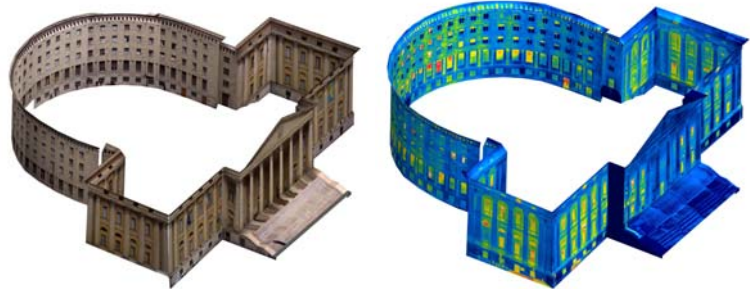


Figure 9. Palazzo Barbieri in Verona, Italy. The reconstructed 3D model of the exterior walls, visualized with the visible and infrared texture.

A second case study, shown in Figure 9, regards the 3D-infrared model of Palazzo Barbieri, a historical building located in Verona, Italy. The 3D geometry was obtained using 29 images acquired using a SRL Kodak DCS Pro with 13 Mega pixel. On the other hand, to produce the infrared 3D model, 150 IR images acquired with the FLIR P640 thermal camera have been used. The final goal is to measure correctly the surface temperature of the historic building, nowadays used as city hall. To correctly evaluate the thermal behaviour of the structure it is necessary to know (i) emissivity, calculated knowing the surface temperature of some reference object points, (ii) distance from the object, (iii) atmospheric temperature, (iv) relative humidity, (v) internal temperature, (vi) wind speed.

4. CONCLUSIONS

In this contribution we reported the use and integration of actual digital surveying techniques for the documentation, conservation and restoration of heritages. Even if photogrammetry by itself is nowadays able to provide for dense, detailed and accurate 3D models at different scale, we believe that the use and integration of data coming from

more accurate measures and 3D results. We used special targets and a dedicated testfield has been realized (Figure 7a). Furthermore, in order to obtain clear targets in the IR spectrum, some tests on the emissivity of different materials have been done (Figure 7b).

Once the precise interior parameters of the IR camera have been recovered, in order to register IR and visible images, some features are detected on the photographs and with a bundle adjustment the two image sets are aligned.

In Figure 8 a textured detail of the castle's courtyard shown in Figure 6 is reported. Through this 3D textured model it is possible to analyse deeper the structure and the frescoes as the IR data, registered onto the 3D geometry, provide for useful quantitative analysis.

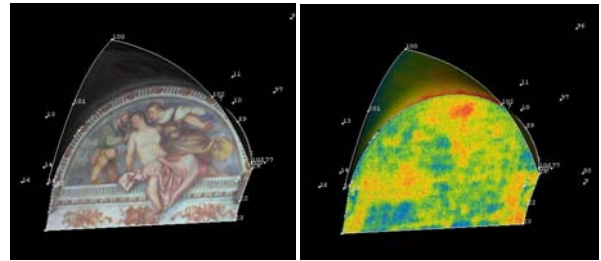


Figure 8. A detail of the internal courtyard, reconstructed using digital visible images and afterwards textured using also IR data, to allow quantitative considerations and documentations.

multiple sources provide for better results and more complete studies and documentations. Digital images acquired in the visible spectrum and range data are generally used to recover the 3D geometry and texture while for more deep analysis and studies, IR and UV data must be also used. The integration procedure is very useful for conservators and restorers as they have at their disposal a complete set of information spanning the different characteristics of the object under investigation and maybe including also other data coming e.g. from other chemical / physical analysis.

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