Polynomial texture mapping: a new tool for examining the surface of paintings

Joseph Padfield and David Saunders
Scientific Department
The National Gallery
Trafalgar Square
London WC2N 5DN
United Kingdom
E-mail: Joseph.Padfield@ng-london.org.uk; David.Saunders@ng-london.org.uk

Tom Malzbender
Hewlett Packard Laboratories
1501 Page Mill Road
Palo Alto
CA 94306, USA
E-mail: tom_malzbender@hp.com

Abstract

Polynomial texture mapping (PTM) offers advantages over traditional raking light photography for examining and documenting the surface texture and shape of paintings. It is less expensive and computationally intensive than structured light or laser-based scanning techniques. Several small paintings and mock-up paintings have been examined and it is shown that PTMs are able to record surface features including craquelure, planar distortion, wood grain, canvas weave and *pentimenti*. By making images before and after physical change, the PTM technique can monitor and map change to the surface texture and shape of paintings. Future development of the system is described briefly.

Keywords

paintings, surface texture, impasto, treatment, alteration, PTM, raking light

Introduction

Although many of the photographic methods used in the technical examination and documentation of paintings during conservation treatment now have improved digital analogues, raking light photography has received relatively little attention. A raking light photograph, made by casting light across the surface of a painting at a very low angle, highlights any surface texture or irregularities, including incisions, impasto, raised or flaking paint, and damages or deformations of the canvas or panel.

There are two major problems with this form of examination. As raking light images are normally made with the lights in only one, or perhaps two, positions, the information captured depends strongly on the choice of lighting position; a raking light photograph designed to accentuate one area may not reveal features in another part of a painting. Second, because it is difficult to document the position of the lights accurately enough to allow them to be returned to exactly the same location, a comparison between images made before and after a painting has undergone some physical change, perhaps as a result of conservation treatment, is rarely possible.

There are several methods available to look at the surface of a painting in a more quantitative and reproducible manner, including laser scanning (Beraldin et al. 2003) or imaging under structured light (Guidi et al. 2004). Both these techniques work well and show great promise, but the equipment needed is both specialized and very expensive, and it is difficult to store the large quantity of data generated. In the recent study of Leonardo da Vinci's *Adoration of Magi*, the size of the data files meant that the whole painting (240 cm × 240 cm) could only be examined at low resolution, with a high-resolution study reserved for a central (58 cm × 77 cm) portion (Guidi et al. 2004).

Polynomial texture mapping

To overcome some of these drawbacks, the authors have been investigating the application of polynomial texture mapping (PTM) to the improved examination of surface features of paintings. PTMs were first developed for rendering applications in three-dimensional (3D) computer graphics, but also have been used in 2D image processing applications (Malzbender et al. 2001). PTMs are compact representations of the appearance of a surface under varying lighting conditions, which can be produced either from images of a 'real' surface or analytically from a mathematical model; the approach described here is image-based. The technique has previously been applied successfully to render the surface detail on three-dimensional museum objects, including an Egyptian *Ushabti*, cuneiform tablets (Malzbender et al. 2001), and fossils (Hammer et al. 2002).

The advantage of a PTM is that it allows the viewer to simulate on the computer screen the effect on the appearance of the painting of moving a point source of light to any position between the viewer and the object. The painting can be seen under 'normal' illumination, but can also be viewed as if lit by a raking light that can be moved through 360° around the object. Because the PTM rendering is independent of where the lights were located during the image acquisition phase (as it interpolates between these positions) comparisons can easily be made between PTMs made before and after changes or treatments. Finally, by extrapolating the data, it is possible to render the image as if it were lit from a lighting direction that is more 'raking' than is physically realizable; the resultant increased contrast is often helpful for visualizing surface detail, as described in one of the examples that follow.

The PTM software developed at Hewlett Packard Laboratories in Palo Alto requires a series of images of the painting made under varying, but well-defined, lighting conditions; normally 24–50 images are taken, each with the surface illuminated by a point light source from a unique direction. These images, along with information about the position of each of the lights, are passed to the software and rendered into the model of the painting surface described above. A description of the mathematical basis of the PTM technique is not included here; interested readers are referred to the paper describing its development (Malzbender et al. 2001).

This study aims to show that PTMs can help to overcome the two disadvantages of simple raking light photography using relatively inexpensive equipment and modest computer power. First, through the examination of several small paintings from the collections of the National Gallery and Tate, London, the authors set out to demonstrate that typical surface features, including impasto and planar distortion, can be rendered easily visible and documented. A second part of this study examined a series of mock-up paintings on canvas or panel before and after they had been subjected to physical alteration, for example dropping or flattening of impasto, to assess the reproducibility of the PTMs and their value in documenting change.

Making polynomial texture mappings of paintings

It is possible to produce a PTM by supporting a painting on a standard easel in front of a digital camera and to acquire the set of images required for the PTM software by moving a single photographic light between each exposure. It is necessary to measure the position of the light accurately before each acquisition, which is time-consuming and prone to error. While the National Gallery was evaluating the usefulness of the PTM software for examining paintings, this approach was tested, but was quickly rejected in favour of a system comprising a camera and a set of lights in fixed positions.

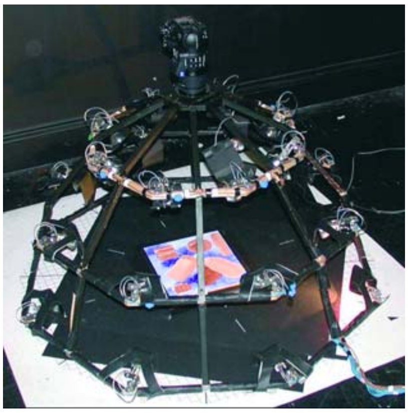

Figure 1. The prototype lighting dome created at the National Gallery

A prototype system was designed to make PTM images of small paintings (Figure 1). This comprises an octagonal wooden 'dome' supporting 24 lights in three tiers, each of which can be selected individually. These 12 V, 50 W tungsten halogen lamps illuminate the painting at angles of about 60, 30 and 2°; the last corresponds to raking light. To reduce reflections, the reflectors of the lamps not in use were shrouded with matt black material and the structure of the dome was painted black.

The images for the PTM are made with a digital camera mounted at the apex of the dome; originally a Nikon Coolpix 995 camera was used, but this has been replaced by a higher-resolution Sony DCS-F828 camera. Before examining a painting, a set of reference white target images is made by illuminating a matt white Teflon sheet with each lamp in turn. The images of the painting are then made; the acquisition process takes around 10 min, during which time the painting has been exposed to a total of 800 lux h, equivalent to around 4 h on display in the Gallery.

At this stage adjustments can be made to the set of files to account for slight rotation of the image with respect to the camera, to rotate paintings with a 'portrait' format through 90°, to reduce the resolution if required, and to crop the images. The colour of each image is corrected by reference to the corresponding image of the white target illuminated with the same lamp. Finally the images and a data file (defining the number of images, the filenames for each image file, and x, y and z coordinates for the light source at the time of capture) are passed to the rendering software to produce the completed PTM file.

Test paintings and mock-ups

First, several small paintings, chosen because they exhibited some of the more common structural features found in easel paintings on panel or canvas supports, were imaged (Table 1). These paintings were imaged only once, to render visible and document their surface texture and defects.

Table 1. Paintings examined by PTM

Artist	Title	Inv. No. *	Size (cm)	Medium and support	Features highlighted by PTM
Frans Hals	*Portrait of Jean de la Chambre at the Age of 33*	N6411	16.8 × 20.6	Oil on panel	Wood grain, gritty texture, impasto, dust
Georges Seurat	*The Seine seen from La Grande Jatte*	N6558	25.7 × 15.7	Oil on panel	Panel preparation, brushstrokes, *pentimenti*
Georges Seurat	*The Rainbow*	N6555	24.5 × 15.5	Oil on panel	Panel preparation, brushstrokes
Jacques-Emile Blanche	*Portrait of Francis Poictevin*	L689	16.5 × 26.7	Oil on canvas	Cusping, point distortion, impasto, dust
Jules-Louis Dupré	*Willows, with a Man Fishing*	N2634	27.0 × 21.6	Oil on canvas	Impasto, craquelure
Workshop of Dirk Bouts	*The Virgin and Child*	N708	16.1 × 21.3	Oil/egg on panel	Barbe, craquelure
Catharina Van Hemessen	*Portrait of a Man*	N1042	29.2 × 36.2	Oil on panel	Panel crack, gritty texture
Adolphe Monticelli	*Subject Composition*	N5018	15.9 × 21.0	Oil on panel	Thick impasto, dust

*N, National Gallery painting; L, Tate painting on long-term loan to the National Gallery.

Ten mock-up paintings were created, six on canvas and four on panel. The canvas paintings comprised a medium weight canvas tacked on 20.6 cm × 25.5 cm wooden stretchers, whereas the panels were oak (22.4 cm × 24.6 cm). Both the canvases and panels were then primed with acrylic gesso and painted with tube alkyd paints (titanium white, ultramarine, and burnt sienna). The construction and paint application were designed to replicate the surface features observed on paintings (Table 2), although no attempt was made to simulate the effects of ageing at this stage. These mock-up paintings were imaged using the PTM system before and after priming, and after the paint layer had dried. They were then subjected to some of the physical changes that might affect paintings, as summarized in Table 2, before re-imaging to create another PTM for each mock-up.

Table 2. Mock-up paintings examined by PTM

No.	Support	Features highlighted by PTM	Physical change	Differences highlighted by PTM
C1	Canvas	Strong impasto	Flattening (c.f. lining)	Flattened impasto, transferred canvas weave
C2	Canvas	Strong impasto	Punctured	Large local distortion, crushed paint, cracking
C3	Canvas	Low impasto, canvas weave	Scratched	Local distortion, cracking
C4	Canvas	Low impasto, canvas weave	Overpainted	Texture of underpaint clearly visible
C5	Canvas	Brushstrokes, canvas weave	Dropped from 1.5 m	Planar distortion, slack canvas
C6	Canvas	Brushstrokes	Climatic cycling*	No change seen
P1	Panel	Strong impasto, brush and palette knife	Impact	Damaged impasto, dents, crack
P2	Panel	Brushstrokes, wood grain	Climatic cycling*	Slight concaveness
P3	Panel	Brushstrokes, wood grain	Snapped	Displacement, paint loss at fracture
P4	Panel	Impasto, brush marks	Overpainted	Texture of underpaint clearly visible

*Temperature maintained at 25 °C while relative humidity cycled from 30 to 80 per cent every 8 h for one week.

Results

As the whole essence of the technique described here is the ability to view the surface as lit by sources at various angles (no mathematical measurements or 3D models are currently produced), the rendering of single 2D images in this paper can only serve to illustrate the features found, and not their dynamic appearance when viewed using the PTM software. Accordingly, the PTM files for most of the examples described below can be found on a web-site created to accompany this paper at http://cima.ng-london.org.uk/ptm/ (accessed 27 June 2005). The low- and medium-resolution PTMs can be viewed directly from the site; the high resolution PTMs can be downloaded and opened using free viewing software from http://www.hpl.hp.com/ptm/ (accessed 27 June 2005).

Figure 2. Rendering of the Portrait of Jean de la Chambre at the Age of 33 from the PTM, showing the painting lit as though by raking light from the left

Examination of paintings

The PTM renderings from the paintings detailed in Table 1 clearly displayed the ability of the technique to detect and display features including impasto, cracks, general and point surface deformations, canvas weave, wood grain and even *pentimenti*. The scale of the features captured varies from fine canvas weave or wood grain and individual brush strokes, to areas of thick impasto and distortion of the surface of a panel painting caused by desiccation of the wooden support.

Figure 2 shows a rendering of the *Portrait of Jean de la Chambre at the Age of 33* by Frans Hals (National Gallery, NG 6411) from the PTM visualization of this painting, as if illuminated by raking light from the left. The brush strokes in the young man's cheek, ear and forehead are evident, as is the creamy paint in the sitter's ruff. However, the image of this painting is also characterized by two other features. First, the strong wood grain is visible in the PTM visualization because of the unusually thin paint layers in this painting, which allow the grain of the wooden panel to become evident in low-angle light. The second feature is the liberal scattering of dust on the surface of the panel, particularly visible in the dark passages of the painting. Although this emphasizes the need to ensure the painting surface is free from dust before imaging, a closer examination of the image revealed that not all the material first thought to be dust was easily displaced. The gritty texture of the surface in some places is very like that reported in paintings containing lead (or other metal) soap protrusions (Higgitt et al. 2003, Van der Weerd et al. 2002).

The rendering of *Willows, with a Man Fishing* by Jules-Louis Dupré (NG 2634) shown in Figure 3 provides a good example of how a PTM can show structural effects in canvas paintings. In the sky it is possible to see the raised edges of the craquelure. In the sky above the right side of the central tree, a circular crack can be seen which is typical of a point impact, suggesting that the painting has been subject to this type of shock at some stage in its history.

Figure 3. Rendering of Willows, with a Man Fishing from the PTM, showing the painting lit as though by raking light from the top right

Figure 4. Rendering, showing a painting lit as though by raking light from the extreme left; the lighting position has been extrapolated using the procedure described in the text

Canvas deformation of a different type can be seen in the rendering of a detail from a third painting, Figure 4, where cusping can be seen at the left side of the canvas. This image, which has been made by extrapolating the lighting position as described above, also provides some information about the nature and depth of the paint layers and the technique employed by the artist. The background paint, to the left of the image shows a raised lip of paint, where the artist has painted the background up to the edge of a figure, which was probably painted earlier.

Pentimenti, or 'changes of mind' by the artist between the initial design stages of the painting and its finished state are often visible using other imaging techniques such as infrared reflectography or X-radiography. However, the PTM visualization technique has also proved to be a useful additional tool for this type of study. Figure 5 shows one rendering from the PTM file for *The Seine seen from La Grande Jatte* by Georges Seurat (NG 6558). To the left of the painting a triangular set of brushstrokes is easily visible, which represents the sail of a boat on the Seine that does not feature in the final painting.

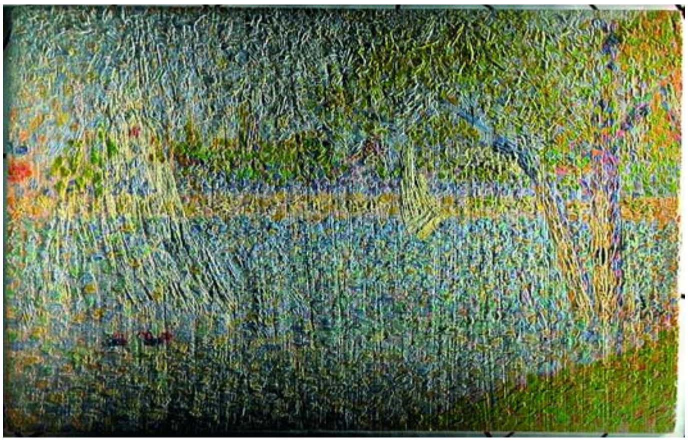

Figure 5. Rendering of The Seine seen from La Grande Jatte from the PTM, showing the painting lit as though by raking light from the right

Examination of mock-ups

The surface features of the test canvases and panels are summarized in Table 2, along with a description of the changes made to these mock-up paintings and the results seen using the PTM visualization. All the PTMs for the mock-up paintings can be viewed in detail on the web-site given earlier (http://cima.ng-london.org.uk/ptm/); here we describe, and illustrate in two dimensions, a few of the results recorded.

A first set of PTMs was made for the bare canvases or panels; the main features are the weave of the canvas, which appears rather fuzzy due to the nap of the canvas, and the grain and saw marks on the wood panels. The set of PTMs made after priming show slight cockling near the corners of some of the canvases, due to the changes in tension when a wet ground is applied and subsequently dries. The PTMs of painted canvases clearly show the weave of the support, the brushstrokes or impasto and, in some cases, deformation of the canvas at the inside edge of the stretcher. The PTMs for the painted panels still show wood grain and saw marks, in addition to the brushstrokes or palette knife marks.

Figure 6 shows renderings from the PTMs made for canvas sample C1 before and after the high impasto was flattened against a heavy weave canvas. The impression of the canvas weave and deformation of the impasto can be seen particularly clearly around the edges of the painting in the rendering to the right.

Figure 6. Canvas sample C1 before (left) and after (right) flattening of the impasto. Renderings from the PTM, showing the painting lit as though by raking light from the top: note the crushed impasto and impressed canvas weave

Figure 7. Rendering from the PTMs of panel sample P4. Left, before overpainting as though lit by raking light from the top; centre, after overpainting as though lit from the top; right, after overpainting as though lit from the top left

Renderings from one of the two overpainted mock-ups are shown in Figure 7. To the left is the top left corner of panel P4 before it was overpainted, rendered as if lit by raking light from the top. The centre image shows the same area after overpainting, again as if lit from the top. In the overpainted area, the brushstrokes of the new layer are more clearly visible than those for the original paint. However, if the lighting position is changed so that the area is lit as if from the top left, the brushstrokes and impasto from the original layer become more prominent (Figure 7, right). When viewing the PTM on the computer screen it is possible to move slowly between these two lighting states interactively to observe the gradual change in the prominence of the two paint layers.

A third example is presented in Figure 8, which shows renderings for canvas sample C3 before and after the painting was scratched from behind. The distortion is clearly visible in the rendering at centre of the figure, but even more evident in the image to the right, which was produced by subtracting the renderings made before and after the canvas was damaged. In addition to the local distortion caused by the scratch, it is possible to see cracking of the paint around the deformation and slight shifts in the prominent brushstrokes to the right of the scratch. The latter are probably rendered visible because of a slight overall horizontal stretching of the canvas in response to the force applied during scratching.

Figure 8. PTM renderings for canvas sample C3 before (left) and after (centre) scratching. The image to the right is the result of subtracting one of these renderings from the other

The subtraction to the right of Figure 8 is only possible because the before and after PTMs can be precisely superposed and the lighting direction selected to be exactly the same in each rendering; such a comparison would be extremely difficult using raking light photography.

Conclusions

The results show that a system based on a standard PC, an inexpensive digital camera, free software and a lighting system costing less than €500 can be used to produce PTM renderings of the surface of paintings. The PTM technique can provide detailed visual representations of the surface structure of paintings in a controllable and reproducible fashion. By allowing the lighting angle to be varied, more features can be rendered visible than would be seen if raking light from one direction alone were employed. The shape and texture of individual features are also made more obvious by the ability to examine them as if lit from different positions. PTM visualization has been used to study features that result from ageing, such as craquelure and distortion of the support, and fine details such as signatures and small retouchings.

Comparing PTM renderings made before and after physical changes to the painting shows how promising the technique is for the examination of alterations in the texture and shape of paintings; by carefully controlling the conditions of image acquisition, PTM renderings of two states of a painting have been made that can be subtracted to highlight changes. This process will prove particularly useful to examine paintings before and after they travel on loan, or during the course of a structural treatment.

The lighting dome built at the National Gallery has been successfully used to make images of several smaller paintings, but its use is limited by the restriction on the size of paintings that can be examined (limited to around 40 cm × 40 cm). To address this issue, the authors are developing a larger lighting/imaging system capable of making PTMs of paintings up to 2 m × 2 m, with a higher resolution camera, and using photographic flash lamps to reduce the light and heat exposure during imaging.

Finally, the current study on mock-up paintings will be extended to examine the role of the PTM system in monitoring and documenting physical changes caused by conservation processes such as tear-mending and retouching.

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