Thermography in Analysis of Works of Art: Choice of the Optimal Approach

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Abstract
The work presented provides an overview of the use of infrared methods in the analysis of works of art. Special attention is paid to the use of thermographic methods applied to oil paintings for the purpose of defectoscopy and study of composition. Several active thermography approaches are discussed and optimal methods are considered. The work includes several examples of the application of thermography to real paintings as well as mock-up samples.

Keywords: thermography, noninvasive analysis, artworks

1. Introduction
Among the most important problems for those who deal with objects of art is estimation of the condition of the piece. Of particular interest are the presence of defects, their shape and degrading effects caused by them. A serious restoration process often requires conducting pre-restoration analysis of the piece to be restored.

Analysis methods of objects of art evolve. A few centuries ago a conservator could rely mostly on his own experience, but today conservators are equipped with a number of modern diagnostic techniques coming from industrial and scientific applications.

Most of the methods applied to the analysis of works of art today may be grouped in two main types – namely, the materials analysis methods (these do not give information on the piece as a whole) and methods for analysis of the structure (imaging methods). This work is devoted to thermography, which belongs to the second group of methods aiming to extract information on defects and inclusions.

2. Thermographic methods
2.1 General
Thermographic methods (or, simply, thermography) involve a group of techniques often used in industry for diagnostics of solid structures such as composite materials, metals, plastics, etc. Since the end of the 20th century thermography started being used in the delicate field of analysis of works of art as well.

The main principle of thermography lies in observation of temperature distribution on the surface of the object of interest. In the case of passive thermography (no heat is manually supplied to the sample), a researcher would most likely determine the presence or absence of sources/leaks of heat, because they cause non-uniformities in the surface temperature distributions. If the sample is initially in thermal equilibrium, and its structure is of most interest, the researcher may use the active thermographic approach. Active thermography often allows for taking advantage of the configuration of the stimulation, which may provide the possibility of quantitative measurements.

Most of the methods in thermographic analysis utilize various solutions of heat equation [1]:
\[
\frac{\partial T}{\partial t} = \sum_{i=1}^{3} \frac{\partial}{\partial x_i} \left( \alpha \frac{\partial T}{\partial x_i} \right)
\]

(1)

where \( \alpha = k/\rho c \) is thermal diffusivity of the material, \( x_i \) is arbitrary coordinate, \( k \) is thermal conductivity, \( \rho \) is the mass density, and \( c \) is the heat capacity [1].

2.2 Pulse thermography

Pulse thermography (often referred to as PT) may probably be regarded as the most straightforward of all the thermographic techniques. The experimental procedure requires application of a short heat pulse on the surface of the sample with subsequent observation of the evolving thermal distribution by a thermal camera [2, 3].

An instantaneous thermal stimulation is often delivered by a powerful flash lamp. The heat deposited on the surface starts propagating towards the deeper (colder) layers of the sample, which results in decreasing the surface temperature [4]. In cases where the heat front hits some structural non-integrity, the surface temperature in this area would differ from that where no inclusions are present (Figure 1). This allows for the determination of the presence of defects and has been used for analysis of wood, plasters, walls, as well as a number of other samples where the temperature contrast due to the defect could be resolved [4].

![Figure 1. Explanation of Pulse Thermographic Technique.](image)

2.3 Thermal signal reconstruction

According to [1], the surface temperature contrast for a semi-infinite sample which received amount of energy \( Q \) at time moment \( t=0 \) in a very thin layer of material around \( x=0 \) would be dependent on time as

\[
\Delta T(x,t) = \frac{Q}{\sqrt{k\rho c \pi}},
\]

(2)

where \( k \) is thermal conductivity, \( \rho \) is mass density, and \( c \) is heat capacity of the material. This solution of (1) is sometimes referred to as source solution.

As can be seen, in logarithmic terms (1) turns into

\[
\ln(\Delta T|_{t=0}) = \ln\left(\frac{Q}{\sqrt{k\rho c \pi}}\right) - \frac{1}{2}\ln t + \text{const},
\]

(3)

This means that the theoretical graph for a non-defective sample has the shape of a straight line in logarithmic coordinates. The time moment of deviations from this straight line caused
by the presence of any inclusions can be located by taking the second derivative in logarithmic coordinates (Figure 2).

![Figure 2. To explanation of Thermal Signal Reconstruction technique.](image)

This method, referred to as Thermal Signal Reconstruction (TSR), has been introduced by S. Shepard in 2001 [5, 6]. The main point of TSR is that determination of the peak position on the second logarithmic derivative allows one to estimate the thickness of the material layer or the thermal properties of the material. TSR has successfully been applied to the analysis of composite materials, metals and other materials. There are publications on the successful use of TSR in application to analysis of artworks [7].

### 2.4 Pulse Phase thermography

Pulse Phase Thermography (PPT) proposed in 1996 by X.Maldague and S.Marinetti [8] is based on wave-type solution of (1):

\[
T(x,t) = T_0 \exp\left(-\frac{x}{\mu}\right) \exp\left(i \omega t - \frac{x^2}{\mu} \frac{\pi}{4}\right),
\]

where \(\omega\) is the angular frequency of the wave, and \(\mu = 2\alpha/\omega\) is a parameter called diffusion length. This solution indicates that any kind of temperature evolution curve can be represented as the result of superposition of a number of harmonically changing signals (waves), each of which has different penetration depth depending on its frequency and thermal properties of the material due to the factor \(\exp(-x/\mu)\) in (4). The amplitude and the phase of each of the waves can be inspected separately from the others by spectral decomposition.

These thermal waves propagate into the bulk of material, reflect from any possible non-integrities, and return back to the surface, where they interfere with incoming waves. It can be noted that the high-frequency waves decay faster than those with lower frequencies, which means they contribute less to the phase distribution on the surface. This fact is the core of the PPT method, namely, by determining the highest (called blind) frequency which is still able to reach the defect and return back to the surface it is possible to determine the depth or the thermal properties of the material [9, 10] (Figure 3).

PPT has been widely used for industrial purposes; however, there have been attempts to use it for analysis of works of art, which demonstrated applicability of this technique in the field [11-13].
2.5 Principal component thermography

The methods discussed above, though shown to be applicable to the analysis of works of art, are based on a certain kind of physical model and solutions of (1) for certain kind of boundary and initial conditions. This makes the technique applicable to only those cases which satisfy the model.

Principal Component Thermography (PCT) offers a more universal approach, which is not dependent on a physical model of the samples under analysis [14]. The PCT measurement is conducted in similar way as in PT – a sudden flash pulse is applied to the surface of the sample and the thermal imager acquires a series of snapshots. This forms a 3D array of data containing the temperature decay curves for each point in the field of view of the imager.

Unlike PPT, where the solution is represented in an orthogonal basis of harmonics, PCT constructs an ad-hoc basis from the set of temperature evolution curves measured. The basis vectors are constructed from the data collected using a procedure called singular value decomposition (SVD):

$$ A = U \cdot S \cdot V^T, \quad (5) $$

where $A$ represents the 2D array of data collected which is a reshaped initial 3D array (stack of snapshots) collected by thermal imager. $U$ is the orthogonal set of vectors (referred to as principal components) sorted by how much variance of the initial data they describe. In most cases, the first 4-5 vectors contain most of the informational content, while the other vectors contain just uncorrelated noises. By disregarding the higher vectors one can clean the noises significantly. The first vector usually represents the results of non-uniformity of surface heating (e.g. those caused by different heat absorption), while the second and third vectors often reflect those factors which less influenced the surface temperature – in many cases those are the defects and inclusions under the surface of paint. Thus, by inspecting those it is possible to get information on the subsurface structure of the sample under analysis [2, 13].

The main feature of PCT which makes it promising for the analysis of works of art is its non-dependence on any physical model. It is important to remember though that the orthogonal basis is constructed individually for each experiment, and thus differs from one measurement to another. This introduces a certain unpredictability to the interpretation of the resulting images – for example, the detachments which appear warmer (brighter) in PT images may
appear both brighter and darker in PCT images (i.e. image may appear both positive and negative).

3. Examples of analysis

3.1 Panel paintings

In order to demonstrate the applicability of thermographic methods to analysis of wood, two artificially made samples were analyzed (Figure 4) [15]. The samples represented a wood panel selectively covered with fish glue before being covered with gesso. The selective covering caused a detachment to be formed in the regions not treated with glue.

As can be seen, the defects on these plates appear to be undetectable by near infrared, which is used by conservators for its ability to penetrate through the layers of paint. Thermography allows for seeing the contours of the defects in these samples. At the same time, it can be seen that application of post-processing techniques (PPT and PCT) increases the visibility of the defect (Figure 4).

![Figure 4. Analysis of panel paintings with manually introduced defects: a) Visible image; b) Near-infrared image; c) Thermal image after flash application; d) PPT image; e) PCT image.](image)

Similar defects can be observed in Figure 5, demonstrating the results of thermographic analysis of a panel painting by J. Linnel. The defects are observed as dark spots unlike those in Figure 4.

![Figure 5. Linnel, John. Job offering a sacrifice on his return to prosperity. 76x56 cm, oil on panel, Hamilton-Kerr Institute (HKI 2032), Cambridge, UK.](image)
Thermography can be of use when extraction of wood grains is necessary. From the point of view of thermography, the medullary rays represent inclusions with thermal properties different from the surrounding wood, which makes them detectable with thermographic methods. It is worth noting that the PCT image in Figure 5 reveals faint wood grain structure. It may be expected that higher PCs would be of use when the grain structure is of interest.

Wood grain structure can be clearly seen in Figure 6 together with a defect in the top left corner, which appears as a brighter spot similar to the defect in Figure 4e.

![Figure 6. Unknown. Tempera, wood. Private collection, Windsor, Canada.](image1)

![Figure 7. Comparison of results of visible, near infrared (NIR, 0.7-1.1 mkm), short-wave infrared (SWIR, 0.9-1.7 mkm) and thermographic (PCT) imaging. Unknown. Portrait. Oil on canvas. Private collection, Windsor, Canada.](image2)
3.1 Canvas paintings

Canvas paintings represent a type of sample different from panel paintings. In most cases canvas based paintings are thinner than panel paintings and thus cool down much faster. This requires a larger number of thermal snapshots to be collected in less time, which makes slow microbolometeric cameras harder to use for this application.

Figure 7 demonstrates the result of analysis of a portrait. The jacket of the person appears to be impenetrable for the infrared light (apparently, due to a high concentration of carbon in paint), which is a common method for revealing the alterations in paintings. However, the thermographic image demonstrates the presence of the feature (cross) painted over.

The goal of analysis of canvas paintings often includes the structure of canvas threads. In particular, the canvas cuspings may give information on the locations of the stretching nails. In Figure 8 one can see a result of thermographic analysis of a single area on Jordaens' Satyr at the Peasant's House. The canvas of this painting contains several additions (Figure 9) and, as Figure 8 shows, the cuspings are clearly seen on the central piece of canvas. This indicates that the central part once represented a complete stretched painting before it had been extended.

Figure 8. Retrieving the configuration of canvas cuspings by PCT method.
J.Jordaens, Satyr at Peasant’s House, Oil on canvas, c.1622. State Pushkin Museum, Moscow.
4. Safety of thermographic methods to the works of art

One can notice that many museums and galleries prohibit the use of photographic cameras by visitors. This is usually explained by the possibility to accelerate the decay of the paint layers by bright light.

On the other hand, these precautions are often caused by reasons other than just the safety of exhibitions. These may include economic reasons (if the gallery makes a profit from selling their own photos), copyright reasons (e.g. if the gallery exhibits pieces of a third owner), ethical reasons, and a number of others.

According to [16], the yearly exposure a painting at the National Gallery in London is allowed to get should not exceed $6 \times 10^3$ lux·hour (i.e. $5.8 \times 10^6$ lux·s per day) with illuminance of 200 lux. Taking the exposure delivered to the flash lamp used for this research ($13.9 \times 10^3$ lux·s) it can be seen that a daily exposure limit corresponds to approximately 400 flashes, which is much less than the number of flashes necessary for conducting analysis of a single painting. However, care should be taken in order to minimize the portion of UV in the exposure light as the UV delivers much more degrading effect to varnish and paint layers than the visible light.

5. Conclusion

In this work a number of artworks have been analyzed using the thermographic defectoscopy technique. This work and a number of those by other authors demonstrate the general applicability of thermography to the analysis of pictorial art.

Due to the general unpredictability of the structure of most works of art it appears difficult to apply thermographic methods which are based on certain models of "ideal" samples such as those having a flat, uniform surface, and where the heat is deposited only in a very thin layer of surface material. In such models it is usually assumed that the sample would behave similarly to the ideal case until the heat front from the surface would hit the opposite side of the sample or any kind of defect. However, there are certain doubts. The lack of data on thermal and optical properties of artistic materials leads to uncertainties in estimation of how
effective the initial heating is (e.g., how thick is the surface layer receiving the heat) and how this affects the results. Also, since the structure of the paint layers is random, and the surface may not be flat (especially for \textit{impasto} paintings), this also contradicts with the model of the ideal sample.

Due to these facts it appears promising to use the models which are adaptive to each particular kind of sample. Among such methods PCT appears to have a very reasonable background.

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\section*{References}


