The Feasibility of Flash Thermography for the Examination and Conservation of Works of Art

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This study investigates the feasibility of flash thermography for the examination and conservation of works of art: paintings, works on paper and sculpture. Thermography is a non-destructive technique for the identification of subsurface defects in materials. It is based on the propagation of surface-deposited heat through into the material. Differences in propagation between defect and defect-free areas result in a difference in the surface temperature of the material. The surface temperature is mapped over time by imaging with a mid-infrared digital camera. A xenon arc lamp is used to provide the initial source of radiation, and signal processing is typically applied to the collected data to reduce noise and to enhance key signal characteristics. This technique offers the possibility of investigating the structure of paintings and paper, particularly in cases where other non-destructive examination techniques do not provide sufficient information, for example subsurface delamination and layer structure. The results indicate that thermography is a good technique for detection of paint delamination and the degree of adhesion between layers, particularly in canvas paintings. It also successfully detected wood grain in situations where X-rays did not, although it was not effective for detecting voids or defects in wood.

INTRODUCTION

The aim of this research was to investigate the suitability of flash thermography for the examination of works of art as an aid to their conservation; especially its ability to identify subsurface features, often invisible areas of vulnerability and damage. Other non-destructive techniques (NDT) commonly used in a conservation studio, such as X-radiography, steady-state near infrared (0.7–3.0 μm) reflectography and examination with ultraviolet radiation, have limited or no capability to reveal these features. This paper explains the flash thermography technique and its applications, and reports the results of the experimental investigations, including the limitations found and an assessment of potential risks to works of art. This research was conducted as part of a collaborative project between The Courtauld Institute of Art (CIA), the National Physical Laboratory (NPL) in the UK, the Museum of Modern Art (MoMA) in New York, and Thermal Wave Imaging Inc., Detroit, both in the USA.

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PRINCIPLES OF THERMOGRAPHY

Objects at a finite temperature emit radiation in the infrared region of the electromagnetic spectrum. Thermography uses medium wavelength (MWIR) 3–5 μm or long wavelength infrared (LWIR) 8–14 μm (as opposed to the near infrared (NIR) 0.74–1 μm or short wavelength infrared (SWIR) 1–3 μm, commonly used in steady-state infrared reflectrography) to measure the propagation of thermal energy through a structure by monitoring the surface temperature variation of the sample.

There are two types of thermography: active and passive. In passive thermography the sample is examined under steady-state conditions (no application of external heating) making use of existing thermal differences between defect and defect-free regions. Without externally applied thermal excitation, the surface temperature distribution of a sample examined is not related to its subsurface structure and provides limited information. Passive thermography is commonly used in forest fire watching, maintenance evaluation, power generation evaluation, military surveys and

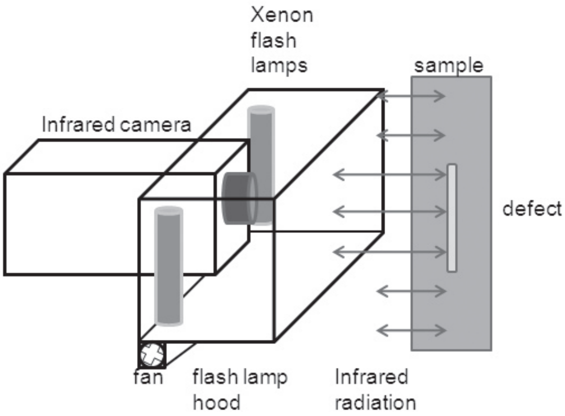


Figure 1 *Diagram of the ThermoScope® and set-up.*

medical examination [1]. In active thermography the sample's thermal response is measured as it returns to thermal equilibrium after an external excitation. Flash thermography utilizes fast active excitation produced by a xenon flash lamp, emitting radiation typically in the ultraviolet (UV) to LWIR range [2]. For objects which are usually in a state of thermal equilibrium, including works of art, active excitation is necessary for detection of subsurface features.

The presence of subsurface defects in the sample either retards or accelerates the flow of heat, causing transient changes in the surface temperature that are detected by the infrared camera. For example, a void blocks the flow of heat because air is a thermal insulator compared to the surrounding material. This causes the region above the void to stay hotter for longer than the surrounding area. Conversely, where there is a subsurface inclusion with greater conductivity than its surroundings, the surface above the inclusion will cool more quickly.

Infrared cameras working within part of the 0.7–5.0 μm wavelength range, without integrated flash hardware or signal processing software, are found in conservation studios and conservation science laboratories. In principle, these cameras can be used to acquire thermographic data. Hence, one objective of this research was to attempt thermography with the Inframetrics FLIR infrared camera at the Museum of Modern Art (MoMA) in New York. This digital camera consists of a 256 × 256 pixel charge-coupled device (CCD) PtSi detector, sensitive over the full spectral range of 1–5 μm. In this project, it was used with a lens that acted as a spectral filter, passing only radiation between 3 and 5 μm. The results obtained with this camera are summarized herein. A full comparison between the Inframetrics infrared imaging camera used to acquire thermography data and a dedicated ThermoScope® thermography instrument (described below) is given elsewhere [3].

FLASH THERMOGRAPHY EQUIPMENT AND DATA PROCESSING

Two versions of the ThermoScope® flash thermography instrument were used for the study at MoMA (ThermoScope® II), and in the UK at NPL and CIA (ThermoScope® I). The system used at MoMA consisted of a diffuser hood containing two xenon flashtubes energized by a 1.8 kJ capacitor, a 320 × 240 pixel InSb focal plane array (FPA) sensor, with a micro Stirling internal cooler, and a 12 bit, 60 Hz frame capture. The system was mounted on a tripod (see Figure 1) [4]. The system used in the UK differed in that it had a single xenon flash lamp within the diffuser hood and a 316 × 255 pixel CCD sensor with a micro Stirling internal cooler and a 12 bit, 50 Hz frame capture.

The ThermoScope® captures an infrared image sequence that spans the entire flash and cooling period. The collected sequence is processed by software (MOSAIQ™) using the thermographic signal reconstruction (TSR™) technique (see Figure 2). The result of the TSR process is a smoothed, noise-reduced replica of the time history of each pixel intensity or, equivalently, a grey-scale 'video' that is a record of the sample's surface temperature response. The videos can

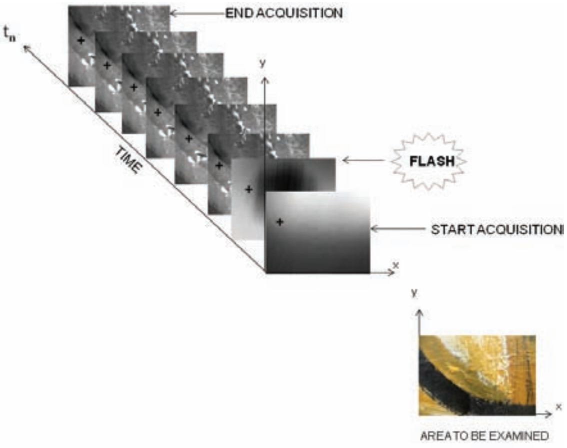


Figure 2 *The flash thermography process. Several hundred frames of raw data are recorded, which represents the time history (t_n–t_1) of each pixel, marked by a cross in the acquisition images.*

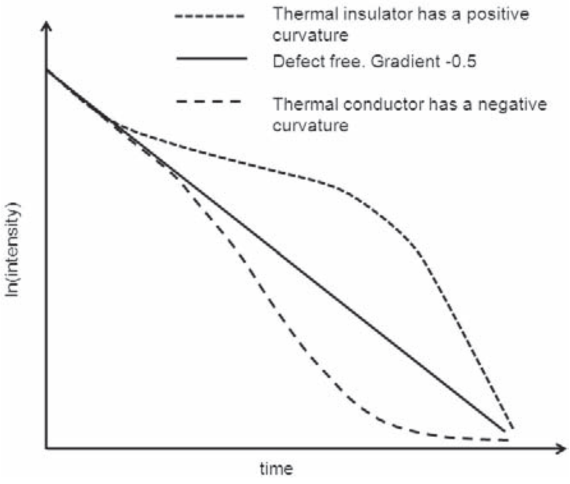


Figure 3 *Generic log(T) vs. log(t) graph for a semi-infinite, defect-free sample.*

be displayed as the TSR-processed intensity data (R), or the first (1d) or second (2d) logarithmic time derivatives of the intensity. The software uses auto-contrasting of each grey-scale frame to highlight possible subsurface features. For highlighted pixels, log(intensity) versus log(time) [log(T) vs. log(t)] curves can be plotted of the raw, first and second derivatives. The behaviour of these curves depends on the thermal effusivity, diffusivity, and thickness of the sample, so that deviations from normal behaviour of any of these properties (e.g. voids, different paint composition, anomalous bonding to canvas) can be readily identified [4]. For example, Figure 3 shows the log(T) vs. log(t) graph for a semi-infinite, defect-free sample (e.g. a sample with no back wall), which has a characteristic linear slope of −0.5. Deviations from this straight line are indicative of subsurface thermal discontinuities. For a homogeneous material the time at which the deviation from the linear behaviour occurs is related to the depth and thermal diffusivity of the material, and is independent of the diameter of the feature causing the discontinuity. Those pixels that deviate from linearity are highlighted by differentiation with respect to log(t), and can be characterized by their inflection points and maxima (see Appendix B).

Previous applications of thermography

The introduction of commercially available infrared cameras in the late 1960s enabled infrared examination to be applied in many disciplines. Subsequent developments in electro-optical and signal processing techniques led to more advanced infrared inspection systems. The potential of thermography for non-destructive testing has been recognized by the aerospace composites industry for several years, often replacing ultrasound or radiography for the detection of delaminations, porosity, trapped water and adhesive failure [5, 6]. Recent advances in technology have meant that modern thermographic NDT systems are now fully automated and capable of quantitative measurement of wall thickness, defect depth or thermal diffusivity with an accuracy and sensitivity comparable to ultrasound.

Previous applications of thermography for the examination of works of art have focused on panels, frescoes, stone sculpture and paper. Miller's 1977 feasibility study of the thermographic examination of voids in panels indicated promising results for the technique's applicability to works of art on wooden panel [7]. Miller's results are compared with those from the present research, in a later section of this paper. Thermography has been used for the examination of frescos, from diagnosing their condition to verifying the quality and success of treatments. The thermal excitation was provided by flash lamps, lamps, scanning lasers or hot air jets [8]. Meinlschmidt carried out thermographic inspection of watermarks in 60 drawings attributed to Rembrandt and his students [9]. Using a heated plate as the thermal excitation source, his results show the applicability of transmission thermography to drawings and paintings on paper.

Flash thermography has also been compared to other NDT techniques currently being evaluated for their possible applications in conservation; this comparison is given elsewhere [3].

WORKS OF ART EXAMINED

Examples have been drawn from the collections of the Museum of Modern Art (MoMA), New York and The Courtauld Institute of Art, London. These were selected to provide a range of examples to assess the applicability of thermography for the examination and conservation of traditional and modern works of art, executed on canvas, paper, wood and metal (see Appendix A). Two of the ten works are reported in detail in this paper in order to illustrate the main features of the technique. The results for six other works (listed in Appendix A), which are beyond the scope of this paper to describe in detail, are discussed more briefly in relation to the limitations of the technique.

(a)

(b)

Figure 4 (a) Robert Motherwell, Personage with Yellow Ochre and White *(1947), 1828 × 1370 mm, Museum of Modern Art, Art © Dedalus Foundation, Inc./Licensed by VAGA, New York, NY. (b) Detail of area (140 × 110 mm) of delaminating paint examined with flash thermography.*

For those works where successful analysis was possible, further 'model' samples were made to investigate the type, size and depth of subsurface features that are identifiable, as well as the sensitivity and limitations of the technique. The relevant results from those tests are stated in this paper, details of all the tests on 'model' samples and all ten case studies are reported elsewhere [3].

The examination of delaminating paint layers

In order to evaluate the potential of flash thermography for the detection of delaminating paint layers, a painting on canvas from the MoMA collection was chosen: *Personage with Yellow Ochre and White*, 1947, by Robert Motherwell [1915–1991], which exhibited delaminating paint to varying degrees, as well as protrusions that appeared to be either blind cleavage or areas of thicker paint (see Figure 4a). These areas were thought to consist of at least three overlying passages of paint, possibly in different media [10].

Thermographic examination focused on an area near the centre of the painting seen in detail in Figure 4b. The ThermoScope® I was placed 150 mm away from the painting. A flash pulse at 38% maximum power was used with a capture elapse time of 2.5 s. The surface temperature of the painting was recorded every 0.25 s for 3 minutes. The images captured were then processed by the MOSAIQ® software to produce the thermograms.

Figure 5 shows the raw (R) thermogram at 0.334 s where delaminating paint, visible in this image as white, is revealed soon after the flash pulse. The log(T) vs. log(t) curves, shown in Figure 6, corresponding to the pixels marked by letters in Figure 5, provide more information. The curves for areas of defect-free paint (a and b in Figure 6) cool uniformly, with a slope approximating to −0.5, as expected for defect-free uniform materials. Differences in the y-intercept of these curves are due to differences in emissivities and heat capacities of the paint passages to which the curves correspond. Curves c and d in Figure 6 correspond to areas of blind cleavage and flaking paint respectively. Both of these curves show a slow initial cooling relative to defect-free areas. The slopes are minimal, indicating that these areas are staying

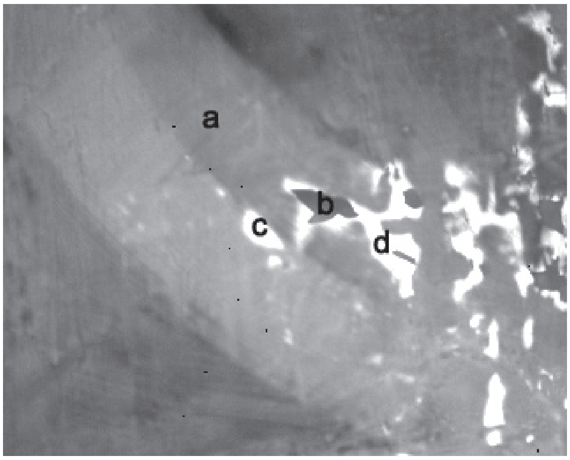


Figure 5 *Raw log(T) vs. log(t) thermogram at 0.334 s for part of the area shown in Figure 4b*

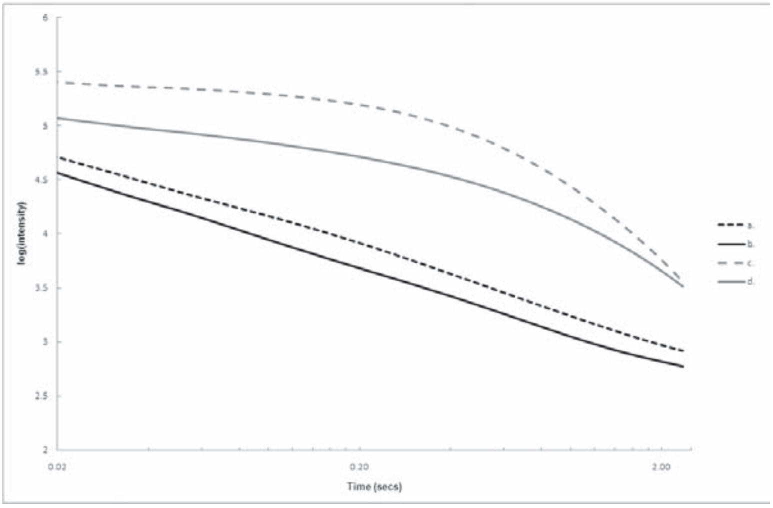


Figure 6 *Raw log(T) vs. log(t) plot for pixels marked with letters in Figure 5.*

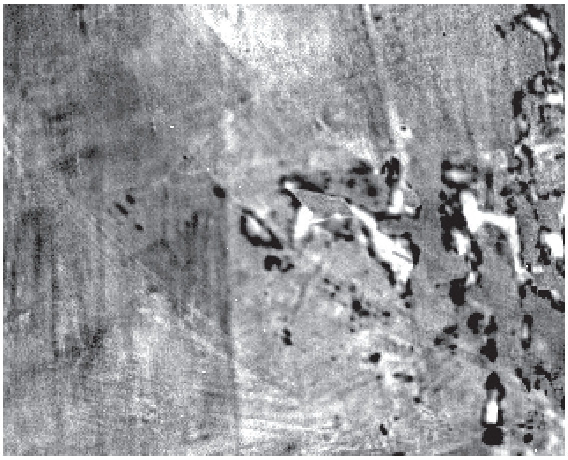


Figure 7 *First derivative thermogram at 0.334 s for the area shown in Figure 5.*

hot as there are insulating air-filled voids beneath them. The slope then becomes negative, indicating that the heat has eventually found an alternative path to conduct away.

At 0.334 s, the first derivative thermogram (Figure 7) shows the areas of delamination with greater clarity, highlighting areas of thermal contrast and hence differences in the cooling within and around the volume of the void. Faster cooling areas show up as black at the edges of the white delaminations. The first derivative log(T) vs. log(t) graph (Figure 8) shows the points of inflection for the data, with distinctly different curves for the defect-free areas of paint (curves a and b) compared to areas of paint delamination. In the first part of curves c and d for the delaminating areas, the rate of the cooling is almost zero. After approximately 0.2 s the steeper negative slope indicates cooling occurring more rapidly. The first derivative log(T) vs. log(t) curves confirm that the areas visible as white in Figure 5 are areas of delaminating paint that stay hotter for longer than defect-free paint areas.

Further interpretation of the data can be achieved by using the characteristics of the second derivative curves. Areas with similar cooling characteristics can be mapped on the thermogram by selecting values on the second derivative curve, at any point in time, that exhibit the same behaviour as a chosen pixel. The same areas of interest were chosen at 0.334 s (see Figure 5). By selecting the second derivative log(T) vs. log(t) c and d curves at 0.334 s (Figure 9), all pixels with the same cooling behaviour, areas of delamination, were mapped as red in the 2d thermogram (Figure 10). Therefore, more subtle differences in thermal behaviour can be mapped to give an overview of the degree of delamination.

While many of the areas of flaking, imaged by thermography, were visible with surface examination, thermography allowed an assessment of the extent of the delamination that was occurring and provided the conservator with a valuable tool for assessing the vulnerability of the work. Rigid areas of paint that had

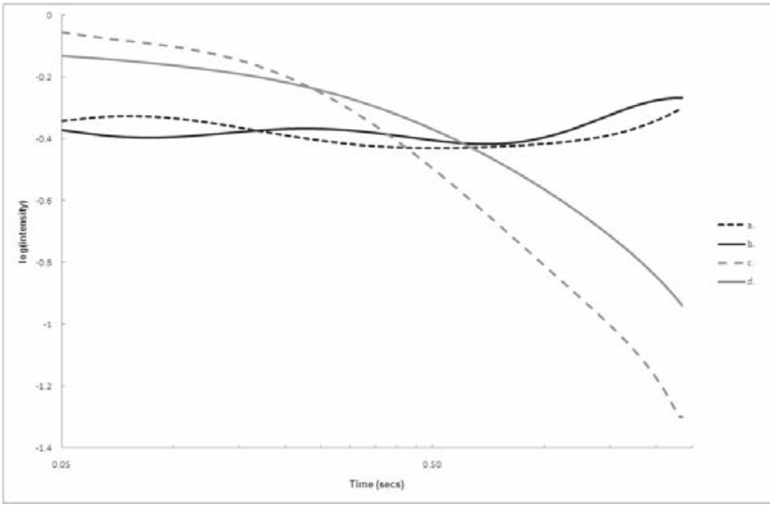


Figure 8 First derivative log(T) vs. log(t) curves for pixels as identified by letters in Figure 5 at 0.334 s.

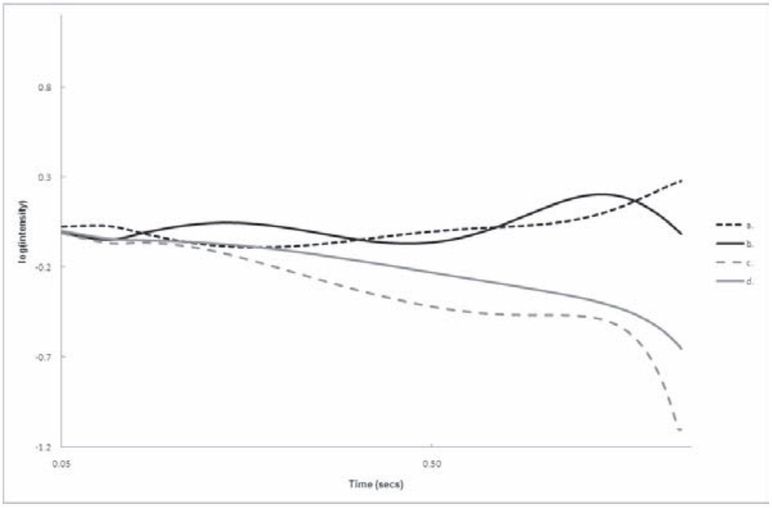


Figure 9 Second derivative log(T) vs. log(t) curves corresponding to pixels indicated by letters in Figure 5.

been thought to be solid protrusions of paint were found to be vulnerable regions of blind cleavage.

The consolidation of delaminating paint – post-treatment examination

In current conservation practice the success of a consolidation treatment is assessed empirically, often by gently touching the treated area to see whether it moves. The central areas of delamination (close to areas indicated in Figure 5) on Motherwell's *Personage with Yellow Ochre and White* were subsequently consolidated with Beva 371 using a heated spatula. Surface examination and empirical assessment by the conservator indicated a successful treatment. Thermographic examination, however, revealed the true extent of penetration of the adhesive and actual success of the consolidation. In the first derivative thermogram after consolidation, faster cooling areas show up as black at the edges of the white delaminations (see Figure 11). A visual comparison

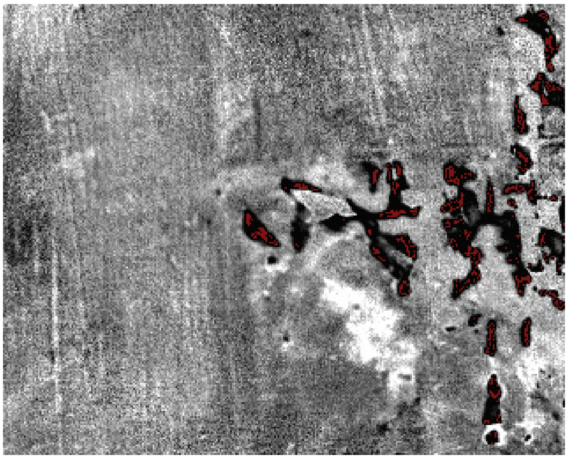


Figure 10 Second derivative thermogram at 0.334 s. Regions mapped as red indicate areas of delaminating paint.

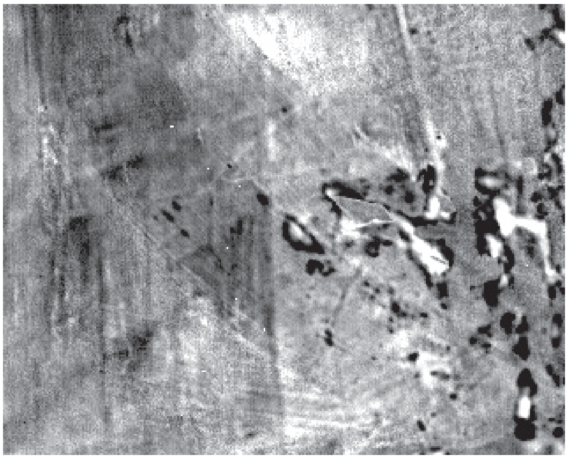


Figure 11 Detail of delaminating paint after consolidation. First derivative thermogram at 0.344 s.

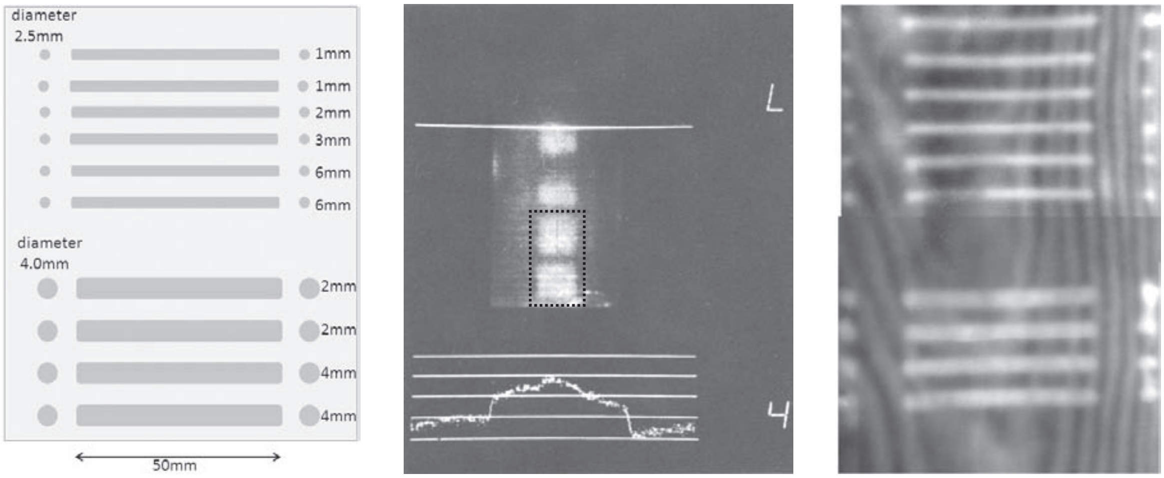
of Figures 7 and 11 shows that the majority of the delaminating areas remain white after consolidation and therefore are still not in thermal contact. Hence, complete adhesion has yet to be achieved.

Flash thermography applied to panel paintings

A panel painting from the Courtauld Collection, *Virgin and Child Enthroned with Saint Lawrence, Saint John the Baptist, Saint Monica and Saint Augustine*, by Gerino d'Antonio Gerini [1480–1529], was chosen because splits in the planks revealed worm channels and wood loss close to the gesso preparation layer. However, examination with the ThermoScope® I showed that, although it was possible to identify delaminating paint, even large, 1 cm diameter voids in the wood could not detected. The orientation of the defect was also significant. Cracks in the ground or paint were identifiable only where there was a delamination parallel to the plane of the painted surface. A vertical crack through the painting could not be identified as it does not interrupt the flow of heat to a sufficient degree to produce significant thermal contrast.

Miller's 1977 study explored the feasibility of thermography for subsurface voids in panels using a radiometer system sensitive to temperature changes of 0.2°C, and a broad-band infrared lamp as the active source. Based on his results it was perhaps surprising that the ThermoScope® system did not detect the voids close to the surface. Miller's samples consisted of surface channels and holes of varying depth and diameter drilled into a piece of softwood as illustrated in Figure 12a. The exposed surface was then covered with a layer of mulberry tissue adhered with gelatine size and a layer of gesso applied on top. In the study, voids in the image showed as white regions as seen in Miller's original thermogram (reproduced in Figure 12b). He reported thermography to be capable of detecting surface channels from 3.2 mm (1/8 inch) to 0.8 mm (1/32 inch) in diameter where grouped together. The only hole visible was of diameter 4.8 mm (3/16 inch) drilled to a depth of 4 mm.

For comparison, two blocks were made: a replica of Miller's D-4 sample; and a sample with voids made by drilling vertically (relative to the surface to be examined) into a pine wood block, to produce holes with diameters 1–10 mm, to depths of 3–40 mm, and horizontally to produce subsurface channels 2–4 mm in diameter running parallel to the surface of the panel at depths of 1 and 2 mm beneath the surface. No gesso layer or tissue was applied. Both blocks were examined using the ThermoScope® I. Figure 12c shows the thermogram for the replica block. The voids are visible as white, and as in Miller's original thermogram (Figure12b), subsurface channels of diameters 3.2 mm (1/8 inch) and 4.8 mm (3/16 inch) are visible. Comparison of the thermograms shows, first, that the ThermoScope® I has a higher spatial resolution, imaging the channels and holes with greater clarity; it also shows the grain of the wood (Figure 12c). Therefore, one might expect that the subsurface channels of diameters down to 0.8 mm in the sample block would be visible. However, this was not the case. For this



(a) (b) (c)

Figure 12 (a) Schematic diagram of the replica of Miller's wooden void sample panel D-4 [7]. (b) Area within dotted line is Miller's original thermogram for panel D-4 containing channels and holes of diameter 1/8 inch (≈ 2.5mm) and 3/16 inch (≈ 4mm), [7]. (c) Detail of the raw thermogram obtained using ThermoScope® I for the replica D-4 block sample.

sample, the heat must travel through a body of insulating wood before the flow is interrupted by the void. As Miller found, the voids which lay directly under a layer of thin gesso rather than in the body of the wood were detected. Even though the distance from the surface for both samples was the same, the higher thermal diffusivity of the gesso compared to the wood was sufficient for heat to travel through it. Thus, visualization of these voids was possible. Thermographic examination of voids in panel paintings and in the model sample found that voids of a minimum diameter of 6 mm were only visible at a maximum depth of 2 mm [3].

Model sample testing indicated the limitation for the examination of thermally similar materials such as voids in wood fillers, wood fill in wood and chalk/gelatine fills in chalk gesso grounds. Plaster of Paris sample testing indicated that only voids with a depth half that of their diameter were detected [3]. However, previously unseen wood grain (where the preparation layer was absent and not visible with X-radiography) was revealed in a sixteenth-century oval panel (see Appendix A).

PRACTICAL LIMITATIONS OF FLASH THERMOGRAPHY FOR WORKS OF ART

Six additional works of art (Appendix A) and model samples were also briefly examined with the ThermoScope® I in order to further identify aspects of conservation that might be suited to flash thermography investigations. The significant findings from those examinations [3] are summarized as follows:

Compositional changes in canvas paintings

Red and Orange (1955) by Mark Rothko [1903–1970], in the collection of MoMA, was painted with a semi-absorbent preparatory layer and thinly painted design layers onto cotton duck canvas. The thermogram did not provide additional information about compositional changes when compared to the 1–3 μm infrared reflectogram for this painting. This is probably because of the fast cooling of the thinly applied paint layers and the lack of thermal contrast between different passages of pigment or media. This is in contrast to Motherwell's *Personage with Yellow Ochre and White*, which has a preparatory layer and thicker paint layers. In this case, the thermograms highlighted a third composition (by mapping areas with similar characteristics using the second derivative curves), other than that of the current painting, which was not identified by X-radiography.

Identification of weave

For two paintings, thermograms showed the canvas weave and, in one case, the lining canvas as well. However, it was difficult to differentiate between the weave of the original and lining canvas as the weave configurations were similar.

Voids between a canvas and its lining

The detection of voids in lining canvases was assessed by testing model samples using canvas (pre-primed with acrylic) for the primary and lining support [3]. Thermography revealed voids as small as 0.5 mm in diameter. When a 15 μm paint film (alkyd) was applied, resolution was reduced to 4 mm diameter with greater definition for the titanium white film compared to the ivory black film. This was because the titanium white was transparent to MWIR. When the paint thickness was increased to 25 μm, it was no longer possible to see any of the voids.

Superimposed delaminations

The thermogram of a glue paste-lined painting by John Ferneley Snr [1782–1860] *Dark Bay Hunter* (1825), private collection, revealed delamination of the upper paint layers, and at the same location delamination of the lining canvas. However, where delamination had occurred between multiple paint layers superimposed on top of each other, it was difficult to identify features below the paint, because the flow of heat had been interrupted by the air between the upper delaminating layers which dominated the surface temperature.

For defects in uniform, homogeneous samples, the point at which the log(T) vs. log(t) curve for a defect deviates from the log(T) vs. log(t) curve for a defect-free sample indicates the depth of that defect. However, because the paintings had heterogeneous structures, when delamination of paint occurred at different interfaces within a single examined area, it was not possible to distinguish the depth at which it was occurring.

Surface topography

Works of art which had large variations in topography, such as spherical objects, were more difficult to examine with thermography because the flash excitation was non-uniform and there was an uneven surface at which thermal contrast was detected. Where more gradual changes in topography occurred, for example warped panel paintings or smooth sculptural objects, it was possible to obtain useful results.

PARAMETERS OF THE THERMOGRAPHY TECHNIQUE

Spatial resolution

High spatial resolution was required because of the small scale of subsurface defects. The standard lens used on the NPL ThermoScope® I focused on an area of 100 × 70 mm at the minimum object-to-flash hood distance possible (with the flash hood just touching the object). With the CCD array of 320 × 256 pixels, this gave a projected pixel size on the object of approximately 0.3 mm. To identify a defect it is necessary to have at least three pixels, thus the minimum spatial resolution will be typically 1 mm. An optimum flash hood-to-object distance was found to be 150mm. For inspecting areas greater than 100 × 70 mm, a set of sequences covering the entire area was recorded and subsequently processed into a mosaic using the MOSAIQ® software. At a flash hood-to-object distance greater than 600 mm, ambient thermal noise dominated the images; while at 1500 mm, heat convection across an object dominated the image.

Surface reflection and emissivity

Highly reflective surfaces such as metallic sculptures are not amenable to flash thermography due to optical reflectivity of the metal. The light reflects off the surface and therefore very little heating occurs.[1] Consequently, it was not possible with thermography to examine the internal structure of MoMA's *The Newborn* (1920) by Constantin Brancusi [1876–1957]. The signal-to-noise ratio was further reduced by infrared radiating from the surroundings (camera, hood and computer) reflecting off the surface of the sample into the ThermoScope®.

Transparency to infrared

Transparency to infrared sometimes affects thermographic interpretation more than the emissivity of paint passages. Emissivity contributes to the y-intercept of log(T) vs. log(t) curves, but the contribution from emissivity is significantly reduced by the differentiation used in the TSR processing. Thermographic examination of materials is complicated where a specimen has an infrared-transparent top layer because the majority of heat will be absorbed, not at the uppermost surface,

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[1] *In the aerospace industry this is remedied with surface preparation such as the application of a surface coating; however, this is not a feasible option for works of art.*

but at the first surface that is not infrared transparent. Therefore, knowing the transparency of paints to infrared is required for the identification of the position of subsurface features. Data on the infrared transparency of materials is available for materials used in industry but has not been found for artists' materials in the 3–5 μm range. Thermographic images of painted-out samples of various pigments in oil, alkyd and acrylic have shown that, for example, titanium white and ultramarine oil and alkyd paints are transparent to 3–5 μm infrared radiation while chromium oxide green and ivory black absorb it [3].

The feasibility of performing thermography using a standard infrared camera working in the 3–5 μm wavelength range

The MoMA Inframetrics FLIR infrared camera was used to acquire thermograms by using a lens that transmitted in the 3–5 μm wavelength range only and halogen lamps normally used for steady-state infrared reflectography as the source of thermal excitation. It was found that thermograms obtained of the reflected surface heat were dominated by the surface emissivity. This effect masked the thermal contrast of subsurface defects regardless of the energy of the lamps.[2] Thermograms obtained from transmitted heat (halogen lamp one side and Inframetrics camera on the otherside) revealed voids when they were greater than 10 mm. Thermal features relating to the paint layer were not discernible.

The ThermoScope® I provided better detection of features for the same objects and thermal excitation set-up in reflection. This is because the transient thermal effects are fast; the frame rate of the ThermoScope® system was 60 Hz compared to the 30 Hz of the Inframetrics camera tested. It is the post-processing software which significantly improves the detection ability, by calculating first and second time derivatives of the data to obtain rates of change and normalize surface emissivity. The thermal signal reconstruction (TSR) post-processing compresses a significant amount of data which enables simultaneous viewing and analysis of multiple data sets. The successful application of thermography employing infrared cameras already used in conservation is feasible, if they are combined with fast and suitable signal-processing algorithms. The considerations which should be taken into account are:

- Synchronizing the flash with the start of the acquisition.
- A fast frame rate to capture fast transient changes. A 50 and 60 Hz frame rate is adequate.

In principle, it is possible to extract pixel values using available imaging-processing software. However, a typical acquisition of 10 seconds involves 500 frames, each with a typical pixel count of 80000. Therefore, optimized processing software is required to make this a feasible task. One of the main strengths of the ThermoScope® system is its processing efficiency, enabling the process to be completed typically within 5 to 10 seconds.

RISKS TO WORKS OF ART

The heat and light output of the flash thermography equipment was quantified to assess any potential risks to works of art. The spectral range and illuminance of the ThermoScope® I xenon flash was measured at NPL [2]. The calculated UV content of the xenon flash was found to be 139 $\mu W \cdot lm^{-1}$. This exceeds the recommended 75 $\mu W \cdot lm^{-1}$ for paintings and therefore may be cause for concern. However, the UV component could be filtered out as this part of the spectrum does not cause thermal excitation.

The illuminance of the xenon flash was measured as 276204 lux at full power, approximately 1000 times the 200 lux limit recommended for easel paintings. The 200 lux recommendation is for continuous light sources with the risk of damage assessed over long periods of time (weeks and years). The duration of the flash was 31 milliseconds, approximately equivalent to 17 seconds of exposure to a fluorescent strip lamp. (The ThermoScope® I has a flash truncation option which produces a true rectangular flash pulse with 1 millisecond duration, and minimizes the exposure of the object.)

For the examination of works of art, a reduced lamp power of 38% for canvas paintings and 13% for works on paper was found to provide the necessary subsurface information. For objects with greater volume or insulating properties, such as panel paintings and sculpture, it was found necessary to use 100% power.

Using a DT-612 k-type thermocouple, sampling at 4 Hz, a temperature increase of 3 ±0.1°C was measured at the object surface directly after the flash pulse. This reduced to ambient after a few seconds as the heat diffused through the object.

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[2] *Temperature increases of up to 8.6°C above ambient temperature were induced by the halogen lamps.*

CONCLUSIONS

Flash thermography has identified subsurface features where other NDT techniques commonly used in the conservation studio, such as X-radiography, 1–3 μm infrared reflectography and examination with ultraviolet radiation, have been unsuccessful.

The examination of case studies drawn from the Courtauld Institute of Art and Museum of Modern Art (MoMA) demonstrated the feasibility of thermography in the identification of the following subsurface features:

- the delamination of ground and paint layers on paintings;
- the delamination of lining canvases with both natural and synthetic adhesives;
- tears in canvas paintings obscured by patches, fill material and overpaint;
- watermarks within works on paper which were not visible on the surface;
- in the absence of an X-ray-absorbing preparation layer, the weave of a canvas and the wood grain of a panel;
- underlying compositions regardless of whether the underlying passages contain X-ray-absorbing pigments and the uppermost composition does not;
- mapping of the degree of adhesion during and after consolidation treatments.

The repeatability of results obtained with flash thermography was demonstrated by successful examination within individual works or art and between different works. In general a 5 second acquisition time was found to be sufficient for the examination of canvas paintings with increased acquisition periods required for works of large size.

An empirical rule of thumb for thermography is that a defect must be twice as large in diameter as it is deep to be imaged and identified. The research has shown that, because of the heterogeneity of works of art, the ability to visualize and detect defects is dependent on:

- the thermal properties of the materials and defects including the emissivity, thermal diffusivity and conductivity;
- the degree of uniformity of layers in thickness and composition;
- the transparency of pigments and media to SWIR and MWIR wavelengths (0.74–5 μm);
- the thickness of paint and ground layers;
- the optical reflectivity of a surface (0.35–0.74 μm);
- the thermal reflectivity of a surface (0.74–5 μm);
- large variations in surface topography.

Examination of works of art and model samples to determine characteristic log(T) vs. log(t) curves and peaks for particular materials and defects proved unsuccessful. Interpretation of the curves and images produced is essential where combinations of materials with different thermal properties are superimposed in a work of art. They need to be analysed with reference to the work itself to enable the correct interpretation and identification of a feature. In the conservation studio there is very limited capability for the non-destructive imaging and identification of subsurface features that relate to the condition of a painting. Thermography offers the conservator a NDT tool which will aid in the identification of these features.

APPENDIX A: WORKS OF ART EXAMINED WITH THE THERMOSCOPE® AND INFRAMETRICS CAMERAS

Constantin Brancusi [1876–1957] *The Newborn*, version I, 1920 (close to the marble of 1915). Bronze, (14.6 × 21 × 14.6 cm), Lillie P. Bliss bequest, MoMA.

Mark Rothko [1903–1970] *Red and Orange*, 1955. Oil on canvas, 1755 × 1415× 40 mm, Mary Sisler bequest, MoMA.

Albert Gleizes [1881–1953] *Portrait of Igor Stravinsky*, 1914. Oil on canvas, 129.5 × 114.3 cm, bequest of Richard S. Zeisler, MoMA.

Jim Dine [born 1935] *Five Colourful Feet of Tools*, 1962. Oil on canvas surmounted by a board on which painted tools hang from hooks, 141.2 × 152.9 × 11 cm, Sidney and Harriet Janis collection, MoMA.

Robert Watts [1923–1988] *Chrome Cabbage*, 1964. Chrome plate over plastic cabbage, 13.3 × 18 × 17.2 cm, base 6.2 × 20.7 × 20.7 cm, Patricia Phelps de Cisneros, Emily Rauh Pulitzer and Richard S. Zeisler funds. MoMA.

Robert Motherwell [1915–1991] *Personage with Yellow Ochre and White*, 1947. Oil on canvas, 182.8 × 137 cm, gift of Mr and Mrs Samuel M. Kootz, MoMA.

John Ferneley Snr [1782–1860] *Dark Bay Hunter*, 1825. Oil on canvas, private collection.

Unknown artist, *Portrait of a Young Man*, sixteenth century. Oil on panel, private collection.

Robert Walker [1599–1658] *Portrait of Oliver Cromwell*, c. 1650. Oil on canvas, private collection.

Gerino d'Antonio Gerini [1480–1529] *Virgin and Child Enthroned with Saint Lawrence, Saint John the Baptist, Saint Monica and Saint Augustine*, early sixteenth century, Courtauld Collection.

APPENDIX B: THERMOGRAPHIC SIGNAL RECONSTRUCTION (TSR)

The log(T) vs. log(t) relationship of the surface temperature response to flash heating is a useful indicator of the subsurface state of a sample. For an infinitely thick solid, the logarithmic T–t response is a descending straight line with slope −0.5, indicating unperturbed cooling of the surface by one-dimensional thermal diffusion into the bulk of the solid. An internal interface or change in thermophysical properties will affect the diffusion process, result in a deviation from the straight-line behaviour of the logarithmic T–t plot (Figure 13a). For example, an insulating back wall interface which does not allow heat to pass will terminate the diffusion process, and the result will be a flat (slope = 0) line. In this flat regime, any further cooling of the surface will be the result of convection, radiation or lateral diffusion, which depend on environmental variables, and the surface condition and geometry of the sample, rather than the subsurface state of the sample. The useful information for subsurface evaluation resides in the transition between ideal and interrupted diffusion.

The thermographic signal reconstruction (TSR) method is an effective method for identifying pixels that deviate from linearity and for characterizing them by virtue of their inflection points and maxima.

The first derivative [log(T) vs. log(t)] curve, Figure 13b, shows the initial phase of cooling to be a horizontal line with value −0.5, then a transition to a horizontal line of value 0 in the final phase. The second derivative [log(T) vs. log(t)], Figure 13c, deviates from 0 only where there is a perturbation in the diffusion process, in this case the back wall of the sample.

All references to input energy and secondary cooling processes are eliminated by differentiation and therefore deviations from 0 can be said to indicate defects. These curves are for model homogeneous samples with thermally isolated back walls. The materials of works of art are far from uniform in dimension or composition and, as such, variations from the predicted cooling of uniform defect-free samples used in industry to identify defects does not always apply. The raw (R) [log(T) vs. log(t)] curves provide a helpful indication of the cooling of areas, enabling qualitative interpretation of a defect that does not rely on the subjectivity of the operator in recognizing contrast differences. However, the first derivative and second derivative [log(T) vs. log(t)] graphs can be misleading in highlighting thermal differences. In some cases the first derivative [log(T) vs. log(t)] curves highlight the inflection points of the raw

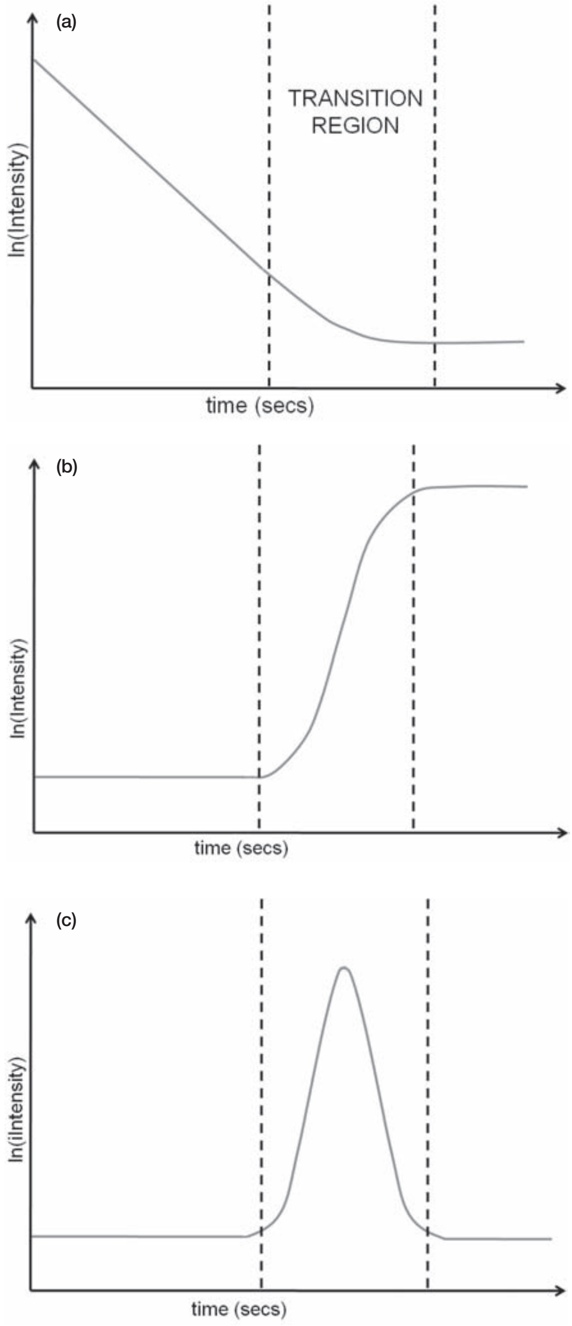

Figure 13 *(a) Raw logarithmic temperature time history of a thermally isolated, uniform defect-free sample. (b) First derivative raw logarithmic temperature time history of a thermally isolated, uniform defect-free sample. (c) Second derivative logarithmic temperature time history of a thermally isolated, uniform defect-free sample.*

[log(T) vs. log(t)] curves and can help to make the defect prominent. The second derivative [log(T) vs. log(t)] graph can be the most useful in differentiating defects if differences in cooling are very clear. However, the second derivative [log(T) vs. log(t)] curve peak, as an indication of defect and defect depth, does not apply to heterogeneous works of art.

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Résumé *— Cette étude explore la faisabilité de thermographie par flash pour l'examen et la conservation des oeuvres d'art : peintures, documents graphiques, et sculptures. La thermographie est une technique non destructive pour l'identification des défauts sous la surface dans les matériaux. La différence de propagation entre les zones défectueuses et celles sans défaut provoque une différence de la température de surface du matériau. La température de surface est cartographiée en permanence par une caméra numérique fonctionnant dans l'infrarouge moyen. Une lampe à arc au xénon fournit la source initiale de radiation, et un traitement du signal est appliqué de façon à collecter les données pour réduire le bruit de fond et améliorer les signaux clés caractéristiques du signal. Cette technique offre la possibilité d'investigation de la structure des peintures et du papier, notamment dans les cas où les autres méthodes d'examen non destructives ne fournissent pas d'information suffisante, par exemple le clivage de sub-surface et la structure en couches. Les résultats montrent que la thermographie constitue une bonne technique pour la détection du clivage des couches picturales et le degré d'adhésion entre les couches, particulièrement dans les peintures sur toile. Elle permet aussi de détecter avec succès la fibre du bois dans des situations où les rayons X ont échoué, mais la thermographie n'est pas adaptée pour détecter des vides ou des défauts dans le bois.*

Zusammenfassung *— In dieser Studie wird die Anwendbarkeit von Flash Thermographie bei der Untersuchung von Kunstwerken untersucht: Gemälde, Arbeiten auf Papier, und Skulptur. Thermographie ist eine zerstörungsfreie Technik zur Identifiziereung von unter der Oberfläche liegenden Materialdefekten. Sie basiert auf der Ausbreitung von in der Oberfläche aufgenommener Wärme in das Material. Unterschiede in der Ausbreitungen in Bereichen mit und ohne Defekt führen zu Unterschieden in der Oberflächentemperatur des Materials. Die Oberflächentemperatur wird ortsaufgelöst mit einer im Mittleren Infrarotbereich arbeitenden Digitalkamera aufgezeichnet. Eine Xenon Bogenlampe dient als anfängliche Strahlenquelle. Die gesammelten Daten werden so verarbeitet, dass das charakteristische Signal verstärkt und der Hintergrund reduziert ist. Die Technik eröffnet die Möglichkeit, Papier und Gemälde strukturell zu untersuchen, insbesondere dort, wo andere zerstörungsfreie Techniken nicht genügend Information liefern, beispielsweise bei Delaminierungen der Oberfläche. Die Studie zeigt, dass Thermographie eine gute Methode zur Detektion von Delaminierungen von Malschichten und den Grad der Haftung zwischen den Schichten bei Leinwandgemälden ist. Darüber hinaus konnte erfolgreich die Holzstruktur untersucht werden, auch dort, wo normale Röntgentechniken versagten. Allerdings war die Methode bei der Untersuchung von Fehlstellen oder Defekten in Holz nicht nutzbar.*

Resumen *— Esta investigación trata sobre la viabilidad de la utilización de la termografía por flash para el examen y conservación de obras de arte: pinturas, obras sobre papel y escultura. La termografía es una técnica no-destructiva para la identificación de defectos superficiales en los materiales. Se basa en la propagación de calor aplicado a la superficie adentro del propio material. Las diferencias en propagación entre áreas con defectos y áreas libres defectos resultan en una diferencia en la temperatura superficial del material en cuestión. Se obtienen unos mapas de distribución de las temperaturas en función del tiempo en forma de imágenes, tomadas con una cámara que opera en la región media del infrarrojo. Una lámpara de arco de xenón se utiliza como fuente inicial de la radiación, y el procesado de la señal es típicamente aplicado a los datos recolectados con el fin de reducir el ruido y amplificar las características de la señal clave. Esta técnica ofrece la posibilidad de estudiar la estructura de los cuadros y del papel, especialmente en casos en los que otras técnicas no destructivas no aportan suficiente información, por ejemplo en casos de descohesión bajo la superficie y la estructura de las capas. Los resultados indican que la termografía es una buena técnica para detectar la separación entre estratos y para valorar su grado de cohesión, especialmente en pinturas sobre lienzo. También detecta bien la veta de maderas cuando los rayos X no lo consiguen, sin embargo no es efectiva para localizar defectos o huecos en la madera.*