Measuring Changes in Cultural Heritage Objects with Reflectance Transformation Imaging

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Abstract — Sites and objects of cultural heritage — from art to ancient inscriptions to ruins — are under constant attack by time and the environment. While much is known about how material components change from laboratory-based artificial aging, very little is known about the process or rates of change of actual objects and sites in situ. Reflectance Transformation Imaging (RTI) is a quantitative method that captures surface normals. In our case, it provides detailed information on the geometry of the object surface. We show that RTI can be quantified for use as a method for measuring change in cultural heritage objects.

The past decade has seen the rapid evolution and application of computational photography methods to document important works of human heritage, from art and architecture to archives and archaeology. The next logical step involves defining just how reproducible and precise these methods can be to use them to measure rates of change for important works of cultural heritage. The need is to move to calibrated, quantitative image datasets for reproducible imaging.

We measure the precision of computed surface normals, which define the basic repeatability of RTI. Our results show that the average included solid angle for RTI sensitivity fitted to the Hemispherical Harmonics (HSH) polynomial function is 0.003 steradians (3 sigma), while the older Polynomial texture map (PTM) method is much less sensitive (0.5 steradians). The absolute sensitivity of the method is the minimum variation of the normal that can be statistically considered a change of the object. It is calculated considering the average value of the normal of each single pixel. The solid angle of the cone of variation represents the statistical limit (3 *σ). Analysis of multiple RTI data sets from objects that have changed between image capture sessions results in a map of change that can easily be evaluated by conservators.

Index Terms— Rephotography, Cultural Heritage, measuring damage, normals, Reflectance Transform Imaging, RTI, Polynomial Texture Mapping, PTM.

I. INTRODUCTION

RTI is a method that captures how a complex material interacts with light—an important advance in our ability to investigate and monitor works of art that complements other imaging methods such as spectral imaging. Originally developed[1] to create realistic CGI effects on complicated illumination geometries on textured surfaces such as skin and textiles, it has been adopted by the cultural heritage community for a number of objects. Cultural heritage applications include cuneiform, petroglyphs, wax tablets and objects with surface relief and features[2, 3]. While spectral imaging reports on surface phenomena, RTI provides information on the physical changes in the object itself as it reports on surface geometry. These changes include parchment cockling and distortion, movement of wood objects and flaking of stone, to name a few.

Change measurement requires quantitative imaging methods, rather than just visually appealing images. Measuring change requires a before and an after image, quantitated well enough, with low noise, to make useful comparisons. Regardless of the imaging method, the first step is to understand the sources of noise (or instrument variability) in images. Poor images mean that any comparison method has poor sensitivity to change, since we cannot differentiate image change from uncertainly in the measurement. We are after precision, not accuracy (although that is nice!). Spectral imaging is already being used for monitoring the Dead Sea Scrolls[4, 5, 6]. That work showed that there are two critical issues; (1) Measuring the imaging method noise/errors and reducing it as much as possible; (2) The largest source of error is image registration between the before and after.

II. QUANTITATIVE RTI

In recent years, the need to improve quantitative imaging techniques for monitoring purposes has become increasingly relevant. Quantitative imaging includes the development, standardization and optimization of imaging acquisition protocols, data analysis and results interpretation in order to have a validated, reliable and precise method.

RTI is a term used to describe a broader family of image-based recording methods in which information about surface reflectance is captured per pixel. RTI images are created from multiple digital images of an object shot from a stationary
camera position: in each image, light is projected from a different known, or knowable, direction. Lighting information from the images is mathematically synthesized to generate a model of the surface, in the form of surface normals for each pixel, and used for enhancing detail. A surface normal is a vector perpendicular to the local surface at any given pixel; we will focus on normals for measuring change[7].

Gabov et. al [8] has also suggested the use of RTI as a method for looking for changes in outdoor stone carvings. While the work does show spalling of the statue, it is done by visual inspection and does not present a quantitative approach to a long-term monitoring methodology. However, the work does validate the notion of using RTI normals as a measure of change in objects.

A. RTI CAPTURE TECHNIQUE

Camera – We used Nikon D3X DSLR camera with a 50 mm macro lens. The images are 6048 x 4032 pixels. The camera was operated tethered to a PC.

Reflective sphere – We used a black reflective sphere to locate the lighting angle in each photograph. The processing software is able to identify automatically the light direction on the sphere.

Light – A wireless synched flash light source illuminated the surface of the object to produce the highlight point in the reflective target. The object was illuminated from multiple light positions, creating a virtual dome, using 15°, 30°, 45° and 60° lighting angles and moving the flash following a pattern with radial spokes. The power of the flash light was set to illuminate enough the surface of the object. The light was separated from the surface of the object at a consistent distance of 2x the object’s diameter.

B. GENERATING SURFACE NORMAL

After capturing all images, each with a different light position and the same camera position, all the pictures, and respective light direction, for each single pixel is collected from all the images and fitted to the polynomial function (PTM or HSH). There are two main ways to describe the reflectance function: using polynomial texture map (PTM)[9] and using Hemispherical Harmonics (HSH)[10]. The HSH approach is superior in term of 3D rendering because PTM uses only 6 coefficients of a biquadratic polynomial to describe the surface normal while a third order HSH uses 16 coefficients.

We used open source software to build the RTI images from the raw image set and then calculated the normals separately; RTI Builder from Cultural Heritage Imaging (culturalheritageimaging.org). We computed and extracted surface normals using both mathematical methods and we measured the precision of each method, which define the repeatability of RTI.

III. CHANGE DETECTION PRINCIPLES

The objective of this research is to define how reproducible and accurate RTI methods are in order to develop a monitoring methodology to automatically recognize areas that have changed. By monitoring the normals over time it is possible to detect the small-scale morphological and physical changes in an object. A normal can be considered changed only if the value exceeds the region of statistical control which is defined by 3σ around the average value of each pixel. This region corresponds to a confidence level of more than 99%. The average normal of each pixel was accomplished by recording and computing 5 replicated normals of a model drawing; this baseline of normals set the timeline to zero and constitutes the characterization of the object. In this phase the object can be considered “in statistical control”.

The absolute sensitivity of the method is the minimum variation of the normal that can be statistically considered a change of the object: the larger the variance of the baseline normals, the less sensitive the method is. A surface normal of a pixel is a vector perpendicular to the local surface that provides information about 3D shape of the surface. The region of the statistical limit (3σ) of the vector of the normal is represented by a cone (figure 1) with a defined solid angle given by the measured distribution of normal; a normal can be considered changed only if the monitored vector is outside of the cone.

![Fig. 1. Cone with ellipsoid base (dot line) that represents the region of the statistical limit within which a normal can be considered not changed.](image)

IV. RESULTS AND DISCUSSION

A. RTI REPEATABILITY AND SENSITIVITY

For this research we imaged a model drawing (Fig. 2a) and measured the repeatability of computed surface normals by recording in five separate imaging sessions all the images. We computed the normals both using PTM and HSH and calculated the average variability. The normal is described representing the vector using Cartesian coordinates \(x, y,\) and \(z\), the average variability is calculated as standard deviation/mean*100 for each pixel. The average variability for PTM is 26%, 17%, 3% for \(x, y\) and \(z\), instead for HSH is 0.8%, 1.9% and 1.9% for \(x, y\) and \(z\) (table 1).

<table>
<thead>
<tr>
<th>RTI average variability: PTM and HSH</th>
<th>variables</th>
<th>PTM</th>
<th>HSH</th>
<th>diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x)</td>
<td>26%</td>
<td>0.8%</td>
<td>-97%</td>
<td></td>
</tr>
</tbody>
</table>
Table 1. RTI average variability computed using PTM and HSH polynomial functions: the variability was calculated both using Cartesian and spherical coordinates.

<table>
<thead>
<tr>
<th></th>
<th>PTM</th>
<th>HSH</th>
</tr>
</thead>
<tbody>
<tr>
<td>y</td>
<td>17%</td>
<td>1.9%</td>
</tr>
<tr>
<td>z</td>
<td>3%</td>
<td>1.9%</td>
</tr>
<tr>
<td>phi</td>
<td>19%</td>
<td>1.7%</td>
</tr>
<tr>
<td>theta</td>
<td>6%</td>
<td>0.7%</td>
</tr>
<tr>
<td>rho</td>
<td>58%</td>
<td>1%</td>
</tr>
</tbody>
</table>

We calculated the sensitivity of the method, which is the minimum variation that can be statistically considered a change of the object and which is directly correlated to the repeatability of the method. The statistical limits of each normal are represented as a cone, as described before: the absolute sensitivity is measured in steradians percentage and is calculated dividing the solid angle of the cone by the hemispherical space (4π) which represents the all possible positions that a normal can have. The average included solid angle of the cone is 0.003 steradians for HSH, while for PTM method is 0.5 steradians, much less sensitive (Table 2).

We also calculated the absolute sensitivity of phi and theta as angle: for PTM the sensitivity is 17.4% and 1.6% for phi and theta instead for HSH the sensitivity is 0.5% and 0.8% for phi and theta.

Table 2. Absolute sensitivity of PTM and HSH computed normals.

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>PTM</th>
<th>HSH</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVERAGE SOLID ANGLE</td>
<td>0.5%</td>
<td>0.003%</td>
</tr>
<tr>
<td>PHI</td>
<td>17.4%</td>
<td>0.05%</td>
</tr>
<tr>
<td>THETA</td>
<td>1.6%</td>
<td>0.8%</td>
</tr>
</tbody>
</table>

We also measured the repeatability of RTI dome method in which each light is fixed. Table 3 shows the average variability for HSH using movable flash light and a dome: the average variability for flash light is 0.8%, 1.9% and 1.9% for x, y and z and for the dome is 1.2%, 1.8% and 1.2% for x, y and z.

The repeatability of the RTI dome is pretty much the same of the movable flash light technique but one of the advantages of this approach is that the light position is fixed and the acquisition time is cut down.

Table 3. RTI average variability computed using HSH from movable flash light technique and RTI dome method.

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>Flash light</th>
<th>Dome</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>0.8%</td>
<td>1.2%</td>
</tr>
<tr>
<td>y</td>
<td>1.9%</td>
<td>1.8%</td>
</tr>
<tr>
<td>z</td>
<td>1.9%</td>
<td>1.2%</td>
</tr>
</tbody>
</table>

B. DAMAGE DETECTION IN A DRAWING

The derived statistical limits from variance of the five RTI replicates have been used to compare the normals before and after damage. Figure 2 shows the color image of the drawing we used for this research: figure 2a represents the undamaged drawing and figure 2b represents the drawing after damage. After characterizing the natural variability of the method and of the object, we damaged the drawing by creating two small holes (red circles) and a scratch (red arrow).

Figure 3a shows the map of change for the y values of the normal: red and blue pixels represent the areas where the normals are statistically changed. In figure 3b there is the color image of the drawing: white pixels are the changed pixels. They show up as changes in the normals as the act of scratching and punching the paper distorts the paper surface a bit.

Figure 4 shows the map of change of the normal in presence of a bend (fig. 4c) on the drawing. The behavior of the two sides of the wave are different (blue and red areas) because the direction of the normal are the opposite respect with the camera. At the top of the wave the normal didn’t change because the normals now are still about the same as the flat part. Figure 4d represents the intensity map of change of each
Fig. 4. Maps of change of normal in presence of wave of the paper. (a) shows the bend, with light from the upper left, (b) shows with light from lower right, (c) shows binned classification on changes, while (d) is a heat map showing the amount of change.

V. CONCLUSIONS

The aim of this research was the development of a reliable RTI imaging method for monitoring changes in cultural heritage objects. RTI provides detailed information on the geometry of the object surface. We showed that RTI can be reproducible and quantified to the level where it can be used as a practical method for measuring change in objects. We found that computing surface normals with HSH is more reproducible than using the older PTM method, and is therefore more sensitive to changes. We developed a monitoring protocol which includes an imaging protocol, the extraction of the normals and comparison within statistical limits.

We characterized the variability of a drawing, computed the statistical limits and then damaged the object. We then captured the RTI and compared the normals to the limits: the method was able to detect the damage automatically.

In conclusion, this new approach to RTI offers a useful strategy for monitoring physical change in important cultural heritage objects.

ACKNOWLEDGMENT

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REFERENCES