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Quantifying and Mapping Induced Strain in Canvas Paintings Using Laser Shearography

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ABSTRACT. Evaluation of museums’ condition standards used for the exhibition of canvas paintings requires a quantitative technique capable of measuring strain induced by changes in temperature, relative humidity, and the thermomechanical effects of light, as well as the effects of ambient vibration. This paper presents advances in developing a customized shearography system for temporal characterization of strains that occur on canvas paintings when subjected to changes in exhibition conditions. The shearography system performs measurements of displacement derivatives along two orthogonal shearing directions and is synchronized with an IR camera to provide thermal maps of the area analyzed. Innovations incorporated into the system include a real-time temporal phase unwrapping algorithm, high-resolution fast Fourier transform methods to calibrate applied shearing levels, and algorithms to produce maps correlated to the temporal domain that locate strain vectors as they occur on the surface analyzed. This research also includes methods for isolating thermal-induced components from randomly induced mechanical vibrations through integration of IR imaging data. As a verification and exploration of the fault detection capabilities of our shearographic system, we have performed preliminary experiments that compare measured gradients of displacement with slopes of surface topology obtained by reflectance transformation imaging (RTI). Preliminary analysis indicates good correspondence between spatial patterns, indicative of surface cracks, in both shearographic and RTI data. The capability of the system to detect discontinuities in paint surfaces as well as to measure and map associated strain vectors as a function of changes in condition parameters is herein illustrated. Our multidomain approach, incorporating strain, thermal, and topographical data, has the potential to inform larger ongoing discussions regarding conservation standards for the exhibition of artwork as well as improving defect detection and evaluation of restoration techniques.

INTRODUCTION

Shearography is a full-field, nondestructive, noncontact, optical method that uses coherent light to conduct strain and vibration analysis (Hung, 1982). The method is highly sensitive for measuring load-induced surface displacement gradients and can effectively detect surface and subsurface discontinuities (Schnars and Jüptner, 1994; Steinchen and Yang, 2003; Lee et al., 2014). Although similar to holographic interferometry, shearography differs in that instead of measuring displacement, it measures gradients of displacement.

One of the primary advantages of shearography over holography is its relative insensitivity to environmental disturbances. Other advantages include range, mobility, versatility, ease, speed, and relative low cost. For these reasons, applications of shearography continue to grow, particularly as a method for defect detection in the aerospace, automotive, and
wind power industries, where the performance of coatings and laminated surface construction is critical.

As a highly sensitive technique for measuring gradients of displacement, shearography also has great potential for applications in art conservation (Groves et al., 2009a, 2009b; Sfarra et al., 2011; Meybodi et al., 2012; Morawitz et al., 2013). In recent years, the majority of shearography-based research into art conservation applications has taken place in Europe, with the Institute for Technical Optics at Stuttgart University and the Foundation for Research and Technology–Hellas (FORTH) in Crete, Greece, each being research hotbeds. Most of the research has focused on detecting delamination or structural flaws in panel or wall paintings (Kalms and Jueptner, 2005; Morawitz et al., 2013). Tornari and her group at the Institute of Electronic Structure and Laser–FORTH spearheaded the development of a hybrid portable interferometry-shearography system entitled “MultiEncode: Multifunctional Encoding System for Assessment of Movable Cultural Heritage,” in which a shearography-based system was developed to monitor the condition of paintings before and after transport (Groves et al., 2007; Tornari et al., 2009). This project also led to the development of a fringe database for using fringe patterns unique to each work as a method of authentication. Previous work (Georges et al., 2014) incorporating thermography, holography, and shearography has also indicated a multidomain approach to fault detection in complex multimaterial, multilayered objects with structural and mechanical complexity similar to that of paintings.

**PRINCIPLES AND METHODS**

The shearographic system allows for quantitative evaluation of deformations of an object and, more specifically, the spatial derivative, or slope, of the deformations. In general, the shearographic system allows for comparison between two or more distinct states of the object of interest, typically before and after application of a controlled excitation (Hung, 1982). The deformation of the object induces optical light path changes that lead to optical light phase changes in the optical setup of the shearographic system. Each state of the optical phase and intensity in the optical system, encoded within a shearographic interferogram, is recorded via a digital camera. By analyzing and comparing the phase differences between the interferograms, corresponding to each state of the object, the spatial gradient of the object’s deformation can be quantified.

**Optical Setup**

Our shearographic setup, shown in Figure 1, is based on a Michelson interferometer and works by capturing laser light reflected from the optically rough (Hung, 1982) surface of an object, which is illuminated with an expanded laser beam. Some of the reflected laser light passes through a lens into the shearographic interferometer, where it is split into two identical beams and is later recombined at the camera sensor with a slight spatial offset (optical shear) between the two beams (Huang, 1997),
as shown in Figure 1. The interference between the two beams, forming the original and the sheared image, gives rise to an interferogram, which consists of spatially varying intensity and phase patterns, also known as fringes.

**Measurements of Displacement Gradient through Optical Phase**

The specific interference pattern at each moment in time is a result of multiple parameters, including the geometrical and optical characteristics of the environment and surfaces that the laser light passed through or reflected from, which means that the interference pattern is also dependent on the geometry of the object of interest. Any deformations in the object, as long as they alter the laser light path, will induce a corresponding change in the optical phase of the interference pattern at the camera sensor. On the basis of the optical configuration of our shearographic system, assuming the illumination and observation (z axis in Figure 1) directions are coaxial, the optical phase change $\Delta \Omega$ is related to the spatial gradient of displacement of the object $\vec{\nabla}$ along the observation direction of the system (Hung, 1982):

$$\Delta \Omega = \frac{4\pi \delta w}{\lambda} \Delta s,$$  \hspace{1cm} (1)

where $\lambda$ is the optical wavelength, $s$ and $\Delta$ are the direction and magnitude of the applied optical shear respectively, and $w$ is the displacement of the object along the observation direction. Assuming that the observation direction of the shearographic system and the surface normal of the object (assuming an approximately flat object) are aligned, $\vec{\nabla}$ becomes proportional to the spatial derivative of the out-of-plane displacement of the object. Our shearographic optical setup allows for optical shear in vertical ($x$ axis) and horizontal ($y$ axis) directions as well as any combination of the two. This allows for individually extracting $\frac{\partial w}{\partial x}$ and $\frac{\partial w}{\partial y}$, corresponding to the vertical and horizontal spatial derivatives of the out-of-plane displacement of the object.

These displacement gradients partially define the full strain tensor $S$, which is composed of nine components, six shear strain and three tensile strain components located along the diagonal of the tensor, as described in the following equations (Chen, 2014):

$$S = \begin{bmatrix}
\frac{\partial u}{\partial x} & 1/2 \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) & 1/2 \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \\
1/2 \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) & \frac{\partial v}{\partial y} & 1/2 \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right) \\
1/2 \left( \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right) & 1/2 \left( \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) & \frac{\partial w}{\partial z}
\end{bmatrix},$$  \hspace{1cm} (2)

Shearing in $X$ and $Y$ individually:

$$\frac{\delta w}{\delta x} = \frac{\lambda \Delta \Omega}{4\pi \Delta x},$$  \hspace{1cm} (3a)

$$\frac{\delta w}{\delta y} = \frac{\lambda \Delta \Omega}{4\pi \Delta y}.$$  \hspace{1cm} (3b)

**Measurements of Optical Phase Changes**

Most camera sensors, including the one that is used in this setup (Pike-100B with KAI-1020 CCD sensor, AVT, Stadtroda, Germany), are sensitive only to the intensity, and not the phase, of the light. As a result, several methods have been developed for the retrieval of the light phase, and popular methods include fringe skeletonization (Osten et al., 1994), phase stepping (Creath, 1985), and Fourier transform–based methods (Takeda et al., 1982; Ge et al., 2001). Our shearographic system uses a custom-made automated phase sampling technique (Harrington et al., 2010, 2011), which is based on a four-step temporal phase sampling method (Creath, 1985). The four-phase-stepping approach is implemented on the basis of the need for developing a high-resolution, quantitative, and real-time measuring system. The method allows for quantification of the phase distribution of an interferogram by recording its intensity four times (at four camera frames), each with an incremental phase shift of 90° from the previous one. Each controlled phase step is achieved by a custom-made phase stepper (shown in Figure 1), the details of which are given later in this work. One set of four phase-stepped frames is related to the phase change, which is defined as follows (Chen, 2014):

$$\Delta \Omega(x,y) = \Omega(x,y) - \Omega(x,y)$$

$$= \tan^{-1} \left[ \frac{(I_4 - I_3)(I_2 - I_1) - (I_4 - I_1)(I_2 - I_3)}{(I_4 - I_3)(I_2 - I_1) + (I_4 - I_1)(I_2 - I_3)} \right],$$  \hspace{1cm} (4)

where $I_{1,2,3,4}$ are the four phase-stepped shearograms in the reference state and $I'_{1,2,3,4}$ are the corresponding data in the deformed state. It can be seen that the phase change is calculated on the basis of only intensity information. In essence, four images are collected at the reference state, and four images are collected in the deformed state, and then this equation is calculated for every pixel at every time instance relative to another reference time instance. In the case of continuous measurements with thousands of data frames (each containing four images), the reference and deformed data frames may be defined arbitrarily by the user in order to compare the differences in the optical phase between two data frames, which, in turn, corresponds to the gradient of displacements that occurs between the two instants.

This optical phase sampling method assumes that during the capturing of the required four interferograms at each deformation state, the object and the surrounding environment are steady and do not induce a significant phase change on their own. The adequacy of this assumption has been verified through pilot tests in the museum environment based on the test setup described later in this chapter, as well as based on the literature (Kalms and Jueptner, 2005; Morawitz et al., 2013). This optical phase sampling method was chosen because of its superior spatial resolution, allowing for a quantification of the phase sampling at each pixel individually. The specific choice of the number of phase shifts and phase step size was defined on the basis of pilot studies of shearographic measurements on oil-on-canvas paintings in our laboratory settings.
(Chen et al., 2014; Khaleghi et al., 2014) as well as literature (Kalms and Jueptner, 2005; Morawitz et al., 2013). Further work might be needed to find an optimal phase sampling technique and corresponding acquisition parameters; however, the ones used in this work were deemed sufficient for our preliminary work.

**Temporal Unwrapping of Optical Phase Changes**

Because of the use of the arctangent function in equation (4) to calculate phase differences, the resulting phase data “wraps” within a range of –π to π radians, which causes spatial discontinuities in the spatial distribution of the measured phase across the recorded image. This wrapping of data is particularly challenging when measuring displacements that occur over an extended period, and as the displacement gradient increases, repeated wrapping occurs, and the resulting image becomes increasingly difficult to interpret. It is therefore necessary to de-modulate or “unwrap” the data.

Existing spatial phase unwrapping algorithms have limited capabilities in the analysis of interferometric images of objects undergoing physical deformations that result in a large number of phase discontinuities (>50 cycles of phase across the field of view). The temporal phase unwrapping algorithms developed in this research and on the basis of existing methods (Huntley and Saldner, 1993) overcome this limitation. The basic idea behind the method is that the phase change at each pixel is measured as a function of time and is unwrapped along the temporal dimension independently of the neighboring pixels (Dobrev et al., 2012; Kreis, 2005). The temporal unwrapping method (Chen, 2014) relies on the assumption that the phase change between any two consecutive frames is between –π and +π. This is an adequate assumption for this application because although the object may be undergoing large deformations, the temporal rate of the deformations is relatively slow. Typical significant changes for the range of our shearographic system and setup take >1 s to develop under typical testing conditions in museum settings, whereas the camera recording is done at 60 frames/s, resulting in <70 ms to capture a set of four images. The effects of random noise, which might contribute to significant phase variations between frames, has been suppressed with the use of spatial averaging filters with a size (i.e., 3 x 3 pixels) adjusted on the basis of the smallest features (i.e., <1 mm) that were considered to be important for this research. Although surface cracks could be much smaller, we assumed that their effect on the local deformation patterns will be sufficiently large in space to be detected by the shearographic system. Additionally, because of the inherited scalability of the optical system, analyzing a smaller region with a greater level of spatial detail and sensitivity is just a matter of adjusting the zoom lens or the shear, without any change in the overall analysis procedure.

**Calibration of the Measurement Sensitivity**

An important point to make from equation (1) is that the sensitivity of the system is highly affected by the amount of shear. Therefore, it is important to quantify the shear amount in order to convert the phase data from radians to appropriate engineering units.

This research implements a method based on the shift theorem of the Fourier transform that allows for the direct estimation of the shear amount without any pre- or postcalibration procedures (Figure 2). The technique is based on existing computer vision methods used to estimate camera motion during television broadcast (Bracewell et al., 1993; Licsár et al., 2003). The idea behind this method is that the 2D fast Fourier transform (FFT) of the superposition of an image and its sheared twin (i.e., the case of shearograms) will result in a 2D power spectrum, the magnitude of which is sinusoidally modulated with a period inversely proportional to the shear amount (Khaleghi et al., 2014). Typically, the images are captured individually and superimposed digitally, although in the case of shearograms, the two images are superimposed optically and are captured simultaneously, but this does not change the general principle of the method. For

![Figure 2](image-url)

**FIGURE 2.** Illustration of the mathematical principle behind the automatic shear estimation algorithm. A power spectrum of the 2D FFT of a shearogram: (a) with no shear, (b) with shear in the horizontal (x) direction, and (c) with shear in the horizontal (y) direction. The corresponding modulation period is indicated (Chen, 2014).
example, for a horizontal shear (i.e., along the x direction), the relation between the period $T_x$ of the modulation in the 2D FFT power spectrum (Figure 2b) and the shear amount $x_0$ can be expressed as (Chen, 2014)

$$x_0 \approx \Delta x \frac{N}{T_x}$$

where $\Delta x$ and $N$ are the pixel size and number of pixels in the shear direction, respectively. By automatically extracting the period of the modulation in the FFT of the shearogram, we get the shear amount in the system. A novelty of our work (Khalegi et al., 2014; Dobrev et al., 2012; Chen, 2014) is in the development of automatic software for shear estimation and its application for shearography analysis. This tool greatly simplifies and accelerates the measurement procedures, as it does not require any calibration after each adjustment of the shearographic system, thus allowing for rapid optimization of the recording parameters relative to the response of each new sample or loading procedure.

**TEST SETUP**

Initial tests in this research used shearography to see if a thermomechanical response could be detected on the surface of an oil painting as a result of simply turning on and off lights such as those used in a typical photography session. The setup mimicked the same configuration used at the time by the museum conservators for photographing works, the only difference being that the camera was replaced with the shearography instrument and workstation (Figure 3).

The shearography instrument constructed at Worcester Polytechnic Institute (WPI) is a mobile system that utilizes an adjustable tripod, a computer workstation, and an uninterrupted power supply (UPS) to power the system between relocations. In this case, the coherent light source is a 473-nm laser (50 mW, Diode-pumped solid-state [DPSS], Oxxius, Lannion, France), and the measuring head consists of a custom-built interferometer, a camera lens (zoom lens, 12.5–75 mm, model 53-153, Edmund Optics, Barrington, New Jersey, USA, and a camera (Pike F100B, AVT) interfaced directly to the computer workstation (Figure 3). The measuring head has an approximate size of 25 × 25 × 25 cm, excluding the lens and the IR camera, which can be easily removed or changed in accordance with the needs of each experiment. The size of the shearographic optical head, excluding the lens, laser, and IR camera, is 25 × 7 × 7 cm. The laser was mounted directly next to the lens, aligned approximately (i.e., <2° deviation) parallel to its optical axis. The laser beam, with a diameter of <0.3 mm, was expanded to a circular spot with a diameter of ~40 cm. The camera consists of a Truesense KAI-1020 CCD sensor, which has a resolution of 1,000 × 1,000 pixels at

![FIGURE 3. Schematic of the shearography setup during initial tests.](image-url)
7.4-μm pixel pitch. The camera exposure time was 10 ms, with a frame rate of 60 frames/s. Phase shifting was achieved through a custom-made phase stepper based on a customized piezoelectric transducer (PZT; PAS005, Thorlabs, Newton, New Jersey, USA), driven by an analog output card (DAQ, NI USB-6343, National Instruments, Austin, Texas, USA) via a piezo controller (MDT694B, Thorlabs). All of the above components were combined into a compact optical head, shown in Figure 3.

Connectivity in the instrument includes firewire B from camera to laptop, USB 2.0 from DAQ to laptop, and Bayonet Neill-Concelman (BNC) cables from DAQ to PZT amplifier and camera (the camera triggers the DAQ, which then steps the PZT). The instrument is also equipped with an IR camera (FLIR A310) connected via GigE to the laptop in order to correlate thermal data with the shearography data. Excluding the IR camera, the instrument costs a few thousand dollars, the most expensive component being the camera. The control software was custom written at WPI (Harrington et al., 2011) and allows for the automatic continuous synchronization between camera frames and phase stepping, full control of all system settings (exposure, frame rate, recording speed, etc.), and storage of data and live display of the current phase map referenced to any desired frame.

A 473-nm, 50-mW laser was used essentially because it was the least powerful of the lasers available in the lab at the time in order to minimize the thermal excitation of the painting while providing sufficient illumination of the area of interest to allow shorter camera exposure times and higher recording speeds. The laser's coherence length is >10 m; however, a long-coherence laser is not necessary, and previous research (Falldorf et al., 2003) has shown the possible use of a white light source with limited coherence length (i.e., temporal coherence of <50 μm). One of the main constraints for use of a short-coherence light source is the maximum observable gradient of the object's surface, which is dependent on the applied shear and the direction of illumination (Falldorf et al., 2003). Tests with laser diodes from pointers, with a coherence length of <0.5 mm and a cost of <$10, indicate that sufficient amounts of shear can be achieved for quantitative analysis of flat objects (Chen, 2014), similar to pictures. Although this assumption may not hold at the steep walls of cracks on the paint surface, we assume that the cracks will influence the deformation of flat areas in their proximity, which in turn will be sufficient to estimate the location of the cracks within the spatial resolution of the system (i.e., <0.5 mm).

The initial setup (Kaleghi, et al. 2014) (Figure 4) positioned the system 1.8 m from the painting analyzed, allowing for the full field of view (FOV) range available with the objective lens. However, because of power limitations of the laser, the FOV was kept to 0.35 m, leaving the spatial resolution of the measurements to be 0.15 mm/pixel. The loading source in these initial tests was two Lowel Tota-lights with 500-W halogen bulbs, each equipped with a diffusing umbrella and positioned at 45° angles 2.3 m from the painting. The spectrum of the lights covers nearly the full visible range, including the laser's 473 nm, as well as a sufficient amount of infrared radiation for thermal excitation of the sample. The initial testing consisted of a 60-s loading period with the lights on, then a 60-s recording time immediately after turning the lights off (unloading period), which resulted in a 0.7°C increase in surface temperature of the painting in the loading cycle. Because of the high power of the lights compared to the laser, the shearographic system's camera saturated during the loading cycle. As a result, only the unloading period (lights off) was shearographically recorded.

The painting used throughout this research was an unlined, late nineteenth-century oil on canvas that is privately owned. The paint surface exhibits a network of craquelure and, to a lesser extent, drying cracks throughout, a few scattered paint losses, and a small puncture. The paint thickness varies from thin to areas with moderate impasto.

Previous work combining shearography and thermography has indicated the potential advantages of IR cameras in

FIGURE 4. The CAD model of the instrument (left) and the realized instrument (right). (Chen, 2014; Chen et al., 2014)
shearographic inspection (Georges et al., 2014). The integrated IR camera enabled researchers to map the surface temperature of the painting throughout the process. The temperatures across the full surface of the painting, the frame, and the background wall were recorded. The temperature uniformity across the paint surface was within 0.2°C, and the average temperature change was within 0.3°C–0.6°C, with smaller changes at the periphery and larger changes at the center of the picture. The spatially varying temperature changes can be explained by better heat dissipation at the edge of the painting surface because of its proximity to the frame and stretcher structure. A 6-min equilibration period took place in between loading-unloading cycles, enabling researchers to start from the same temperature during each run.

CONTROLLED TEMPERATURE EXCITATION TESTING

Since the shearography system allows for recording with one shear direction at a time, at least two recordings are needed to capture the X (horizontal) and Y (vertical) components of the spatial gradient of the out-of-plane deformation individually. We verified the reliability of such a method by performing at least three measurements, each following the procedure described in the previous section, in each shear direction, which indicated a standard deviation of <5% of the maximum detected slope of deformation. The X and Y data sets were then combined to create a cumulative gradient of displacement map with a magnitude converted into microstrains, the unit preferred for representing such data (bottom row in Figure 5). The reference for all measurements, at each thermal cycle, was the first measurement (four phase-stepped frames) immediately after turning off the lights. Data in the bottom panels in Figure 5 refer to an example measurement made 10 s after turning off the lights. The data appear to indicate displacements that correspond to a dense crack network. Note the relatively large displacement gradients along the top and right margins roughly corresponding to the underlying stretcher bar support.

The 10-s time mark, indicated in Figure 5, roughly corresponds to the maximum spatial density of contours (fringes) of the wrapped phase (Figure 5, top middle panel) that could be still unwrapped via conventional spatial phase unwrappers (Ghiglia

FIGURE 5. Analysis of an oil painting on canvas showing the transient response to thermal loading. An image of the upper right quadrant of the painting that was analyzed (top left) and the corresponding maps of wrapped and unwrapped optical phase measurements taken during a 10-s period of cooling immediately after turning the lights off (top middle and right). Color-coded gradient of displacement maps in the X and Y shear directions (bottom left and middle, respectively) and the absolute value of the combined gradients of displacement of both X and Y data sets with the scale in microstrains (bottom right). Painting analyzed: Untitled, oil on canvas, unknown artist, private collection.
and Pritt, 1998). However, since the response of the painting reached a relatively stable state only after 1 min, recordings were done for 60 s, at which point the spatial density of the wrapped phase contours becomes too high. Thus, only the temporal phase unwrapping algorithm was used for all recordings in this paper. The first 10 s have been presented as an illustration of the analysis approach, and a detailed analysis of the full 60-s cooling cycle will be included in a future work.

Temporal variations of the derived gradients of displacement can be viewed relative to each other in Figure 6. The ability to correlate strain to the temporal domain can be used not only to chart thermomechanical response but also to inform our understanding of equilibration properties of the object analyzed (Figure 6). This could be achieved by combining the full-field displacement gradient measurements with the full-field temperature data from the IR camera in order to obtain intrinsic material properties such as local heat coefficients and thermal time constants, which can be used to optimize the preservation conditions for each picture individually.

In order to provide more detailed information for the deformation pattern and cracks, we combined the magnitude and direction information of the combined data for both the X and Y deformation gradients into a single display, as shown in Figure 7 (right), where corresponding color-coded arrows indicate the direction and magnitude of deformation gradients. It should be noted that although the vectors are expressed in plane, since they show the spatial direction of the highest slope of deformation, the deformations and the corresponding strains are occurring out of plane. Superposition of the resultant strain map on a ghost image of the area analyzed can help correlate gradients of displacement information with features present on the paint surface or under it.

### IN SITU GALLERY TESTS

Following the tests that mimicked the Worcester Art Museum’s lab photography setup, investigations shifted into the Worcester Art Museum galleries. On a two-day span in July, when the museum was closed to the public, a small painting on exhibit was replaced with the test painting, and the shearography instrumentation was set up in the gallery to monitor changes that occur over the course of a typical day-night cycle. In this case, the light loading was provided by broad washes of light from a pair of ceiling-mounted 50-W halogen bulbs 4 m away. For comparison, the same region of the test painting was analyzed. The combination of lower-power lights and the larger distance from the painting resulted in greatly reduced negative effects of the museum lighting to the shearographic system, such as local saturation and reduced fringe contrast, and allowed continuous operation regardless of the state of the lights. Preliminary noise floors tests of the shearography system under such conditions indicated $-\lambda/15$ phase variation, equivalent to $-8 \mu\varepsilon$.

**FIGURE 6.** Gradient of displacement maps over a 10-s period of cooling when shear is in the Y direction (top row) and in the X direction (middle) and the resultant gradient of displacement maps when both shear directions are combined (bottom).
Setting appropriate acquisition parameters was a critical step, particularly regarding frame rate in order not to overwhelm the computer’s memory capacity and the analyst’s capacity to process the data. Data were taken in a time-lapse manner by making one measurement, consisting of four phase-stepped frames taken in a burst at 60 frames/s, every 10 s for a total duration of 27 hours, resulting in ~10,000 measurements (i.e., ~100 GB).

Temperature and relative humidity (%RH) data for the gallery were recorded internally in the museum’s HVAC system throughout the course of the investigation and varied from 46.8% to 49.8% RH and from 23.1°C to 24.4°C. The recorded temperature and %RH timeline was also used to plot significant events, such as the beginning and ending of shearography analysis and when the lights were turned on or off (Figure 8, top). Shearography data were later analyzed to see if correlations exist between changes in gallery conditions and strain responses in the paint surface.

The amount of data acquired with the shearography instrument is substantial and presents a challenge for postprocessing. Ongoing work with processing software seeks to assist with this process. Efforts thus far have focused on examining data for correlations between detectable strain and changes in gallery lighting. Data revealed that even in the tightly controlled climate of the gallery, the paint surface underwent a detectable thermomechanical response when the lights were turned on or off (Figure 8, bottom row).

The maps in Figure 8 show that the greatest (i.e., 100–120 με range) strain incurred shortly after turning on the lights is along the edge of the canvas, whereas the center appears relatively stable. The reverse is true when turning off the lights. The low (i.e., 20 με) level of strain detectable (noise floor is <10 με) during the stable state, represented here by Figure 8a, is likely related to ambient vibration. As the analysis progressed, it became increasingly apparent that the sensitivity of the shearography instrument enables clear correlations to be drawn between exhibition conditions and physical changes in the painting.

Future work on this experiment will involve application of the temporal unwrapping software in a memory efficient way on the full data set. Once this is complete, the next step could be the comparison between the full shearographic data and the climate control parameters in order to analyze the response of the picture. Such a comparison could help us devise a scheme for the optimization of the climate control parameters to minimize strain fatigue on the painting while minimizing energy consumption.

### CORRELATING SHEAROGRAPHY DATA TO TOPOGRAPHICAL FEATURES

The final component of this investigation explored how to improve capabilities for correlating shearography data with existing topographical features on the surface of paintings. This general problem is noted in the literature and was encountered firsthand when trying to relate shearography data to the network of cracks evident on the test painting. The images shown in Figure 8 of gradients of displacement and strain vector maps illustrate how processed shearography data can be overlaid with conventional camera images of the corresponding area. However, because of the lack of quantitative information about the topological features captured in conventional camera images, the encoded color information about the paintings surface may not be representative of the painting’s surface topology and underlying...
structure. The discrepancy between color information and surface topography makes a direct comparison with shearographic data more difficult to interpret.

In order to facilitate comparison with a greater level of detail, we utilized the visually rich surface imaging technique of reflectance transformation imaging (RTI), and we explored it as a possible complement to shearography data. Because of limitations with the FOV of the available RTI system (lighting array designed by the Cultural Heritage Imaging Corp., San Francisco, California, USA), only about 50% of the area, as shown in the previous two experiments, was available for comparison with the shearographic system. For direct side-by-side comparison with the gradient of displacement maps, the specular enhancement viewing function available in RTI viewing software (RTIViewer V1.1, Cultural Heritage Imaging Corp.) was initially considered, as it enhances the visible details of the topography of the paint surface (Figure 9, middle). However, in order to remove any subjectivity in relating gradients of displacement to physical features on the painting, other approaches were considered. The improved functionality of the most recent RTI viewing software allows one to generate per-pixel surface normal data, which quantifies the in-plane and out-of-plane slope of the shape of the painted surface. The surface normal is related to the slope of the surface shape and therefore can be interpreted as a collection of two pieces of information: the magnitude and the direction of the slope of the local shape. A slope with larger magnitude indicates steeper surface features such as those at the crack boundaries and walls. For this reason, magnitude information was extracted from the surface normal data and further color coded such that deep blue or red indicates high positive or negative slope and green indicates no or very little slope of the surface topography (Figure 9, right).

Our main hypothesis behind such an approach is that surface cracks, detectable through the RTI surface normal data, will...
produce a significant strain pattern in their close vicinity, which will be detectable with our shearography system. On the other hand, cracks close to the surface, but without visual indication via the RTI system, will also produce a significant strain pattern in their vicinity, which would affect the surface strain pattern and in turn would also be detectable by the shearographic system.

The first part of this hypothesis is supported by an example of details shown in Figure 10, where there is a clear correspondence between the strong gradient of displacement present and the presence of a high spatial slope indicative of a crack. On the other hand, the second part of our hypothesis is supported by other details analyzed, which showed areas with little to no correlation between shear and RTI data, possibly because of the presence of subsurface discontinuities that are not related to surface topographical features. To our knowledge, this may well be the most exacting correlation between displacement gradients and surface topography. Ultimately, the aim is to combine future work involving material fatigue and failure thresholds with multidomain

strain-induced damage such as crack propagation is likely to occur in paint surfaces. Future work will incorporate more rigorous comparison between shearographic and RTI data based on visible and subsurface paint defects. Additionally, work will be expanded via correlation with other domains, such as X-ray and optical coherence tomography (OCT), to further confirm the effectiveness of the blend of RTI and shearography data and to establish better testing methods and detection procedures.

CONCLUSIONS

The shearography system developed at WPI provides researchers with the ability to quantify and map induced strain using gradients of displacement. Directional vectors of these gradients of displacement can also be mapped in order to better understand the response of painted surfaces to different loadings. Temporal unwrapping algorithms of displacement gradients enable researchers to directly correlate displacement response to events in time. Furthermore, a complementary approach using shearography and RTI provides a more exacting degree of correlation between displacement gradients and surface topography.

Ultimately, the aim is to combine future work involving material fatigue and failure thresholds with multidomain
shearography-based measurements in order to make fully informed recommendations on how to optimize a sustainable approach for climate control standards in museums.

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