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Infrared vision for artwork and cultural heritage NDE studies: principles and case studies

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This text briefly presents the basis of 'infrared vision' in the context of cultural heritage studies. Infrared vision here encompasses near-infrared as well as thermal infrared schemes of inspection. The theory is briefly presented and attention is then focused on several non-destructive evaluation (NDE) case studies in cultural heritage: painting artwork, under-painting lettering retrieval and the investigation of Egyptian pyramids through the ScanPyramids Mission, led by the Faculty of Engineering of Cairo University and the HIP (Heritage Innovation Preservation) Institute.

1. Introduction

Among the many non-destructive evaluation (NDE) techniques around[1], infrared vision[2,3] is used in this paper for the inspection of cultural heritage artefacts and monuments. Infrared vision is the broad term that encompasses imaging techniques that are sensitive to infrared wavelengths from 0.75 μm (just past the visible spectrum) up to 1000 μm in the terahertz band (right before the microwaves). In this paper, the discussion is restricted to the near-infrared (NIR) region, roughly 0.75 μm to 3 μm, and the thermal bands (called infrared thermography or IRT), roughly 3 μm to 14 μm.

2. Theory overview

This section presents the essential concepts in a very brief manner; interested readers are invited to probe into the various references to find out more. For the following discussion, it is also interesting to recall the image formation schemes, which come directly from Planck's Law[4]. As with visible imagery, NIR inspection requires illumination (as it is based on a non-thermal reflection process), while IRT is based on the self-emitted radiation of the observed targets. This will obviously affect the required inspection process as will be explained below.

Hence, the use of NIR inspection requires the target to be illuminated with a NIR source and a snapshot image is recorded with the NIR camera (these cameras can be equipped with indium gallium arsenide (InGaAs) detectors sensitive in the shortwave infrared (SWIR) region of 0.9 μm to 1.7 μm). NIR illuminators (for example narrow NIR LED arrays or even simple old-fashioned incandescent light bulbs) and NIR cameras are commercially available (see Figure 1). Visible cameras that have had IR filters removed can also be used and will provide interesting results to distinguish some pigments (for example cobalt blue in fresh paintings). Such silicon charge-coupled device (CCD) cameras are sensitive up to about 1 μm. For example, although standard visible glass lenses are transparent in the NIR band (following the graph 'Transmittance of Optical Materials'[1]), they are corrected for aberrations only in the visible band and not in the NIR band and thus one can expect distorted images when using these. NIR imagery is generally displayed as shades of grey, which correspond to different levels of digitised illumination (see Figure 4(b)). However, as with NIR cameras, IRT cameras are also commercially available and they are sensitive to the radiation emitted from the target in the IR wavelength band, for example 8-12 μm for the so-called longwave infrared or LWIR. Contrary to NIR, however, IRT images do not require illumination since IRT cameras are sensitive to the energy irradiated from the target, following Planck's Law[4]. Interestingly, the obtained images can be calibrated into temperature if appropriate conditions are met[4]. Pointing such a camera at a target could thus reveal the temperature distribution over its surface. In IRT, two approaches are possible: passive and active.

In passive IRT, no action from the inspector is needed to record significant temperature values on the target. For instance, in the case of electrical maintenance, the electrical current flowing through a connector may cause local heating due to some abnormal internal thermal electrical resistance. Monitoring this connector temperature with an IRT camera will thus reveal such a problem, for example if a hot-spot of more than (typically) 5°C is observed.

In active thermography, the target is at thermal equilibrium and thus no significant temperature difference could be recorded over its surface. Hence, it is necessary to bring (or remove) energy to the sample. This could be, for instance, the case for a painting that is at room temperature and that could be heated or cooled for its infrared inspection. In the context of this paper, two approaches are deployed in active thermography: pulsed thermography (PT) and modulated thermography (MT). As the name implies, in PT a short pulse of energy is applied to the specimen, for instance using powerful flashes (see Figure 2(a)). In MT, light projectors are used (see Figure 2(b)) and the heating follows a periodic modulation, generally following a sine wave pattern (see Figure 3).

As energy is brought to the specimen, the interaction of this energy with the specimen generates thermal waves (TWs). TWs were discovered by Ångström and Fourier in the 19th century[5,6]. They propagate and decay into the specimen and, at subsurface interfaces, they bounce back and travel up to the specimen

[1]Available at: https://www.newport.com/n/optical-materials

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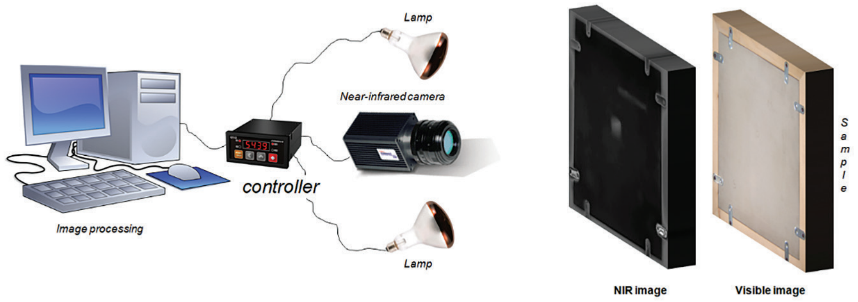


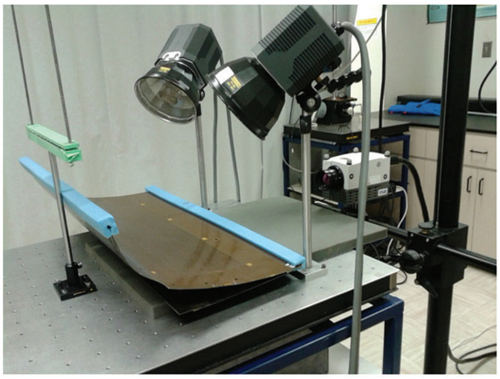
Figure 1. NIR set-up with 0.9-1.7 µm camera

surface where they manifest themselves as temperature variations, which are picked up by the IRT observing camera. In PT, a 'bouquet' of TWs at different frequencies[4,ch9] are launched into the specimens. In MT, the TWs are limited to the single frequency used during the stimulation. Frequency is important here, since low-frequency TWs propagate deeper than high-frequency TWs and this is in fact expressed well by the thermal diffusion length μ expressed by[7]:

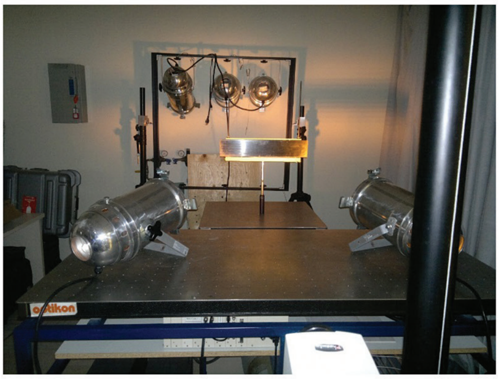
$$\mu = \sqrt{2k/\omega\rho C} \quad \text{..................} \quad (1)$$

with thermal conductivity k (in W m^{-1} °C^{-1}), density ρ (in kg m^{-3}), specific heat C (in J kg^{-1} °C^{-1}) and modulation frequency ω of the TWs in rad/s ($\omega = 2\pi f$, f being the frequency of the TWs in hertz). Hence, in PT, IRT probes all depths, while in MT, IRT concentrates on a range of depths[8].

An important difference of IRT inspection with respect to NIR inspection is the observation time. Due to the required travelling of the TWs in the sample, IRT inspection is not an instantaneous process. In PT, one experiment consists of recording the temperature decay over the specimen surface during the period of time corresponding to the return of the TWs on the front surface of the specimen. In MT, the lowest possible stimulation frequency f is generally selected following Equation (1) in order to probe deeper (this obviously imposes a long inspection time). What is observed with the IRT camera on the specimen is the oscillating temperature field following the return of TWs on the front surface. Rather than concentrate on the amplitude of this returning temperature field, the time shift, called the time delay or simply the phase, with respect to the initial modulated stimulation is recorded (Figure 3).



(a)



(b)

Figure 2. (a) Pulsed thermography set-up with high-power flashes (6.4 kJ each); (b) modulated thermography set-up with light projector (1000 W each)

3. NDE of cultural heritage artefacts and monuments

NDE of cultural heritage artefacts and monuments is important, for instance to assess their current state of conservation, to prevent forgery (it is obviously very difficult to reproduce the visual front appearance as well as the structure underneath a painting) or to discover some interesting features present under the surface (such as the artist's initial sketches, voids, etc). In the next section, NIR, PT and MT procedures are deployed in various contexts of cultural heritage NDE[9].

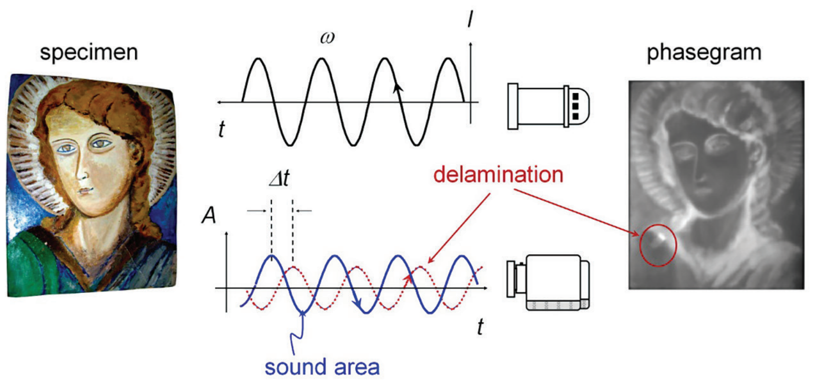


Figure 3. Modulated thermography stimulation following a sine pattern. Top: signal injected into the specimen; bottom: collected return signal exhibiting a shift in time between defective and non-defective zones due to the propagation into the specimen. Phasegram image shown on the right (for the specimen shown on left)

3.1 Case Study 1: Artwork imaging

In this section, a 30 cm × 40 cm painting referred to as *The Madonna* was inspected following the techniques described in the previous section[2].

Figure 4(a) shows a visible photograph of *The Madonna*, which was inspected by NIR (Figure 4(b)) and by PT (Figure 4(c)). It is interesting to see what each technique reveals about this piece of art. The visible photograph is limited to the first surface paint layers. The NIR illumination penetrates

[2] A detailed study of this piece of art first appeared in[11].

(a) (b) (c)

Figure 4. ***The Madonna*: (a) visible picture; (b) NIR image at 0.9-1.7 µm; (c) thermal PT image (processed following the PPT concept at *f* = 75 mHz, see text)[11]**

deeper, up to the surface preparation made of chalk and gypsum. The NIR camera (0.9-1.7 µm) reveals the underdrawings and the signature of the artist. Finally, PT enables a deeper probing, up to the support (canvas): some disbondings at the canvas interface clearly show up. In the case of PT, the recorded image sequence was processed following the concept of pulse phase thermography (PPT)[10] with a TW frequency of 75 mHz[8]. As seen, the three approaches (visible, NIR and PT) are complementary and reveal different aspects of this specimen.

3.2 Case Study 2: Mural painting imaging

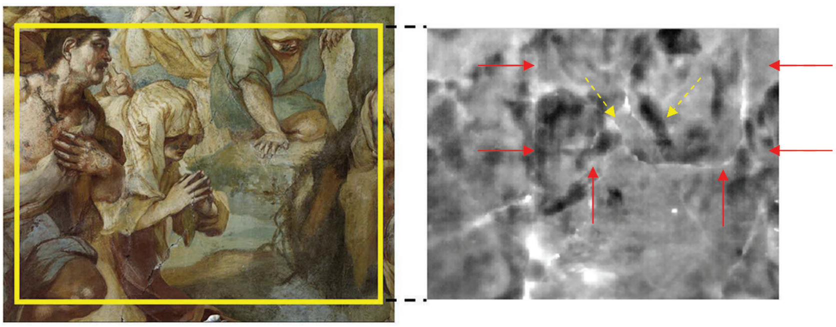
The main difference between a panel and a mural painting is that the first is a movable object, while the second (without considering separation or tear procedures) is an unmovable object. In both cases, mechanical vibrations such as quakes can seriously damage the shallower or the deeper layers[12]. In this section, a part of a fresco, described in depth in[13], was inspected by infrared vision[3]. Interestingly, some cracks that were repaired in 1994, having an overturn pinnacle form and indicated by the dotted arrows in Figure 5, reappeared due to the 2009 quake that seriously damaged the city of L'Aquila (Italy) and its surrounding area. They can be noted above all if the PT image (processed following the PPT approach) is compared to the visible image. In this case, a very long heating phase lasting 180 s was administered by one 2 kW lamp. It enabled the TWs to propagate in-depth by conduction up to a buried structure constituted by heterogeneous materials.

Although the whole shape was retrieved by additional thermographic campaigns, the solid arrows point out the lower part of an ancient window. This finding will obviously be important for the restorer called to repair the artwork.

3.3 Case Study 3: Toll bridge wood panel

In this section, a wood panel[4] was inspected following the techniques described in the previous section. A bridge was built over the River Jacques-Cartier at the Déry fishing site about 50 km west of Québec City, Canada, in 1804. A toll was then established to cover the cost to erect and maintain the bridge and was in operation up to 1910. Toll rates were indicated on the panel, which is 2 m × 1 m in size, both in French and English. Following numerous complaints from the users, toll rates were decreased in 1845. Figure 6 shows the bridge and the wood panel, which is now displayed in the local museum. Interestingly, it was believed that the panel was simply repainted in 1845 with the new toll rates. Our laboratory was contacted to inspect the panel: NIR and PT NDE procedures were deployed. PT revealed that indeed some inscriptions were present under the visible paint layers at some locations. NIR was then deployed in these areas and was able to retrieve some words, but flipped 180º, such as 'C...R TOLL' (car toll), as shown in Figure 7. This confirmed that indeed the current panel is the one used before 1845 and that it was subsequently sanded to erase as many of the previous markings as possible, and then turned upside down and repainted to its current state. This finding was obviously important for the local museum.

Figure 6. Left: Toll bridge at Déry fishing site *circa* 1900 (in Québec Province, Canada); Right: Toll bridge wood panel in 2015[14]



(a) (b)

Figure 5. The discovery of the *Statue of Our Lady* fresco by G Farelli (L'Aquila, Italy): (a) visible picture (on the left); and (b) thermal PT image processed by the PPT technique (on the right)[13]

[3]A detailed study of this piece of art first appeared in[12,13].

[4]A detailed study of this piece of art first appeared in[14].

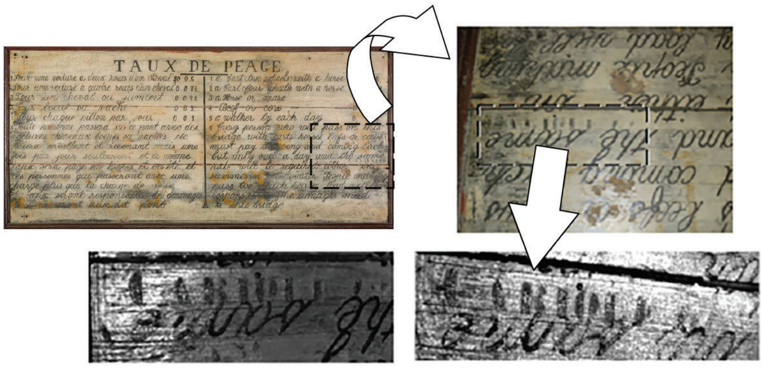


Figure 7. NIR imagery of the toll bridge wood panel revealing some under-painting inscriptions: 'C…R TOLL'. Bottom left: NIR inspection using an LED illuminator at 0.85 µm; right: in the range of 0.9-1.7 µm using a broad light bulb source[14]

3.4 Case Study 4: Great Pyramid of Khufu

The Université Laval group partnered with the Heritage Innovation Preservation (HIP) Institute[5] and the Faculty of Engineering of Cairo University, which are leading the ScanPyramids mission. One of HIP's missions is to use advanced NDE technologies in the study of cultural heritage. In 2015, the HIP Institute established the ScanPyramids project with the objective of bringing answers to questions related to the monumental Old Kingdom constructions of Egypt, including the Great Pyramid of Khufu, such as 'How was it built?', 'How was it designed?', etc. Interestingly, the HIP Institute and Faculty of Engineering (Cairo University) have gathered several researchers from different fields for the ScanPyramids mission: Université Laval and J C Barré from LedLiquid for infrared thermography and the CEA (the French Alternative Energies and Atomic Energy Commission), Nagoya University (Japan) and KEK (High Energy Accelerator Research Organization, Japan) for muons tomography technology.

The Great Pyramid of Khufu was built *circa* 2551-2528 years BC by Pharaoh Khufu[15]. This pyramid is astonishing from several aspects, for instance: with a height of 146.59 m (several metres less now), it has been the tallest building on earth for millennia; its base of 230.33 m is a perfect square to ±4.4 cm and is perfectly aligned at 0°3'6" to the north. It is estimated that 2.3 million blocks of stone, said to weigh on average *circa* 2.5 tons were used, whilst beams used for the stress-relieving chambers above the King's Chamber have been estimated to weigh from 50 to 80 tons. Even today, its magnificence intrigues and fascinates. For instance, hundreds of videos on the internet considering the pyramids are acknowledged by millions of viewers.

The objective of the team is to deploy passive IRT and MT, as described in Section 2, to help the HIP Institute in its mission. Passive IRT is interesting to deploy because if, for instance, some hidden cavities linked by ducts are present in the pyramid close to outside faces, air at different temperatures (heated by the sun or cooled by the ground) could circulate thanks to natural convection, with a steady-state or near steady-state temperature difference on the pyramid surface that could be observed by an IRT camera as a result. Obviously, in such cases unknown cavities need to be close to the outside surface for the thermal contrast to be visible. In fact, a rule of thumb[4] states that to be perceived by IRT on the surface, a subsurface structure should have a size at least equal to its depth (and obviously larger sizes are preferred).

MT could also be deployed to reveal deeper structures by exploiting TWs as described before. To confirm the possibility of such a deployment, the MT procedure was deployed on a four-storey tall stone wall of a building on the campus of Université Laval. Daily solar cyclic heating served as thermal stimulation since it is the easiest heating approach for large outdoor structures. For six days, the temperature over the wall was recorded with an IRT camera (see Figure 8)[18]. In the university case, the stone thickness was ~20 cm and thus, following Equation (1), observation of TWs over a period of around two days was sufficient to probe that thickness (observation over six days enabled the signal-to-noise ratio to be improved, hence the quality of the result). For the same approach to be foreseen for the Great Pyramid of Khufu, lower-frequency TWs are needed. In fact, in order to probe as deep as possible, the lowest available frequency TWs are preferred. Obviously, the lowest frequency is the annual temperature cycle, which on average goes from +18°C to +35°C in Cairo[16]. This would enable the MT procedure to probe about 4 m beneath the surface.

In the case of Figure 8, the IRT camera (model Jenoptik IR-TCM, 384 × 288 pixel uncooled detector, sensitivity bandwidth 7.5-14 µm) was fixed and provided enough spatial resolution on the wall, which was about 20 m in height. For Khufu, with a height of ~147 m, to achieve the same spatial resolution several IRT cameras would be needed but instead, since IRT images need to be acquired at a rate of about one every 20 min, mounting one single IRT camera onto a programmed pan-tilt unit would enable temperature information to be recorded on one full pyramid face, with good enough spatial resolution by mosaicing individual IRT images.

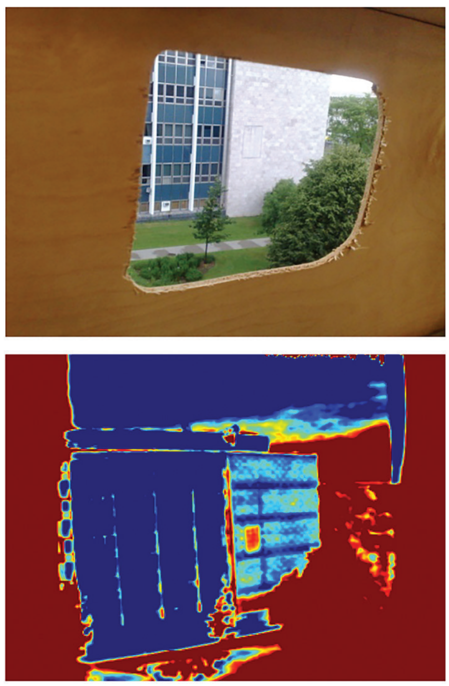


Figure 8. Visible photograph of Vachon building on Université Laval's campus (top) as seen through a hole in a veneer panel from a nearby building. Bottom: MT phasegram image recorded after cyclic solar heating over six days

[5]http://www.scanpyramids.org / www.hip.institute

The ScanPyramids team deployed passive IRT on the site and Figure 9 shows an example of what was referred to as 'thermal anomaly No 1' at the base of the east face of Khufu's Pyramid. This anomaly was observed during the day and during the night. Several tests were conducted to be sure that the observed IRT images were not due to some artefacts such as direct solar irradiation, environmental reflections, etc. On a preliminary test, a three-hour sequence was recorded and processed from a 200 m distance as a way to validate the spatial resolution and camera optics from the point of observation. This sequence was processed by the PPT technique and the resulting phasegram is presented in Figure 9(d). This result confirms that this anomaly presents a thermal signature significantly different from the neighbouring blocks, although it is difficult to provide details about its nature. One possible explanation is that this thermal anomaly is related to a hidden cavity (the thermal behaviour being due to the internal natural convection as explained previously). To better understand this, a simple cavity was modelled with a fine element modelling program reproducing the observed experimental conditions. Figure 10 provides some possible explanations for this thermal anomaly. For instance, it is possible that this particular layout of stone blocks, with different thermal properties, originated from different locations (different quarries). At the moment, however, no definitive conclusion can be drawn with infrared techniques. Many hypotheses have to be taken into account and the simulation models are indeed complex. The advantage of infrared techniques in the case of the pyramids is that they help to identify points of interest on huge surfaces that deserve other complementary NDE techniques for architectural and 3D studies.

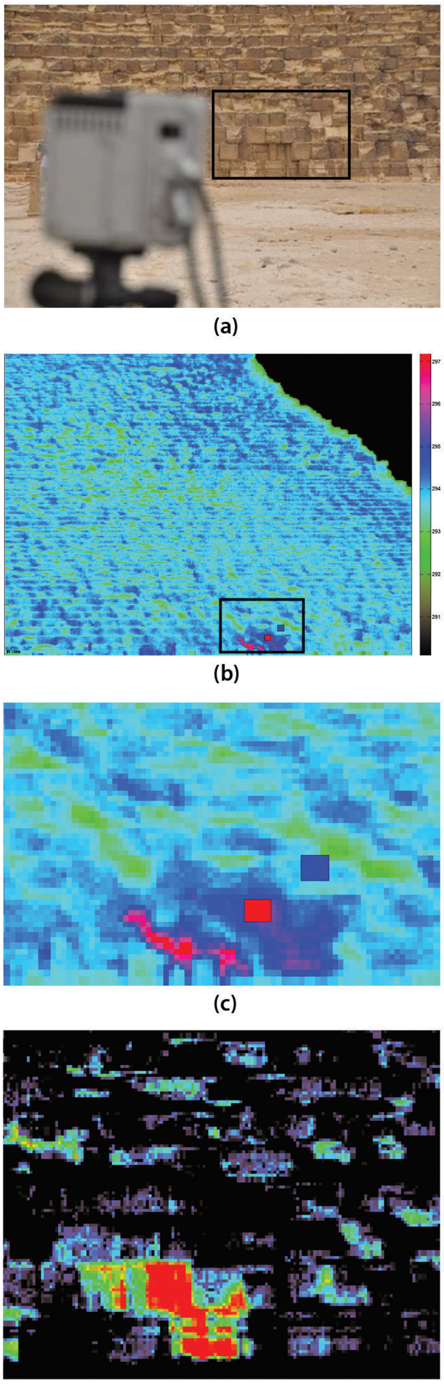


Figure 9. Passive IRT sequence recorded by the ScanPyramids team, aiming at thermal anomaly No 1 at the base of the east face of Khufu's Pyramid: (a) photograph showing the area of interest (black rectangle); (b) raw thermogram acquired 200 m from the pyramid highlighting the location of anomaly No 1; (c) magnification of the area of interest; and (d) result after processing a three-hour sequence by PPT *Source: ScanPyramids team*

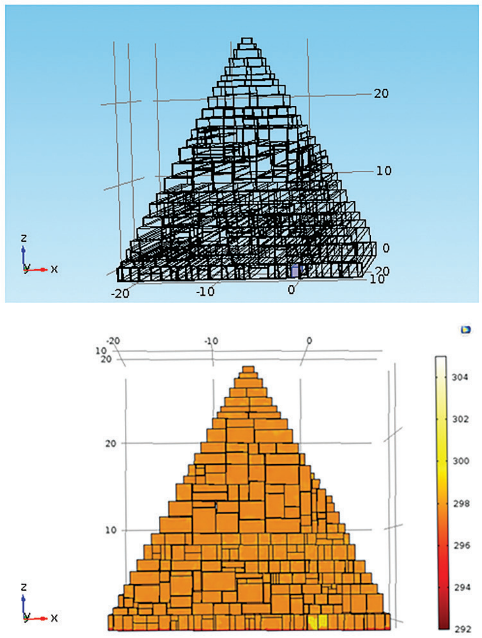


Figure 10. Thermal modelling of a cavity inside the pyramid using finite element modelling in COMSOL. Top: meshing (with 124,000 tetrahedral mesh elements and 78,163 triangular mesh elements); bottom: corresponding passive IRT image in the morning

Another point of interest was found in the north face of the pyramid, in an area showing two sets of chevron-like stones, one on top of the other (not shown). After performing a three consecutive 24-hour thermographic survey, it was found that the top chevrons presented a thermal behaviour significantly different to the bottom chevrons. A 24 h cycle allows probing of a few centimetres into the blocks; however, it is possible that these particular stones are much thicker than that (several centimetres to a few metres). A thermal wave having a much lower frequency would be needed in order to probe close to the targeted depths. The seasonal annual cycle would indeed provide such a means and a new 365 day mission is currently being prepared. In the meantime, the Faculty of Engineering (Cairo University) and the HIP Institute asked the group of the University of Nagoya (Japan) to set up, in the descending corridor below the chevron zone, several muon emulsion plates to confirm whether there was a void or not; the official report is available in[17].

As explained previously, long-lasting MT measurements (several months to one year) would provide more information about possible deeper features. At the time of writing this article, such measurements have not been started. It is expected that the discussed pan-tilt unit with the IRT camera will be deployed on site in early 2018.

6. Conclusions

In this paper, IRT was presented in the context of NDE for art and cultural heritage applications. Both passive and active approaches can be deployed; a brief theory was presented as well as a few representative applications. Judicious use of the spectral bands and procedures (for example NIR, IRT-PT and IRT-MT) could yield interesting information on a variety of specimens, from paintings to historical monuments. Moreover, thermal modelling of the structure can help in understanding the experimental results. It is believed that the 'best is yet to come', with more exciting applications and interesting discoveries in cultural heritage applications, especially when coupling together various NDE methods; this is clearly the strategy for the future. A good example of this is the ScanPyramid mission, which offers such a possibility in the case of the monumental Old Kingdom constructions of Egypt.

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