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# APPLICATIONS OF REFLECTANCE TRANSFORMATION IMAGING FOR DOCUMENTATION AND SURFACE ANALYSIS IN CONSERVATION

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***Abstract***

*Conservators at Universitat Politécnica de Valencia, Spain, explore the advantages and potential applications of Reflectance Transformation Imaging (RTI) as an innovative instrument for the documentation and analysis of texture of cultural objects undergoing conservation treatments. A computational photography technique, RTI creates highly accurate and interactive images, where objects can be illuminated from different directions and through a variety of filters to emphasize their surface texture and color. RTI was implemented to try the technique effectiveness for performing detailed examination and diagnostics on a variety of materials, including paintings, works on paper, wooden sculptures, metals, and stone. Resulting images yielded new and valuable information in the identification of manufacturing techniques and assessments of surface condition that were not previously recognized through direct examination or any other photographic techniques. RTI also proved highly effective for detailed documentation of painting and paper objects before and after treatments, helping to assess many subtle changes on pictorial layers and paper supports caused by conservation processes. RTI is an affordable and accessible resource which would be beneficial for to both cultural institutions and individual conservators for the interpretation and evaluation of cultural heritage.*

***Keywords:*** *Reflectance Transformation Imaging; Texture; Computational Photography; Raking light; Surface examination.*

## Introduction

Surface texture is, along with color and form, one of the most important visual cues that help perception identify the physical characteristics of everything that surrounds us. Visual texture allows the eye to recognize the materials an object is made of, whether it is rough, smooth, glossy, porous, matte, polished, and etcetera. Additionally, the combination of shadows and highlights produced by illumination conditions on the texture patterns makes it possible to see matter in three dimensions. Texture qualities are further explored by conservators because they reveal the ways a creator has manipulated some materials to create an artwork or cultural object, and the transformations those objects have experienced over time.

However, surface texture is a quality that could suffer alterations caused by aging, use, damage, or even due to conservation treatments. Most importantly, color and texture are some of the main sources of information conservators use to diagnose the physical condition of a cultural object

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as degradation is manifested in the form of deformations, abrasions, losses, scratches, pitting, cracking, incrustations, corrosion, delamination, efflorescence, and many other problems that modify and negatively affect the original patterns of color and texture the artist had intended. Information extracted from an object's current state is essential to discover and prevent causes of deterioration, plan appropriate treatments, and to evaluate treatment outcomes since it is part of the physical evidence that serves as a basis for the conservation procedures to follow [1]. Unfortunately, documenting texture remains a challenge because what the eye perceives of it's the result of a dynamic interplay between the object's shape and the illumination, which cannot be fully captured by photographs, technical drawings, or with any still images.

Given that precise and detailed knowledge of the appearance of artworks prepares conservators to introduce accurate theoretical interpretations about them and therefore, to preserve them better, tools that increase our ability to identify, document, study and monitor surfaces and their transformations are essential. One such tool is Reflectance Transformation Imaging (RTI), which offers a new method to register, transmit, and accurately analyze texture in a simple, accessible and fast manner. RTI is a computational photography method that creates digital images of an object that conveys tridimensional information of its texture and color using conventional photographic equipment. Unlike traditional photographs, RTI images are interactive so they allow users to illuminate the object from different directions and see it through a variety of filters to considerably emphasize its topography. The aim of this paper is to explore some of the RTI benefits and potential applications in conservation contexts. Through examples we set out to demonstrate the advantages of using RTI to register and analyze surface features that can help identify manufacturing techniques, surface condition, and assess textural changes produced by conservation treatments.

### *Texture documentation and analysis*

Working towards a more objective interpretation of surface information on cultural heritage, conservators have tried multiple ways to document, compare and study texture. Contact methods such as molds and imprints are still used to register texture because of their similar tridimensional nature, although the high risk of damage they pose to fragile, painted, highly textured or porous surfaces makes them less than ideal methods. Because of this, there has been a marked emphasis on experimentation with new imaging techniques that allows accurate assessment of surfaces without unnecessary contact with the object.

In general, texture imaging has been carried out in two ways: through precise spatial measurements or through images that accurately represent the object's texture [2]. Laser scanners are examples of spatial measurement techniques. Although very precise, the appearance of texture and its relation with illumination changes are not rendered with these methods as they would be when viewing the actual object; and the cost of the instruments and the technical knowledge needed to produce useful data put them too far beyond the reach of most individual conservators and small-budget institutions to be considered universal solutions. Other techniques that rely on a combination of metrics and images have been studied by Vernhes and Whitmore [2], whose experimentation focused on capturing digital photographs of unpainted canvas illuminated from various angles to characterize perceived texture and to identify changes of surface brightness and regularity; and by Henriques y Goncalves [3], who applied a combination of landscape metrics and color zones to identify areas of losses in painting layers. Although such methods are promising, their application to different materials besides paintings or to other conservation issues is still limited.

Images have long been used to record scientific examinations, but have not been frequently used as analytical tools to relate to the physical properties of cultural objects [4]. Perhaps the most traditional and simple method for texture documenting through images is raking light photography, which uses oblique and low angled illumination aimed at the surface to emphasizes its topography by shadow contrast. Unfortunately, as an analytical instrument, raking light has important limitations that make it less useful for surface characterization: due to its bi-dimensional nature it cannot truly represent the three-dimensionality of a surface, there is usually loss of information, and it presents an editorial and subjective nature. According to Payne [5], in order to properly represent the three-dimensionality of an object, a raking light photograph must have good tonal contrast between reliefs, but since particular topographical patterns may be visible only when they are illuminated from certain angles, the photographer must select which information to highlight and what is to be left in the shadows. This results in images of limited accuracy because what actually is an interactive experience between lighting, surface, and observer gets condensed into a few, usually random shots, which reduce the amount of data captured and exposes it to the subjective decisions of the photographer [6]. In addition, still photographs have the disadvantage of making it difficult to register the exact position of the light, so it is almost impossible to achieve the same illumination conditions needed to compare images made before and after some deterioration has occurred or a conservation treatment has been carried out [7-8].

With the arrival of computational photography, which combines information from a sequence of digital photographs to create a new representation that contains information not recognized previously on the original source [9], surface texture can now be recorded and studied on screen in a format that closely resembles the experience of direct examination of the physical object. Frischer y Dakouri-Hild [10] stressed the important contributions accurate images provide in the examination and understanding of ancient artifacts: they facilitate cognition of large amounts of data, promote the perception of unforeseen emergent properties, highlight problems in the quality of the data, make clearer the relationship between macro and microscopic features, and are excellent means of immediate communication of evidence. As an advanced form of raking light, RTI combines the same color quality and resolution found in digital photographs with data of light interaction on surface forms, as well as knowledge of human perception to create images that precisely represent 3D shape characteristics. And, unlike other techniques, RTIs are produced using simple photographic equipment and open-source software, making it an accessible and affordable method to be adopted by conservators and researchers worldwide.

***Reflectance Transformation Imaging***

RTI uses a sequence of digital photographs of a fixed object, each one taken from the exact same position but illuminated from different angles to capture data of its shape and color, and then synthetize it into a mathematical model of the surface [11]. These models, originally known as Polynomial Texture Maps (PTM), were first introduced by Tom Malzbender from the Hewlett Packard Research Laboratories in 2001 as an application for rendering three-dimensional models using digital photographs [12].

In general terms, an RTI is created from the reflective patterns of a surface -the highlights and shadows resulting from the object topography and the light source position- which are used to calculate surface normals. A normal is the imaginary vector perpendicular to the point where the light touches the surface. When an object is illuminated from different directions, the reflection patterns of each segment of the surface are captured in the corresponding pixel of each photograph and subsequently, through a set of mathematical calculations made by RTI software, called RTIBuilder, the normals are identified [13]. Since each encoded normal corresponds to a point on the object, the whole set provides a complete and accurate "description" of its topography [14]. Once surface configuration is synthetized, it is possible to create a digital map that reproduces pixel by pixel the surface texture as well as its color and reflective properties. When viewed through an RTI visualization program, the RTIViewer, the map appears as a conventional photographic image, but as the user moves the virtual light on screen, the model replicates the reflective patterns of the real object, allowing the perception to see it in three dimensions [11]. This interactive quality makes it possible to illuminate the object from different directions, amplifying the contrast between surface details through the simulation of an infinite number of raking lights. Furthermore, RTI takes its name from its ability to modify the reflectance of the virtual model without affecting the topographic information. Through the application of various rendering filters it is possible to further enhance contrast between high- and low-reliefs or independently adjust reflectance or color values, revealing details about surface irregularities which are impossible to obtain by other photographic means, laser scanning, or even by direct visual examination of the object itself [9] (Fig. 1).

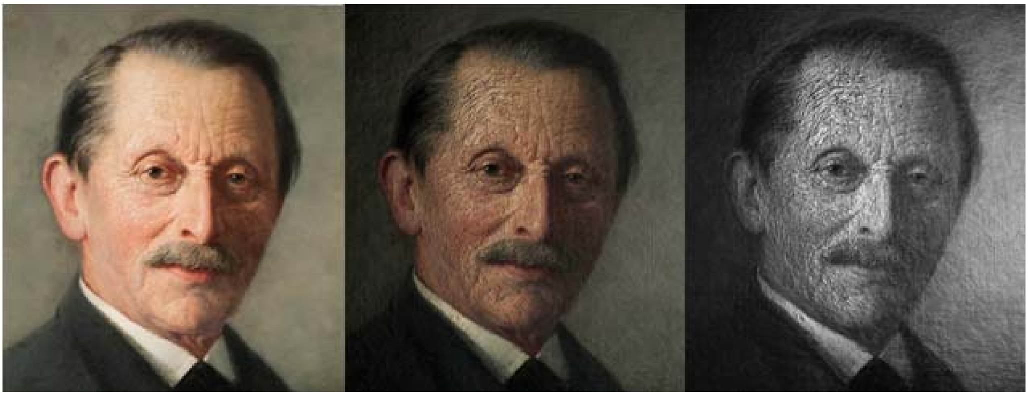

**Fig. 1.** Oil on canvas texture visualized in RTI with flat light (left), diffuse gain filter (center), and specular enhancement (right).

### *RTI in conservation*

From its conception, RTI was recognized as a valuable tool for the documentation of cultural heritage. And in fact, one of the first examples used to introduce RTI was a 4000-years-old Sumerian tablet from the Babylonian collection at Yale University [12]. After the development of a capture method with portable lights and more automated computer programs by researchers from Cultural Heritage Imaging (CHI), RTI has been adopted by many cultural organizations around the world, since the simplicity of the method and the large amount of visual information it provides make it an excellent means to document, study, and disseminate cultural heritage.

The unique possibility offered by RTI to create exact digital replicas of cultural property which reproduce not only a still image of a surface, but a complete visualization of the interaction of light with its texture using conventional photographic equipment can be of great benefit to conservators. Besides documentation, conservation institutions and professionals around the world have already recognized the potential applications of RTI as a tool for non-destructive analysis of surfaces, although perhaps because of its recent implementation, there are very few papers dedicated to this particular topic. Among the most relevant articles is Padfield, et. al [7] research in 2005, which shows that PTMs could accurately record paintings and mock-up samples surface features and condition before and after undergoing intentional physical damage. In 2010, Karsten and Earl [15] published a report in which changes of surface details on archaeological waterlogged wood being conserved were recorded using traditional and innovative recording techniques (drawings, photographs, X-radiography, silicon casting; and laser scanning and PTM) to compare their accuracy, time and skills required, and simplicity of data use. This report concludes that PTM provides accurate surface geometric data, color, and texture information; and is less expensive and time consuming than laser scanners (although the scanners do provide morphology measurements that are also important for comparisons). Payne [5] also has undertaken a comparative study of imaging techniques, namely 3D laser scanning, CT scanning, and PTM, and the potential use of each for preservation and accessibility to cultural heritage objects. Among her conclusions, Payne also highlights the PTM ability to create interactive, high-resolution images of objects in order to document surface features and condition, along with its affordability and accessibility. In one of the few articles that focus on RTI applications for conservation treatments, Kotoula and Kyranoudi [16] examine archaeological numismatic examples from Greek and Roman origin. During this project, RTI allowed the authors to identify coin manufacture techniques and evidence of usage by the cracking patterns found on the surface; to record the actual treatment process, and to evaluate the results of cleaning procedures, helping conservators decide whether or not a second cleaning was necessary.

There are other publications, mostly online blogs and website posts, which demonstrate the rapid diffusion of RTI adoption amongst conservators around the world. Among them are large cultural institutions (Georgia O'Keeffe Museum [17], The National Gallery [8]), education centers and independent professionals (Queen's University [18], Cultual Heritage Sciene Open Source [19]) which regard RTI as a useful tool to visualize evidence of manufacturing techniques such as subtle details of brush strokes, printing marks (Taw Conservation Center [20]), tool marks, painting application sequences on Greek ceramic vessels (Worcester Art Museum [21]); and a variety of condition issues such as ink flaking in illuminated manuscripts (CHI [11]), scratches and fungus on daguerreotypes (Smithsonian's MCI [22]), fine or abraded reliefs on coins [9], metal corrosion [23], or blisters on paintings caused by heat (Worcester Art Museum [24]). However, complete reports of RTI used for conservation treatments are still very limited.

## RTI acquisition

For this study, several objects undergoing treatment at Universitat Politécnica de Valencia Conservation Department (UPV) and at the Valencia Institute of Conservation (IVCR) were photographed as examples of different materials, textures, and degrees of deterioration, in order to establish a more complete treatment record, analyze surface condition, and serve as the basis for future analysis of textural changes on surface topography and brightness after undergoing treatment. Also, a group of test samples of a new filling material for bone reconstruction developed at UPV were photographed to help evaluate its textural properties after abrasion and texturizing tests.

RTI creation has been well described by CHI through a number of articles and end-user manuals available online [11]. In brief, RTI is usually carried out in three stages: first, capturing images of the object; second, processing the texture map; and finally, visualizing the final RTI image. In order to calculate how light is reflected from a specific surface and to extract the surface normals from the image samples, it is necessary to know the exact position of the light source used in each photograph. This is done by either using a structure with lights called a light dome or by executing the Highlight method (HRTI). Developed by CHI around 2006, the HRTI method allows for the light source position to be registered on each photograph and then calculated afterwards [11]. To do this, the fixed object is photographed along with two shiny black spheres and illuminated by a light source (a flash or a lamp) manually held in position (Fig. 2). For each photograph, the light is moved to a different position and angle, always maintaining the same distance from the subject, thus creating an imaginary dome around it.

**Fig. 2.** Conservators during data capture using the RTI Highlight method, where a light source is moved around the object and a new image is taken for each light angle.

During processing, the RTIBuilder is used to detect the black spheres on the photographs and to calculate the exact position of the light source by identifying the position and the angle of the specular highlight reflected on each of the black spheres. The relationship between the light source and the patterns of shadows and highlights registered on the photographs allows for the calculation of surface normals, and consequently, the object's topography and reflective properties. This information is then synthetized into a digital texture map in either an .rti or a .ptm format (depending on the logarithm selected by the user). This file can then be visualized through the RTIViewer as a photographic image that reproduces the same tridimensional and reflective characteristics found on the actual object. In addition, RTIViewer makes it possible to extract still images using different filters that help emphasize particular textural, color or reflectance features for a more detailed and clearer understanding of surface characteristics.

## Results

In this project 36 objects were photographed, creating around 70 .rti and .ptm files of paintings, prints, and watercolors; wooden, metal, and stone objects, and textiles. Here, only a few examples are used to showcase the benefits and potential applications of RTI for specific conservation tasks such as identification of manufacturing techniques, condition diagnostics, treatment assessments, monitoring, and for the evaluation of new conservation materials.

### *Identification of manufacturing techniques*

RTI has helped to discover textural features that are imperceptible to the naked eye or through other inspection techniques, or that could not be properly recorded with raking light photography. For example, in a 17th century watercolor landscape from the collection of the Real Colegio del Corpus Christi in Valencia, Spain; by decreasing the color values and enhancing its reflectance, it was possible to see the subtle impressions left on the paper where the artist had outlined the buildings and road (Fig. 3).

**Fig. 3.** Watercolor detail visualized in RTI with flat light (left), and specular enhancement (right). When the color values are reduced and reflectance increased, it is possible to see the faint outlines on the road and rectangular structures (upper left area). Deformations, wrinkling, joints, and fold marks are also enhanced through specular filters.

Since the watercolor technique usually does not leave any impressions on the paper support and it "disappears" when the color information is reduced, it was possible to differentiate where the artist used a harder tool (pencil or ink pen) to delineate this piece, leaving a fain mark on the paper support. In a second case, RTI served to clearly identify and document the use of different papers in the creation of a colored print from “Libro de Actas de La Escuela de Cristo,” a 17th century book from the Diocesan archives of Valencia. By using diffuse and specular filters, as well as raking illumination angles, it was made evident that the vertical laid lines on the main illustration were not present on the rest of the page (Fig. 4), proving two different papers were used to make a single page.

**Fig. 4.** Colored print detail visualized in RTI with flat light (left) and specular enhancement (right); using the same illumination direction. RTI allows to appreciate the vertical laid lines within the illustration that are not present on the rest of the piece (right side of the image), evidencing two different papers on a single page.

***Condition assessment***

In search for evidences to generate condition assessments, RTI proved to be a remarkable tool because the combination of lighting, magnification, and rendering filters served to discover size, location, extent, and character of apparent damage, and to document alterations that produced changes on textural patterns and glossiness. Damage that could be better visualized on different surfaces included cracking on painted surfaces, flaking, losses, surface deposits, scratches, pitting, holes, incisions, metal corrosion, cupping, deformation of supports, shrinkage, breakage, sagging, delamination and flaking. Among the most striking examples of the information disclosed through RTI was the 16th century oil on panel entitled “El Calvario.” Using specular filters and oblique lighting, damages such as deformation on the wooden panels, cracking of the painting layer, scratches, holes, and even the brush strokes were made evident (Fig. 5). Moreover, it was possible to identify texture and brightness discontinuities that indicated where repainting or previous cleaning had been performed (Fig. 6).

Since RTI allows control over reflectance, color and illumination direction parameters, it can be adapted to the qualities of different materials. In the case of the Real Colegio del Corpus Christi’s watercolor mentioned above, using diffuse and specular filters resulted in a better visualization of the general damage, helping to clearly document the fact that in the past this piece had been rolled up, causing the right side area –what was the outer layer - to be considerably more damaged that the rest (Fig. 7).

**Fig. 5.** Detail panel painting "El Calvario", visualized in RTI with flat light (left) and specular enhancement (right). RTI offers a clearer and more detailed view of the wood support deformation, and the cracking, scratching, losses, and cupping of pictorial layers.

**Fig. 6.** "El Calvario" visualized with flat light (left) and specular enhancement (right). The dark and less glossy areas correspond with areas where varnish has been removed during cleaning.

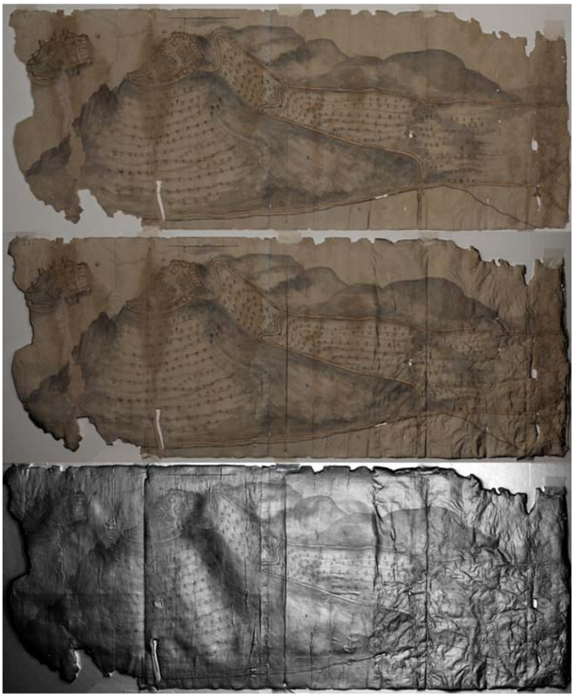

**Fig. 7.** Watercolor visualized in RTI with flat light (top), diffuse gain (center), and specular enhancement (bottom). While all these images are illuminated from the same direction, RTI filters help improve our perception of actual surface condition.

***Treatment documentation, monitoring, and evaluation***

Direct conservation treatments are meant to slow down or reverse the effects of ageing or deterioration on cultural heritage. Since treatments should not cause changes to the original character of the artwork, conservators are challenged to develop effective processes that also introduce the least variations to the objects appearance. However, even with the most careful treatments there are certain risk of causing changes on surfaces that could range from the most subtle to the extreme, where consolidations, flattening, cleanings, or heavy protective coatings, for example, could significantly alter the textural patterns, brightness and color perception of the original work. Therefore, in order to help monitor and assess surface changes during conservation treatments, RTIs could be used as digital replicas of the object. Since they closely resemble the experience of observing the real object, they can help to accurately compare it at different points during the process, providing a precise visual representation of the surface in a controllable and reproducible lighting environment. During this project RTI was used on “San Pablo,” a 16th century oil on panel painting from Cathedral of Valencia, which had countless blisters caused by a fire during the Spanish Civil War of 1936. While the largest deformations of the painted layers (between 1 to 10 cm in diameter) were easy to observe and document using raking light, areas with small blisters (less than 1mm) could not be properly registered. Using RTI, conservators were able to capture detailed images of the pictorial layer before and after consolidation and planar correction were carried out, in order to monitor its condition and to evaluate the effectiveness of the process (Fig. 8).

**Fig. 8.** Three details of panel painting "San Pablo" surface, visualized with RTI before (left column) and after (right column) blisters were consolidated and flattened.

By reproducing similar lighting conditions and eliminating color information, it was possible to prove that while wider blisters could be mostly returned to their original planar position, the narrower ones had suffered considerable plastic deformation (they had experienced the most distortion in a smaller area) and could not be completely flattened. Also, RTI served to better visualize blisters that had raised edges from trapped material underneath and some others that inevitably collapsed down and broke during process. Due to the fact that this is an ongoing project, these RTIs will continue serving in the future to monitor and evaluate the complete treatment.

### *Conservation materials evaluation*

As well as with treatments, conservation materials used for consolidation, adhesion, cleaning, protection, and so on, also influence the appearance that an object will have afterwards. While it is desirable that those substances cause no changes in the appearance of the original work, in the case of reconstruction, fillings and retouching materials, it is also important that they closely emulate the original's physical and visual properties. The scientific analysis and selection of appropriate materials is a continuous activity aimed to discover each material's suitability for conservation applications. Physical tests routinely carried out include those that look for perceptible changes on their surfaces, such as loss or gain in glossiness, the presence of cracks, bubbles, deformation, abrasion, etcetera, showing the material response to accelerated deterioration. Just like the quantification and characterization of surface damage on artwork surfaces, measuring the amount of abrasion, cracking or bubbling on a material sample is still carried out by visual analysis. Consequently, given its ability to emphasize surface features, RTI was considered as an innovative way to analyze textural and glossiness changes on a group of samples of a new stucco paste intended for archaeological bone fillings, currently under development at UPV. These samples, made of an acrylic resin base, were subjected to linear abrasion tests after being subjected to accelerated aging using humidity, high temperature and UV radiation. Erosion resulting from 5, 10, and 15 cycles with a Taber® Linear Abraser was photographed using RTI. Resulting images allowed to significantly increase contrast between texture reliefs, even on samples were abrasion was very faint, which resulted in a better and more objective comparison of outcomes. On another test, stucco samples were carved with different tools to prove whether the stucco could be worked on to match the different textural finishes found on archaeological bone. On these, RTI also greatly enhanced contrast between high- and low- reliefs, making it possible to easily perceive even the slightest marks left by sandpaper (Fig. 9).

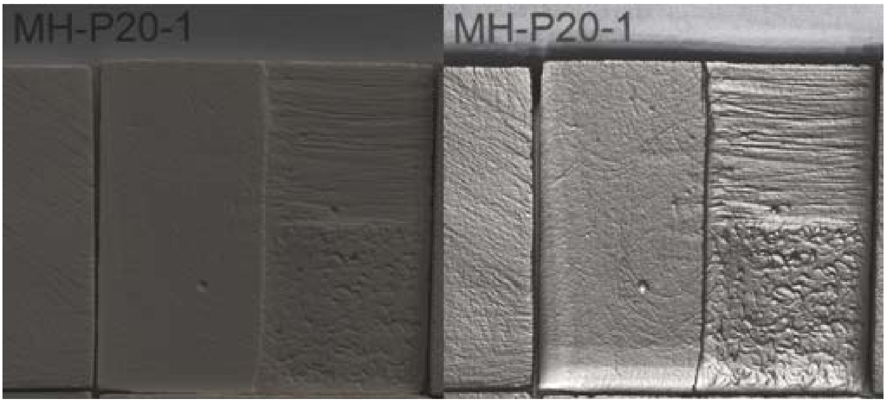


**Fig. 9.** A test sample of texturized bone filling is seen under an oblique light angle (left) and with RTI specular enhancement (right).

## Conclusions

RTI images created during this project have revealed textural information not discernible through direct observation, with magnifiers, nor with raking light photographs. RTI has a unique ability to show surfaces under varying illumination directions, degrees of magnification, and rendering filters which offers conservators greater capabilities to evaluate both textural and brightness patterns in a quick, dynamic and intuitive manner. These qualities give RTI certain advantages over traditional raking light photographs, because a single file contains thousands of potential images that can be manipulated to highlight textural attributes according to each researcher's particular objectives; regardless of the original photographer's intent or the lighting directions used during capture.

When capture, processing, and archiving of RTI files are conducted and documented methodically, they can be used as exact digital surrogates of the object, suitable to derive accurate information about its surface configuration. Although each RTI holds only a single view of the object, its capability to show it in three dimensions breaks down physical barriers and allows for better assessments and comparisons than still photographs, when the actual object is not suitable for handling, its surface has changed due to conservation processes or deterioration, or it has been destroyed. RTIs have a tremendous communicative power to our perception, which facilitates immediate recognition of large amounts of data, assists in color and textural information documentation and transmission, and could serve as objective evidence to build critical arguments when formulating a course of action. This makes it an effective instrument for registration, condition assessment, manufacturing technique identification, monitoring, and evaluation of conservation treatments, among others.

Although objects larger than 1.5m became difficult to capture in a single photographic set because proper illumination would have required larger spaces and more powerful light sources than were readily available during this project, RTI remained an outstanding tool to be used on a variety of artwork materials, from paintings to wooden sculptures, paper, stone, or metals. Considering that many conservators already possess the photographic equipment and the digital photography knowledge required for image acquisition, the straightforwardness of this method and its adaptability to different capture settings, RTI can realistically be considered an affordable and accessible instrument to be widely adopted and used routinely in conservation contexts. This is a great achievement, given the fact that, currently, individual conservators and cultural institutions around the world have few resources to adopt new technological tools that would benefit the preservation of their cultural heritage.

Despite being an emerging technology, RTI has tremendous potential in the conservation field; and evidence of its quick expansion is found in numerous videos and blogs posted online by cultural entities. The huge amount of information contained in a single RTI and its immediate communicative power could help conservators to examine artwork surfaces in a more detailed and comprehensive manner, and in consequence, to be better prepared to enter accurate theoretical interpretations about the composition of cultural property, its condition, and the need of and effectiveness of conservation treatments.

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