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Ultra High-Resolution 3D Laser Color Imaging of Paintings: the Mona Lisa by Leonardo da Vinci

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ABSTRACT: During the autumn of 2004, a team of 3D imaging scientists from the National Research Council of Canada (NRC) was invited to Paris to undertake the 3D scanning of Leonardo's most famous painting. The objective of this project was to 3D scan the Mona Lisa – obverse and reverse – in order to provide high-resolution 3D image data of the complete painting to help in the study of the structure and technique used by Leonardo. This paper describes some challenges associated with scanning the Mona Lisa and presents results of the modeling and analysis of the 3D data including preliminary measurements of the thickness of the varnish layer.

1 INTRODUCTION

At the request of the Paintings Department of the Louvre, the Centre de recherche et de restauration des musées de France (C2RMF) undertook the study on the Mona Lisa. This study coincided with the move of the painting to the new Salle des États and is considered the most extensive scientific examination on a painting ever undertaken. A team of 39 specialists with backgrounds in art history, conservation, photography, physics, engineering, chemistry, optics and digital imaging from seven institutions took part in this study (Mohen 06). As part of this project, the NRC developed a portable "high resolution" 3D camera system optimized for the scanning of paintings. In May 2004, testing of the portable color prototype system was done at the C2RMF by scanning a series of Renoir paintings (Blais 05). The 3D scanning of the Mona Lisa was subsequently undertaken over two nights, October 18-19, 2004.

The main objectives of this work were: (1) to document and precisely measure the distorted shape of the poplar panel on which the Mona Lisa is painted, (2) to examine surface features of the composition, the craquelure in the paint layer, the split in the panel, surface lacunae and, (3) to help the study of both the painting's state of conservation and Leonardo's technique, in particular his *sfumato*.

3D imaging is a completely new unconventional approach for the detailed examination of paintings and other objects, and as a conservation tool (Taylor 03, Godin 02). It creates a very accurate archival quality virtualized 3D model of the object which allows detailed exploration and study without any risk of damage.

One of the key objectives of this research also included the demonstration and comparison of this new emerging technology with existing well proven imaging methods. It compares advantageously to other more conventional methods such as color and infrared photography, infrared reflectography, and emissiography.

In the case of the Mona Lisa, 3D imaging corroborated key historical findings. Using historical documents and information obtained from new scientific images, art historian Bruno Mottin demonstrated that the cloth she was wearing was an unambiguous physical proof that Madonna Lisa had given birth before the commissioning of the painting (Mohen 06) as suggested by several authors (Kemp 06, Zöllner 05). Much publicized in September 2006, these observations were also corroborated using 3D laser imaging (Blais 07). Another property that is unique to 3D imaging is the potential of measuring the thickness of the transparent varnish. This physical property was unexpected and is currently the subject of further investigations.

2 3D IMAGING

The primary advantage of using a high-resolution optical 3D color laser scanner for the recording of works of art such as the Mona Lisa is that it yields a very accurate archival quality "3D Digital Model" of the exact shape as well as the color reflectance of the object. 3D imaging may seem a-priory a strange solution for the study of paintings which are assumed to be intrinsically bi-dimensional. Subtle heights variations due to brush strokes or paint thickness, cracks, wood grains, and warping make precise shape information invaluable. This record can be used to make very accurate measurements and to monitor changes over time; it can also be studied for art history and conservation applications. Another advantage of the 3D laser scanner technology is that, as an optical technique, it does not contact the surface of the object.

A custom built 3D high-resolution portable color laser scanner capable of acquiring 3D images at a depth resolution of 10 µm (about 1/10 the diameter of a human hair) was brought to Paris to scan the complete painting - obverse and reverse. In operation, the system scans a small (less than 100 µm diameter) "white" laser spot from a RGB (red, green, blue) laser source over the complete surface of the painting in order to produce a high-resolution archival quality 3D digital model of both shape and color of the painting's surface (Figure 1). The laser is low power and safe for scanning works of art (equivalent exposure of 20 minutes @ 50 lux). The triangulation based detection system simultaneously records the shape (x,y,z) measurements and the color (R,G,B) reflectance from the spot on the painting in perfect registration. Details of the triangulation principle and scanning method are available in (Blais 05, Taylor 03).

In the maximum resolution configuration used for this project, the system provided a lateral spatial (x and y) resolution of 0.060 mm and a depth uncertainty of 10 µm (0.010mm). This resolution, as well as the lower one used for the reverse, were imposed by time constraints: priority was given to acquiring the obverse at the higher resolution. The laser scanner head is mounted on a linear translation stage on a rail supported by two tripods. The translation stage moves the scanner across the painting to digitize a band of approximately 20 cm in length and 4 cm in width. A total of 72 sequential bands for the obverse and 68 for the reverse and sides were recorded over the entire painting, stitched and merged by software to form a complete 3D and color model.

The obverse (front) side was scanned with the frame in place during the first night. The back and sides were scanned during the second night. A first band in the back was scanned then one traverse removed that resulted in an important change in the shape of the painting of 3 mm due to the pressure applied by the frame (Mohen 06). Finally the frame was completely removed, and the reverse (back) and the four sides were measured: the scans were registered, stitched and blended to complete the 3D model. The distortion induced by the pressure exercised by the frame was numerically compensated.

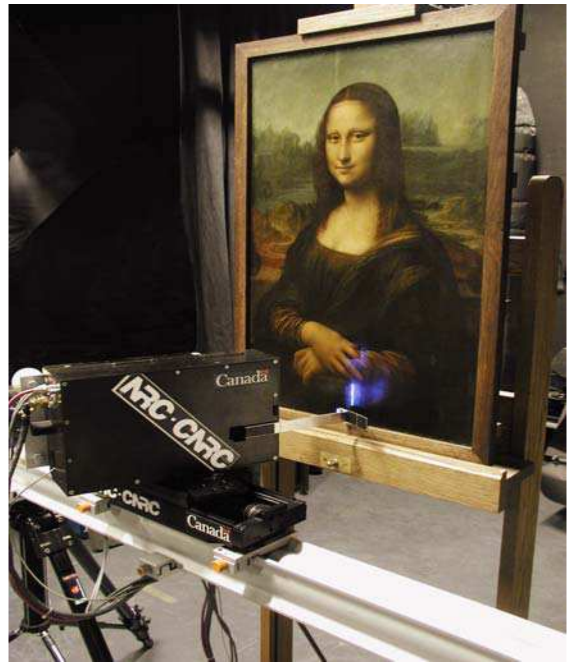

Figure 1: The high-resolution color 3D scanner.

Figure 2: The virtual 3D Mona Lisa – observe

Each scanning session was subject to specific security conditions. With very few exceptions, the number of individuals allowed in the immediate proximity of the painting at one time was limited to four in order to maintain the temperature and humidity conditions surrounding the painting. All manipulations of the Mona Lisa were carried out by restorers.

Figure 3: The virtual Mona Lisa – Reverse

The physical dimensions of the poplar panel are 79.4 cm × 53.4 cm, at a 3D sampling resolution of 60 µm (0.06 mm): this corresponds to an image of 12800 × 8800 pixels or the equivalent of a 113 million pixels camera. Figures 2 and 3 show views of the 3D model of the Mona Lisa which consists of 330 million 3D polygons, the basic geometrical primitive used by 3D graphic processor boards for rendering.

THE VIRTUAL 3D MONA LISA

The shape data recorded by the scanner can be used to generate contour plots and color coded elevation maps as demonstrated in (Mohen 06, Blais 07) which provide convenient and familiar representations of the overall shape of the panel. Figure 4 clearly shows the pronounced curvature of the poplar panel. Here, the 3D model was virtually cut in half to reveal the detailed profile of the panel.

A method frequently used to enhance the detailed shape of the surface of the panel is synthetic shading of the model. One or several light sources can be directed from any direction to examine the surface relief on the painting. Using a low angle of incidence on the surface simulates raking light, a standard method for the examination of paintings. Ambiguities caused by changes in surface color are completely removed using only shape information. Figure 5 illustrates such an artificially shaded monochrome image of the obverse side. The surface relief due to the wood grain structure is clearly visible. The 12 cm split from the top edge to the head, which has been stabilized during an earlier conservation treatment, is apparent. A faint outline of the head, the crack patterns and some other elements of the landscape are also visible.

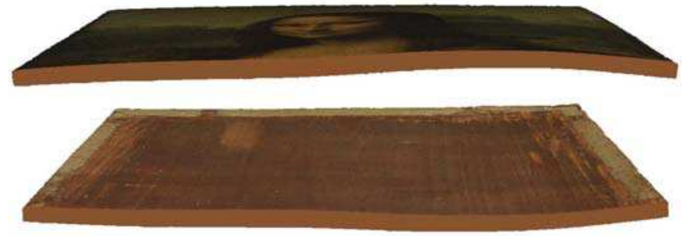

Figure 4: The 3D Mona Lisa is virtually cut to highlight the warping of the poplar panel.

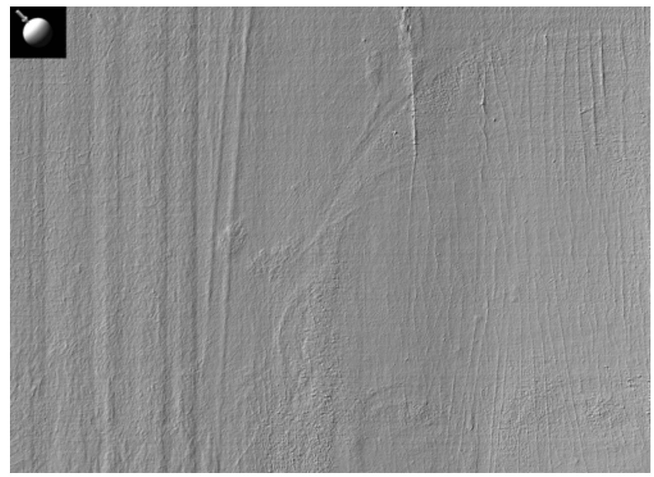

Figure 5: Some details of the pictorial layer.

The presence of a barb, a crest of paint located between the poplar panel and the frame is highlighted in the 3D image (Figure 6) demonstrating that Leonardo painted the panel after it had already been set into a frame. The back of the panel also shows clear evidences of saw marks documenting previous attempts at trimming the panel (Figure 7). Similar observations can be made for the insect cavities in the back and sides of the panel (Figure 6).

A closer examination of the painting shows that apart from the surface relief due to the wood grain structure, previous restorations and craquelure features, particularly in the landscape areas, very few surface relief details relating to the painting composition itself are apparent. As such, in contrast to other paintings scanned previously and which typically records the surface relief details from brushstroke, there is very little pictorial composition 3D relief on this painting.

The second aspect, which is also closely related, concerns the application of multiple thin semi-transparent layers or glazes using the *sfumato* technique. The absence of brushstrokes and the very subtle heights variations detected is an example of Leonardo's famous technique of applying successive extremely thin semi-transparent layers of glaze. The delicate shadows in the face around the eyes, nose, and mouth are the results of extremely flat layer

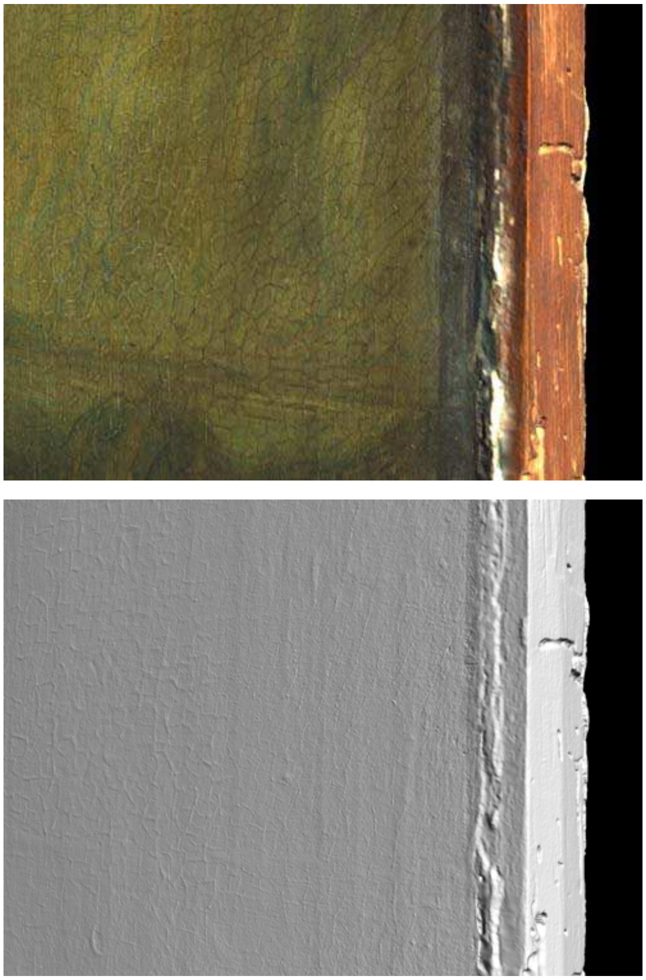

Figure 6: Presence of a barb, shaved panel, and details of the craquelure pattern.

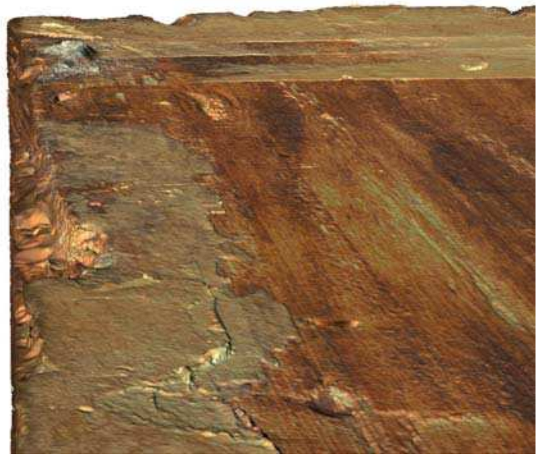

Figure 7: Saw marks on the back of the poplar panel.

Figure 8: The red laser component of the virtual 3D model is used to highlight details and the transparency of the dress.

composition called "*sfumato*" or "*smoke like*" appearance. More information is available in (Mohen 06).

THE COMPOSITION

Three conventional 2D imaging techniques that were used by the C2RMF to examine and analyze details of the composition of the Mona Lisa are infrared photography, infrared reflectography and electron emission radiography or emissiography. Collectively these techniques are used to examine features on works of art which are difficult or impossible to see with the naked eye due to the fact that the varnish layer has yellowed and darkened or that the original composition has been changed and over painted by the artist.

To date, Mona Lisa's clothing has been little studied. In 1625, Cassiano dal Pozzo complained about the dark varnish that made it difficult to interpret. As art historian Bruno Mottin has observed using infrared reflectography:

"The model's whole body is covered in transparent veils that spill onto the left shoulder, fall onto the back of the chair, and run alongside the line of the right arm. According to Jacqueline Herald, this transparent overlayer was called a guarnello and was an indoor garment worn only by young children, pregnant woman, or woman that recently gave birth. Lisa Gherardini (Madonna Lisa) did give birth to her second son, Andrea, on December 1, 1502, before the painting was commissioned in 1503." (Mohen 06).

These observations are corroborated by the red color laser data recorded by the 3D scanner. The red laser wavelength (658 nm) penetrates the pictorial layer deeper than the blue (442 nm) or green (532 nm) wavelength but less than IR. Also, because the laser beam is very well focused it will penetrate deeper than conventional illumination by reducing the scattering between the different particles of pigments.

Figure 8 shows the result of extracting the red wavelength from the virtual 3D model of the Mona Lisa; simple contrast enhancement techniques were used to remove much of the uniform background light and to amplify the details of the dress as well as the bonnet and the balustrade. It shows clearly the semi-transparent overlayer guarnello dress that covers the shoulders. In the back of Mona Lisa's head is also the evidence of a bonnet that holds the hair (Mohen 06, Blais, 07). A few locks of the undulating hair on both sides of the face, rather than a loosely flowing mass of hair, is another indication of the presence of a bonnet to hold the hair up in a bun that was evident in both infrared photography and in the laser image.

It is even more interesting to note that the red laser image provides information that is not obvious in conventional imagery and, in several cases, barely visible even in infrared. For instance the balustrade or railing of the loggia crossing transversally the whole painting behind Mona Lisa is clearly visible in the laser image of Figure 6. One horizontal line can be seen in infrared reflectrography; the laser image shows parallel lines that appear to correspond to the low wall and balustrade.

Other observations can be made for what appears to be two rocks visible in the river bed hidden by the hills (highlighted in Figure 8) and for the two columns, although a more thorough analysis is needed to confirm these observations. Both laser and infrared reflectrography images also highlight other details of the planning of the composition that shows clearly that Leonardo changed his mind at a few occasions (Mohen 06).

THE VARNISH LAYER

The presences of small raised localized features in the 3D images, especially in the areas of the hair on either side of the face, had been left unexplained in (Mohen 06). But subsequent experimental measurements in October 2005 on the Mona Lisa provided clues of an unexpected optical property of 3D laser imaging.

Figure 9 combines information from three different sources in perfect registration for the detailed study of the painting: shape information, color, and images acquired using a telemicroscope. Registration of images is easy to do in 3D because perspective and scaling are perfectly known. The range image shows geometrical "bubbles" that are not visible in the telemicroscope image (center) and are white and floating over the paint layer in the color image (left).

Figure 10 shows a simplified model of the pictorial layer showing a finely cracked translucent layer of old and modern shiny varnish/glaze. Let assume a directional light source (A-B) illuminating the painting. Because the surface of the varnish is shiny, an important amount of light will be deflected (C) while some will be diffused by the pigment surface (D). A very small deformation on the surface can potentially generate white specular reflections, either back to the measuring instrument (E-F-G) or an observer (H). The thickness of the transparent layer can be obtained by measuring the height of the reflections (E-F-G) with respect to the background (D) and compensating for the index of refraction of the medium. This property was verified by measuring a surface through a finely scratched microscope slide cover.

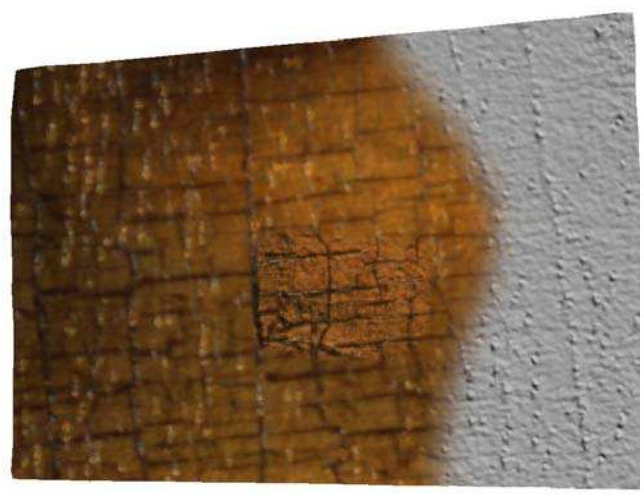

Figure 9: Superposition of color, range and telemicroscope images showing details of the craquelure pattern close to left eye of Mona Lisa.

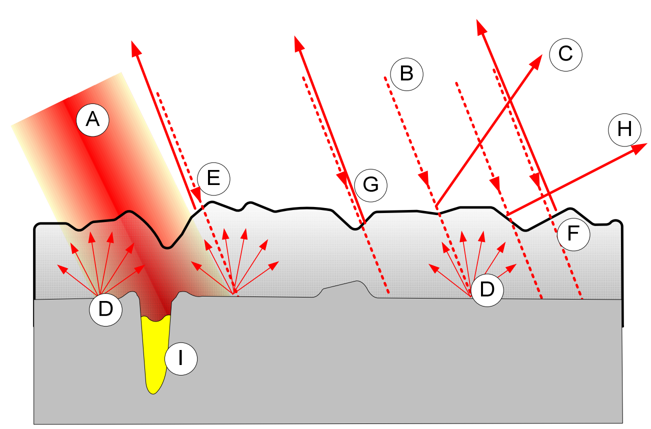

Figure 10: Simplified model of the paint layer including a translucent layer of finely cracked old varnish and/or transpar-

ent glaze.

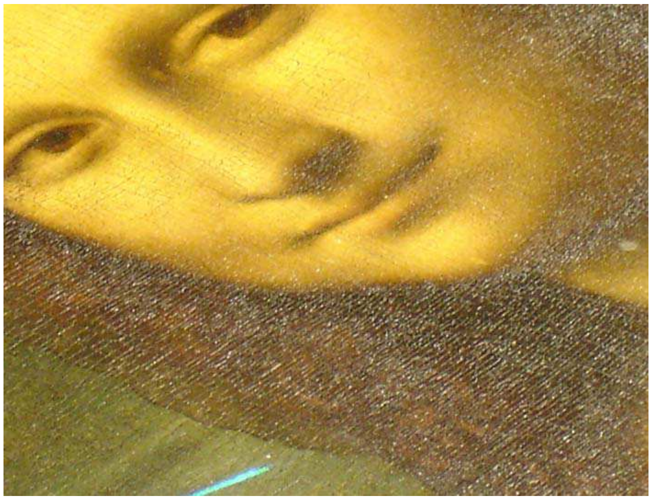

Figure 11: Reflections from ambient lights on the Mona Lisa during the 3D scan.

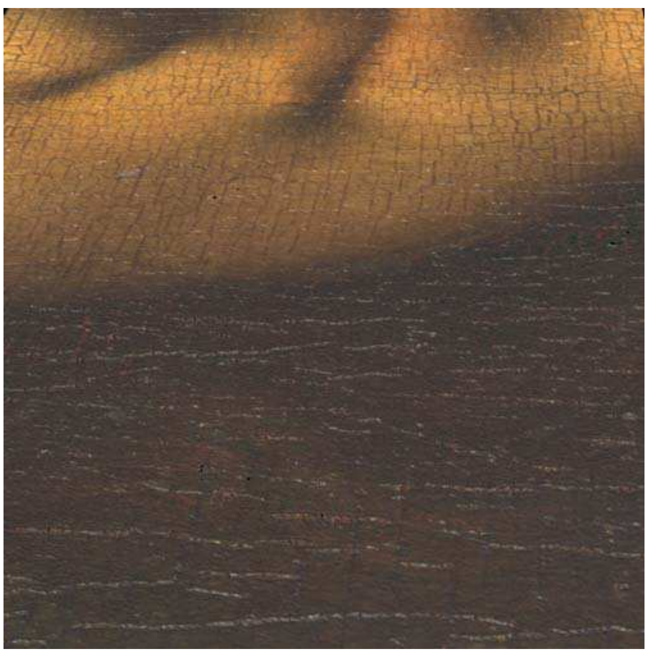

Figure 12: The virtual 3D Mona Lisa fine craquelure pattern from the painting (darker color) and from the varnish layer (white reflections).

Comparing the height of these white structures with the background colored image yields variations in the thickness of the translucent layer of the Mona Lisa between 0.11 mm and 0.17 mm on average. It is important to note that these values are still approximate until the exact index of refraction and the effects of penetration in the opaque paint layers are perfectly mastered.

CONCLUSION

The advantages of using 3D imaging have been clearly demonstrated on many occasions in the past for the study of some of the world's most celebrated works of art. The Mona Lisa project has brought a completely new perspective to this emerging field. This project was part of the first extensive experimental study performed since 1952. One of the key objectives was to obtain a very accurate and detailed 3D model to provide an archival quality record of the real object. But even more important is that experts can now manipulate and analyze the virtual object at their own leisure, which is practically impossible on real works of art such as the Mona Lisa.

The study of the shape of the panel and the details of the pictorial layer presented in this paper are just a few examples of uses of the 3D data for the detailed analysis of the overall shape of the painting, the technique of the artist and the effects of time on the pictorial layer such as for the cracks and the split. The red laser wavelength showed interesting optical properties of penetration through the pictorial layer that corroborates other imaging techniques and assists in better understanding the painting such as the dress and the bonnet, and some details of the background that are becoming visible behind the personage. The thickness of the varnish is another important potential measurement offered by 3D scanning.

These interesting physical properties of 3D laser imaging are still under investigation, but they have already been shown to help further explain Leonardo's painting technique.

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