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Blais, François; Taylor, John; Cournoyer, Luc; Picard, Michel; Borgeat, Louis; Godin, Guy; Beraldin, Jean-Angelo; Rioux, Marc; Lahanier, C.; Mottin, B.

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More than a poplar plank: the shape and subtle colours of the masterpiece *Mona Lisa* by Leonardo

François Blais, John Taylor, Luc Cournoyer, Michel Picard, Louis Borgeat, Guy Godin, J.-Angelo Beraldin, Marc Rioux,
National Research Council Canada, Ottawa, Ontario, Canada.

Christian Lahanier, Bruno Mottin,
Centre de Recherche et de Restauration des Musées de France, Paris, France.

ABSTRACT

During the autumn of 2004, a team of 3D imaging scientists from the *National Research Council of Canada* (NRC) were invited to Paris to undertake the 3D scanning of the most famous painting by Leonardo. The objective of this project was to 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. Unlike any other painting scanned to date, the *Mona Lisa* presented a unique research and development challenge for 3D imaging that is described in this paper.

Keywords : *Mona Lisa*, *Joconde*, 3D imaging, laser scanner, color.

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. In addition to *NRC's Visual Information Technology Group* and the *Centre de recherche et de restauration des musées de France* (C2RMF), other institutional partners included the *département des Peintures du musée du Louvre*, the *CNRS university Montpellier II* and *CNRS university Poitiers*, the *INRA-CNRS université Nancy I*, and the *University of Florence*. Preliminary results have been published in [1][2].

In 2003, the NRC and the C2RMF started collaborating on a research project to evaluate the potential of 3D applied to paintings and museum artifacts. As part of this project, the NRC developed a portable "ultra high resolution" 3-D camera system optimized to scan paintings. In May 2004, to test the initial portable color prototype system, NRC took the scanner to the C2RMF to scan a series of Renoir paintings [3]. The 3D scanning of the *Mona Lisa* was subsequently undertaken during the autumn of 2004. The 3D team had access to scan the painting for only a few hours over two nights, October 18-19, 2004. NRC's role was to scan the complete painting, obverse and reverse, in order to prepare a complete high-resolution archival quality 3-D model.

The main objective of this work was:

- to document and precisely measure the distorted shape of the poplar panel,
- to examine surface features of the composition, the craquelure in the paint layer, the split in the panel, surface lacunae and,
- to help the study of both the painting's state of conservation and *da Vinci*'s technique, in particular his sfumato.

3D imaging is a completely new approach, currently under development, for the detailed examination of paintings and as a conservation tool. It creates a very accurate virtualized 3D model of the *Mona Lisa* (Figure 1) used for the precise exploration and the study of paintings and objects of art without any risk of damage to the object.

Because 3D is a new technique, one of the key objectives of this research also included the demonstration and comparison of this new emerging technology with existing well proven methods. In the case of the *Mona Lisa*, 3D imaging can precisely corroborate key historical findings. It compares advantageously to other more conventional methods such as color and infrared photography, infrared reflectography, and emissiography.

One of these key historical finding that was much publicized by the media in September 2006 is that *Madonna Lisa* had given birth before to the commissioning of the painting as suggested by several authors [4][5]. Using historical documents and new evidences obtained from these new scientific images, the historian Bruno Mottin demonstrated that the cloth she was wearing was an unambiguous physical proof [1][2]. Some examples of these scientific evidences will be presented in this paper, using images from the 3D laser scanner.

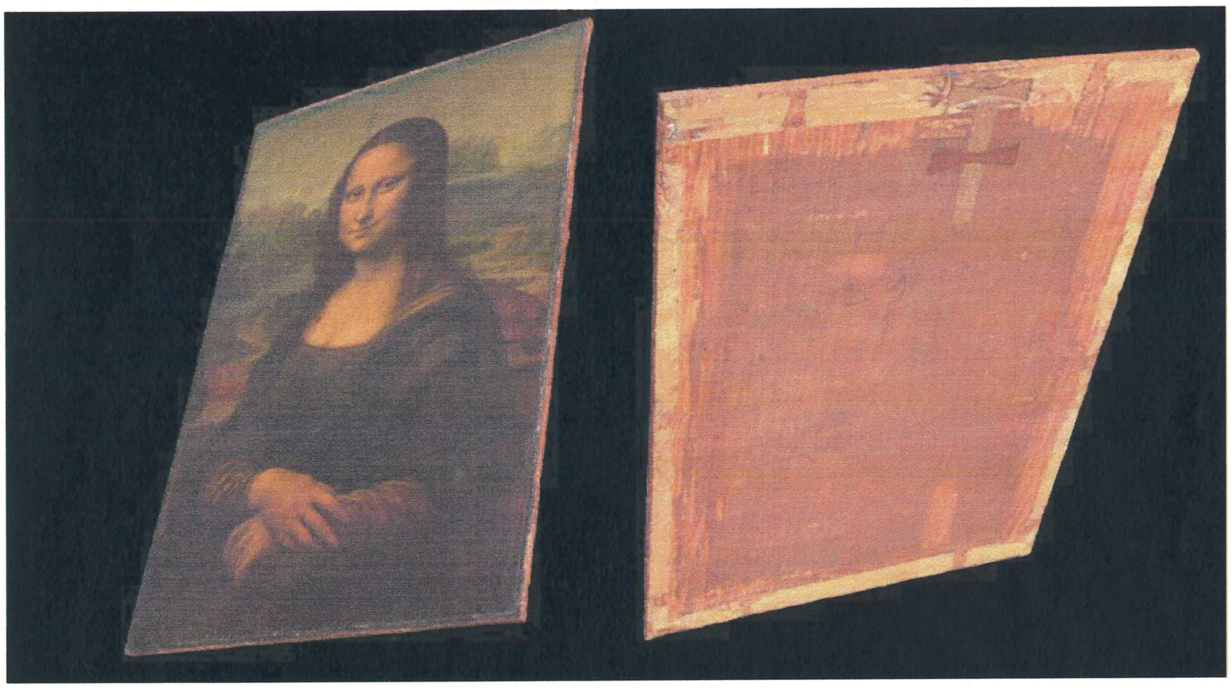

Figure 1: The virtual 3D *Mona Lisa* – observe and reverse. Sampling resolution for this model is 0.06 mm × 0.06 mm for the observe (front) and 0.10 mm × 0.10 mm for the reverse (back) and sides. Depth resolution is 0.01 mm.

3D IMAGING

The primary advantage of using a high-resolution optical 3-D laser scanner for the recording of works of art such as the *Mona Lisa* is that it records a very accurate archival quality "3-D Digital Model" of the exact shape as well as the color of the object. This record can be used to make very accurate measurements of the shape of the object, to monitor changes over time; it can be studied for art historical and conservation. Another advantage of the NRC 3-D laser scanner technology is that as a non-contact optical technique; it does not touch the surface of the object.

For the *Mona Lisa* project, a 3D high-resolution portable color laser scanner designed and built by NRC and capable of acquiring 3D images at a depth resolution of 10 µm or about 1/10 the diameter of a human hair was brought to Paris to scan the complete painting - obverse and reverse. The triangulation-based system scanned a low power white laser spot over the painting in order to produce a high-resolution archival quality 3D digital model of the shape and color of the painting's surface. In operation, the system scans a small (less than 100 micron diameter) "white" laser spot from a RGB (red, green, blue) laser source over the complete surface of the painting. The laser is low power and safe for scanning works of art. 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 reference [3] [6].

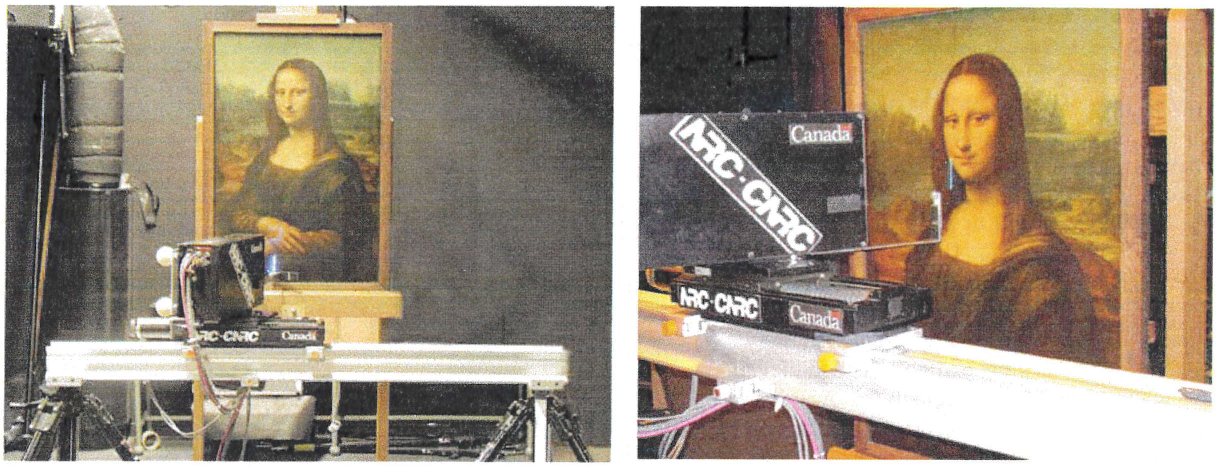

Figure 2: The high-resolution scanner set up used to scan *Mona Lisa*. The painting is shown mounted on an easel. The laser scanner camera is shown mounted on a linear translation stage supported by two tripods.

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). Views of the high-resolution scanner set up used to scan *Mona Lisa* are shown in Figure 2. The laser scanner camera is mounted on a linear translation stage supported by two tripods. The translation stage translates the camera across the painting to digitize a band approximately 20 cm in length and 4 cm in width as shown by the bluish laser line. Sequential bands are recorded over the entire painting and are stitched and merged to form a complete 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 the frame removed that resulted in an important change in the shape of the painting of 3 mm due to the pressure exercised by the frame [3]. Finally the frame was completely removed and the reverse (back) and the four sides were measured, and registered, stitched and blended to complete the 3D model. The distortion induced by the pressure exercised by the frame was numerically compensated; the correctness of this compensation is still under study.

Each scanning session was subject to specific security conditions. The number of people present was controlled and, 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 were carried out by restorers. During the 3D scans, the main team was composed of two experts from NRC, one supervisor from the C2RMF and one restorer, except for certain visual tests and specific operations, for which special authorization was granted.

The physical dimensions of the painting are 77 cm x 53 cm, at a 3-D sampling resolution of 60 micro-meters (0.06 mm) this corresponds to an image of 12800 × 8800 pixels or the equivalent of a 113 million pixels camera. By comparison, current consumer market digital cameras are currently limited between 8-14 million pixels. The complete 3-D model of the *Mona Lisa* consists of 330 million 3-D polygons, the basic geometrical primitive used by 3-D graphic processor boards for rendering. By comparison, most current 3-D models are limited to only a few million polygons.

THE VIRTUAL 3D *MONA LISA*

As mentioned, the objective of this project was to scan the *Mona Lisa*, obverse and reverse, in order to provide high-resolution 3D image data of the complete painting to (1) record the overall shape of the panel, (2) document surface features such as the relief due to the wood grain structure, the crack in the panel, edge features and surface lacunae and (3) provide high resolution pictorial layer images to assist in studies related to the artists' technique as well as for conservation examination. Figure 1 shows the final 3D model.

The shape data recorded by the scanner can be used to generate contour plots and color coded elevation maps, which accurately document the overall shape of the panel. As shown in Figure 3, the painting has a pronounced convex deformation or curvature due to warping of the poplar wooden panel. The deformation is lowest at the edges and rises by approximately 12 mm in the area surrounding the left shoulder and upper left arm. Figure 4 clearly shows the pronounced curvature of the poplar panel. Here, the 3D model has been virtually cut in half to show the complex detailed profile of the poplar panel.

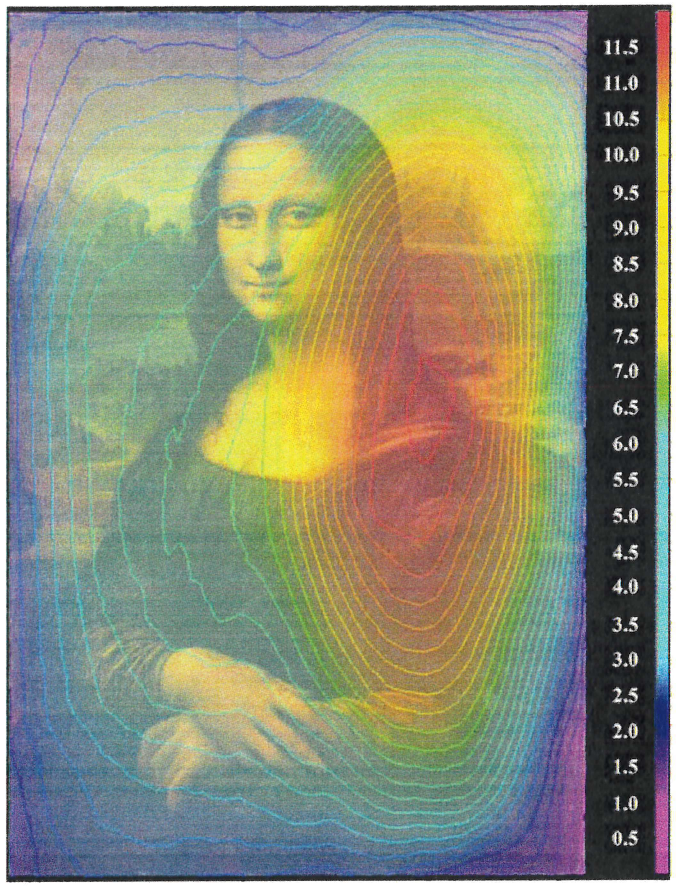

Figure 3: Combination of contour plots and color coded elevation maps to highlight the curvature of the poplar panel.

A popular method used to illustrate the detail shape of the surface of the panel is the use of artificially shaded images. For this technique, the shape data recorded by the scanner is used to generate a monochrome image of the painting, the color is virtually removed. A light source can be directed - or artificially shaded - from any direction to examine the surface relief on the painting. Figure 5 illustrates such an artificially shaded monochrome images 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 in an earlier conservation treatment, is apparent. A feint outline of the head, the cracks patterns and some other elements of the landscape are also visible.

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 using the NRC high-resolution scanner, which typically records the surface relief details from brushstroke, there is very little pictorial composition 3D relief on this painting [3].

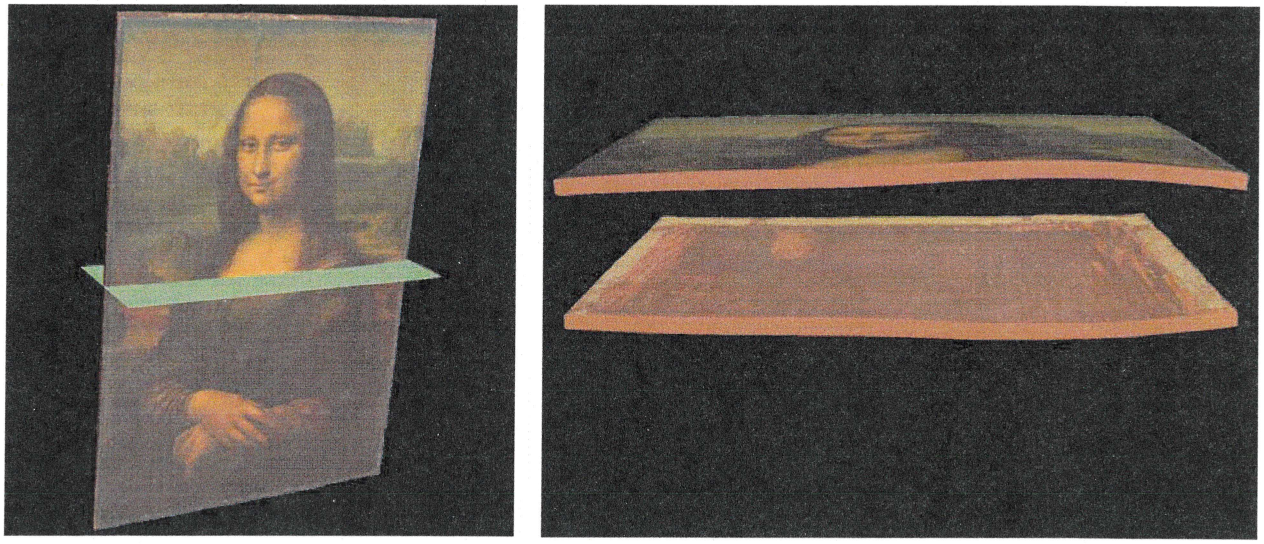

Figure 4: The 3D *Mona Lisa* is virtually cut and repositioned to highlight the warping of the poplar panel

The second aspect, which is also closely related, concerns the application of multiple thin semi-transparent layers or glazes using the *sfumato* technique. Studies undertaken to date by NRC on paintings which have a relatively basic structure consisting of a transparent varnish layer on top of an opaque paint layer, such as the Renoir suite of paintings previously scanned at the C2RMF, show that the laser beam penetrates through the varnish layer and is reflected back to the scanner from the immediate surface of the paint layer. This results in a detailed recording of the shape of the surface structure of the immediate surface of the paint layer below the varnish, including the 3D relief of the brushstroke details.

Therefore, the absence of brush strokes 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 this extremely flat smoked type layer composition called "*sfumato*". More information is available in [1].

THE COMPOSITION

Two important tools that have been used to analyze the composition of the *Mona Lisa* are infrared reflectography and emissiography.

- Infrared photography covers the light wavelength from 750 nm to 1000 nm. In the case of the *Mona Lisa*, a filter was used to further limit the wavelength to 900 nm and above.
- Infrared reflectography is based on the same principle as infrared photography but uses a different detector which is sensitive up to 2000 nm and thus makes it possible to penetrate further the more opaque pigments. Image resolution is however very limited and requires the generation of a mosaic of smaller images.
- Emissiography is an X-ray technique that consists of recording the electrons emitted by the surface of an object when it is stimulated by very high energy X-Ray beam. This emission is recorded on the emulsion of a film place in very strict contact with the surface of the painting. To insure close contact with the surface of the painting, controlled pressure is exercise with foam.

In the case of the 3D laser scanner, the red laser wavelength (658 nm) will also penetrate 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 is expected that the red laser beam will penetrate slightly deeper than conventional illumination by reducing the scattering between the different particles of pigments.

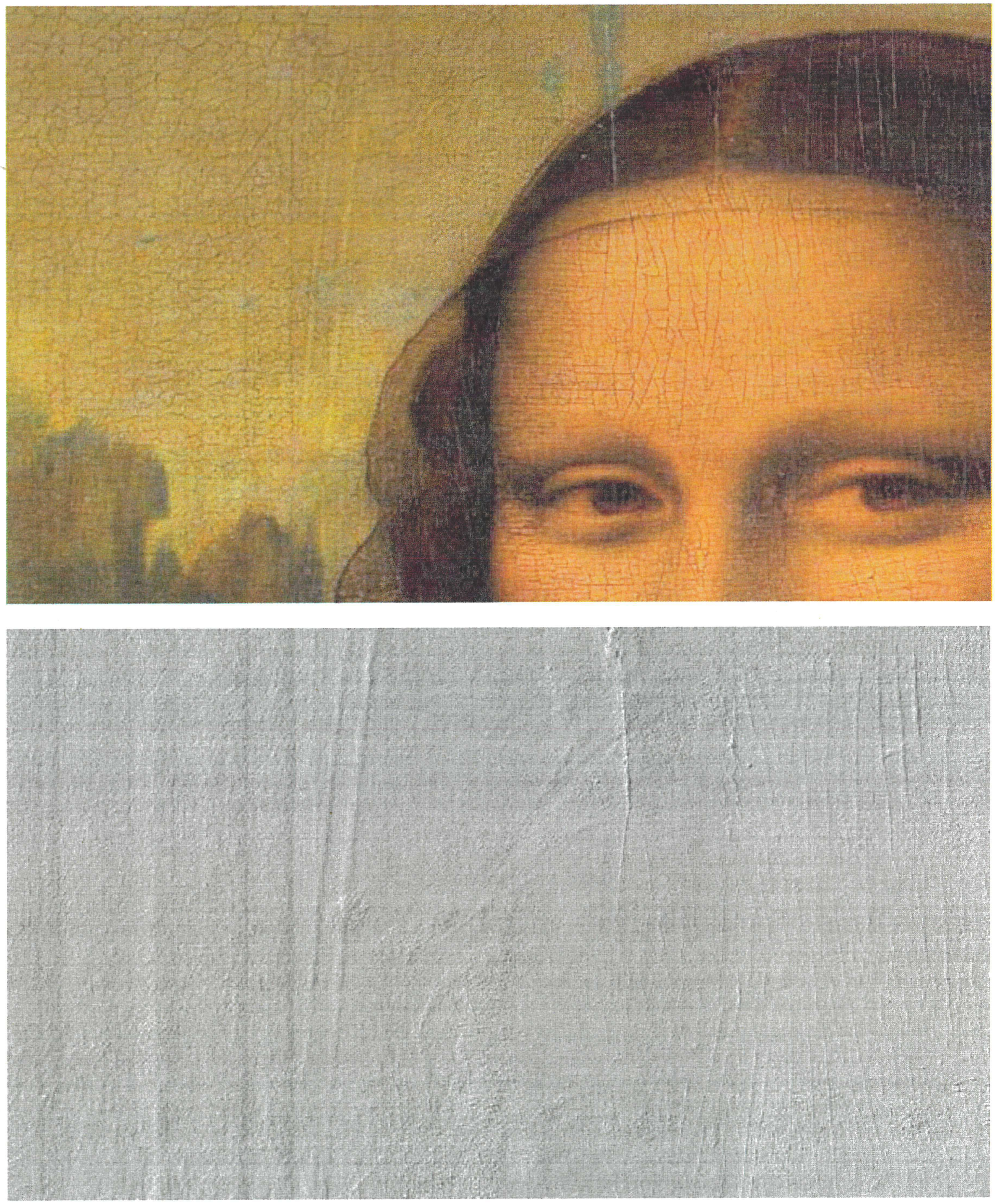

Figure 5: Details of the pictorial layer using raking light, the complete absence of brushstrokes is the result of a technique mastered by Leornardo. Only the craquelure pattern, wood grain, some contour along the edge of the head and eyes, and the 12 cm split (top of the picture) are visible.

Figures 6 to 8 show 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.

The *Mona Lisa*`s clothing has not been much studied. In 1625, Cassiano dal Pozzo complained about the dark varnish that made it difficult to interpret. As Bruno Mottin pointed out: "the most spectacular result of infrared reflectrography" and here 3D color imaging is that "it shows the full extent of the gauzes which envelop the *Mona Lisa*. 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 gave birth to her second son, Andrea, on December 1, 1502, before the painting was commissioned in 1503." [1]

Figure 6 shows clearly the semi-transparent overlayer dress that covers the shoulders. Figure 7 is a zoom section that better shows this historical discovery. In the back of *Mona Lisa*'s head is also the evidence of a bonnet that holds the hair, Figure 7. 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 [1] that was put in evidence in both infrared photography and in the laser image.

It is even more interesting to note that the red laser image provides further information that is normally not evident, even in infrared reflectrography image. For instance the balustrade is clearly visible in the laser image of Figure 6; a very small curved contour is seen behind Madonna Lisa, crossing transversally the whole painting. Other details of the planning of the composition that shows clearly that "Leonardo changed his mind at a few occasion are also highlighted using this technique such as the small finger of the left hand that indicates he intended to show a more tightly clenched on the back of the seat instead of the relaxed posture we see today (Figure 8) or the architectural elements added after the balustrade and the foreground of the landscape were painted (Figure 6)" [1].

CONCLUSION

The advantages of using 3D imaging has been clearly demonstrated on many occasions in the past for the study of important historical object of arts. The *Mona Lisa* project has brought a completely new perspective to this emerging field that is 3D. 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 the virtual object at their own leisure which is totally impossible on real object of arts such as the *Mona Lisa*. In the case of the *Mona Lisa*, the painting is now behind a bullet proof glass to prevent damages and which further limits access to the painting. This project was part of the first extensive experimental study performed since 1952.

The study of the curvature, the shape of the panel, and the details of the pictorial layer are just a few examples of using 3D that were presented in this paper. An important unexpected results obtained with the laser scanner is that the returned signal from the red laser wavelength, for example, has interesting unexpected optical properties that can corroborate key historical events such as the dress and the bonnet that Madonna Lisa was wearing, and some details of the background that are becoming visible behind the personage. These interesting physical properties are still under investigation but a key immediate consequence, they help further explain Leonardo's painting technique.

Figure 6: The red wavelength from the virtual 3D model of the *Mona Lisa* combined with simple contrast enhancement techniques is used to highlight the details and the transparency of the dress as well as the bonnet and the balustrade behind in the background as well as behind *Mona Lisa*.

Figure 8: Details of the bonnet behind the head.

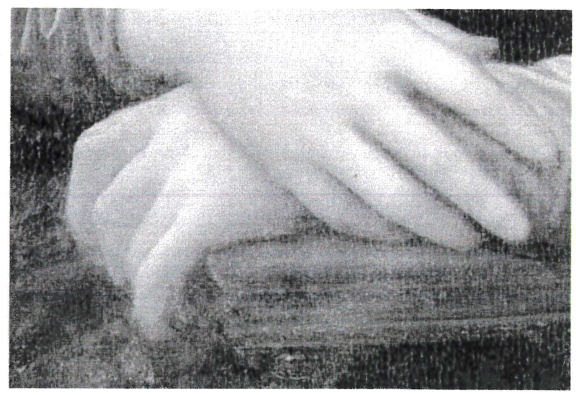

Figure 7: Details of the semi-transparent overlayer dress that covers the shoulders.

Figure 9: The small finger of the left hand shows clearly that Leonardo changed his mind on a few occasions.

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