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Quantitative evaluation of the Reflectance Transformation Imaging and Normal Integration technique in profilometric application.

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Abstract. This article provides a quantitative analysis of the ability to faithfully reproduce the profile of objects using the Reflectance Transformation Imaging (RTI) coupled with Normal Integration technique. The study was conducted using *ad hoc* designed and built reference targets. It was possible to compare the profiles obtained using RTI technique with those realized using more conventional profilometric and 3D techniques such as micro photogrammetry, laser scanner and optical profilometry. It has been seen that the RTI technique is especially valid in the reproduction of high spatial frequencies and that it is very suitable for the study of cultural heritage, as it is portable, fast and low-cost.

1. Introduction

In recent years, various techniques have been developed based on the acquisition of multiple images of the same object, which have now become a standard in the documentation of archaeological finds, also thanks to their low cost [1].

One such technique is Reflectance Transformation Imaging (RTI). RTI is an imaging technique for estimating the intensity and direction of reflectance on an object, with the aim of representing that object in different directions of incident light. This kind of imaging has rapidly become a widely used solution for the documentation, recording and decoding of cultural heritage objects, as it allows the estimation of image enhancements, emphasizing details [2,3]. The result of these methods of mathematical synthesis of the lighting information is the production of a normal map. Subsequently, it is possible to reconstruct the profile of semi-flat objects starting from the integration of the normal map, given by the RTI, i.e., Normal Integration. The method used for the normal integration is the one described by Queau et al. in [4].

RTI has been a known technique for many years now. This method has been applied on many types of archaeological finds [5,6,7]. Many studies have been done to highlight its pros and cons. The normal integration technique from the normal map has also been known for many years, as it is very popular for graphic modelling in video games [8]. In the field of cultural heritage, this type of 3D modelling has already been used [9,10]. The normal integration has shown some limits in the representation of low spatial frequencies. However quantitative studies on the efficiency in object reproduction of RTI with normal integration have not yet been conducted.

In this study we propose the quantitative study of the potential of the RTI technique with Normal Integration for profilometric applications on semi-three-dimensional objects and its accuracy in the reproduction of the considered artifact. To do this, ad hoc profilometric targets have been designed and realized [1] and therefore analysed to quantitatively compare the results of the RTI and Normal Integration with different and standardized techniques: micro-photogrammetry, laser scanner and optical profilometry.

2. Materials and Methods

2.1. Profilometric targets

Since the aim of the research was to quantitatively evaluate and compare the differences between the 3D model obtained through normal map integration and the other standard methods, *ad hoc* targets have been used. Targets were designed using the CAD software Inventor and realized using the stereolithography 3D printer (Formlabs Form2). Each target consists of a tile (2 x 5 x 0.5 mm) where one face has extrusions, in the case of embossed/negative reference targets, or intrusions, in the case of debossed/negative reference targets, of known and variable heigh and thickness (Fig. 1). Targets were also varnished with three different colours (white, gray and black), to test the effect of colour on the rendered profiles.

Figure 1. *The targets are formed by four series of five marks divided in columns, each with variable height or width. The first two columns have marks of different heights, but the same thickness. The last two have extrusions of different thicknesses, but the same height.* ***a)*** *embossed/positive reference target with extrusions;* ***b)*** *debossed/negative reference target with intrusions,* ***c)*** *white, gray and black version of the same target.*

2.2. RTI and Normal Integration

RTI was used to obtain the RGB normal map image of the object where each RGB value represents a direction of the surface normal vector. Normal integration allows to reconstruct the profile of semi-three-dimensional objects starting from the information contained in the normal map obtaining the three-dimensional rendering of the subject's surfaces [4] as well as the profile. To compute the RTI image, 40 images were shot using a Nikon D810 camera (7360 × 4912 pixels, 16-bit RAW images) coupled with a Nikkor 105mm f/2.8 D Macro. The light source was a Godox WITSTRO AD360 flash with a power peak of 360 W. The pipeline of the method used to obtain the object profile is showed in Fig. 2.

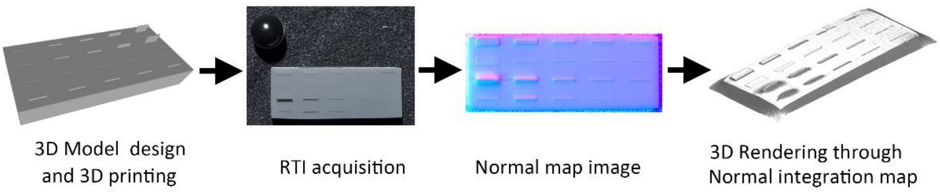

Figure 2. *Pipeline of the target profile rendering by means of RTI and normal map integration.*

2.3. Micro photogrammetry
Micro-photogrammetry is based on the principles of traditional close-range digital photogrammetry but allows the generation of a measurable 3D model of a small object with a significantly higher level of magnification and detail. The instrumental set-up uses the same camera and the same lighting system previously employed in the RTI acquisition. The peculiarity of the method is the use of the technique of Focus Stacking to overcome the problem of limited depth of field of the scene imaged. A recent released open-source Structure from Motion software was used.

2.4. Laser Scanner
The Laser Scanner is an electronic tool that provides the spatial coordinates of a cloud of points belonging to an object. This device is based on a time-of-flight laser sensor that calculates the distance between the instrument and a surface by timing the round-trip time of a pulse of light emitted by a diode. The measurements were carried out at the Arvedi Laboratory of Non-Invasive Diagnostics at the Museo del Violino of Cremona. The 3D scan proposed in this work was performed using a RS3 Integrated Scanner (a linear laser scanner with a stated accuracy of 30 μm) mounted on a mobile arm with 7 degrees of freedom (Romer Absolute Arm 7-Axis "SI") both produced by Hexagon Metrology. PolyWorks suite software was used as main scanning and editing software.

2.5. Optical Profilometer
High resolution optical profilometer SensoFar with confocal lenses with a resolution of 0.01 μm was used at the INRiM institute. The profile is obtained through interferometry on the Z-axis and moving the target on the X-Y plane to acquire an extended area of the surface.

3. Results
The complete profile was obtained for the white, gray and black reference targets by means of RTI, micro-photogrammetry and laser scanner and showed in Fig. 3 and 4. Optical profilometry were, at this stage, applied to test the maximum resolution with selected nine target marks. RTI and laser scanning technique were both efficient to give a 3D model while micro-photogrammetry was not able to generate a 3D model due to the absence of recognizable patterns since the target was completely monochrome.

3.1. Comparison of the results obtained on the embossed/positive reference target

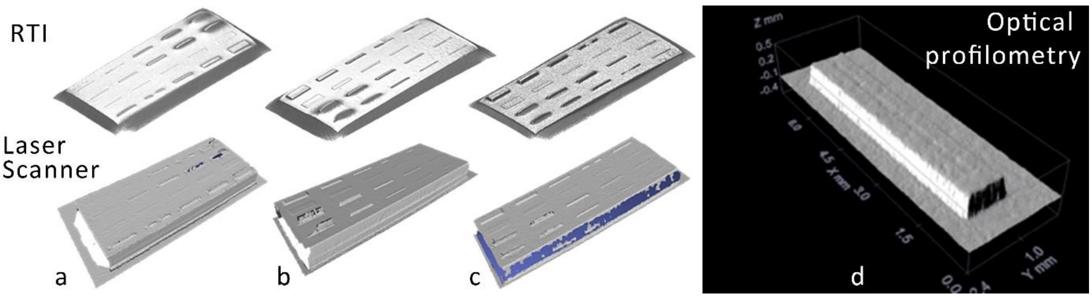

Figure 3. a) *white positive target;* ***b)*** *gray positive target;* ***c)*** *black positive target;* ***d)*** *extrusion of height 0,3 mm and width 0,3 mm, from the gray positive target.*

3.2. Comparison of the results obtained on the debossed/negative reference target

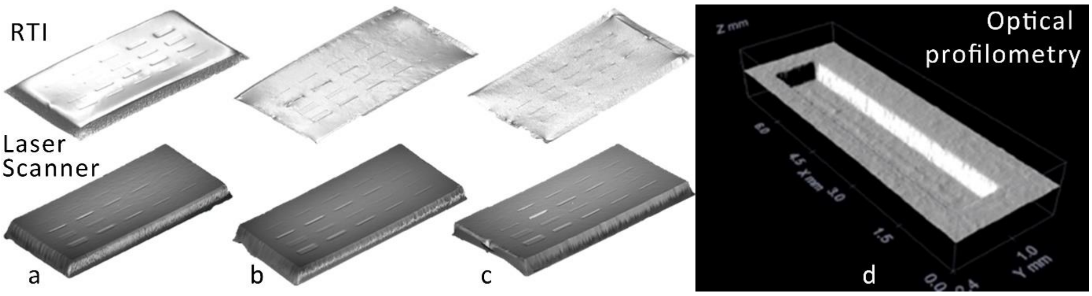

Figure 4. ***a)*** *white negative reference target;* ***b)*** *gray negative reference target;* ***c)*** *black negative reference target;* ***d)*** *intrusion of height 0,3 mm and depth 0,3 mm, from the gray negative target.*

3.3. Quantitative considerations

With each method of profile measure is associated an error in the rendering. As an example, the dimensions of the measured gray target marks have been plotted and showed in Fig. 5 compared to the theoretical values set in the 3D digital model and successively 3D printed.

For the embossed/positive target, the quantitative analysis of the results showed that RTI coupled with normal integration can reproduce the height with an error below 10%, for extrusions up to 0.5 mm high. We noticed that the colour of the target plays a role in the accuracy of the reproduction, having the errors increased with lighter colours. Nevertheless, it has a very good resolution for the high spatial frequencies and the smaller extrusions are very well reproduced. However low spatial frequencies are quite distorted and need to be corrected with shape-specific reference.

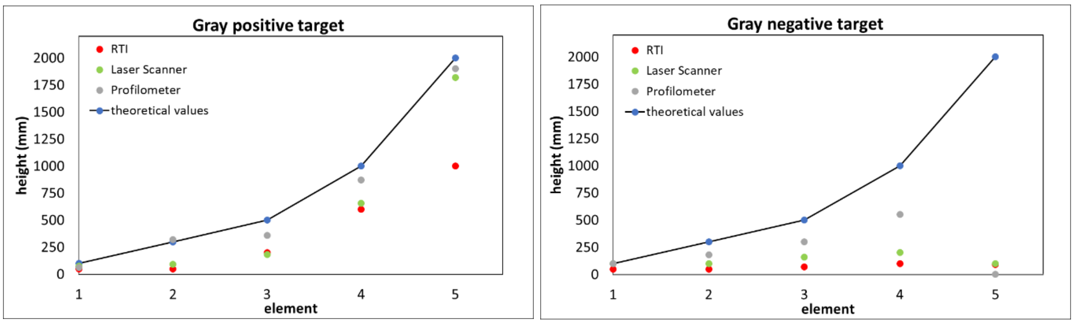

Figure 5. *Theoretical values are shown on the x axis, experimental values on the y axis in mm. Thus, it is possible to appreciate the distance of the measured values from the actual values.*

In Fig. 6 is represented a detail of a single negative element from the normal map image to the height profile obtained through integration and the comparison with the same detail obtained through the profilometer. Although a distortion is present, the small details are well rendered and can be comparable with those visible in the profilometric plot.

The laser scanner was able to reproduce with greater accuracy the low spatial frequencies but showed some errors in the reproduction of the smaller extrusions while the optical profilometer showed the best results for the marks considered. For what concerns the negative target, it is not possible to estimate the depth of intrusions with neither RTI nor with the laser scanner. The error of the measurement is for most cases of the order of magnitude of the depth of the intrusions. Also in this case, the profilometer showed the best results. An interesting result is the ability of normal integration map to represent very high spatial frequencies such as those in the texture caused by the irregularities ranging between 5 and 10 μm, measured with optical profilometry.

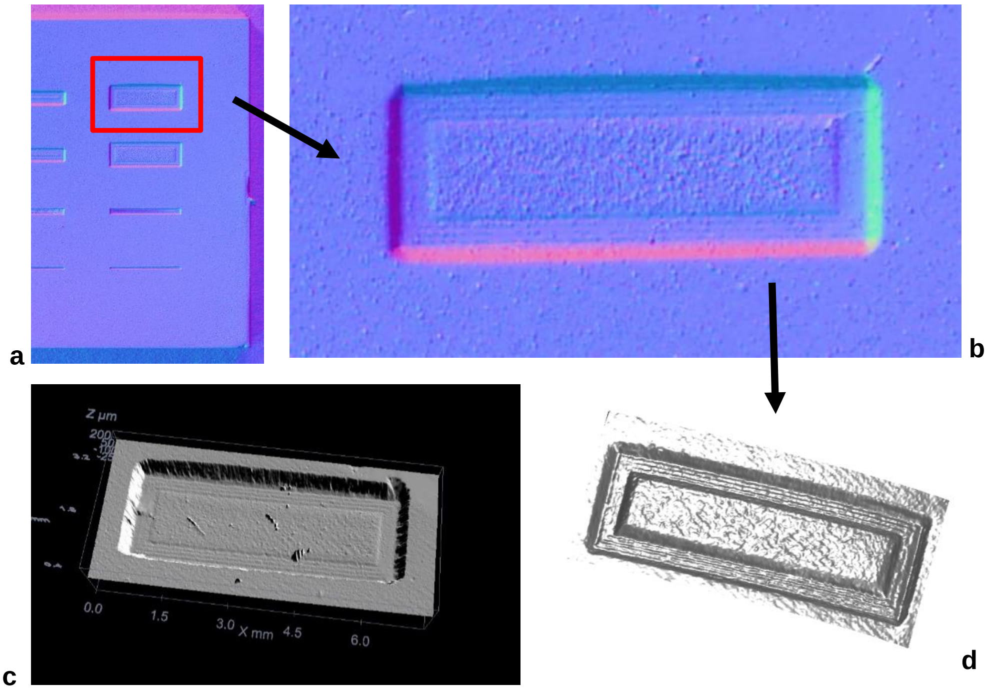

Figure 6. a) *normal map negative target;* ***b)*** *macro-image normal map of a single element of the negative target indicated in the red rectangle;* ***c)*** *element in profilometric plot;* ***d)*** *element after integrated normal map integration.*

4. Conclusions

Optical profilometry was the best technique able to reproduce exactly the profile having as a cons the measuring time very consuming and the non-portability. Laser scanner has lower deformation than RTI technique but a higher time of measure and a limited ability in reproducing the high spatial frequencies. Micro-photogrammetry needs more recognizable patterns to produce a valid 3D model with the considered targets. RTI coupled with normal map integration showed an excellent resolution, up to 5 µm with not negligible errors in low frequencies representation that can be conveniently corrected in post processing. It is a low-cost technique which only requires a camera and a flash light. Each measurement requires only about ten minutes, it is portable for *in situ* measurements and the post processing is fast making RTI an excellent method for the characterization of cultural heritage surface. As noted above, the colour of the target plays a role in the accuracy of the reproduction.

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