TEMPERATURE MONITORS WORKS OF ART HEALTH AS HUMAN BEINGS

E. Grinzato[1]
[1] CNR-ITC, Padova, Italy

Abstract: A review of different cases studies concerning heritage buildings, frescos, archaeological ceramic and wood paintings, shows as Thermal non Destructive Testing and Evaluation is particularly effective examining works of art. Nevertheless, in spite of fascinating images, a quantitative and reliable diagnosis is difficult. Hence, in many cases particular equipments and procedures must be arranged.

Established techniques allows to monitor different pathologies affecting historical buildings and passive or active approaches are presented. The analysis of the temperature signal allows exploring new applications as the structural analysis or the comfort evaluation. Examples of algorithms and testing procedures are selected in order to give an overview of the thermographic method capabilities.

Thermal properties as diffusivity or effusivity are extremely useful for the material characterisation. In addition, their mapping is an effective investigation tool for TNDE. Trends and suggestions for different applications are pointed out.

Introduction: A large literature is growing about Thermal non Destructive Testing and Evaluation (TNDT/TNDE) [1]. Progress of IR thermography makes this method, alone or combined with others, a suitable tool. Today, highly resolute equipments or much cheaper ones are applied in combination either to sophisticated data reduction algorithms or simply looking at thermal images and exploiting the operator expertise.

TNDT/NDE is a typical indirect measurement and temperature is a perfect informative parameter when shallow defects are investigated. Temperature monitors an incredible number of different phenomena because any physical and chemical process involves heat, at last. In this sense, imagination is necessary to take advantage of opportunities given by this method. Particularly, works of art are more and more issued for economic and cultural reasons. For this application the concept of "defect" is much broader than in industry, including object's knowledge and its status monitoring. In fact, usually the real history of precious items has been lost along centuries and the NDT target becomes the discovery of hidden information, but fast, reliable and self-explicative results are needed. Furthermore, the surface temperature, moisture and airflow distribution are key factors for the comfort of people working inside a renewed historical building. New perspectives are now opening to thermography in these fields.

The thermal method has been demonstrated extremely useful for works of art, mainly because of his optical nature, flexibility and imaging characteristic. Unfortunately, just to mention a few problems encountered to test unique pieces, consider actual strong limitations of heating or touching, the lack of any reference, a very complex structure and surface clutter. In practice, there is a great difference inspecting monuments, like historical buildings or much smaller objects, than can be moved into a lab. In the former case, portability of the equipment and productivity of algorithms are key points. Think about inspecting 10000 m^2 frescoed walls, during the restoration activity, with scaffolds and very concentrated people around. Fortunately, portable items can be tested inside the workshop and very advanced techniques are now available bridging thermography and the photothermal method. Generally, a laboratory work is fundamental to set up the procedure, even for buildings. In fact, preliminary tests on samples of the inspected part, built by specialized workshops according to original recipes are used to optimize the experimental procedure. Mathematical modelling is widely used to test data reduction algorithms, to evaluate effects of different variables and to simulate real tests. Unluckily, the simulation by numerical or analytical models is not a trivial task, due to the complexity of the target and large unknown in thermal properties, geometry and boundary conditions.

Finally, it must be noticed that there are so many different applications and possible uses of TNDT that a simple list is quite difficult. The presented selection is based mostly on the purpose to give a review of main application and processing algorithms. Each case study gives a different technique and data reduction, according to the particular goal. The mathematical bases and details of procedures will be found on annexed bibliography.

The first part of this paper deals with historical buildings, reviewing well established techniques and also giving new trends. The following section gives some applications dedicated to ceramic and wood painting.

Historical buildings monitoring: The fastest way to test a building is to work in steady state, with a passive approach. Even if a passive qualitative monitoring is chosen, mathematical modelling of the thermal problem allows deciding if and when thermography is appropriate to a particular case. The first presented example deals with the moisture mapping inside the historical arsenal of Venice [2]. The moisture excess within building is a major cause of damages, energy spending and discomfort. Moisture is dangerous even because activates biological or chemical attacks, if linked to pollution. Most of ancient buildings are affected by the presence of moisture, due to the high porosity of materials. Water capillary rising from the ground turns out into a characteristic almost horizontal frontier. Other moisture causes, as surface condensation, leakages from roof or piping give different patterns. Localized high water concentration get soon to saturation, while in many cases the extent of the moist zones will not appear visually and are not close to the failure. On the contrary, IR image shows on the surface the extent of moisture spread, but a careful analysis is needed Therefore, thermography is effective in founding the moisture source, because of temperature analysing both in space and time domain.

There are many techniques suitable for the moisture detection by thermography [1,3]. Here is illustrated the simplest one, a passive technique working in steady state where data are processed by a statistical tool. A crucial point is due to changes of surface optical properties as a result of the moisture itself. Emissivity varying in the IR measuring band and absorptivity in the visual band could bring on false alarms. It is interesting to observe that water staining of the surface or mold and actual water content of each point are not proportional. Such a visual indication is symptomatic but sometime misleading, because it appears suddenly when moisture concentrates, but remains after the surface dried out. Time analysis is quite important for the moisture control, but it requires normally a long lasting observation time and a correlation on seasonal and weather events [4]. Generally, the choice of the right time to perform the test is of great importance, because various phenomena are activated by the moisture accumulation. In fact, building is submitted to slow varying but “noisy” boundary conditions and different heat fluxes may interact each other in destructive or additive sense.

The Historical arsenal of Venice is nowadays passing from the Italian navy property to be converted for civil purposes. Most of buildings correspond to large hangars made in brick in different ages ranging XI-XVII centuries. The passive approach followed here allows mapping qualitatively the moisture distribution due to the cooling effect of water evaporation [5]. Thermal scanning of the internal surface of the *Tezone 105* is reported in fig.1a (East side on the top and West on the bottom). The investigation of a nearly 1000 m^2 surface requires the shot of several thermograms, which will be composed in a mosaic. Some removable markers are placed on the surface in order to know ambient temperature and locating recorded thermogram [6] (a visual image is taken for each field of view). The classification of the surface in homogeneous areas is achieved in natural, almost-steady, thermal state. The phase changing rate depends on air temperature and relative humidity levels. During the test, the best environmental conditions require a medium-high transpiration. It is mandatory a relative humidity (RH) lower then 80% in the boundary layer and air temperature not below 6-7 C°. The inspected surface has to be kept out of direct heating at least for 6 hours before the scanning, because different absorption coefficient of the surface causes effects contrasting the evaporative cooling. Hence, it is a good practice recording temperature and RH for 24 hours before and during the thermographic taken. The identification of the damp areas is achieved by the comparison between the temperature of the dry and moist surfaces. For instance, two sections of interest (marked on fig.1a) are combined in fig.1b and processed. The superimposed histogram of fig.1b clearly indicates with the first peak a colder and therefore moist area, corresponding to the west side.

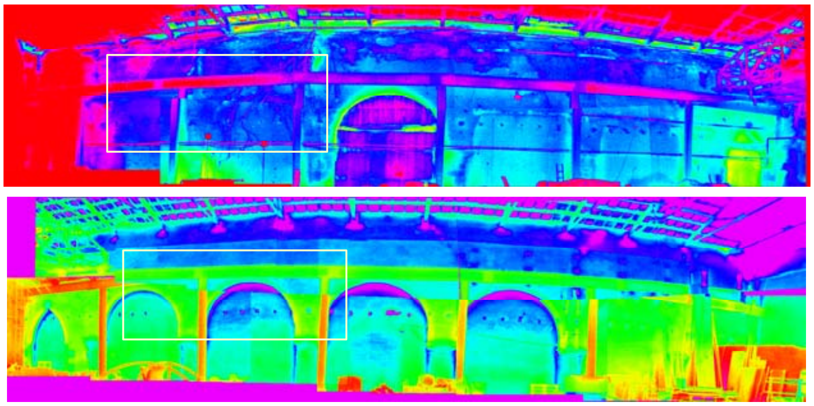

Fig. 1a: Moisture monitoring by statistical analysis of the historical arsenal of Venice (*Tezone* 105): thermograms of internal walls (top West, bottom East), the marked areas have been composed on fig.1b

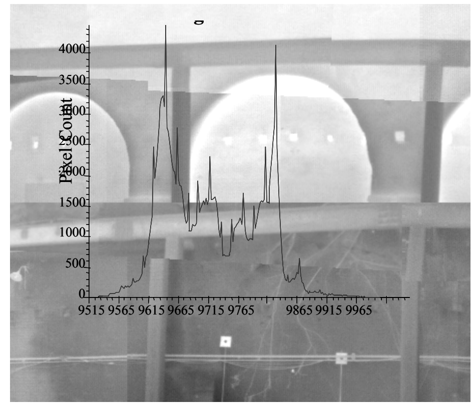

Fig. 1b: sections of the aside thermograms and superimposed their histogram indicating the higher water content of the West wall

Fig. 2a: upper part of the inner court of the Malpaga (BG, Italy) castle and the inspected area

Fig. 2b: bonding pattern as detected below fresco by thermography using the passive solar heating and a transient technique mapping apparent effusivity

The second example refers to an Italian castle (XIV-XVI century) using a transient technique driven by the solar irradiation [7]. An interesting use of thermography is discovering of the bonding pattern below the plaster layer and locating hidden structures [8]. The main purpose of the inspection is to verify the age of a part of the castle, because it is known that it was expanded along the time. The original building has been done using rounded shaped stones coming from the nearby river, while the more recent part has been built up using bricks and ashlars. Any destructive technique is excluded, because of precious fresco covering. Here, the underlying idea is the use of the temperature excess due to sun coming out from the shadow, as shown in fig.2a. This approach is related to the wide surface to be examined, hard to be reached without a complex scaffold. A sequence containing 120 thermograms was taken in the 8-12 μm spectral band, at 10 s intervals. The main problem arises from the varying of the thermal process starting point. The data reduction algorithm relies on a simplified 1D thermal model approximating the 0.5 m thick wall to a semi-infinite body. Hence, a linear temperature increasing vs. the square root of time is expected. The fig.2b shows the slopes map for any pixel obtained in the linear region. The round shape of lighter dots, clearly indicate the raw used stones. Other interesting findings are the closed arch-like window, placed around the centre of the inspected zone (5x3 *m* wide) and the previous floor line, as indicated by the markers [9].

Detachments between surface finishing layers and supporting walls have been deeply analysed both in laboratory and in situ [9,10,11]. Frescoes have been tested mainly using active, transient techniques.

Guidelines for the inspection procedure involve:

1) heating uniformly the surface (about 10 *K* above room temperature) using radiative or convective extended heat sources or with a moving linear one [12];
2) storing the sequence of thermograms at the proper sampling frequency during heating and cooling rate for 10-15 minutes (depending on the fresco thickness;
3) processing the whole bunch of data with one algorithm for transient TNDT as Thermal Tomography (TT), Pulsed Phase Thermography (PPT) or Lock-in Thermography (LT) [1,13].

Fig. 3a: experimental set up for the Romanino's fresco delamination testing (Malpaga castle)

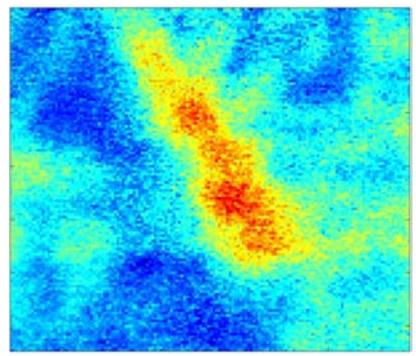

Fig. 3b: *timegram* as produced by Thermal tomography, corrected for the 3D heat diffusion

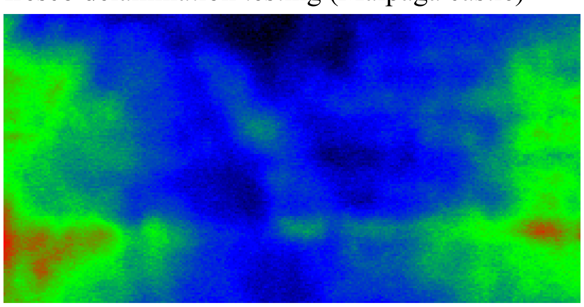

Fig. 3c: thermogram belonging to the IR sequence, taken at the best observation time.

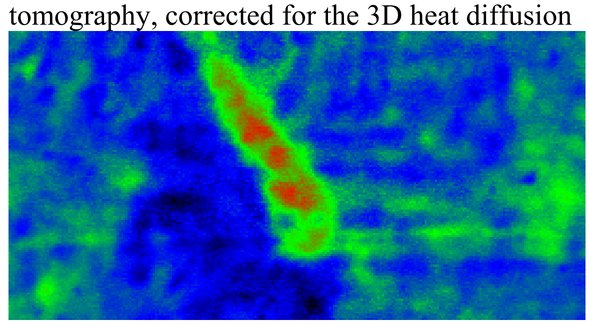

Fig. 3d: *phase* map as produced by PPT performed using the same raw data

Heating is typically performed by using IR lamps, delivering about 2000 W m^{-2}, for 60-300 *s*. A thermogram sequence must contains: the initial image, taken just before heating, the image of maximum temperature taken at the end of heating and the image at the optimum observation time, for the most relevant class of defects.

The test, performed on a fresco by Romanino at Malpaga castle, adopts TT for TNDT (see fig.3a). A thermograms sequence produces two synthetic images, mapping for each pixel the maximum normalised temperature difference with a reference area (*thermal contrast*) and the time of the maximum contrast (*timegram*). Unfortunately, the underlying 1D thermal model fails, due to the 3D heat diffusion generated by the surface different energy absorption. Calculating by numerical model the surface temperature history for the whole surface, submitted to the actual heating, gets rid of this effect [14], Figure 3a illustrates the experimental set up and fig.3b: the result of the 3D correction by the enhanced TT. Fig.3c shows the raw thermogram at the best observation time for the fresco delamination. Effects of the uneven heating are clearly seen at left and write edges of the field of view. Fig.3d corresponds to the phase map given by the PPT, confirming as this technique is much less affected by the uneven heating of the surface.

Accessing the mechanical status of a structure is a hard task for any NdE method. The thermoelastic effect is growing interest for metal and composites, coming out from the simple laboratory fatigue testing. Up today a few works [1,15] have been issued to the structural evaluation demonstrating a potential use of thermography in situ. Normally, the classical compressional strength destructive testing is well correlated to other properties of matter as elastic wave longitudinal pulse velocity or thermal diffusivity. An integrated method has been proposed [16] exploiting tight correlations between thermal properties and elastic characteristic. An experiment was performed at the Santa Chiara's church (XV-XVI century Cagliari, Italy) aiming to evaluate effectiveness of some restoration works, especially for cracks repair in the main facade. Hence, an in situ ultrasonic survey integrated with thermography was carried out in some indoor sectors of priority interest.

Ultrasonic tests have been carried out along six parallel profiles at different levels from the floor in order to know the elastic state of the wall. Fig. 4a shows the ultrasonic longitudinal velocity map above the choir, interpolating data measured with 0.2 m transmitter-receiver distance. Different tests in situ and lab established that results are relative around a mean value, which depends on different aspects, as the transmitter-receiver distance. Notwithstanding this, the velocity variation is a good indicator of the integrity state of the material. The low velocity areas in the map represent fissures and other damages. This statement can be verified looking at fig. 4a where the velocity map is merged with the visual image indicating some puttied cracks. The zone *A* is an example where the low velocity field develops downwards, inside the material beyond the plaster layer. In sector B, the shallow crack corresponds to a low velocity zone only in its lower part. In sector C and D, we can notice a good correlation between fissure and low velocity zone. In general, correspondence between low velocity zones and cracks, indicate poor success of the structural restoration works made in different times or a restoration limited to the shallowest part of the masonry.

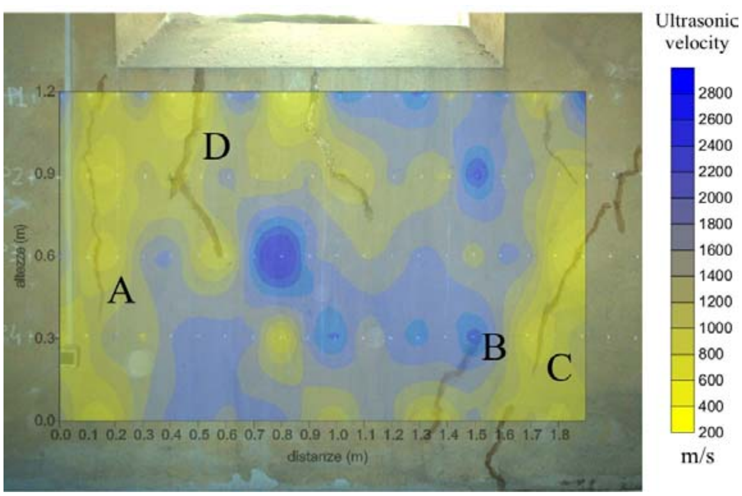

Fig.4a: S. Chiara, elastic wave map merged to a visual image

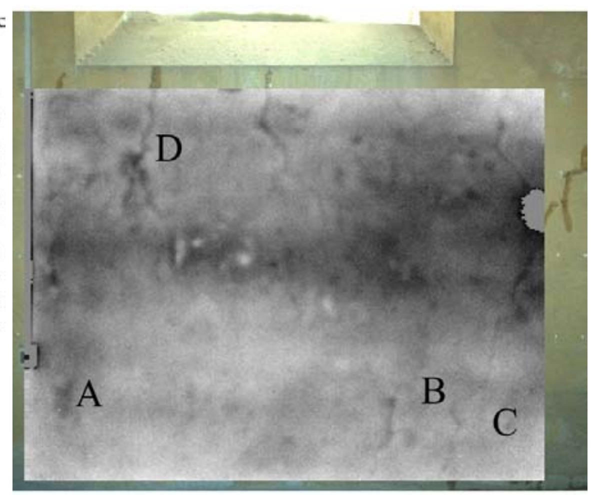

Fig.4b: Thermal analysis of the upper choir structure

Thermal analysis has been performed heating the surface by means of an air gun, scanning the wall perpendicular to its surface and parallel to the floor. A standing FPA thermal camera is used for the temperature monitoring. The sequence acquired was processed pixel-wise, considering the wall as a thermally thick slab and therefore analysing it within a suitable time window. The assumption is that thermal waves propagating in depth are affected by diffusivity and they can be seen as the superposition of various exponential components. Figure 4b shows the logarithm of the ratio between first and zero order magnitude images given by the PPT algorithm [13]. Generally, a good correlation between thermal and elastic wave analysis was found; hidden features are clearly identified and linked to the visual state of restoration. Thermography provides fast and well spatially resolved results, while ultrasounds can penetrate the masonry thickness. The thermal analysis is illustrative of the real cracks net at the hidden interface between masonry and plaster. For instance, looking at zone *D* of fig.4b it is worth noting as repaired cracks, visible on the surface, actually continues and branches off itself. Furthermore, weak areas (light grey) surround in some zone a dark spot, as site of the repair materials injection.

The last example refers to the indoor comfort monitor especially important for renewed historical buildings, where limitations in the HVAC plant intrusion and large volumes exist. The correct temperature mapping is the starting point both for the radiative flux evaluation [17] and for the convective one. This task is not trivial and conflicts with the desired as cheapest as possible equipment choice. The reported results show usefulness of Computational Fluid-dynamic Codes (CFD) and local fluxes detection. The microclimate monitoring (lasting for 4 years) recorded indoor-outdoor air surface temperature and relative humidity in many points. The Carbon Dioxide concentration points out that natural air ventilation changes are insufficient. A thermographic survey has been crossed with these measurements. The aim was to harmonise the conservation necessity with the visitors' comfort, choosing a HVAC plant for the active control of the indoor conditions. In particular, the condensation risk at the North corner has been evaluated.

Fig. 5a shows the famous *Camera picta* by Mantegna (Mantova, Italy). It was studied in order to predict air movements and pollution due to visitors [18], taking into account the coupled system room-thermal plant. The first step was the whole lateral surface temperature scanning, by means of a motorized dual-band thermographic system. Then thermograms have been composed and geometrically corrected, Finally, CFD has been feed with resampled temperature data and both temperature field at different places and the air flux at chosen points are computed (see fig.5b). In such a way, the committing authority assessed alternative options.

Local fluid dynamic conditions can be also evaluated experimentally by thermography. A testing procedure for the air tightness was recently proposed, where heat is used as tracer [19]. The testing procedure is based on the lock-in technique in order to separate very tiny mass flux from the environmental thermal noise. Efficient energy usage and economy or effective removals of harmful gases are other applications of low velocity fluid-dynamic.

Fig. 5a: the *camera picta* (S. Giorgio castle, Mantova, Italy)

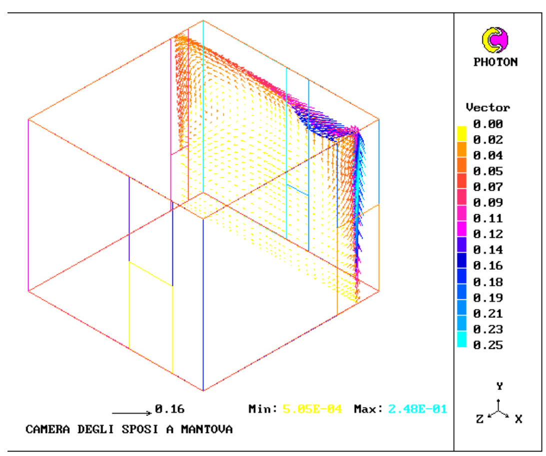

Fig. 5b: results of the CFD simulation using IR images

Others applications, and materials: Wood is one of most difficult materials to be tested by thermography, because it is inhomogeneous and low conductive. Wood paintings are very common in the art history and evaluating their status is a challenging, but important topic [20]. Figure 6a shows a typical set up using photographic flashes (4.8 *kJ* in 5 *ms*) for pulsed thermography testing. The main difficulty arises from the noise content of the thermal signal. A possible solution is the use of a lock-in technique, unfortunately this is time consuming and, more important, generates an average surface temperature not allowed in our case. Therefore, the sequence of thermograms can be processed effectively in the *Ln(T)-Ln(t)* space, instead of the usual temperature (*T*) - time(*t*) scale. In fact, in the *Ln(T)-Ln(t)* space, after the initial pulse any thermally thick, homogeneous material cools down following a straight line of a – 0.5 slope. This allows a linear fitting of data, giving a noise reduction and a data compression capability. Unfortunately, our painting has a multilayer and not homogenous structure. Therefore, a polynomial fitting is more appropriate [21]. Experimental results are shown in fig. 6b, showing the 3rd coefficient map given by the 5th order polynomial fitting.

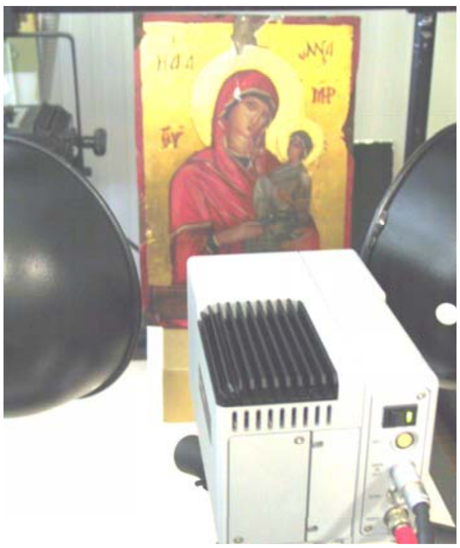

Fig.6a: Pulsed Thermography set up inspecting a wooden painting (photographic flashes and FPA IR camera)

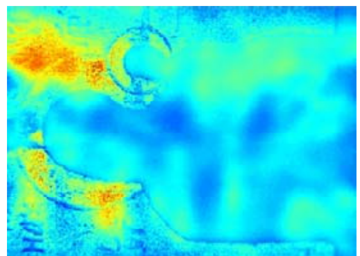

Fig.6b: 3rd coefficient map given by the 5th order polynomial fitting

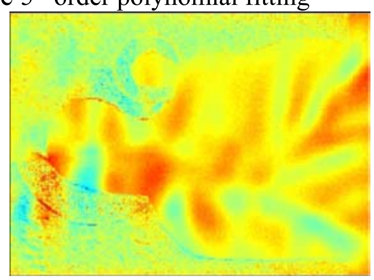

Fig.6c: Principal Component Analysis using the same raw data

Fig.7a: thermal characterisation of Greek ceramic (V° sec B.C.)

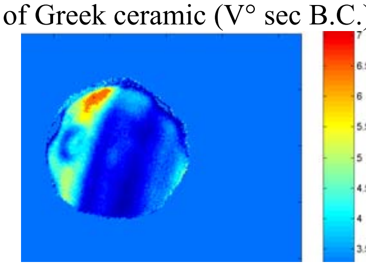

Fig.7b: thickness map, mean diffusivity value: 4.77 10^{-7} m^2s^{-1}

Another data reduction technique, emerging in TNDT is the Principal Component Analysis (PCA), giving similar results (see fig.6c), but with a more predictable behaviour [22]. The emissivity of paint and particularly of gold is normally a problem for this kind of test, but more easily handled using PPT, LT and PCA,

The last case refers to archaeological ceramic (see fig.7a) that is well characterised by the measure of thermal diffusivity and effusivity. The *Flash Method* has been modified [23] to measure diffusivity on authentic and fake pots. After the testing of many different samples, using 3 different techniques, an accuracy of 10% has been found, notwithstanding the non-planar and constant thickness of the pot. An important byproduct of this research is the thickness gauging, which can be very useful for sealed pottery. Fig.7b gives the thickness map of a fragment of Greek ceramic (V° sec B.C.) and the mean value of the diffusivity. Analogous application of thermography concerns bronze statues. The aim is to evaluate the thickness and slugs using a technique derived from the corrosion evaluation on metals by IR thermography [1,13,24].

Conclusions: Different applications of IR thermography to selected case study illustrate usefulness of this method for the work of art study. Many established fields will be complemented to new targets on a short run. New procedures are emerging, exploiting the hardware improvement. Imagination, expertise and standardisation are the key factors for a fast and effective expanding of TNDE.

Acknowledgements: This paper has been possible because of the long lasting cooperation with dr. Paolo Bison, dr. Sergio Marinetti, prof. Vladimir Vavilov, dr. Chiara Bressan and arch. Elisabetta Rosina, thanks to all.

References:

1 *Non Destructive Testing Handbook- Vol.3 Infrared and thermal testing*. Eds. X. P.V. Maldague and P. O. Moore, American Society for Nondestructive Testing, (2001)

2 E. Grinzato, P.G. Bison, S. Marinetti "Monitoring of ancient buildings by the thermal method" *Journal of Cultural Heritage*, Elsevier, 3, pp.21-29 (2002)

3 E. Grinzato, P.G. Bison, S Marinetti, V. Vavilov: "Thermal/Infrared non-destructive evaluation of moisture content in building: theory and experiment". Int. Symposium: Dealing with defects in building, pp.345-357, Varenna (1994)

4 E. Grinzato, F. Peron, M. Strada: "Moisture monitoring of historical buildings by long period temperature measurements"; Thermosense XXI°, pp. 471-482, SPIE vol.3700 (1999).

5 D.R. Jenkins, L.I. Knab, R.G. Mathey: "Laboratory Studies of Infrared Thermography in Roofing Moisture Detection", Moisture Migration in Buildings, pp.207-220.

6 P.G. Bison, C. Bressan, E. Grinzato, S. Marinetti: "Automatic air and surface temperature measure by IR Thermography with perspective correction." SPIE Vol.1821, pp.252-260, Boston (1992)

7 V. Vavilov, T. Kauppinen, E. Grinzato: "Thermal charactersation of defects in building envelopes using long square pulse, and slow thermal wave techniques", *Research in Nondestructive Evaluation*, Springer-Verlag, vol.9 n° 4, pp. 181-200, (1997)

8 E. Rosina, E. Grinzato, E. Robison,: "Mapping hidden wall structures by Quantitative IR Thermography"; Thermosense XXIV°, pp.253-264, SPIE vol.4710, Orlando (2002)

9 E. Grinzato, C. Bressan, A. Mazzoldi: "The quantitative IR Thermography for the diagnosis of frescoes", 4th International Workshop on Advanced Infrared Technology and Applications. pp.345-366 Firenze (1997)

10 E. Grinzato P.G. Bison, C. Bressan, A. Mazzoldi: "NDE of frescoes by Infrared Thermography and lateral heating"; Eurotherm Seminar n. 60, QIRT 98 Lodz, pp.64-67 (1998)

11 E. Grinzato, C. Bressan, S. Marinetti, P.G. Bison, C. Bonacina: "Monitoring of the Scrovegni Chapel by IR Thermography: Giotto at Infrared", J. Infrared Physic and Technology, Elsevier, vol.43, pp.165-169 (2002)

12 P.G. Bison, E. Grinzato, S. Marinetti, A. Braggiotti: "Fresco thermographic inspection by convective heating technique". Review of progress in Quantitative Non-Destructive Evaluation vol.17 pp.1769-1776, Plenum press (1998)

13 Maldague, X., *Theory and Practice of Infrared Technology for NonDestructive Testing*, John Wiley-Interscience, (2001)

14 V. Vavilov, S. Marinetti, E. Grinzato, P.G. Bison, S. Dal Toè, D. Burleigh: "Infrared Thermographic Nondestructive Testing of Frescos: Thermal Modelling and Image Processing of Three Dimensional Heat Diffusion Phenomena", *Material Evaluation*, an ASNT Journal, pp.452-460 (2002)

15 M.P. Luong: "Infrared Thermography of fatigue behavior of concrete under compression", 2nd Int. Conference of Nondestructive Testing of Concrete in the infrastructure, pp.167-176, Nashville (1996)

16 E. Grinzato, S. Marinetti, P.G. Bison, M. Concas: "Comparison of ultrasonic velocity and IR thermography for the characterisation of stones", *Journal of Infrared Physic and Technology*, Elsevier (in press)

17 A. Colantonio: “Verification of dynamic buffer zone wall assembly performance using IR thermography”, Thermosense XXIV°, SPIE vol.4710, pp.288-298, Orlando (2002)
18 E. Grinzato, C. Bressan, F. Peron, P. Romagnoni, A.G. Stevan: “Indoor climatic conditions of ancient buildings by numerical simulation and thermographic measurements” Thermosense XXII°, SPIE vol. 4020, pp. 314-323, Orlando (2000)
19 E. Grinzato, S. Marinetti, P.G. Bison: “Air tightness monitoring by IR thermography”; Thermosense XXVI°, SPIE vol. 5405, pp.132-143, Orlando (2004)
20 B.F. Miller: "The feasibility of using thermography to detect subsurface voids in painted wooden panels;" JAIC 16, pp. 27-35 (1977)
21 E. Grinzato, S. Marinetti, V. Vavilov, P.G. Bison: ”Non-destructive testing of wooden painting by IR Thermography”, pp.81-90, 8th ECNDT, Barcelona (2002)
22 S. Marinetti, E. Grinzato, P.G. Bison, E. Bozzi, M. Chimenti, G. Pieri, O. Salvetti: “Analysis of IR thermographic sequences by PCA”, *Journal of Infrared Physic and Technology*, Elsevier (in press)
23 F. Cernuschi, P.G. Bison, A. Figari, S. Marinetti, E. Grinzato,: “Thermal diffusivity measurements by photothermal and thermographic techniques”, *Int. Journal of Thermophysics*, vol.25, n°2, pp.439 (2004)
24 E. Grinzato, V. Vavilov: "Corrosion evaluation by thermal image processing and 3D modelling"; *Revue Générale de Thermique*, n°37, pp.669-679, Elsevier (1998).