



Worcester Art Museum

# Applications of Surface Metrology to Issues in Art

An *Interactive Qualifying Project* Report

*submitted to the faculty of*

WORCESTER POLYTECHNIC INSTITUTE

WORCESTER, MASSACHUSETTS

*in partial fulfillment of the requirements for the*

Degree of Bachelor of Science

*on the day of  
April 24<sup>th</sup>, 2008  
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## **Abstract**

This work investigates applying surface metrology techniques to issues in art, such as, restoration and identification. It seeks possible areas of collaboration between the Worcester Art Museum and Worcester Polytechnic Institute's Surface Metrology Lab. Surface metrology is the study of measurement and analysis of surface textures, or roughness. We have completed an experiment to demonstrate that scanning laser microscopy and scale-sensitive fractal analysis used on paintings can discriminate brush types and paints.

## Executive Summary

The goal of this project is to apply surface metrology tools to issues in art such as restoration, identification and preservation of art material in collaboration with the Worcester Art Museum (WAM) and Worcester Polytechnic Institute Surface Metrology Lab. We have talked to two people from the Worcester Art Museum conservation lab, Phil Klausmeyer and a colleague to see if they would be interested in such new tools to aid their work.

Surface metrology has been used in engineering areas to understand the creation and behavior of surface topographies but so far, to our best knowledge, it has not been considered a tool for art museums. However, new additions to surface metrology techniques have shown the ability to measure infinitesimal changes in surface roughness. Such capabilities of surface metrology would help art conservators discern different characteristics of a painting.

In this work, we demonstrate how surface metrology can be applied to paintings. We have designed an experiment to discern different brush hair types and different paint material by taking measurements using fine-scaled microscopes and analyzing the results using surface metrology software.

As a result, we were able to discern different brush hair types from each other with 99.9% confidence level except the two that produced similar results. We also successfully differentiated paint materials with 99.9% confidence except for one that did not produce good data.

We recommend that surface metrology techniques can be used to address some of the issues in art like the techniques currently used such as optical coherence tomography or polynomial texture mapping. This technique would help art conservators in their research by giving information about the surface of a painting and by discerning different brush hair types or paint types.

## Acknowledgements

First and foremost we would like to extend our thanks to our advisor Professor Christopher Brown for his patience throughout this project that took longer than most projects. His guidance determined the outcome of this project and we are very much grateful.

We would also like to thank Brendan Powers for helping with us with our measurements, regardless of the time of day. He's always been there for us and he is an important part of the success of our experiments.

We would like to thank the other members of the Surface Metrology Lab who have also provided us with help whenever we needed.

We would like to thank Phil Klausmeyer from the Worcester Art Museum as well as other staff members of the museum for their ideas and their collaboration with us throughout this project. They have provided us with paintings that we could work on and their insights shaped the goal of our project.

We learned a lot when we were working this project and truly enjoyed ourselves and it would not have been possible without the help of these people. We are truly grateful.

# Table of Contents

<b>ABSTRACT</b> .....	<b>I</b>
<b>EXECUTIVE SUMMARY</b> .....	<b>II</b>
<b>ACKNOWLEDGEMENTS</b> .....	<b>III</b>
<b>TABLE OF CONTENTS</b> .....	<b>IV</b>
<b>TABLE OF FIGURES</b> .....	<b>V</b>
<b>LIST OF TABLES</b> .....	<b>VI</b>
<b>1 INTRODUCTION</b> .....	<b>1</b>
1.1 OBJECTIVE .....	1
1.2 RATIONALE .....	1
1.3 STATE-OF-THE-ART .....	1
1.4 APPROACH .....	2
<b>2 LITERATURE REVIEW</b> .....	<b>3</b>
2.1 COMPARISON .....	3
2.1.1 <i>Technical View</i> .....	3
2.1.2 <i>Art View</i> .....	5
2.2 POSSIBLE PUBLISHING RESOURCES .....	7
2.3 TECHNOLOGIES .....	8
2.3.1 <i>Polynomial Texture Mapping (PTM)</i> .....	8
2.3.2 <i>Optical Coherence Tomography (OCT)</i> .....	17
2.3.3 <i>Holography</i> .....	22
2.3.4 <i>Fringe Projection</i> .....	26
2.4 SURFACE METROLOGY TECHNIQUES .....	30
2.4.1 <i>Confocal Microscopy</i> .....	30
2.4.2 <i>Laser Scanning Microscope</i> .....	31
<b>3 EXPERIMENTAL APPROACH</b> .....	<b>35</b>
<b>4 RESULTS</b> .....	<b>36</b>
4.1 VARIABLE: BRUSH HAIR MATERIAL .....	36
4.2 VARIABLE: PAINT MATERIAL TYPE .....	40
<b>5 CONCLUSION AND RECOMMENDATIONS</b> .....	<b>45</b>
<b>6 REFERENCES</b> .....	<b>46</b>

## Table of Figures

FIGURE 1- AN ORANGE WITHOUT BUMP MAPPING AND WITH BUMP MAPPING [15].....	9
FIGURE 2- IN THESE PHOTOGRAPHS, LIFTING PAINT AND CRACKED PANEL CAN BE SEEN (HAWKINSON 2003) .....	9
FIGURE 3- COMPARISON BETWEEN THE PTM (TOP VIEW) AND TRADITIONAL MAPPING TECHNIQUES (BOTTOM VIEW) AS THE LOCATION OF THE LIGHT SOURCE CHANGES (MALZBENDER, GELB ET AL. 2001) .....	11
FIGURE 4- PTM DEVICES (DELLEPIANE ET AL. 2006) .....	11
FIGURE 5- THE PORTRAIT OF JEAN DE LA CHAMBRE AT THE AGE OF 33 FROM THE PTM (PADFIELD) .....	13
FIGURE 6-THE SEINE SEEN FROM LA GRANDE JATTE FROM PTM (PADFIELD) .....	14
FIGURE 7- WILLOWS, WITH A MAN FISHING FROM PTM (PADFIELD).....	14
FIGURE 8- PHYSICAL DAMAGE (PADFIELD ET AL. 2005) .....	15
FIGURE 9- PTM PLANNER TOOL (DELLEPIANE ET AL. 2006) .....	16
FIGURE 10: 50 YEAR OLD TEST PAINTING (LIANG ET AL. 2005).....	19
FIGURE 11: VARNISH LAYER AT POINT B (LEFT), NO VARNISH LAYER AT POINT C (RIGHT) (LIANG ET AL. 2005).....	19
FIGURE 12: VARNISH MEASUREMENTS AT POINT D (LIANG ET AL. 2005) .....	19
FIGURE 13: VARNISH MEASUREMENT AT POINT A (LIANG ET AL. 2005) .....	20
FIGURE 14: 18TH CENTURY PAINTING (LIANG ET AL. 2005).....	20
FIGURE 15: TEST ON POINT A (LEFT), TEST ON POINT B(RIGHT) (LIANG ET AL. 2005).....	21
FIGURE 16: ORIGINAL SAMPLES (LIANG ET AL. 2005) .....	21
FIGURE 17: RESULTS OF DIFFERENT IMAGING TECHNIQUES, INFRARED IMAGING ON THE LEFT, INGaAs CAMERA IN THE MIDDLE AND 1300 NM OCT ON THE RIGHT (LIANG ET AL. 2005) .....	22
FIGURE 18- DOUBLE-EXPOSURE HOLOGRAM FROM WOOD (AMADESI ET AL. 1973).....	24
FIGURE 19- HOLOGRAPHIC IMAGES OF PRIMED WOOD THAT SHOW DETACHMENTS (AMADESI ET AL. 1973).....	24
FIGURE 20- HOLOGRAPHIC IMAGE SHOWING DETACHED REGIONS (AMADESI ET AL. 1973) .....	25
FIGURE 21- HOLOGRAM USING THERMAL-DRIFT METHOD (AMADESI ET AL. 1973) .....	26
FIGURE 22: DIAGRAM OF THE PROPOSED SYSTEM (SPAGNOLO ET AL. 2000).....	27
FIGURE 23: FRINGE PATTERN PROJECTED ON A SPECIMEN (SPAGNOLO ET AL. 2000).....	28
FIGURE 24: RECOVERED PLOT (SPAGNOLO ET AL. 2000) .....	28
FIGURE 25: FRINGE PATTERN IN THE SHAPE OF AN EYE (SPAGNOLO ET AL. 2000).....	29
FIGURE 26: 3D PLOT (SPAGNOLO ET AL. 2000) .....	29
FIGURE 27 EXAMPLE OF A CONFOCAL PINHOLE (REZAI 2004) .....	31
FIGURE 28- SETUP OF LSM (KEYENCE 2008) .....	32
FIGURE 29 HOW IMAGE IS OBTAINED IN THE LSM (KEYENCE 2008).....	33
FIGURE 30 VARIOUS RESULTS OBTAINED BY USING LSM (KEYENCE 2008) .....	34
FIGURE 31- 3D VIEW OF THE ORIGINAL AND MODIFIES SURFACE OF CAMEL HAIR BRUSH.....	36
FIGURE 32- HEIGHT MAPS OF MODIFIED SURFACES FOR FOUR BRUSH HAIR SAMPLES .....	37
FIGURE 33- 3D VIEW OF MODIFIED SURFACES OF FOUR BRUSH TYPE SAMPLES .....	38
FIGURE 34- AREA-SCALE PLOT FOR BRUSH HAIR MATERIAL.....	39
FIGURE 35- F-TEST RESULTS FOR AREA-SCALE, RELATIVE AREA ANALYSES FOR BRUSH HAIR TYPES .....	40
FIGURE 36- 3D VIEW OF ORIGINAL AND MODIFIED SURFACES OF ACRYLIC PAINT SAMPLE .....	41
FIGURE 37- HEIGHT MAPS OF MODIFIED SURFACES FOR FOUR PAINT MATERIAL SAMPLES.....	41
FIGURE 38- 3D VIEW OF MODIFIED SURFACES OF FOUR BRUSH TYPE SAMPLES .....	42
FIGURE 39- AREA SCALE PLOT FOR PAINT MATERIAL .....	43
FIGURE 40- F-TEST RESULTS FOR AREA-SCALE, RELATIVE AREA ANALYSES FOR PAINT MATERIALS .....	44

## List of Tables

TABLE 1- TECHNOLOGY AND ITS APPLICATION IN ART .....	3
TABLE 2- ART APPLICATION AND TECHNIQUES USED .....	5
TABLE 3- LIST OF JOURNALS .....	7
TABLE 4- EXPERIMENTAL VARIABLES .....	35

# 1 Introduction

## 1.1 Objective

The objective of this work is to use the applications of surface metrology to address issues in art such as restoration, identification and preservation of art material in art in collaboration with Worcester Art Museum (WAM) and Worcester Polytechnic Institute (WPI) Surface Metrology Lab.

## 1.2 Rationale

This study is important because it can address many questions about issues in the art world. As Phil Klausmeyer from the Worcester Art Museum conservation lab mentioned, art museums receive many paintings that need to be restored but they do not know what the best approach would be for the specific characteristics of painting. In this case, the surface measurements of a painting can help reveal the patterns applied by the artist while painting the artwork and thus the conservator can use this information to follow the patterns and restore the painting. The same idea can be applied to sculptures as well; it would be possible to get roughness measurements, which would help a scientist to recognize what kind of tools were used while carving the stone. Additionally Kvamme and associates were able to use surface metrology techniques for characterization and detection of archeological sites (Kvamme and Kvamme 2001).

What is interesting to us is that, as much of a quick solution this may seem, it is not commonly used, as can be seen from the literature. Surface metrology has been used in many engineering areas to identify properties of materials but it has not been considered as a major tool for art museums.

The project is going to serve as a bridge between art and surface metrology, and will show the importance and success of such surface metrology techniques in art.

## 1.3 State-of-the-art

New methods in surface metrology have shown the ability to measure infinitesimal changes in the surface roughness. For example, an important use for the High Accuracy Resolution Landscape and characterization System, abbreviated as HARLS-CS, measures the topography of the unexcavated

archeological sites. This system uses a multi-sensor blend of geophysical and remotely sensed data sources. Kvamme and associates have been actively involved in the application of a suite of geophysical systems to archeological site characterization and detection (Kvamme and Kvamme 2001). In addition, the scale sensitive fractal calculations were done in order to determine the diet of the animal from the scratch marks on the teeth (Scott, Ungar et al. 2006). F-test of area scales analyses have been used to differentiate the complexities of the imprint and adjacent regions in Determination of the Resolution of a Dinosaur Footprint study (Wallace et al. 2004).

## 1.4 Approach

The approach would be to make measurements on different art surface and analyses using surface metrology techniques. The results of these analyses will be used to produce enough data to write an initial paper and support proposals for further work. Additionally possible collaboration opportunities will arise between WAM and WPI Surface Metrology Lab.

## 2 Literature Review

This section describes the applications of recent technological devices to art conservation. It talks about why technology is important in analyzing art materials as well as what sort of technologies are used. It describes in detail the recent technologies by talking about their algorithms and several experiments and results and then focuses on the surface metrology side of things. The surface metrology tools are explored in the same fashion, by giving detailed explanation of how they work and how they would be used.

### 2.1 Comparison

In the comparison section, the technologies and their various applications in art are compared to provide the reader a brief overview on which technologies exist and how they can be used.

#### 2.1.1 Technical View

The technical view table focuses on the technology itself and its application to art. The most recent technologies are compared and the references to the texts where information on these technologies can be found are given.

**Table 1- Technology and its application in art**

Technique	Application	Reference
<b>Polynomial Texture Mapping (PTM)</b>	<b>Identification of fossils</b>	<i>"Imaging Fossils Using Reflectance Transformation and Interactive Manipulation of Virtual Light Sources"</i> (Hammer et al. 2002)  Hammer, Ø., et al, 2002
	<b>Recording the surface characteristics of paintings</b>	<i>"Polynomial Texture Mapping: a new Tool for Examining the Surface of Paintings"</i> (Padfield et al. 2005)  Padfield, J. et. al, 2005
	<b>Identification of clay and stone writings</b>	<i>"Polynomial Texture Maps"</i> (Malzbender et al. 2001)  Malzbender, T. et. al, 2001

<p><b>Optical Coherence Tomography (OTC)</b></p>	<p><b>Non-invasive examination of paintings, show structure of varnish layer, give information about underdrawings</b></p>	<p><i>“En-face Optical Coherence Tomography – a Novel Application of Non-invasive Imaging to Art Conservation” (Liang et al. 2005)</i></p> <p>Liang, H., et al, 2005</p>
<p><b>Fringe Projection</b></p>	<p><b>Recording modifications on the surface of cultural heritage materials</b></p>	<p><i>“Contouring of artwork surface by fringe projection and FFT analysis” (Spagnolo et al. 2000)</i></p> <p>Spagnolo, G.S., et al, 2000</p>
<p><b>Laser</b></p>	<p><b>Cleaning of artwork, provide information about uncovered layers</b></p>	<p><i>“Excimer laser restoration of painted artworks: procedures, mechanisms and effects” (Georgiou et al. 1998)</i></p> <p>Georgiou, S., et al., 1998</p>
<p><b>Holography</b></p>	<p><b>Deformation measurements for conservation of 2000-yr-old Chinese Terracotta warriors,</b></p>	<p><i>“Deformation monitoring on ancient terracotta warriors by microscopic TV-holography” (Gülker et al. 2001)</i></p> <p>Gulker, G. et. al., 2001</p>

As can be seen from **Error! Reference source not found.**, some of the technologies have more than one use in art. For example, the polynomial texture mapping technique has three uses in the art world and this list can be expanded. We have limited our table to technologies and art applications that are relevant to our subject of surface metrology.

### 2.1.2 Art View

This section is another version of section 2.1.1. It provides the same information, only it is from an art perspective instead of a technical perspective as presented in Table 2.

**Table 2- Art application and techniques used**

Art Application	Technique used	Reference
<b>Measuring surface characteristics, identification /detection of layers</b>	<b>Polynomial Texture Mapping (PTM)</b>	<i>“Polynomial Texture Mapping: a new Tool for Examining the Surface of Paintings” (Padfield et al. 2005)</i>  Padfield, J. et. al, 2005
	<b>Fringe Projection</b>	<i>“Contouring of artwork surface by fringe projection and FFT analysis”(Spagnolo et al. 2000)</i>  Spagnolo, G.S., et al, 2000
	<b>Optical Coherence Tomography (OCT)</b>	<i>“En-face Optical Coherence Tomography – a Novel Application of Non-invasive Imaging to Art Conservation” (Liang et al. 2005)</i>  Liang, H., et al, 2005
	<b>Holography</b>	<i>“Holographic methods for painting diagnostics”(Amadesi et al. 1973)</i>  Amadesi, S., et al., 1973
	<b>Laser</b>	<i>“Excimer laser restoration of painted artworks: procedures,</i>

		<p><i>mechanisms and effects”</i> (Georgiou et al. 1998)</p> <p>Georgiou, S., et al., 1998</p>
<p><b>Conservation/identification of cultural heritage samples</b></p>	<p><b>3-D Spectral Capture and Computer Graphics Rendering</b></p>	<p><i>“Improving Artwork Reproduction Through 3D- Spectral Capture and Computer Graphics Rendering”(Berns and Carlson 2006)</i></p> <p>Berns et. al., 2006</p>
	<p><b>Holography</b></p>	<p><i>“Deformation monitoring on ancient terracotta warriors by microscopic TV-holography”(Gülker et al. 2001)</i></p> <p>Gulker, G. et. al., 2001</p>
	<p><b>PTM</b></p>	<p><i>“Imaging Fossils Using Reflectance Transformation and Interactive Manipulation of Virtual Light Sources” (Hammer et al. 2002)</i></p> <p>Hammer, Ø., et al, 2002</p>
<p><b>Cleaning/ Restoration</b></p>	<p><b>Laser</b></p>	<p><i>“Excimer laser restoration of painted artworks: procedures, mechanisms and effects” (Georgiou et al. 1998)</i></p> <p>Georgiou, S., et al., 1998</p>
	<p><b>Holography</b></p>	

		<p><i>“Holographic Tests on the Ghiberti Panel- The Life of Joseph”</i>(Bertani, Cetica et al. 1982)</p> <p>Bertani et. al. , 1982</p>
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## 2.2 Possible Publishing Resources

In this project, it is also of interest to find possible journals, where our work or similar studies may be published. We have compiled in Table 3, a list of places who would be interested in such work.

**Table 3- List of journals**

<b>Name of Journal</b>	<b>Published Article Examples</b>	<b>Audience</b>
<b>Journal of Archaeological Science</b>	<ul style="list-style-type: none"> <li>• <i>“A comparative study of wall paintings at the Cypriot monastery of Christ Antiphonitis: one artist or two?”</i> Daniilia et. al., 2008</li> </ul>	<i>Archaeologists and scientists interested in advances in the application of scientific techniques and methodologies to archaeology.</i>
<b>Journal of Non-Crystalline Solids</b>	<ul style="list-style-type: none"> <li>• <i>“Study of color and structural changes in silver painted medieval glasses”</i> Pérez-Villaret. al., 2008</li> <li>• <i>“The development of growth rings on ancient glass surfaces: Description and simulation of the weathering”</i> Bianco et. al., 2008</li> </ul>	Solid state physicists, materials scientists, glass technologists
<b>Materials Characterization</b>	<ul style="list-style-type: none"> <li>• <i>“Determination of pigments in colour layers on walls of some selected historical buildings using optical and scanning electron microscopy”</i> Škapin et. al., 2007</li> </ul>	Materials scientists, metallurgists, microscopists, metallographers, mechanical engineers
<b>Journal of Cultural Heritage</b>	<ul style="list-style-type: none"> <li>• <i>“Painting technique and state of conservation of wall paintings at Qusayr Amra, Amman – Jordan”</i> Bianchin et. al., 2007</li> <li>• <i>“XVI century wall paintings in the “Messer Filippo” cell of the tower of Spilamberto: Microanalyses and monitoring”</i></li> </ul>	Scientists concerned with the preservation and the restoration of monuments and works of arts

	<p style="text-align: center;">Ospitali et. al., 2007</p> <ul style="list-style-type: none"> <li>• <i>“The conservation of the Vecchietta's wall paintings in the Old Sacristy of Santa Maria della Scala in Siena: The use of nanotechnological cleaning agents”</i></li> </ul> <p style="text-align: center;">Grassi et. al, 2007</p>	
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## 2.3 Technologies

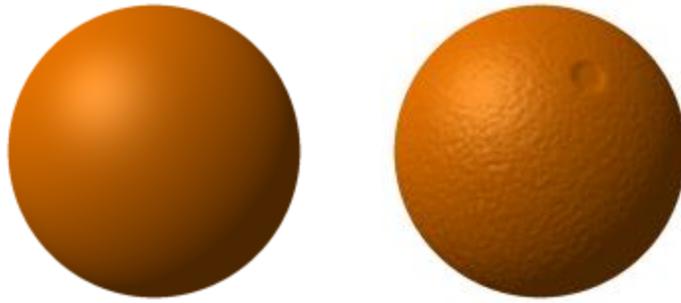
This section describes in detail the technologies that were briefly mentioned in **Error! Reference source not found.** and 2: polynomial texture mapping (PTM), optical coherence tomography (OCT), fringe projection and holography. It talks about the different algorithms and methods used in these technologies, how they are used, certain experiments that are done and their results.

### 2.3.1 Polynomial Texture Mapping (PTM)

One of the methods used in the conservation of artworks is Polynomial Texture Mapping (PTM) developed by Hewlett Packard (HP) Laboratories (Malzbender et al. 2001). Before the development of the PTM technology, other methods were used to record surface characteristics of art pieces, such as traditional texture mapping, bump mapping, raking light photography and laser scanning.

Traditional texture mapping is one of the conventional methods where the image of the object in interest shows some details of its surface properties. Nevertheless if the lighting of the environment where the texture map was captured is different than where the map is being viewed, the surface image looks unrealistic, flat and smooth (Malzbender et al. 2001).

In order to solve the problem with the texture mapping Blinn presented a new method called bump mapping in 1978. Blinn determined that the surface normal on a rough texture has a relationship with the light reflected from the same location. He developed a method where “a texturing function which performs a small perturbation on the direction of the surface normal before using it in the intensity formula” (Blinn 1978). When the texturing function is added to the smooth surface function, the wrinkled surface function was obtained (Blinn 1978) . Figure 1 represents an image of an orange without the bump mapping and with the bump mapping function respectively.



**Figure 1- An orange without bump mapping and with bump mapping [15]**

Even though bump mapping technique gives detailed surface roughness pictures, it is not highly preferred since it is difficult to obtain maps of the large objects due to self-shadowing and intra-object interreflections (Malzbender et al. 2001) .

Raking light technology can easily be applied to the large sized objects as opposed to bump mapping technique. In this method a beam of strong light is “shined across the surface” of the object in interest. The texture of the surface can easily be observed from the shadows obtained (Padfield). The figure2 shows the details recorded by the raking light photography method used on the painting.



**Figure 2- In these photographs, lifting paint and cracked panel can be seen (Hawkinson 2003)**

However, two problems with this method exist. In raking light photography, the light is usually shined to the object from one or two angles. Since the texture information obtained is robustly

depending on the position of the lighting, only one or two area can be observed. Therefore, the surface features of the whole objects cannot be displayed using this method. Additionally raking light technique is not suitable for repeatability and reproducibility since the position of the light reflected cannot be documented precisely. Hence making accurate comparisons of photographs created before and after an object has gone a physical change might be challenging (Padfield et al. 2005)

Laser scanning (Taylor et al. 2002) and imaging under structured light (Guidi et al. 2003) methods are also available. Even though these methods are more quantitative and reproducible, equipment needed is expensive and large, also they cannot store data in large quantities (Padfield et al. 2005). For example in the study of Leonardo da Vinci's Adoration of Magi, could only been examined in low resolution. The size of the painting was 240cm x 240cm and if the data file were obtained in high resolution only a small area of the artwork (58cm x 77cm) (Guidi et al. 2003).

#### **2.3.1.1 Working Principles**

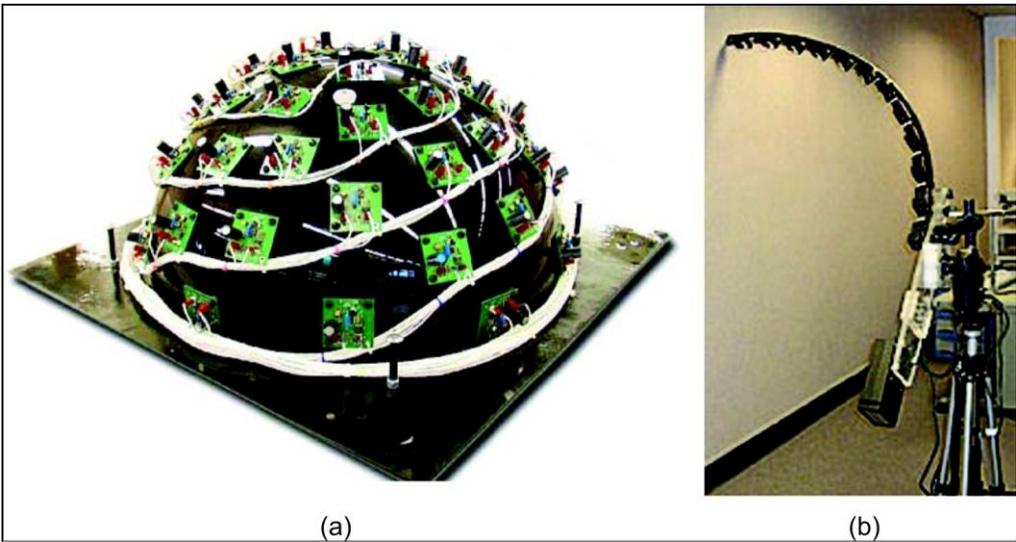
In order to overcome the difficulties cited above, PTM applications are used in three-dimensional (3D) computer graphics, and also in two-dimensional 2D image processing applications (Malzbender, Gelb et al. 2001). PTMs can either be produced analytically from a mathematical model or real images of a surface under varying light conditions (Padfield et al. 2005).

PTM method does not consist of modeling of complex geometry or bump maps; it is a purely image-based technique. The procedure consists of taking several images of an object from the same point of view under an illumination projected from different directions. Therefore texture map of the object where the surface effects, either due to the direction of the light source or the surface characteristics, is displayed (Malzbender et al. 2001). On Figure 3, the comparison between the PTM method and traditional mapping techniques can be viewed as the location of the light sources changes.



**Figure 3- Comparison between the PTM (top view) and traditional mapping techniques (bottom view) as the location of the light source changes (Malzbender, Gelb et al. 2001)**

The PTM instrumentation contains a hemisphere framework and a static camera. Light sources that are either manually placed or mounted on the framework generate illumination from different directions. While using the camera is mounted in the apex of the dome (Malzbender et al. 2001). Figure 4 shows two different PTM devices developed at the HP Laboratories. Figure 4a is a PTM acquisition dome, 90 cm diameter, containing fully automated 50 light sources without a camera dome (Malzbender et al. 2001). It can be used for small objects, nearly 15 cm. Figure 4b, which is a PTM acquisition arc, with 90 degree angle and 150 cm diameter. It can be used to capture pictures of slightly bigger objects. There are 12 strobe lights mounted on the arm and can rotate 360 degree around the camera, which is placed at the center of the arc (Dellepiane et al. 2006).



**Figure 4- PTM Devices (Dellepiane et al. 2006)**

Normally 24-50 images of the object are taken under previously determined lighting condition. Once the images are captured, the data collected and the positioning of the lamps are processed by a software and the model of the object is produced (Malzbender et al. 2001). Before taking the images of the object in interest, photographs of a white Teflon sheet, illuminated with one lamp at a time are taken in order to set the reference values for coloring the digital images for calibration purposes (Padfield et al. 2005).

The biggest advantage of the PTM is giving the viewer the opportunity to observe the image on the computer screen under different lighting conditions. The viewer can see the image taken at a normal light and then stimulate the point light source rotating 360 degrees around the object to see the different texture effects on the object (Padfield et al. 2005).

### **2.3.1.2 PTM Applications**

PTM technology has been used in the art conservation world for numerous different applications. At the National Gallery and Tate in London, scientific department researchers documented two different studies on the paintings in collaboration with Tom Malzbender from HP Laboratories. One of their studies involves recording impasto<sup>1</sup> and planar distortion. The second study examines canvas or panels after they have been subjected to physical alternations like dropping or flattening of impasto (Padfield et al. 2005).

During their studies, the scientists had small paintings that could fit under the “dome” of PTM device. Some of the paintings investigated were Portrait of Jean de la Chambre at the Age of 33 (16.8 X 20.6 cm<sup>2</sup>) by Frans Hals, The Seine seen from la Grande Jatte (25.7 x 15.7 cm<sup>2</sup>) by Georges Seurat and Willows, with a Man Fishing (27.0 x 21.6 cm<sup>2</sup>) by Jules-Louis Dupré. By examining the PTM created for Portrait of Jean de la Chambre at the Age of 33, painted between 1580-1666, it could be understood that the art piece was done on a wooden panel. The grain pattern on the wooden plate is noticeable in the PTM image. Also it could be noticed that the artist used a thin layer of painting hence the texture of the panel is obvious to the viewer. Additionally it is possible to observe Frans Hals’ characteristic brush

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<sup>1</sup> Texture due a thick application of paint. [http://www.tki.org.nz/r/arts/visarts/glossary\\_e.php#i](http://www.tki.org.nz/r/arts/visarts/glossary_e.php#i)

strokes on the portrayed man's cheek, ear and forehead (Padfield et al. 2005). The figure 5, taken from the International Council of Museum, Committee for Conservation webpage, shows the image of the painting created with the PTM.



**Figure 5- The Portrait of Jean de la Chambre at the Age of 33 from the PTM (Padfield)**

The other painting observed by National Gallery and HP Laboratories was *The Seine seen from la Grande Jatte* by Georges Seurat. In that study, the scientists recorded Pentimenti<sup>2</sup>, which are often observed through infrared reflectography or X-radiography (Padfield et al. 2005). As it can be seen on the Figure 6, from the International Council of Museum, Committee for Conservation webpage, there are triangular brush strokes on the left side of the painting that imply the existence of a sailing boat, but the boat does not exist at the final painting.

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<sup>2</sup> Changes in composition which a painter makes while producing a painting ([art.abbottpages.com/glossary.html](http://art.abbottpages.com/glossary.html))



**Figure 6-The Seine seen from la Grande Jatte from PTM (Padfield)**

Finally, surface deformation of the canvas, can be seen in Willows, with a Man Fishing, Figure 7, from the International Council of Museum, Committee for Conservation webpage. Craquelure<sup>3</sup> can be seen in the upper parts of the painting, which notifies that the painting has been subjected to a physical damage (Padfield et al. 2005).



**Figure 7- Willows, with a Man Fishing from PTM (Padfield)**

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<sup>3</sup> Fine pattern of cracks formed on old paintings. It is sometimes used to detect forged art, as craquelure is a hard-to-forge signature of authenticity. ([en.wikipedia.org/wiki/Craquelure](https://en.wikipedia.org/wiki/Craquelure))

After the first half of the study on PTM images of the three paintings were completed, mock-up paintings were made for further examinations. By illuminating the mock-up paintings from different angles; “flattened impasto, transferred canvas weave, local distortions, texture of underpaint, dents and cracks” are observed. For instance, for one of the mock-ups, a sample was scratched from the behind. Pictures of the canvas were taken with the PTM before the distortion and after the distortion. Figure 8 shows that the physical damage made on the painting cracked the paint as well as the cracked canvas. The first Picture displays the image of the mock-up painting before the distortion,, the second one shows the distorted canvas from the PTM and the last one is the subtraction of the “after” image form the “before” image (Padfield et al. 2005).



**Figure 8- Physical damage (Padfield et al. 2005)**

PTM also has many applications beside the investigations of paintings. PTM are used in several Cultural Heritage researches in order to examine the clay cuneiform tablets under different light conditions (Malzbender et al. 2001). This method has also been used in Paleontology to observe high relief fossils (Hammer et al. 2002). Concoidal knapping fractures on ancient stone tools were recorded using the PTM techniques. Moreover, PTM methods can be used in different areas such as “virtual exhibition” (Mudge et al. 2005), investigative work [Morton 03], and actor performances (Wenger et al. 2005).

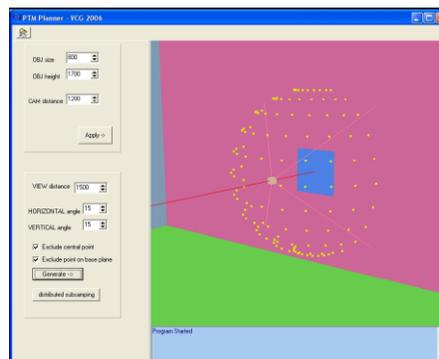
### **2.3.1.3 PTM for bigger objects**

One of the problems with the PTM equipment is that only small objects can fit under the dome of the device. Additionally placing a valuable and unique art piece under many strong lights may not always be the best idea. Also, scientists are working literally on the painting placed under the PTM dome

and they can have a medical emergency like nose bleeding. Therefore placing the painting under the dome of the PTM and leaning on the art piece may cause several problems that are mostly impossible to solve.

In order to solve the problem related to the size of the object a new technique has been developed by ACM Trans. Graph. in Italy (Dellepiane et al. 2006). Since the purpose of their study was to measure medium and large sized objects on the PTM, they used a “virtual” light dome instead of using the framework designed by HP Laboratories and explained previously in the report. Their experiment consists of three steps: 1. Acquisition planning, 2. Acquisition, 3. Data processing. Since placing the object under previously determined light sources was a big part of a successful PTM setup, they created software called PTM Planner. Once inputs: such as the dimensions of the object, height from the floor and distance to the camera, were given the PTM planner gives the array of light and the angles where the light source should be placed. Figure 9 shows a print screen shot from the software developed.

The yellow dots on Figure 8 represent different locations of the light sources created by parallel-meridian grid. It is possible that they do not form a perfect sphere and there might be some points, generated by the PTM planner tools that are below the floor. The user can manually turn off the points that are hard to locate the light source (Dellepiane et al. 2006).



**Figure 9- PTM Planner tool (Dellepiane et al. 2006)**

This type of setup was necessary because the PTM collecting dome created by the HP labs and explained previously was only applicable for the measurements of the smaller objects (15cm). However, PTM collecting arc, developed by the HP labs, was able to take bigger measurements than the dome but still it was limited to a smaller diameter than the “virtual” light dome developed ACM Trans. Graph. in

Italy. Also in order to capture pictures of bigger objects, more powerful light sources than the ones mounted on the arc were needed (Dellepiane et al. 2006).

The steps of the procedure for the picture acquisition are easy to follow; first, the inputs are entered into the PTM Planner tool and “virtual” dome positions for the light source are generated. Once the camera is mounted on the tripod, shutter speed<sup>4</sup> and aperture<sup>5</sup> values are decided and kept constant for all of the photos in order to have a controlled experiment. The light source is positioned according to the data obtained from the PTM Planner tool and one picture is taken for each different light location. Since it is important and almost impossible to keep the camera stable during the whole experiment, a freeware tool is used to align the pictures taken before building the PTM. After creating the PTM of the large art piece, two tools based on the Java PTM Library developed by Clifford Lyon. One of the tools, called HPTM (huge PTM) Builder gets the PTM image and cuts it into smaller sub-PTMs to make it easy to handle for the viewer. The second tool, called HPTM Browser browses the sub-PTMs following a multi-resolution scheme (Dellepiane et al. 2006)

### 2.3.2 Optical Coherence Tomography (OCT)

Another technology used by art conservers is optical coherence tomography (OCT). OCT is actually a technology used for biological examinations, used mostly for imaging of eye and other biological tissues. However, it was recently applied to the art world by Ophthalmic Technologies, University of Kent, Nottingham Trent University and National Gallery of London. For its art application, two different optical coherence tomography systems working at different diameters are used (Liang et al. 2005). In the sections below, we will first discuss how optical coherence tomography system was created and used for biology and then we will talk about how it applies to art and show examples of its power.

#### 2.3.2.1 Background

Optical Coherence Tomography was first developed to produce to examine cross sectional layers of biological tissues. It produced a two dimensional image of the area that was viewed. It was mostly used for eye examinations, especially of the retina and the coronary artery [Huang et al. 1991]. OCT was preferred due to its high resolution (Tearney et al. 1997).

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<sup>4</sup> Measure that controls the exposure time; the slower is the shutter speed, the longer is the exposure time. ([www.microsoft.com/windowsxp/using/digitalphotography/glossary/default.msp](http://www.microsoft.com/windowsxp/using/digitalphotography/glossary/default.msp))

<sup>5</sup> the size of the opening in the lens. In combination with variation of the shutter speed, and variation in film speed (ISO), this will regulate the photograph's degree of exposure to light. ([en.wikipedia.org/wiki/Aperture](http://en.wikipedia.org/wiki/Aperture))

On the art side, examination of paintings had been going on for years. However, the techniques that were used were mostly invasive, meaning that it might have damaged the painting in question. The techniques included taking small samples from the paintings and placing them under a microscope (Liang et al. 2005). This technique was limited since the samples that could be taken from a painting without ruining it was limited. That is why there was a search for methods to perform different analysis on the paintings without damaging the painting.

Recently, OCT was used by the art conservators. It proved to be an important tool since it was possible to work with it with a safe distance away from the paintings. It also provided high-resolution images of the area under question as well as giving information about its depth therefore making it possible to distinguish a painting's underdrawings or information about the varnish.

### **2.3.2.2 Methods**

OCT systems used in art conservation use B-scans and C-scans from reflectivity profiles (Liang et al. 2005). The procedure is similar to the procedure of a confocal microscope, which will be explained in the surface metrology section, however depth scanning is much slower in OCT than the microscope. Slower scanning causes a more thorough scan, resulting in better outcomes that show what is beneath the surface of the painting. The difference between the C-scan and the B-scan is that C-scan is generated at a constant depth whereas the B-scan is generated at depths that vary. OCT systems can operate at 850nm and 1300nm wavelength of light (Liang et al. 2005). It is possible to work with both systems from two or three centimeters away from the painting, and the result could give you a depth resolution of 18 to 20 micrometers. While measuring samples, 1300 nm system is used first since it gives a picture of a larger area. 850nm system is used occasionally to make better comparison between two samples (Liang et al. 2005).

### **2.3.2.3 Varnish Test Experiments**

By using OCT, it is possible to distinguish between the varnish layers of a painting. To test this, two tests were performed. The first painting is a 50 year old painting, which has half of the aged yellow varnish removed and two different kinds of varnishes were applied. The original picture of the painting can be seen in Figure 10. The letters on the painting show different varnish layers. Point A has the original varnish, Point B has the original varnish removed and new varnish applied, Point C has no varnish and point D is the boundary between the old and the new varnish. The first measurements were done by using a 1300nm OCT system. The results showed that there was a thin layer of varnish at point

B and no varnish on point C. The images can be seen on Figure 11. Figure 12 shows the result of measurement done on Point D, which was the boundary between the old and the new varnish layers. From Figure 11 it is easy to see the two different kinds of varnishes. Figure 10 is important for art conservators since it gives a good idea of what kind of conservatory process the painting has gone through and it can work as some sort of a documentation of the process (Liang et al. 2005).



Figure 10: 50 year old test painting (Liang et al. 2005)

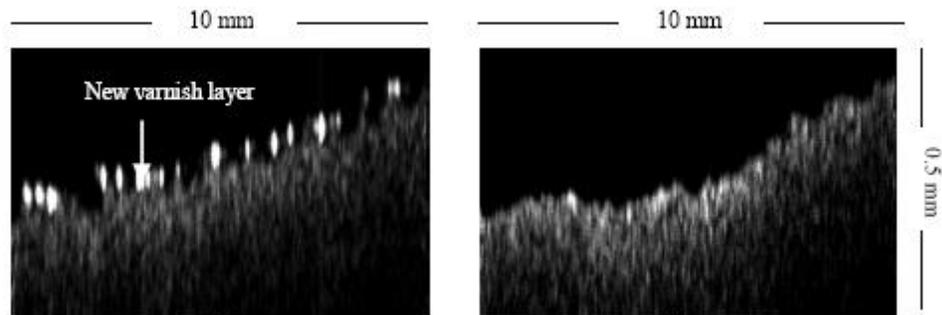


Figure 11: Varnish layer at point B (left), no varnish layer at point C (right) (Liang et al. 2005)

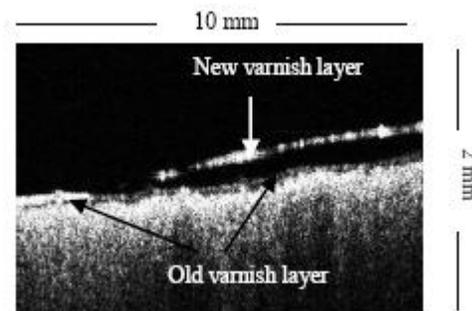
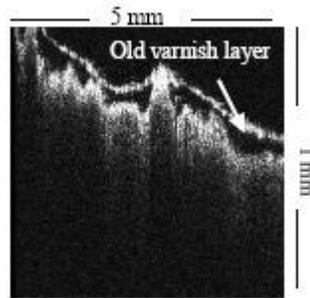


Figure 12: Varnish measurements at point D (Liang et al. 2005)

The Figures 11 and 12 show the success of 1300 nm OCT system. It gives a good enough measurement to differentiate between two different varnish layers and it shows if there is varnish applied to the painting or not. The last measurement done on this painting was by using the 850nm OCT and it was used on Point A. The result gives an idea of the thickness of the old varnish and reinforces the measurements that were done previously.



**Figure 13: Varnish measurement at Point A (Liang et al. 2005)**

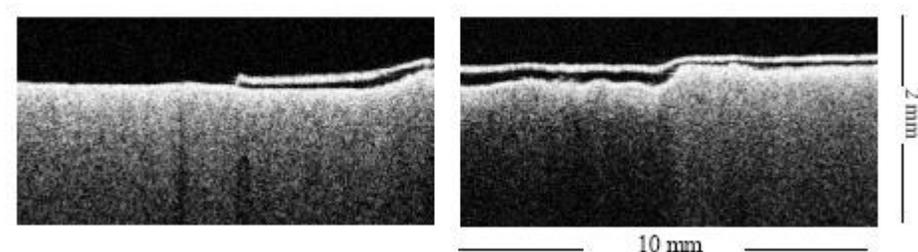
Another set of measurements were done on an 18<sup>th</sup> century painting which had lost some of its varnish and its actual painting, and where the canvas was showing. A picture of the original painting with the test points can be seen on Figure 14. Point A shows two different varnish layers where the upper part has some varnish applied and the lower part does not. Point B shows the new varnish applied after some of the original painting was lost.



**Figure 14: 18th century painting (Liang et al. 2005)**

Both measurements on the two points described above were done by using the 1300nm OCT system. The measurement on point A clearly shows how there is no varnish at the lower end of the

sample. Measurement on point B shows the new varnish applied to the painting (Liang et al. 2005). Both results are shown in Figure 15.



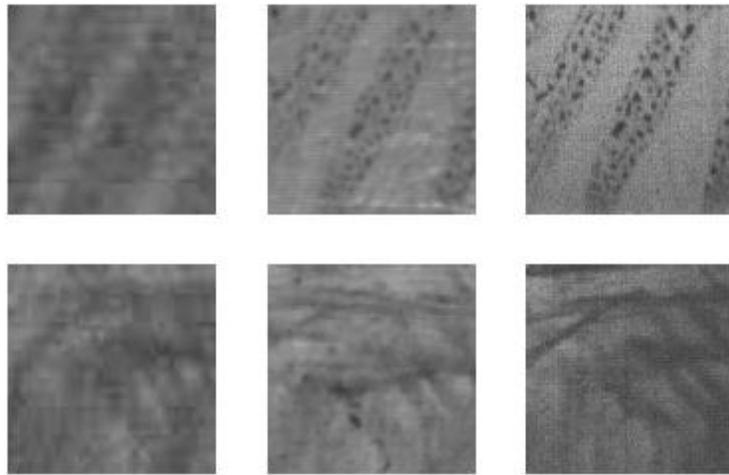
**Figure 15: Test on point A (left), test on point B(right) (Liang et al. 2005)**

#### **2.3.2.4 Underdrawing test**

Underdrawings are the sketches or drawings that the artist makes prior to painting the painting. The artist uses underdrawings to guide his painting. He can also make changes to the painting and not follow his underdrawings at all. Study of underdrawings remains important to art historians and art conservators because it enables them to study the thought process of the artist. Usually museums use infrared imaging of the paintings to detect underdrawings. However, museums also started to use InGaAs cameras, which provide better information about the underdrawings than infrared imaging. (Liang et al. 2005)The most recent technique in the study of underdrawings is the use of OCT system. Figure 16 shows the two original samples that went through the three different systems to study its underdrawings. Figure 16 shows the results of these tests. The first images on the left on Figure 17 is taken by using infrared imaging, the ones in the middle by using InGaAs cameras and the ones on the right by using a 1300nm OCT system (Liang et al. 2005).



**Figure 16: Original samples (Liang et al. 2005)**



**Figure 17: Results of different imaging techniques**, infrared imaging on the left, InGaAs camera in the middle and 1300 nm OCT on the right (Liang et al. 2005)

As can be seen from Figure 17, 1300nm OCT system provides the most detailed image of the underdrawings. The result is most remarkable for the first sample since absolutely no trace of the underdrawings is visible from the original painting. Figure 17 also shows how insufficient it was to use infrared imaging to study underdrawings. The use of more advanced imaging technologies such as OCT definitely helps art historians and improves the quality of research done on the artist or on the painting.

#### **2.3.2.5 Conclusion**

The experiments done by Liang, Gomez, Pedro and Saunders show that Optical Coherence Tomography is a non-invasive technique for study of paintings. It is most helpful for art conservators to give them an idea about what the painting has gone through in terms of conservation with varnishes. It is also helpful to art historians because it provides useful information about the underdrawings of a painting, which gives the art historian an idea about the thought process the artist has gone through. OCT provides two types of measurements that are both important: cross-sectional and in-depth. These measurements are important for the previously mentioned studies.

#### **2.3.3 Holography**

Holography is a rather older method for doing measurements on paintings and analyzing them. It is possible to find articles related to holography and paintings dating back to 1970s. Application of holography to art started with the same problems as OCT: the previous testing methods could damage

the painting. In the next sections, we will discuss how holography techniques were applied to art at the beginning and we will follow its development throughout the years.

### **2.3.3.1 Background**

Holography methods were used to do a damage analysis. The surface that was analyzed first was wood. More of the recent holography techniques are display holography and holographic interferometry. Holographic interferometry is the holographic method that was used previously on wood, only with updated tools. The main targets of holographic analysis are the paintings that suffer from continual adjustment processes due to periodic variations in environmental conditions (Boone and Markov 1995).

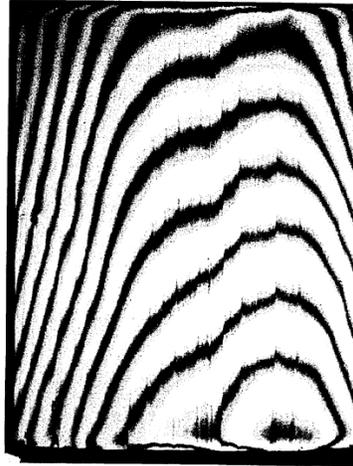
### **2.3.3.2 Method**

Holography consists of a two-step image-forming process. In the first step, image coming from the object is recorded on a photosensitive medium by interfering with light coming from the laser. In the second step, light from the laser alone illuminates the object and an exact copy of the object created. Aim of this technique is to compare the light scattered by the object at one time from different locations or at different times from one location (Boone and Markov 1995). If the object went through any displacements then fringes will appear in the image and we will be able to detect them. This method is advantageous because of its sensitivity and the fact that it does not touch the surface while doing measurements.

Classical holography relies on camera usage and light grabber instead of light-sensitive media for storing the information. However, nowadays a charge coupled device (CCD) array is used, along with a frame grabber, to store information about the waveform. ESPI, electronic speckle pattern interferometry has one disadvantage though and that is the fact that all information about the object is lost. We cannot get a 3D view or anything when we use this ESPI technique with CCD arrays. Whenever there is a need for a concrete image of the object then classical holography methods are used, however ESPI has many engineering applications like image processing and that is why it is preferred in the recent experiments.

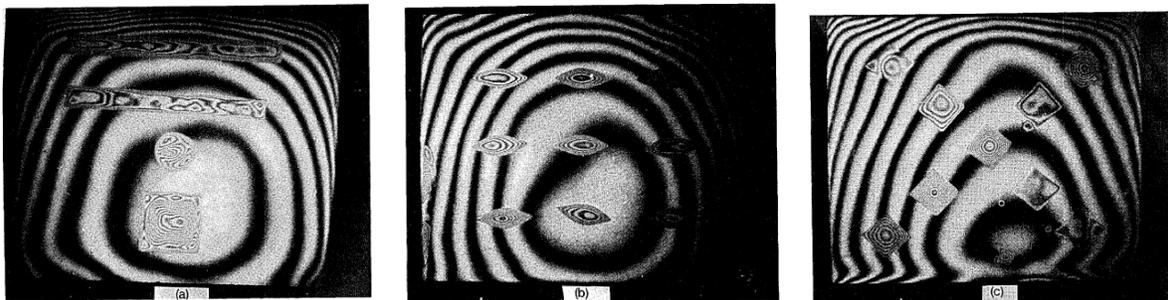
### 2.3.3.3 Experiment and Results

For paintings on wood, the first test that was done was on unprimed wood. The wood was first heated to 40°C and as it was cooling down, double-exposure holograms were made with two minute intervals. Figure 18 shows a sample of the resulting image (Amadesi et al. 1973). You can see from Figure 18 that the pattern is affected by the grains in the wood. This will become an important factor when the tests are done on primed wood.



**Figure 18- Double-exposure hologram from wood (Amadesi et al. 1973)**

The following experiments were done to show the detachment of paintings were carried on primed wood surfaces. The models created had priming layers and detachment of a painting was forced upon it by adding plastic sheets. Experiments were done so that it would take temperature and ambience into account (Amadesi et al. 1973). The results are shown in Figure 19. The detached regions can be seen in the forms of squares and other shapes in the images.



**Figure 19- Holographic images of primed wood that show detachments (Amadesi et al. 1973)**

Another experiment was done on an actual Italian panel painting to look for detachments. Again, double-exposure holography proved to give the best results. From the images, it is possible to see the detachments since fringes depart from their local mean behavior (Amadesi et al. 1973). The method that was used to get the image in Figure 19 called ambient-drift method. Another holography technique is the thermal-drift method and that will be used in the next set of tests. The surface of the painting was again heated up to 40°C and it was left to cool down. The tests were done as it was cooling down. Figure 20 shows the result of the thermal-drift method. If you compare Figure 19 and Figure 20 you can see that it is easier to detect detachments with thermal-drift method rather than ambient-drift method. The abnormalities that are clearly visible in Figure 20 show the detachments. Another important result of these tests is their reproducibility, which makes this technique a valid tool for studying the state of conversion of a painting over time (Amadesi et al. 1973).



**Figure 20- Holographic image showing detached regions (Amadesi et al. 1973)**



**Figure 21- Hologram using thermal-drift method (Amadesi et al. 1973)**

#### **2.3.4 Fringe Projection**

Fringe projection is another method used by art conservators and art historians. It works as a diagnostic method to see the effects of time and other factors on the surfaces. In the following section, we will explain how fringe projection works and give examples of some of the studies done by art conservators.

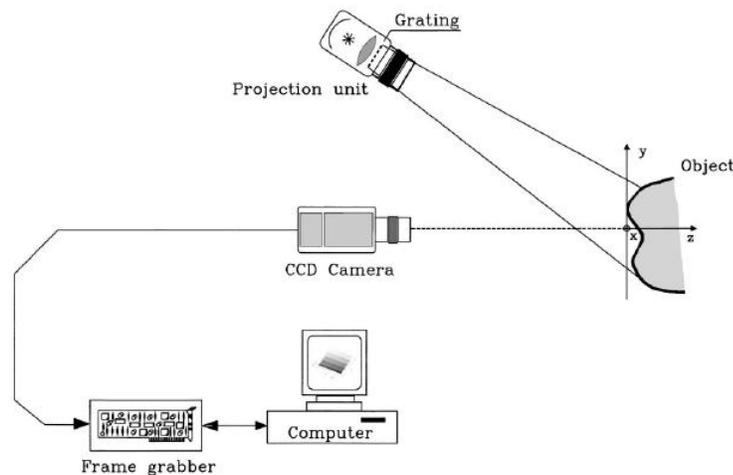
##### **2.3.4.1 Background information**

Even though there has been an increase in the interest of cultural heritage protection; cultural heritage materials are in more danger than ever before. Some of the threats to artworks include population growth, urbanization and natural disasters (Spagnolo et al. 2000). Therefore, to do research on cultural heritage materials, scientific methods are needed. Optical methods have been and still are one of the most popular ways of examining the paintings and other materials. Measurement of surface shapes by optical contouring methods is based on different principles including triangulation, photogrammetry and holography (Spagnolo et al. 2000). Up to the year 2000, photogrammetry was one of the rather popular techniques used. However, its downsides include complexity of measurements and the high cost. Fringe projection technique uses a simpler design, robust software and portable equipment so we think that it might become one of the commonly used techniques.

### 2.3.4.2 How it works

Fringe projection performs artworks profilometry by the projection of a grating onto the surface to be analyzed. Then a quantitative evaluation of the contour is obtained by performing Fourier analysis and phase unwrapping algorithm (Spagnolo et al. 2000).

The system is shown in Figure 22. The CCD camera should be a high-resolution camera to create enough data points on the surface. Images taken by the camera are then captured by a frame grabber and processed by a computer that is connected to the system.



**Figure 22: Diagram of the proposed system (Spagnolo et al. 2000)**

You can see from the figure that the setup of the system is not complex. However, there is a lot of math behind this simple system that includes taking Fourier transforms, taking phases into consideration and a lot of geometry. The actual algorithm for this system is thus long and tedious. Instead of diverging from the main topic in the section, we will present a detailed algorithm in the appendix section and an explanation can also be found in the cited paper of Spagnolo (Spagnolo et al. 2000).

### 2.3.4.3 Experimental Results

Before working with real paintings, Spagnolo and his colleagues worked on some experimental data first. Figure 23 shows the fringe pattern projected on a “specimen with calibrated steps of 20  $\mu\text{m}$ ” and Figure 24 shows the recovered plot (Spagnolo et al. 2000)

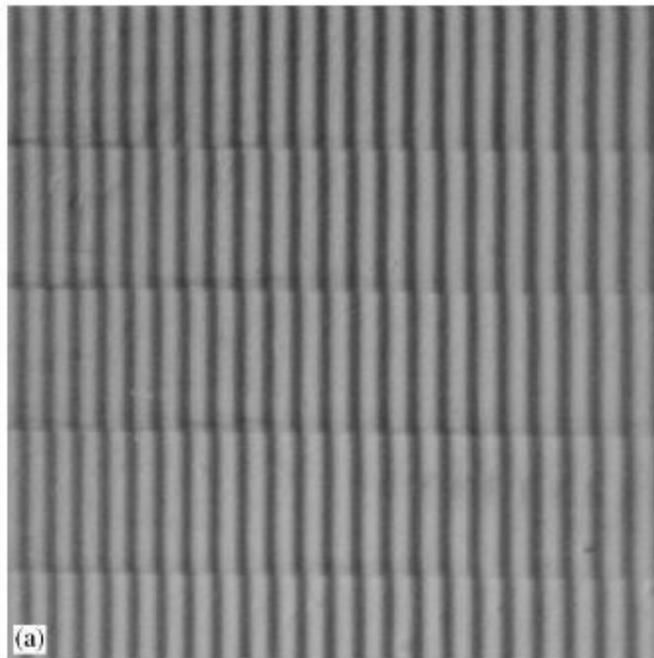


Figure 23: Fringe pattern projected on a specimen (Spagnolo et al. 2000)

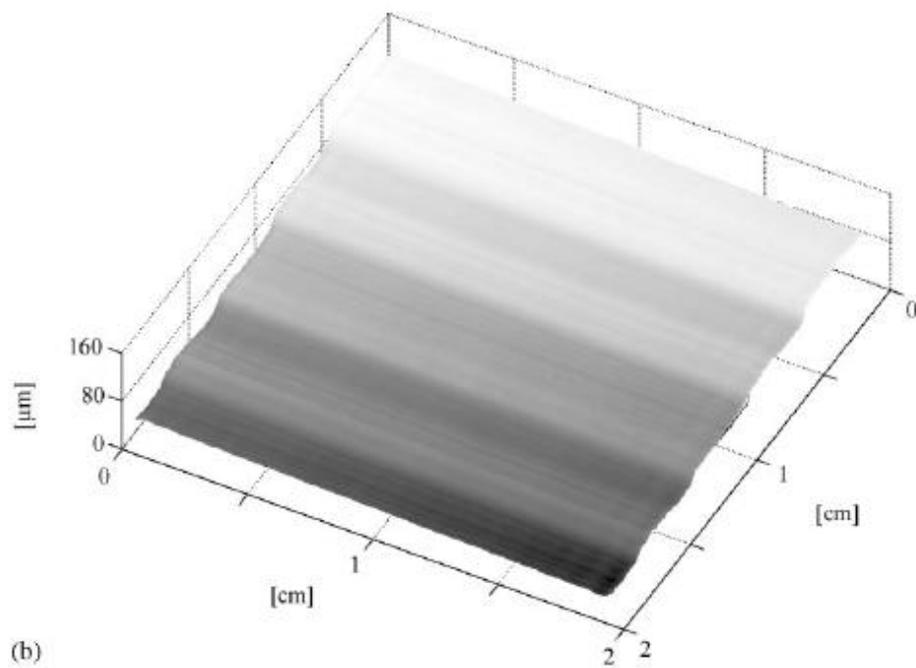
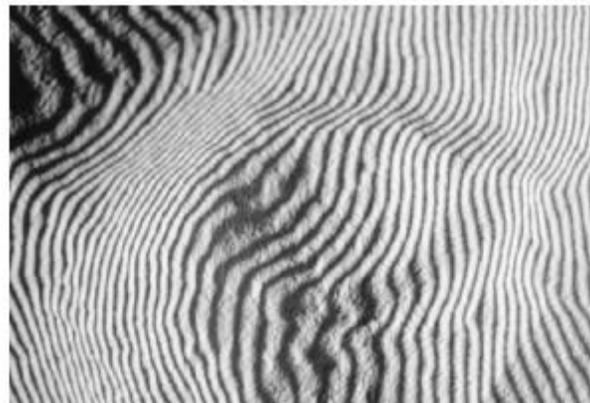


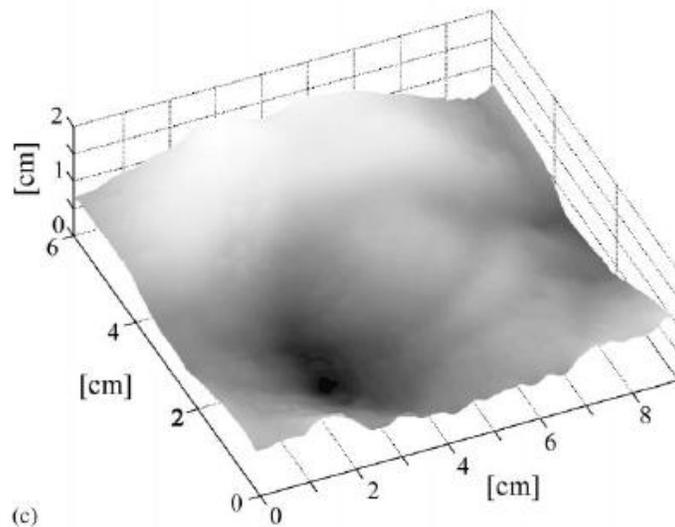
Figure 24: Recovered plot (Spagnolo et al. 2000)

Figure 24 shows different heights of the surface. We can conclude from this result that fringe projection is indeed an effective way of making surface measurements. Extra tests were done on real art work to show how this technique can be used. Some of these tests will be presented below.

One of the most impressive tests that were done was on the marbled statue St. Matthew by Michelangelo. The test was done on one of its eyes. Figure 25 shows the fringe pattern that shows the shape of an eye and Figure 26 shows the 3D plot of the eye.



**Figure 25: Fringe pattern in the shape of an eye (Spagnolo et al. 2000)**



**Figure 26: 3D plot (Spagnolo et al. 2000)**

In Figure 25, it is clear that the test was done on an object in the shape of an eye. The fringe projection makes it possible for us to understand this. After the image was analyzed by the computer program by using the fringe projection algorithm and the corrections were made, the 3D plot of Figure 26 was created. Figure 26 shows that even though the surface may seem smooth it actually is not and it gives another dimension to the surface that we see.

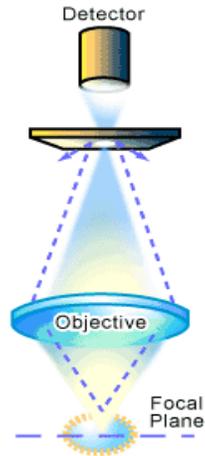
One of the major advantages of fringe projection is that it is relatively simpler to study large objects. It is possible to change the sensitivity of fringe projection by changing the grating pitch or the illumination angle. A shortcoming of this method is that it can only be applied to flat surfaces (Spagnolo et al. 2000)

## **2.4 Surface Metrology Techniques**

In the previous section, methods that art conservators use to distinguish between art pieces and to confirm authenticity were discussed. This section describes the techniques that surface metrologists use in their efforts to characterize surface textures. The two main techniques that we will be focusing on are confocal microscopy and use of laser scanning microscope.

### **2.4.1 Confocal Microscopy**

Confocal microscopy is one of the most widely used techniques in surface metrology as well as in other various fields. The reason it is called confocal is that the microscope has two lenses that have the same focus point, just as the name might imply. It is different from a regular microscope in the sense that there are pinholes that allow light only from the plane of focus to reach the detector as Figure 27 shows (Rezai 2004).



**Figure 27 Example of a confocal pinhole (Rezai 2004)**

This technique allows only the light that is in focus to reach the detector and hence produces excellent quality images. Another variation of this technique is that the position of the focal plane can be changed, or the object can be moved, to create images of the object from different angles and with different depths, which provide a 3D image of the object. Computerized software is used to construct the 3D image of the object (Rezai 2004).

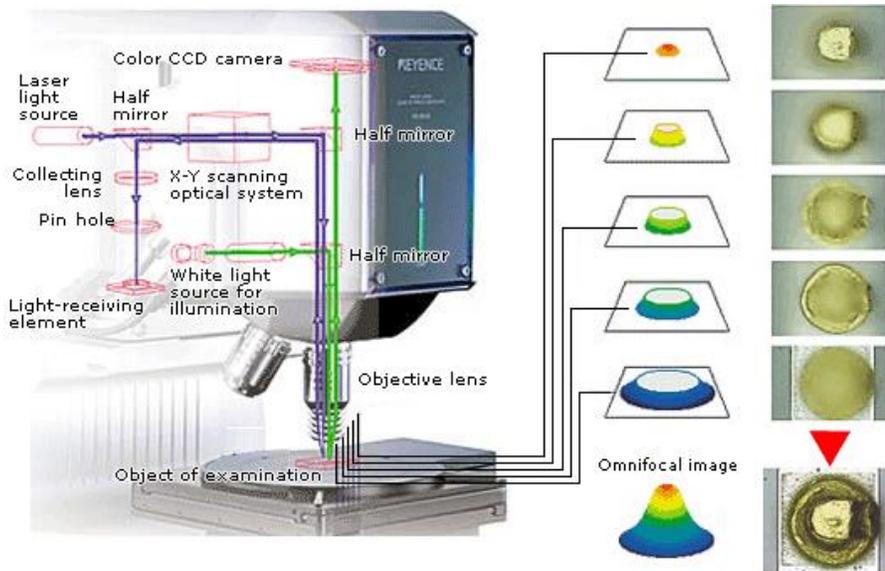
A major advantage of confocal microscope over a regular microscope is the noticeable improvement of the quality of images and the increase in resolution of the images. Confocal microscopes also have a higher sensitivity due to highly sensitive light detectors. Another important advantage of a confocal microscope is that it can produce 3D images of the object whereas a regular microscope only produces a 2D image, not giving any information on the depth of the object.

#### **2.4.2 Laser Scanning Microscope**

Laser scanning microscope (LSM) or sometimes referred to as the scanning laser microscope (SLM) is a type of microscope that is commonly used for making roughness measurements. Keyence is one of the key companies that produces different kinds and high quality laser scanning microscopes.

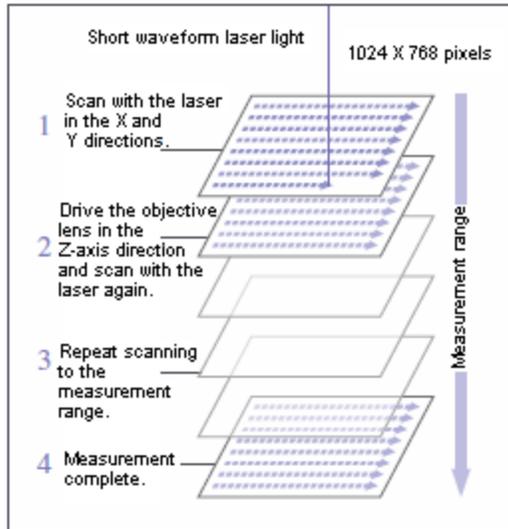
An important feature of the laser scanning microscope is that it combines the convenience of an optical microscope, high definition and ultra depth feature of an SEM and the shape measurement of a roughness gauge (Keyence 2008). It also allows for a color examination of the object in question.

To fully understand how an LSM works, we investigated an LSM that Keyence has produced, VK-9700. The measurement principles and the methods used in this LSM is the same on principle to the other LSMs in the market. The main measurement principle that lies behind the LSM is the use of two different light sources, a short waveform laser light source and a white light source. This enables the user to obtain a lot of necessary information about the object. Figure below gives detailed information on how LSM works.



**Figure 28- Setup of LSM (Keyence 2008)**

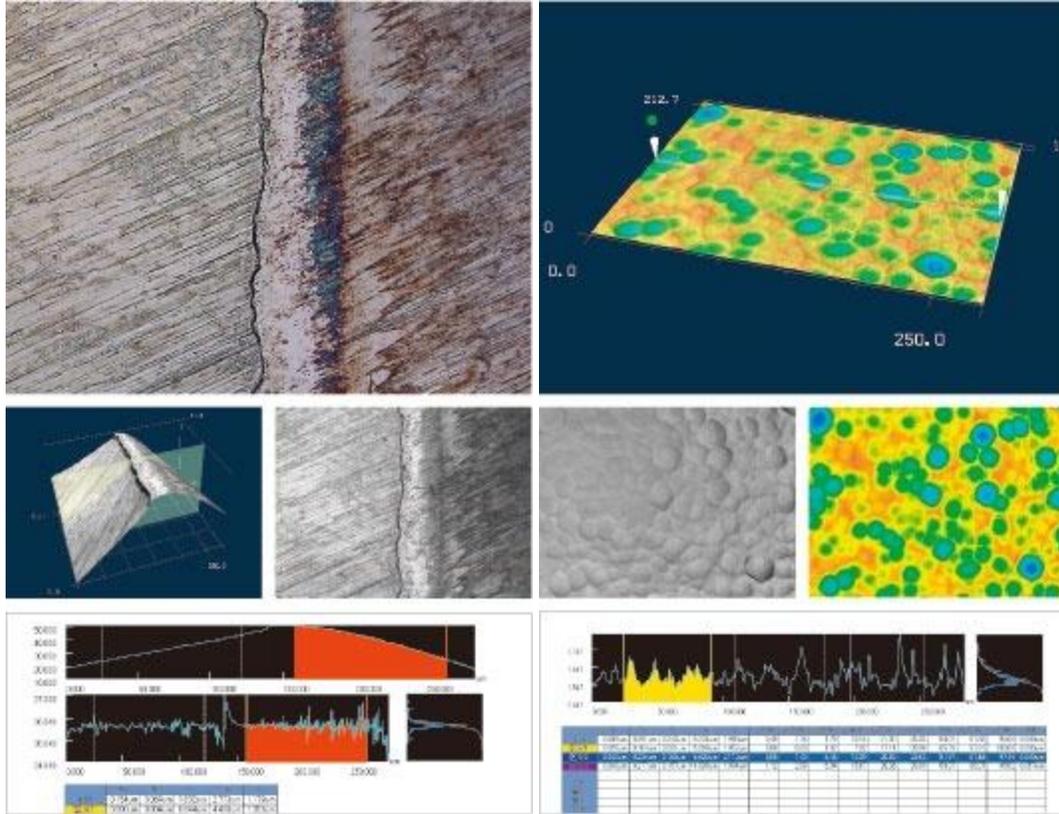
This particular microscope scans the surface of the microscope by using a light beam and an X-Y scan optical system (Keyence 2008). When light is projected on to the surface, light receiving elements detect reflection off of each pixel. Upon this, driving the object lens in the Z-axis allows the user to obtain information about the height. The colored image is obtained by using a CCD camera. The figure below describes the process of obtaining an image in the LSM (Keyence 2008).



**Figure 29 How image is obtained in the LSM (Keyence 2008)**

An advantage of LSM is that it uses a fine linear scale while obtaining the measurements. The linear scale is of 0.001 micrometers. This LSM also uses a higher numerical aperture optical lens, which has a shallower focal depth and thus creates a narrower beam. Another technical advantage is the use of a 14-bit photo multiplier at the receiving end, which enables a good dynamic range (Keyence 2008)

The LSM has applications in various fields, mostly when we want to measure roughness or get information on color intensity. The two figures below show two different applications of LSM and give an idea about the result a user might receive upon using this microscope.



**Figure 30 Various results obtained by using LSM (Keyence 2008)**

The image on the left in Figure 30 is a roughness measurement of a tool blade edge. Even though, it appears completely smooth to the naked eye, we can actually see from the results of the LSM measurements that there is a variance on the roughness. The same applies to the figure on the right, where they have measured the roughness of a silicon wafer (Keyence 2008). Again, silicon wafer appears and feels completely smooth but these results show that it is not the case.

### 3 Experimental Approach

This section talks about the experiments that we performed in order to make the necessary measurements using Keyence LT 8010 sensor with Scanning Laser Microscope (SLM), which is found in the Surface Metrology Lab at WPI. The methodology that we followed was to use the Keyence sensor to make surface height measurements of art-related samples.

For our experiment, we have two variables;

1. Brush hair material
2. Paint type

During the preparation of samples for a variable, we kept the other variable the same to perform a controlled experiment. For instance, while preparing the “brush hair material” samples we used the same paint type. The table xx presents the different variables that we had for the samples.

**Table 4- Experimental variables**

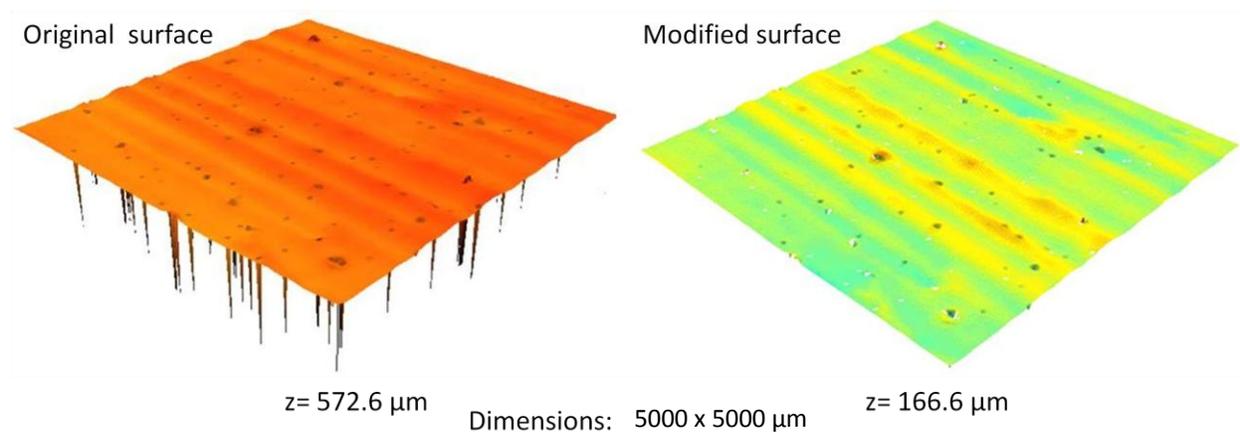
<b>Variable: Brush Hair Material</b>		
	Camel	Brush Type 1
	Taklon	Brush Type 2
	Bristle	Brush Type3
	Sable	Brush Type 4
<b>Variable: Paint Type</b>		
	Acrylic	Paint Type 1
	Oil color	Paint Type 2
	Gouache	Paint Type 3
	Water color	Paint Type 4

## 4 Results

After obtaining the surface measurements both set brush hair material and paint type samples, we performed various analyses using S-Frax software.

### 4.1 Variable: Brush Hair Material

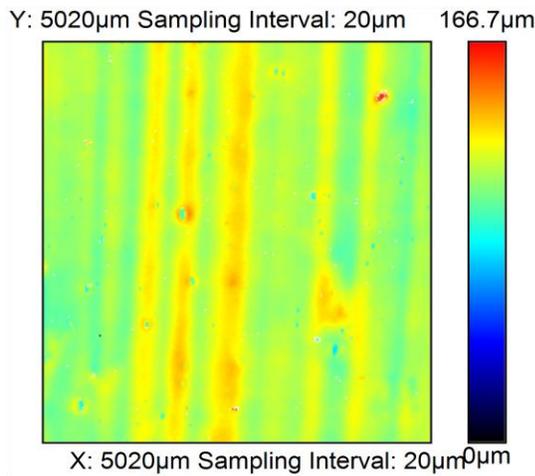
As described in section 3, we had four different kinds of brush types; bristle, taklon, sable and camel. When we examined the 2D and 3D surface images for four samples, we noticed that there were too many peaks on the surface. Therefore, we first leveled the surface and later we modified it with 40% of peak suppression and 80 degrees of slope filter. Figure 31 demonstrates the 3D view of the original and modified surface for brush type 1, which was camel hair.



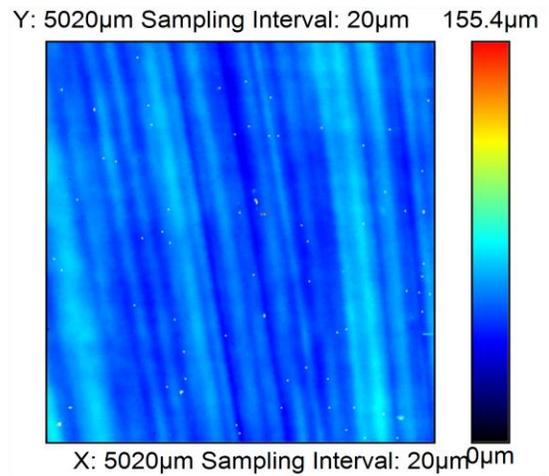
**Figure 31- 3D view of the original and modifies surface of Camel hair brush**

As it can be seen from the Figure 31, the z height of the surface went from  $572.6\mu\text{m}$  to  $166.6 \mu\text{m}$  with the modifications described previously.

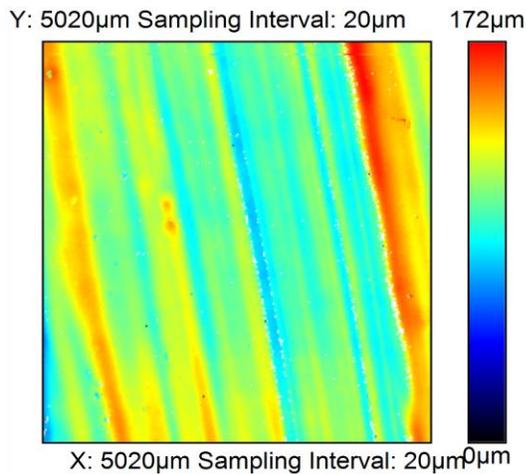
Figure 32 displays height maps for all brush hair sample types of modified surfaces. All of the samples prepared with different brush types are measured using the same parameters, such as x and y-axes, which may be seen in Figure 32. In addition, the z ranges, varying between 148 and 172  $\mu\text{m}$ , may be examined from the same figure.



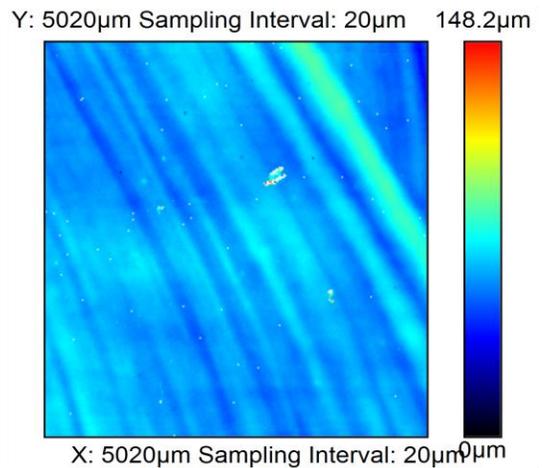
**Camel hair- type 1**



**Taklon hair- type 2**



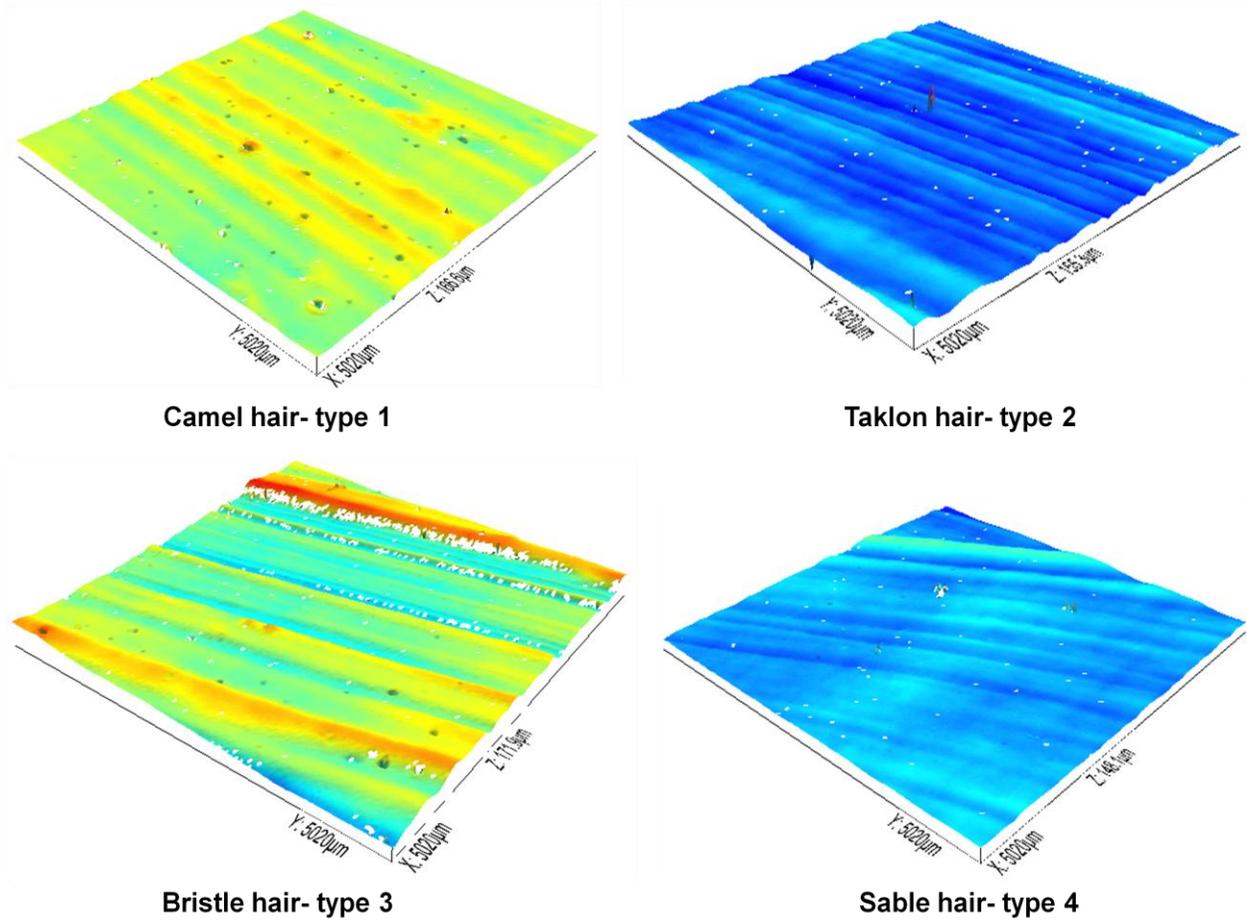
**Bristle hair- type 3**



**Sable hair- type 4**

**Figure 32- Height maps of modified surfaces for four brush hair samples**

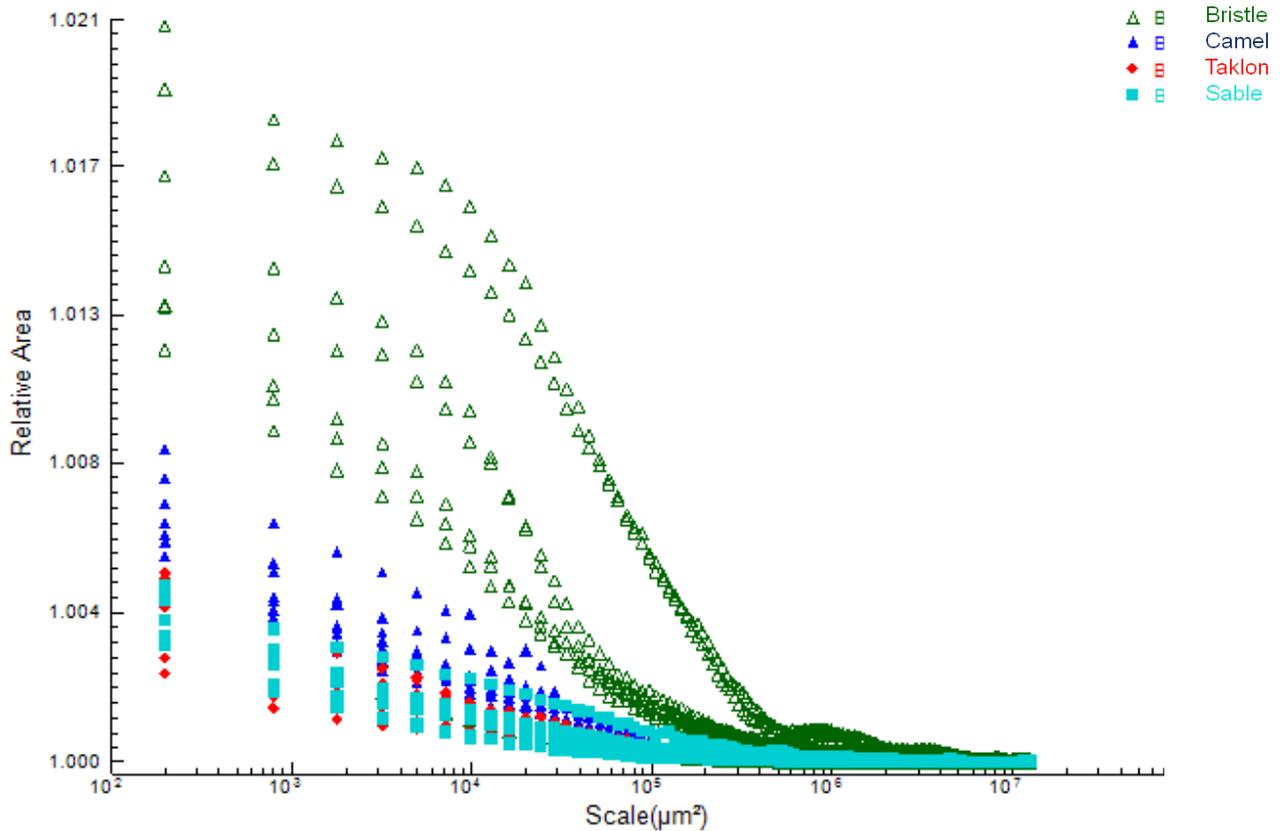
In Figure 33, 3D view of modified surfaces for four brush hair types is presented. As it can be seen, the x, y and z axes are the same as height maps. The texture formed by brush strokes is easily observed from 3D images.



**Figure 33- 3D view of modified surfaces of four brush type samples**

To evaluate the four surfaces, area-scale analyses are done using SFrax software. For the analyses, four corners full overlap method is used. Relative-area versus scale plot for four brush hair type samples is displayed in Figure 34. While examining the area-scale graphs, the first thing to look at is the value of curve at large scales. In our graph, it is seen that they all go to 1 at scales larger than  $10^6$ . Therefore, we can conclude that the surfaces have been leveled appropriately. As it can be seen from the plot, eight locations of the same sample are measured to test reproducibility and repeatability. Even

though type 1, 2 and 4, which are camel, taklon and sable, respectively seem to be reproducible and repeatable, brush type 3, which is bristle is not reproducible and repeatable. Furthermore, it is possible to understand from the plot below that bristle, camel and taklon are discernable since they all create separate family curves. On the other hand, brush sable and taklon are not differentiable from each other.

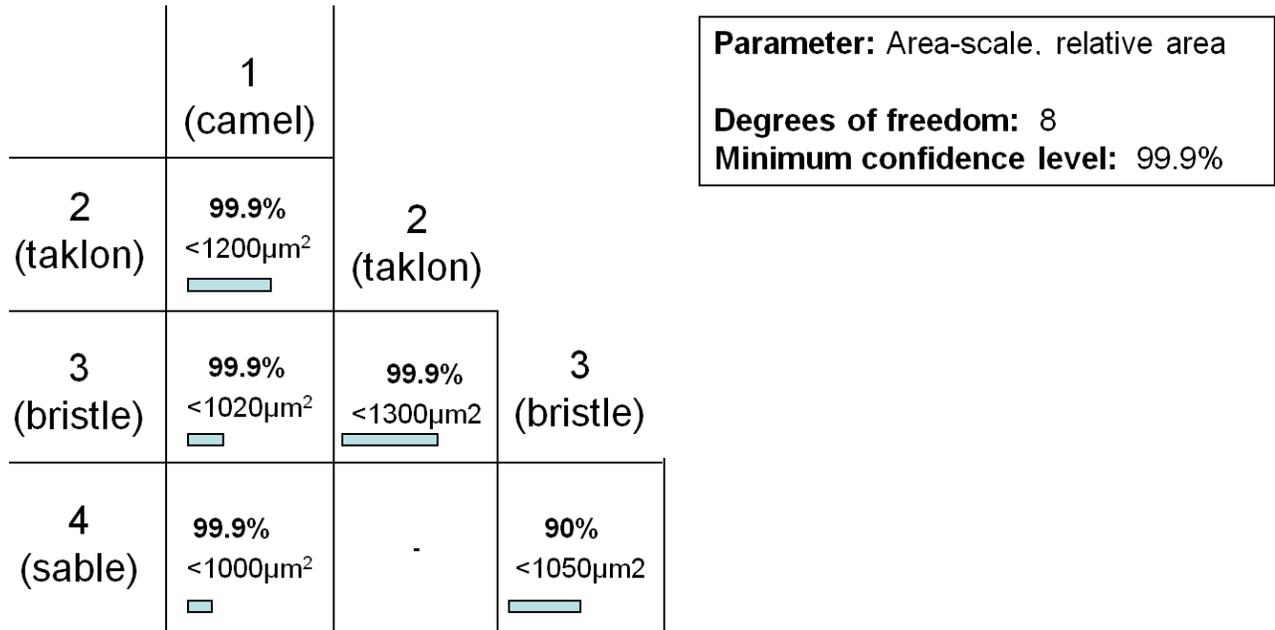


**Figure 34- Area-scale plot for brush hair material**

After completing area-scale analyses, we run F tests on surfaces of brush hair material samples. Figure 35 presents the table that we created with the F-test results. As it can be seen from the figure, all F-test analyses are done with 99.9% confidence level and 8 degrees of freedom. According to the F-test results:

- Camel hair brush & taklon hair brush – discernable at scales smaller than  $1200\mu\text{m}^2$
- Camel hair brush & bristle hair brush – discernable at scales smaller than  $1020\mu\text{m}^2$
- Camel hair brush & sable hair brush – discernable at scales smaller than  $1000\mu\text{m}^2$

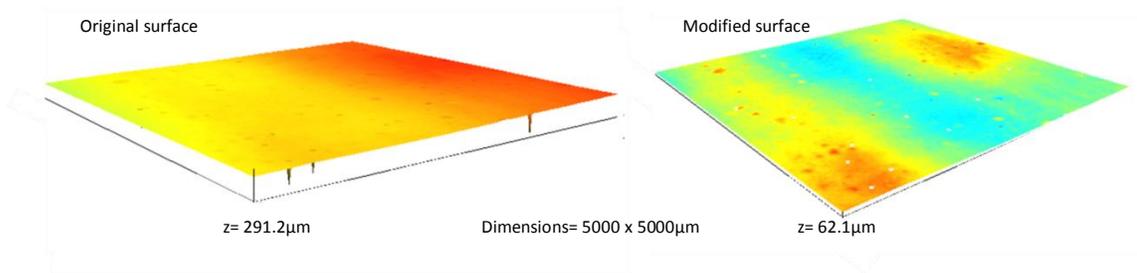
- Taklon hair brush & bristle hair brush – discernable at scales smaller than  $1300\mu\text{m}^2$
- Taklon hair brush & sable hair brush – not discernable at all scales
- Bristle hair brush & sable hair brush – discernable at scales smaller than  $1050\mu\text{m}^2$



**Figure 35- F-test results for area-scale, relative area analyses for brush hair types**

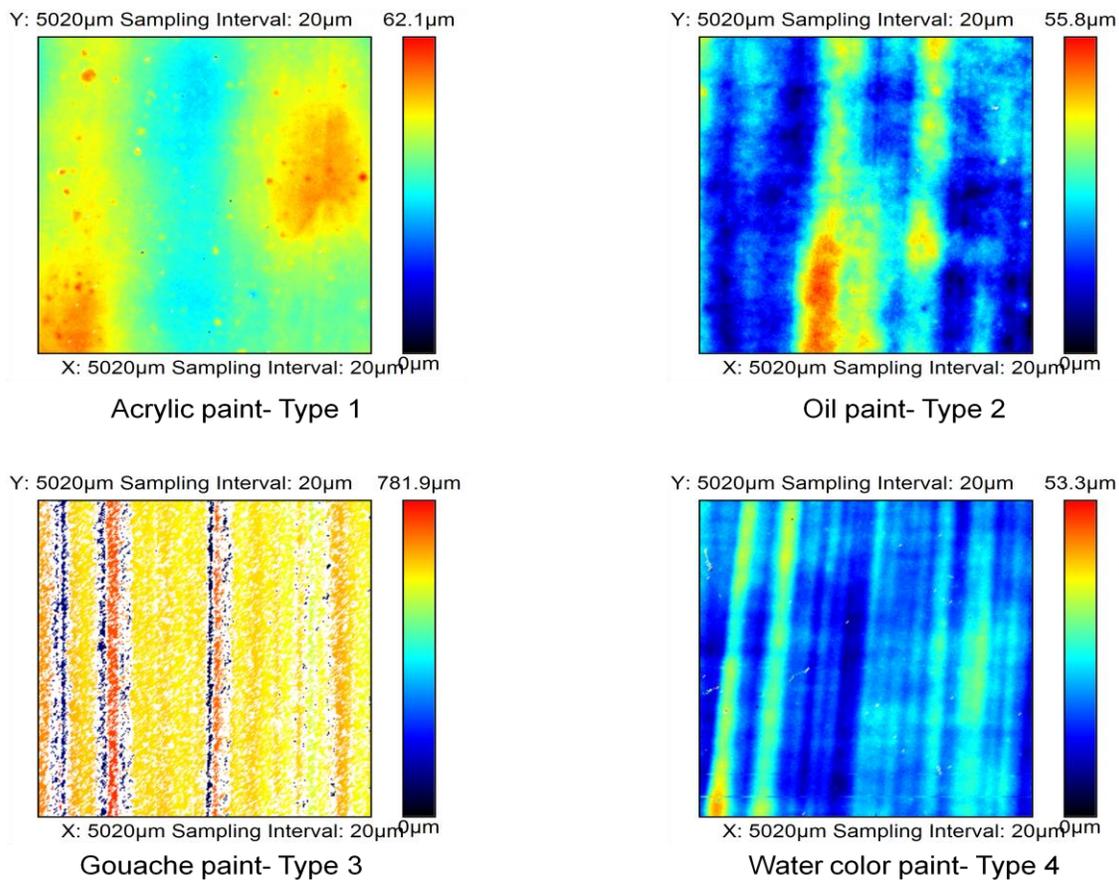
#### 4.2 Variable: Paint Material Type

As described in section 3, we prepared four samples for paint material type, which were acrylic, oil, gouache, and water color. When we observed the surfaces measured for the samples, we noticed that the surfaces had extreme high peaks and low valleys. Therefore we performed a set of surface modifications that are similar to one ones applied to previous samples. First we leveled the surfaces, and then run 80 degrees slope filter and 40% peak suppression on SFrax. Figure 36 displays 3S image of the original and modified surfaces from the measurement obtained for acrylic paint sample. As it can be seen from the Figure 36, the z range of the surfaces went down from  $291.2\mu\text{m}$  to  $62.1\mu\text{m}$  with the applied surface modifications.



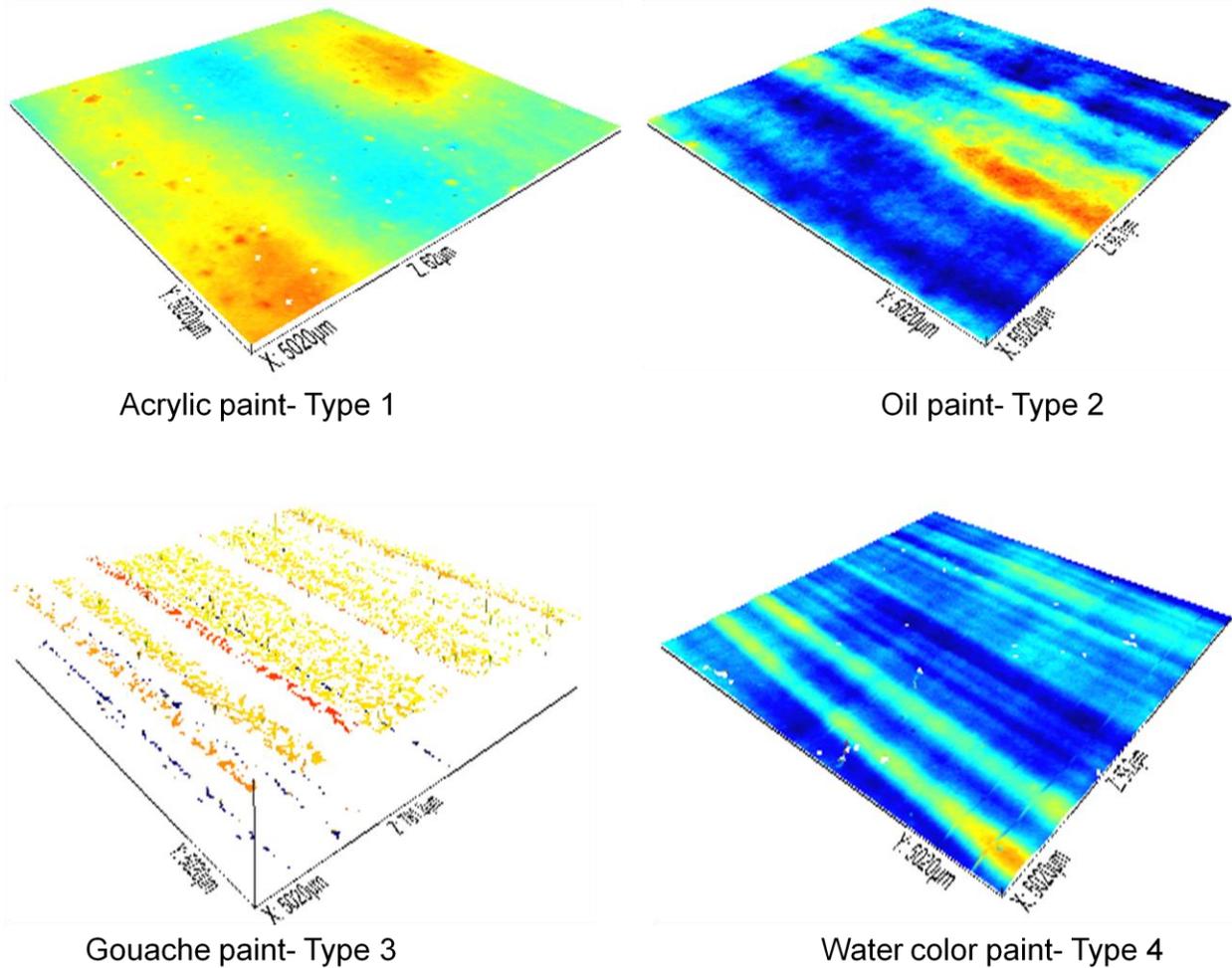
**Figure 36- 3D View of original and modified surfaces of acrylic paint sample**

Figure 37 presents height maps for all paint material samples of modified surfaces. All of the samples were prepared with different paint materials and measured using the same parameters, such as x and y-axes, which may be seen in Figure 37, where z ranges, varying between 148 and 172 µm, may be examined.



**Figure 37- Height maps of modified surfaces for four paint material samples**

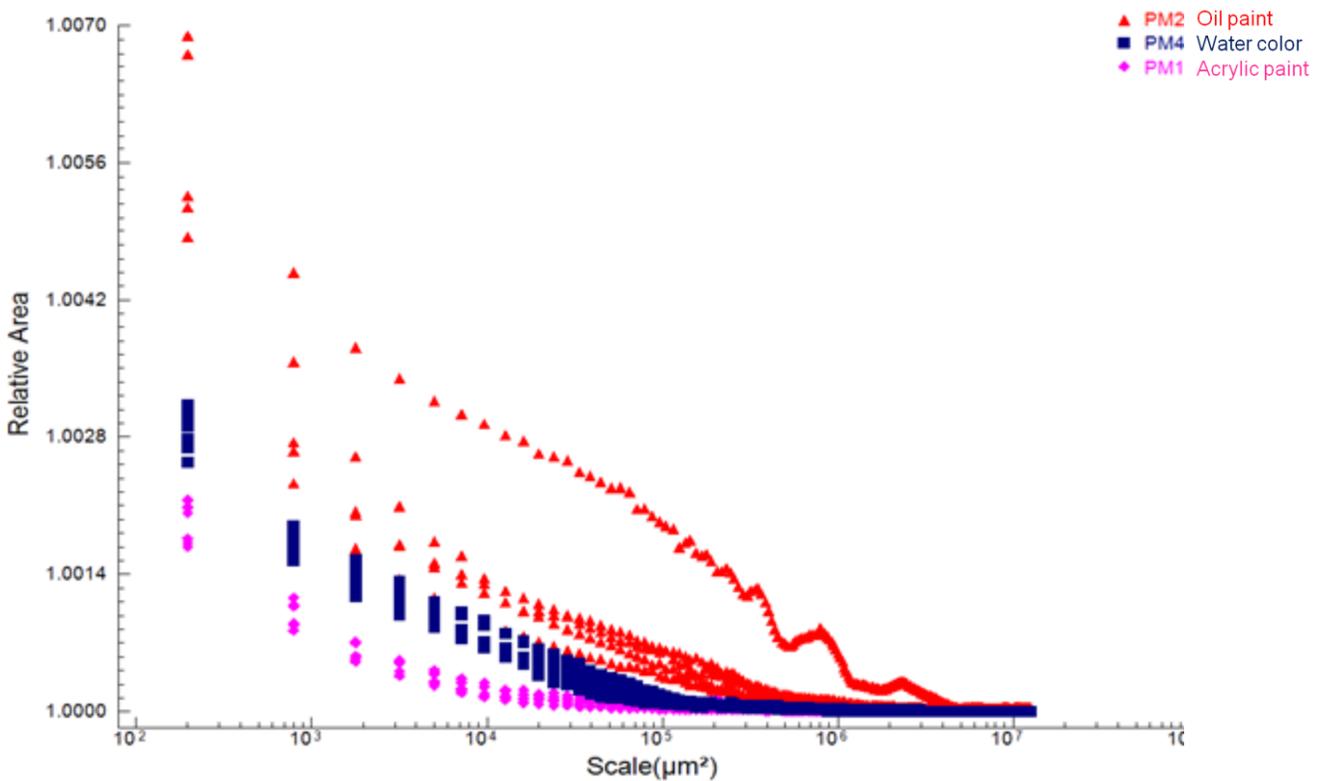
In Figure 38, 3D view of modified surfaces for four paint material types is displayed. As it can be observed, the x, y and z axes are the same as height maps. The texture formed by brush strokes from different paint materials is easily observed from 3D images.



**Figure 38- 3D view of modified surfaces of four brush type samples**

As it can be observed from the Figure 37 and 38, z axes are 62.1µm, 55.8 µm, 781.9 µm and 53.3 µm for acrylic, oil, gouache and water color paint types, respectively. The z range of gouache paint sample is different from the other samples. It can be concluded that the surface modifications applied were not effective in making the surface clear out from extreme peaks and valleys. Therefore, further analyses are not applied on the surfaces obtained from the gouache paint material samples.

To evaluate the three surfaces, area-scale analyses are repeated using SFrax software, using four corners full overlap method. Figure 39 shows relative-area versus scale plot for three paint material samples. From the graph shown, it is seen that all surfaces converge to 1 at scales larger than  $10^7$ . Therefore, we can conclude that the surfaces have been leveled appropriately. Just like it was done for brush hair material samples, the same surface is measured for seven times to test reproducibility and repeatability. Unfortunately, some of the surfaces are not analyzed due to low quality of the measurement. In our plot, there are five measurements for oil paint samples, 4 measurements of water color samples and 6 measurements of acrylic paint samples. In area-scale plot, three curves families belonging to different paint material can be observed. It can be concluded that all three types of paint materials are discernable from each other.



**Figure 39- Area scale plot for paint material**

After completing area-scale analyses, we run F tests on surfaces of different paint material samples, whose results are presented in Figure 40. As it can be seen from the figure, all F-test analyses are done with 99.9% confidence level and 8 degrees of freedom. According to the F-test results:

- Acrylic paint & oil paint – discernable at scales smaller than  $1.1 \times 10^5 \mu\text{m}^2$
- Acrylic paint & water color paint – discernable at scales smaller than  $1.3 \times 10^3 \mu\text{m}^2$
- Oil paint & water color paint – discernable at scales smaller than  $1.3 \times 10^6 \mu\text{m}^2$

	1 (acrylic)	
2 (oil)	99.9% < $1.1 \times 10^5 \mu\text{m}^2$ 	2 (oil)
4 (water color)	99.9% < $1.3 \times 10^3 \mu\text{m}^2$ 	99.9% < $1.3 \times 10^6 \mu\text{m}^2$ 

**Parameter:** Area-scale, relative area

**Degrees of freedom:** 8

**Minimum confidence level:** 99.9%

**Figure 40- F-test results for area-scale, relative area analyses for paint materials**

## 5 Conclusion and Recommendations

- Brush type measurements were successfully done using the Keyence LT 8010 sensor. All of the brush types were discernable from each other except sable versus taklon at 99.9% confidence level.
- Paint material measurements were successfully done except Gouache paint using Keyence LT 8010 sensor. Measured paint materials were discernable from each other at 99.9% confidence level.
- Another method to measure the surface painted with gouache paint type should be developed.
- Surface measurement techniques are encouraged to be used in restoration and conservation of paintings since they are able to tell apart different types of paint materials and brush hair types. The measurement technique is likely to be a great help to define physical properties of paint and/or brush during a restoration case.

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