An improved methodology for extending the applicability of Reflectance Transformation Imaging to confined sites

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***Abstract* – Recent advances in the field of imaging technologies rapidly spread new methods of representing cultural heritage, expanding the possibilities for art historians, archaeologists, conservators and conservation scientists. In this regard, Reflectance Transformation Imaging (RTI) and three-dimensional (3D) modeling using close-range photogrammetry have become rapidly common and widely used by an heterogeneous public, multiplying the possibilities of understanding artworks from different points of view. This paper discusses the results that were achieved by applying these techniques to better understand the surface of a bas-relief owned by the Museo Egizio of Turin (Italy) in a confined site. We were able to successfully enhance the volume of engravings by integrating both RTI and 3D visualization to obtain a new investigation tool with a more suitable illumination.**

I. INTRODUCTION

RTI is a two-dimensional artifact representation technique that has wide use in the world of cultural heritage. It is a visualization tool that makes it possible, from photographs, to provide morphological information of an object's surface. The technique highlights the pattern, reflectivity and shape of a given artwork such as, for example, a coin [1], archaeological findings [2][3] or museum artifacts [4]. This technique is referred to as 2D+, positioning itself in between photography and three-dimensional modeling because the resulting image is dynamic, allowing the angle of light incidence to be changed in order to investigate the surface under different lighting conditions. The method is based on a series of photographs taken by a fixed position camera, varying the position of the illuminant which is moved from time to time by the photographer before taking the next image following a predefined geometric pattern. The light is moved around the subject in a pattern that resembles the metal structure of an umbrella, producing photographs that span from raking light (10°/15°inclination) to nadir, going through intermediate degrees (30°, 45°and 60°). The main limitation of this technique lies in the need to place the illuminant at a considerable distance in order to ensure homogeneous illumination all around the target object, conditions not always easy to achieve especially when the latter is located at significant heights or when it lies next to obstacles that prevent the correct positioning of the light source [Fig.1]. To overcome this limitation, a new methodology is proposed using photogrammetry in place of the photographic method, subsequently rendering the textured model to produce a Virtual-RTI (V-RTI) [5]. The workflow of traditional RTI involves an initial photographic capture phase that precedes the editing phase. The photographs are firstly color-balanced and exported, then loaded into a special software (RTI Builder or Relight) that detects the direction of the illuminant thanks to the presence of a black sphere that marks its position in space [6]. From the light spots on the sphere, the software is able to reconstruct the correct position of the light relative to the work and consequently generate a virtual model that can be handled by means of a free viewer. The sometimes challenging creation of RTIs, which is highly dependent on the artwork location, poses a major limitation to the possibilities of studying artifacts and the advantages that this technique can provide to cultural heritage experts in analyzing complex forms and surfaces.

II. METHOD AND CONTEXT

The case study reported here is the Temple of Ellesiya. Held in the Museo Egizio in Turin (Italy), it was build during the Thutmosis III reign at Ellesiya, not far from Abu Simbel, and was dedicated to Horus of Miam and Satet. The temple interior had an inverted T-plan including a corridor and two side chambers. On the walls are scenes

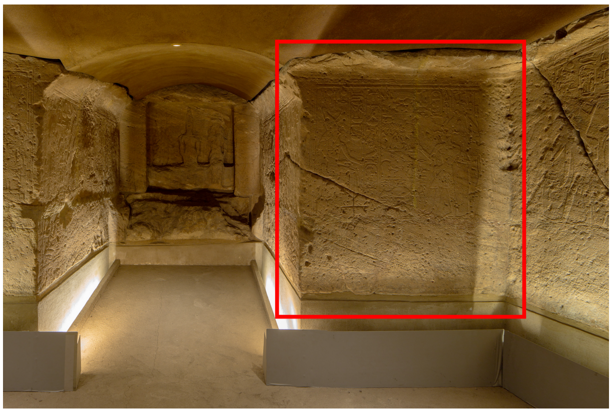

Fig. 1. The bas-relief inside the Temple of Ellesiya at the Museo Egizio. The image highlights the lack of space that prevents the production of RTI.

carved in stone showing the king offering to Egyptian and Nubian deities, hammered out in places during the reign of Akhenaten (1352-1336), and subsequently restored by Ramesses II (1279-1213), who had the triad in the niche at the back reworked to depict Amon, Horus, and the king.

As a result of the decision to flood the Nasser River for the construction of the Aswan Dam, the Temple of Ellesiya was then rescued by UNESCO, brought to Italy in 1967 and reassembled inside the Museo Egizio in Turin, where it is still preserved today. Because of this reason, it represents an astonishing finding especially in light of its well preserved and incredibly detailed bas-reliefs.

An initial and general photographic campaign was carried out when the Temple was first discovered. Subsequently, others images were produced in order to document the museum layout changes over time. In March 2023 the Centro per la Conservazione ed il Restauro dei Beni Culturali "La Venaria Reale" (Venaria Reale, Italy) conducted an in-depth documentation campaign that included high-definition multispectral imaging and many other novel technologies for heritage conservation, to detect and identify traces of pigments that are not visible to the naked eye, including Egyptian blue.

This project allowed us to test V-RTI, a digital photographic workflow that integrates principles from both RTI and photogrammetry, with the aim to enhance the visualization of the surface morphology and improve details readability in confined spaces, as in the case of the bas-relief in the Temple of Ellesiya.

Lighting in the current gallery setup comes from the floor, producing an inversion of the volumes and altering the perception of the excavated figures. In order to correctly illustrate the convex and concave forms, the present case study was chosen to emphasize the importance of lighting from the top, which comes across as more natural and less ambiguous.

III. THE V-RTI WORKFLOW

Multiple methods exist for creating RTIs, including the use of fixed domes [7] or motorized rotating arcs for light placement as well as the implementation of photogrammetry, largely used in massive digitization of museum assets [8], as well as for metrology validation [9] [10] and multispectral analysis [11]. The workflow presented here involves four steps: photographic acquisition, photogrammetry, rendering, and V-RTI reconstruction. While in conventional RTI the light is usually a remotely triggered off-camera lightbulb, manually moved around the subject at certain positions and at a fixed distance, in V-RTI it comes exclusively from a ring-flash directly mounted on the lens into which the light from an in-camera strobe is directed through a connector. By using a front light, the risk of producing incident reflections is considerable, so the source must be polarized through the use of a polarizing sheet shaped as needed. In addition, a circular polarizer is placed in front of the lens, allowing the degree of light reflection to be managed until it is completely contained. In the V-RTI, it is no longer the light that is moving, but the camera instead.

Currently, the greatest limitation of V-RTI lies in the ability to obtain a uniform, shadow-free texture, which is why the final product usually ends up in the visualization of the polygonal mesh only. In this case study, the use of a polarized ring-flash produces reflection-free pictures while using a frontal light, thus providing an accurate texture regardless of the ambient light, which is a step forward compared to examples found so far in the literature.

A. *Photographic acquisition*

Parallel point-of-view images were obtained with a 20.2 megapixels Canon EOS 6D DSLR camera equipped with a 50 mm lens, located about 1 m away from the wall. The artifact is a bas-relief sandstone surface measuring about 170 x 180 cm. Given its size and location, RTI collection is made difficult by the presence of a very close floor and ceiling, together with the adjacent wall. The shots sequence required a progression by vertical and horizontal bands orthogonal to the wall, with an 80% overlap for the short side and 25% for the long one. A greater overlap, especially on the long side (in the range of 50% to 75%), would have generated better detail, but by opting for a smaller overlap the acquisition was addressed in a few minutes, making the work agile also thanks to the use of the ring-flash instead of light-stands or external lights. In order to ensure speed of intervention even in the presence of ambient light, the ring-flash also enabled to record the actual morphology of a surface without it being affected by shadows, collecting information of the constitutive material that would otherwise be difficult to read considering the exposition lighting provided by the museum.

B. Photogrammetry

Once the RAW images are collected, JPEG are exported and optimized for the 3D reconstruction, processing the images through the use of the Structure from Motion software. The primary purpose of V-RTI is to provide a representation as close to reality as possible, which is why the settings of the photogrammetry software will have to be set to maximum values in order to extract the greatest detail available. The workflow consists of a prior lens calibration phase to contain projection errors - a principle that is especially valid for planar subjects - before starting the actual calculation process, which involves a succession of sequential steps starting from the alignment for the identification of the homologous points, based on which a Dense Cloud is then generated. This product is the basis for the construction of the polygonal mesh, consisting of vertices and segments that define the volume and surface of the object, a step before the application of the final high-definition texture generated in the last stage. The OBJ and JPEG files are respectively derived from model and texture, that are crucial steps for the rendering of the 3D modeling software.

C. Rendering

After importing the model and its texture within the modeling software (e.g. Blender [12]), the virtual lighting set is constructed. Following the traditional light point scheme of a normal RTI, 49 lights are arranged in groups of 4 for each of the 12 beams, in addition to the nadiral light, composing the hemisphere that will enlight the textured model [Fig.2]. The virtual dome built around the subject will simulate the movement of the strobe as in a traditional RTI scheme, turning on and off a different spotlight each time. A high-resolution renderings are then produced, resulting in a group of images that are ready to be processed in the final stage. In addition to the three-dimensional model, a black reflective sphere is included in the virtual set, which is used to understand the right position of the light in the space. Renderings can be automated by building up an animation, thus controlling the lights status switching them on and off until the sequence is complete, saving time for future projects. Once the virtual set has been arranged, it will be possible to import, adapt and render a different 3D model each time, scaling its dimension accordingly to the virtual dome.

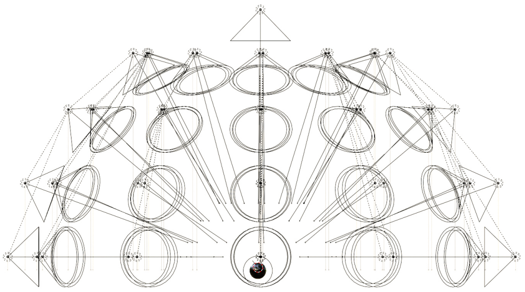

Fig. 2. The V-RTI dome built in Blender.

Light x 0,78 y 0,63

Zoom 19%

Pan x 0 y 0

Rendering mode Diffuse Gain

Gain 2

File i\Ellesiya\3D\RAW-parete-ring\VRTI\PARETE-RING.ptm

Size 5373 x 5105 Format LRGB PTM

Fig. 3. The V-RTI of the bas-relief in the Temple of Ellesiya, lit from an above-right direction, allowing the viewer to perceive the sculpture with the right volume.

D. Building the V-RTI

Once the renderings are acquired, they are loaded into the dedicated software (e.g. Relight [13]) in order to build an RTI. The first step involves recognizing the black sphere containing the light spots related to the various directions, which are necessary for the program to reconstruct the interactive model [Fig.3]. Then, the final RTI can be saved by selecting for different calculation algorithms. The output may be used either locally through a free viewer (e.g. RTI Viewer), or via Web thanks to easy and intuitive visualization platforms (e.g. Ariadne [14]). In addition, a .LP file that describes the sequence can be exported in order to save time for any future calculation.

IV. QUALITY COMPARISON: RTI VS V-RTI

This section shows direct examples in order to compare identical portions of an artwork in both RTI and V-RTI. The case study is a small painting on copper measuring 9 x 13 cm that is rich in small details, useful for direct comparison between the two techniques [15]. The selected areas are those where changes in brush direction, surface flatness defects and differences in pigment deposits are most visible. In order to make a meaningful and valuable comparison, although empirical and purely visual, three exports with different visualizations were produced for each portion, exploiting the potential of the Polynomial Texture Mapping (PTM) algorithm. Each frame was exported using the same settings, light angle and resolution, using three different calculations: Coefficient Unsharp Mask, Specular Enhancement and Normal Map [Fig.4].

The photogrammetric model was made by considering 294 parallel point photographs close to the minimum fo-

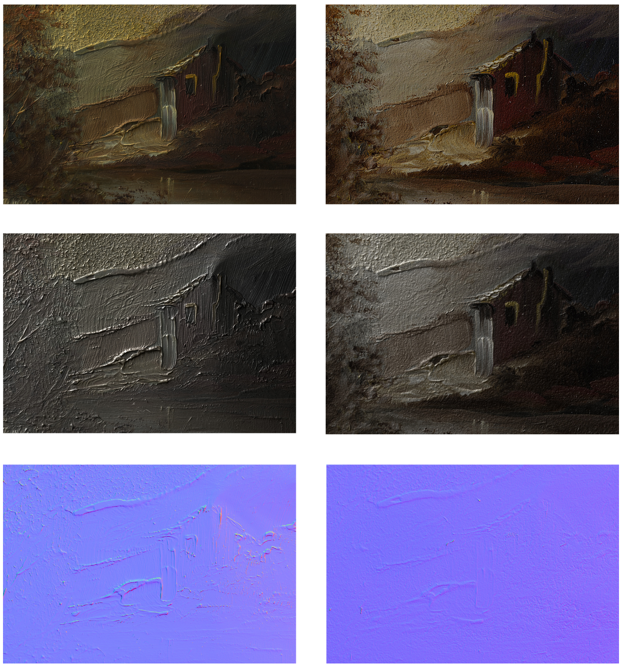

Fig. 4. Comparison between RTI and V-RTI. 1st row, Coefficient Unsharp Mask; 2nd row, Specular Enhancement; 3rd row, Normal Map.

cus distance (about 35 cm), thus at the highest resolution possible for the camera-lens combination, with a Canon EOS 6D DSLR and a Canon 100 mm f/2.8 lens. Image overlap was kept constant in the range of 60 to 80 %, both horizontally and vertically, to maximize data redundancy. The painting was placed on a table while the camera was mounted on a tripod. In order to speed up the acquisition process, it was decided to move the painting by sliding the cardboard on which it was placed following a serpentine pattern. The camera settings prioritized the aperture value (f/18) to minimize problems due to the limited focusing distance [16], while the long shutter speed (2.5 s) took advantage of the continuous light provided by two polarized LED panels to neutralize reflections from the painted surface. Working sensitivity was kept close to the nominal value (160 ISO) to reduce sensor noise and increase detail.

Photogrammetry could be calculated by both commercial and open-source softwares [17]. This workflow included Metashape [18] to generate a 3D model defined by the following parameters:

Table 1. 3D Model specifications.

Product	Resolution	Unit of Measure
Sparse Cloud	29 k	points
Dense Cloud	54 mln	points
Mesh	35 mln	faces
Texture	4600	pixels

V. CONCLUSIONS

This paper discusses a new Reflectance Transformation Imaging (RTI) methodology that involves photogrammetry in order to obtain rendered images of the 3D model (V-RTI). The V-RTI has proven to be useful in all those contexts where it is difficult or impossible to produce a traditional RTI due to space constraints. The unconventional conditions often found on conservation and archaeological sites, as well as on large works (larger than 1.5 m), often limit the analysis, and therefore the study, of those subjects for which the production of an RTI would be of fundamental importance for art historical, archaeological and scientific research. The new method presented so far seems to meet these needs while, in terms of quality, it certainly represents a compromise since the level of detail offered by photogrammetry is still poorer when compared to the results achievable with a traditional RTI.

The case study of the Temple of Ellesiya showed the potential of V-RTI produced through the use of a polarized ring-flash, in a context where it would have been impossible to produce a traditional RTI given the limitations imposed by the work space, offering a novel and enriched interpretation of an otherwise difficult-to-analyze artifact. V-RTI can thus be integrated with other analytical techniques such as multispectral and high-definition imaging, while providing valuable metrical data even if the model resolution (in terms of points and polygons) is not very high, although increasing the overlap between shots and employing a best camera can easily improve the detail level.

The second case study, carried out for the sole purpose of assessing through direct observation the quality gap between the 3D model and RTI, highlighted the limitations of photogrammetry in describing the smallest details even in the presence of a well-defined and polygon-rich model. In particular, the use of polarized light appear to be supportive in the correct 3D reconstruction but eliminates valuable surface information given by the natural specularity of the artifact that is, on the other hand, well revealed by traditional RTI. In addition, it must be considered that the workflow of V-RTI requires an in-depth knowledge of photographic and post-processing techniques, together with the availability of high-performance computing machines and dedicated softwares that are not always easy to use, as opposed to RTI which can also be carried out by operators who are not necessarily specialized, and with the use of fast and intuitive software.

A step forward in the development of this research could be the production of a new ring-flash with two lights instead of one. A greater amount of light would decrease digital noise while increasing image sharpness, improving both polygonal mesh and texture quality.

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VII. DECLARATIONS

The authors declare no conflict of interest.

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