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Artworks in the spotlight: characterization with a multispectral LED dome

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Abstract. We describe the design and realization of a novel multispectral light dome system and the associated software control and calibration tools used to process the acquired data, in a specialized pipeline geared towards the analysis of shape and appearance properties of cultural heritage items. The current prototype dome, built using easily available electronic and lighting components, can illuminate a target of size 20cm x 20cm from 52 directions uniformly distributed in a hemisphere. From each illumination direction, 3 LED lights cover the visible range of the electromagnetic spectrum, as well as long ultraviolet and near infrared. A dedicated control system implemented on Arduino boards connected to a controlling PC fully manages all lighting and a camera to support automated acquisition. The controlling software also allows real-time adjustment of the LED settings, and provides a live-view of the to-be-captured scene. We approach per-pixel light calibration by placing dedicated targets in the focal plane: four black reflective spheres for back-tracing the position of the LED lamps and a planar full-frame white paper to correct for the non-uniformity of radiance. Once the light calibration is safeguarded, the multispectral acquisition of an artwork can be completed in a matter of minutes, resulting in a spot-wise appearance profile, that stores at pixel level the per-frequency intensity value together with the light direction vector. By performing calibrated acquisition of multispectral Reflectance Transformation Imaging (RTI), with our analysis system it is possible to recover surface normals, to characterize matte and specular behavior of materials, and to explore different surface layers thanks to UV-VIS-IR LED light separation. To demonstrate the system features we present the outcomes of the on-site capture of metallic artwork at the National Archaeological Museum of Cagliari, Sardinia.

1. Introduction

Reflectance transformation imaging (RTI) is widely used in the Cultural Heritage field, first and foremost for documentation purposes [1], as well as for enhancing visibility of details with small relief [2] and for the extrusion of the three-dimensionality of the real-word object. The technique is based on capturing multiple images of an object from a fixed viewpoint under different directional illumination.

The acquisition setup can be quite simple, with a camera on a tripod and a hand-held torch that is freely moved around the scene, recovering the illumination direction from highlights on a spherical target (H-RTI). This method is cheap and flexible, but makes light calibration hard and requires careful manual procedures. The counterpart of H-RTI is the dome-based system with higher stability and precision, being based on fixed lights equally sampled in the shape of a hemisphere. Dome solutions are, however, expensive and not too practical to be used for on-site acquisitions. In this paper we describe the design of a novel dome solution using low cost hardware and a reasonably portability making it suitable for both lab and on-site acquisitions. We describe our hardware and software choices, comparing them with prior work. We finally demonstrate the suitability of our system for Cultural Heritage applications, by showcasing an on-site acquisition carried out at the National Archeology Museum of Cagliari, Sardinia.

2. Related work

Several dome solutions have been introduced so far, with different cost requirements, dimensions and running environments [3, 4]. Schwartz et al. [5] presented a complex hardware design and the corresponding calibration and processing procedures for the "brute-force" sampling of a 6D approximation of Bidirectional Texture Functions (BTFs). In addition, their setup is capable of robustly and precisely reconstructing the mesoscopic material geometry, e.g. displacement maps, as well as capturing shape and reflectance of complete 3D objects. The system includes industrial digital video cameras, a rotation stage, LED lamps and projectors. The drawbacks of this arrangement are the high cost and high difficulty of handling outside the lab environment, as well as the need of complex calibration procedure due to many different hardware components. Hameeuw [4] proposed a portable solution extremely easy to use. It is almost a one-click solution that can provide a straightforward RTI acquisition pipeline. The dome is equipped with a 5 million pixel camera or a 29 million monochromatic sensor; it mounts 260 white LED light sources around a 80cm diameter dome. The main design purpose is to make it easy to assemble/disassemble the dome in less than half an hour. This requirement makes it operable both in museum collections or other in-situ scenarios. Recently, other domes have been presented that use both visible and invisible light wavelengths. One example is the Microdome with multispectral RTI capability presented by the RICH team [6]. It is equipped with 228 different LED light sources. Those LEDs are divided in five different spectra: ultraviolet (365 nm), blue (460 nm), red (523 nm), green (623 nm), and infrared (850 nm). A 28 megapixel monochromatic sensor is mounted on top of the dome.

In order to convert the raw image stack into shape and reflectance parameters or high quality relighted images, the calibration of light direction and intensity is required. Over the last decades a lot of methods have been published that deal with different kinds of acquisition setup, and several, non-ideal types of illuminants[7, 8, 9, 10]. Calibration should provide images and metadata suitable for the use with RTI processing/relighting pipeline.

In our work we propose an integrated dome solution coupled with our light calibration and processing software ([11]) able to recover reflectance parameters, relighted images and 3D models and we demonstrate its usefulness in CH applications.

3. Our system

Our dome (Figure 2) features 156 multi-spectral LEDs evenly distributed across 52 light positions over a 60cm diameter hemisphere. All the light sources have a wide aperture in order to stretch the homogeneity of the light intensity as much as possible. The light sources cover 5 bands (see Figure 1): two narrow in the ultraviolet (centered at 395nm) and infrared (centered at 850nm) regions and one broad in the visible to collect the RGB signals of the Nikon D810 DSLR camera with the infrared cut-off filter removed.

The camera is mounted on top of the hemisphere. The dome design has been thought in order to allow for its use in a fixed setup in an arbitrary orientation. This is achieved by integrating all the hardware components to the fixed dome structure, including the camera, as presented in Figure 3. It is possible to scan the objects horizontally, lying on a table by directly placing the dome on top of the acquisition surface (the most common setup for laboratory experiments or even on-site acquisitions, given that the cultural heritage objects allow to be moved) or vertically, on a wall by mounting it on a tripod or other similar mounting accessory (appropriate for immutable objects, such as paintings, frescoes, etc.).

The control unit consists of some control boards (Arduino Mega 2560) and three constant voltage constant current programmable control supply power modules (DP20V2A). The boards drive the switch (on/off) of the single LEDs in the dome, while the power modules are used to tune the intensity of the three sets of LEDs (i.e., UV-VIS-IR). The Arduino boards are interconnected and can communicate with an external PC via USB cable using a serial protocol. This protocol allows a PC program to select and turn on one LED at a time; it is mandatory to wait until a LED is off before sending other commands.

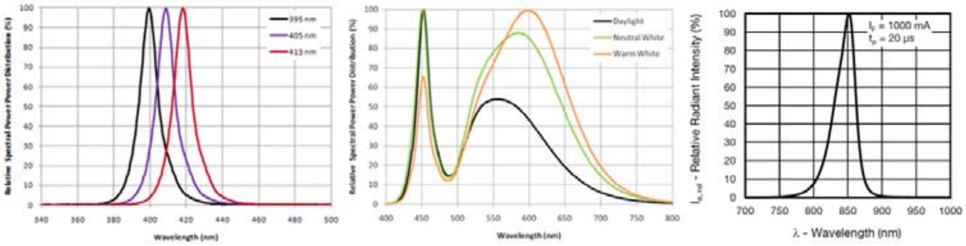


Figure 1. Spectral distribution of the LED spotlights in ultraviolet, visible and near infrared.

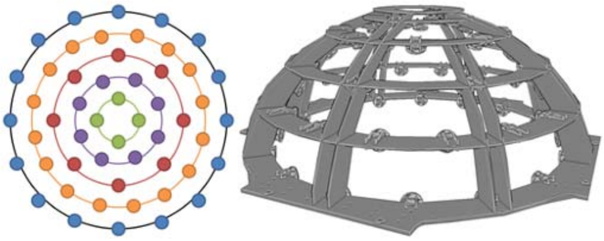
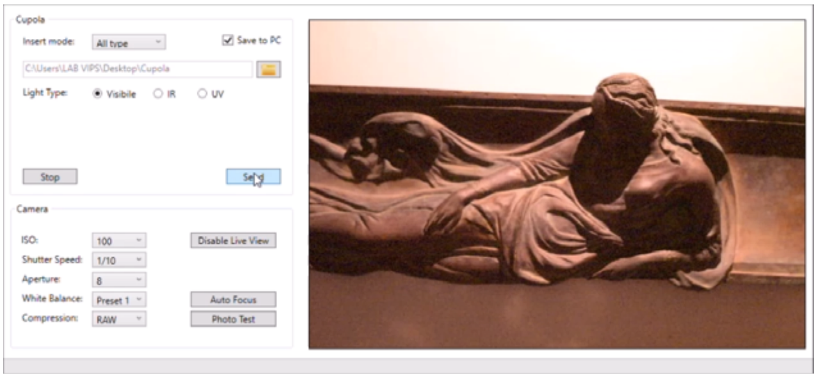


Figure 2. Light position distribution of the dome device.

Figure 3. Several snapshots of the dome device.

3.1. *Acquisition control software*

An user friendly interface has been developed to control the image stack acquisition. The interface enables the easy control of both dome lights (sending commands to the Arduino according to the defined protocol) and of the digital camera by using a software library [12] with access to the camera settings. The GUI allows selection of predefined lights switch and synchronized camera



Cupola
Insert mode: All type
☑ Save to PC
C:\Users\LAB VIPS\Desktop\Cupola
Light Type: ● Visibile ○ IR ○ UV

Camera
ISO: 100
Shutter Speed: 1/10
Aperture: 8
White Balance: Preset 1
Compression: RAW

Figure 4. The graphical user interface of the dome system transmitting the live-view of a captured artwork, together with the camera settings.

capture sequences, or individual switches (Figure 4). The user can view in real-time the change of lights and the illuminated object during the acquisition thanks to the live-view window. The live-view feature is useful as well to visually check the image quality when adjusting the camera settings (ISO, shutter speed, aperture, white balance, image format and focus). The camera settings are optimally configured so as to capture sharp images of the object's surface.

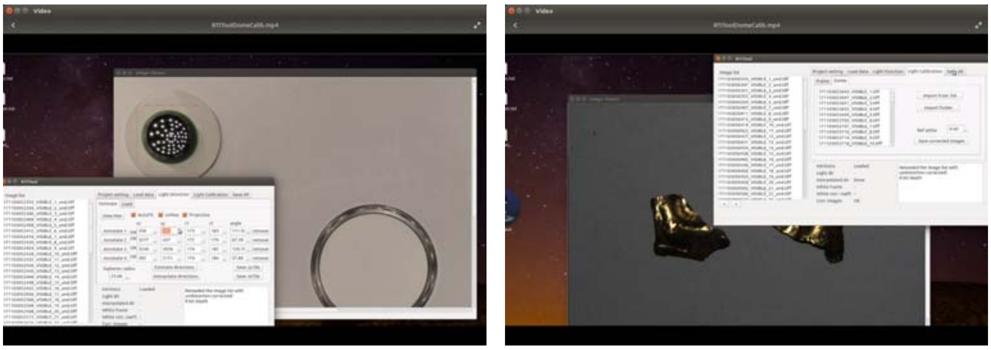
3.2. Light calibration

The dome calibration method use methods and algorithms presented in [11], specifically adapted in order to obtain a preliminary estimation of per pixel light direction and reference illumination in the acquisition region that is then used to correct the image stack acquired during the actual object capture. This procedure consists in capturing two calibration targets at the same focal distance used for the object capture: the first includes four glossy spheres at the corners, and the second is a white Lambertian surface placed perpendicularly to the camera axis (Figure 5).

The image stack obtained capturing the first target is used to estimate per pixel interpolated light direction from the position of highlights on the spheres, as shown in [11]. The second image stack is used at the time of object image processing to correct original images with an intensity correction factors proportional to the measured illumination on the white target.

All these calibration procedures can be easily realized with a custom software tool (RTITool) freely available at *https://github.com/giach68/RTITool*. The tool allows semi-automatic sphere annotation and light direction estimate (Figure 6 (a)) as well as the intensity correction of the object images based on the reference images of the target (Figure 6 (b)). The tool features also

Figure 5. Target with reflective spheres being placed in the acquisition region for light direction calibration.



(a) (b)

Figure 6. Calibration software (RTItool) options for the dome system. (a) light direction estimation tab with the annotations of the four black reflective spheres; (b) intensity correction based on the loaded images of the white frame target.

several options for image preprocessing (e.g.undistortion) and on the fly calibration of RTI stacks based on targets directly added to the imaged scene (white frame and spheres).

The light calibration procedures and the interpolated light direction estimation proved to be effective in improving the accuracy of quantitative parameters that can be derived from the image stacks, e.g. normals and albedo [13].

4. Case Study

The dome has been tested on different artworks (paintings, bas-reliefs, coins). In this paper we present a particularly interesting case study related to an onsite acquisition of a metallic artwork at the National Archaeology Museum in Cagliari, Sardinia, Italy. The digitized object is an ancient gold lamina with historical inscriptions. Named ”Lamina del Sulcis”, it consists of two fragments of an inscription engraved on thin gold leaf ”lamina” (a thin plaque or panel intended to be affixed to some other surface), that was found in the earliest stratum of the Sulcis tophet or infant cremation cemetery (West Sardinia). Only 1.4 cm x 1.5 cm x 0.05 cm in size, the whole lamina is thought to have once been attached to an iron object that has partially damaged its surface. The text has been dated to the 8th-7th centuries BCE on the basis of its paleographic features [14]. This makes the object extremely important for the Mediterranean archaeology [15].

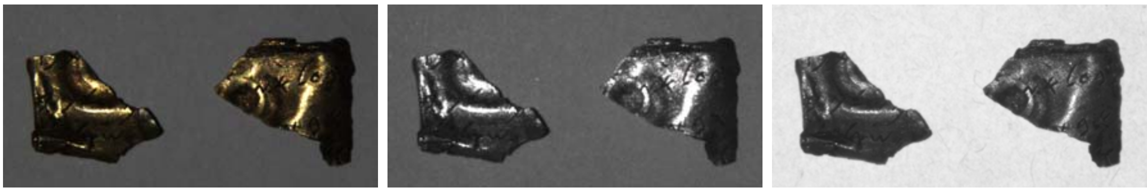
In Figure 7 we show the acquisition setup. Before capturing the object images, the calibration procedure with the sphere target and the white target has been performed as described in Section 3. In the object acquisition setup, reflective spheres have been placed as well in order to allow a potential direct calibration from the acquired images. Different acquisition have been performed using different resolutions.

The RTI processing pipeline described in [11] has been used to extract albedo and normals of the lamina’s surface, as shown in Figure 9.

Particularly valuable for the analysis of paintings, multispectral signal is also of great importance for metallic objects, and can increase the amount of information provided for a particular artwork. Looking at albedo and normal maps obtained with the three different lights it is possible to see that they capture slightly different information.

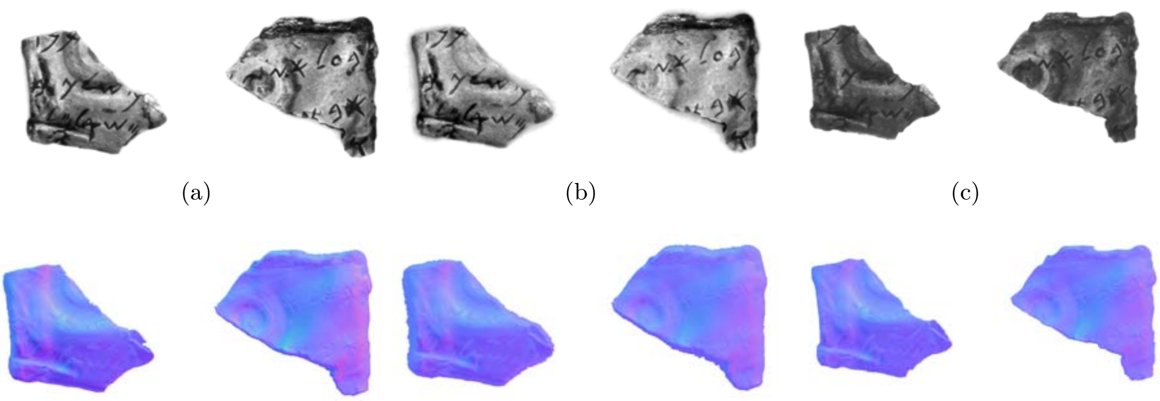
From the reflectance properties of the object it is possible to obtain useful information about it, in this case, for example, reading inscriptions. In [11] we have shown that measures like the Outlier Direction map (Figure 10), counting the number of incoming light directions causing non Lambertian reflection in the target object can reveal surface details. Estimating this map from

Figure 7. The acquisition setup: the dome is placed in order to have the object near the center of its sphere with its flatter part perpendicular to the camera axis.



(a) (b) (c)

Figure 8. Example captured images with the different ligths. (a) visible. (b) IR. (c) UV.



(a) (b) (c)

(d) (e) (f)

Figure 9. Albedo and normals of the lamina, estimated with Photometric Stereo on Visible (a,d), IR (b,d) and UV (c,f) images.

PS fitting and mosaicking (manually) image patches in order to obtain an approximate object reconstruction it is possible to visualize the enhanced inscription as shown in Figure 10. It is possible to see that the map obtained with the IR images better enhances the characters, possibly due to the different shape of the specular highlight in the IR frequency reflectance function.

By relighting the image and simulating the appearance of the object from a virtual light direction, an enhanced visualization of the inscriptions is obtained (see Figure 11). In this case we performed relighting with Radial Basis Function interpolation as shown in [16], allowing a

(a) (b)

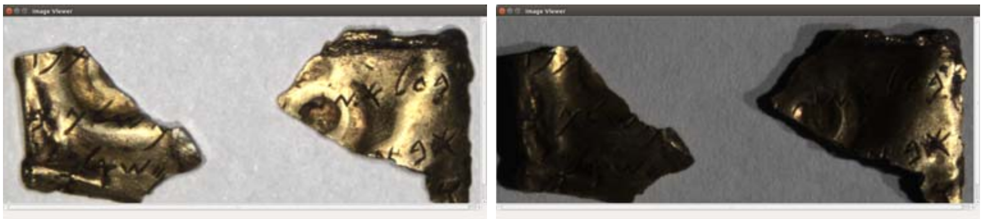
Figure 10. Outlier Directions maps enhancing local specularity of the surface can enhance useful detail. In this case the IR-based enhancement results in more readable characters.

good representation of the specular component of the reflectance.

Moreover, the recovery of the normals allows for a 3D reconstruction that further on leads to the identification of matching points between the two fragments of the lamina. The shape of the object has been obtained by integrating the input normal vector field. A mask identifies the object within the normal map images (Figure 9). Two types of integral have been performed. The first is a one-dimensional integral along the object/mask contour. Since the integral is defined up to a constant, a random point on the contour is chosen to have depth equal to zero. The boundary condition of the linear integral is the depth value of this point, which is the first and last point on the integration curve. Then a surface integral is computed, using the depth of the contour as the boundary condition. In both cases, an approximation of the second derivatives of the surface is employed to build a sparse Poisson based linear system, and it has been solved through a multidimensional Conjugate Gradient method. Figure 12 shows the re-attachment of the two parts into a whole piece, based on the corresponding points with highest matching probability.

5. Conclusion

The dome system presented in this paper is a flexible and reliable solution that can be extremely useful for the digitization of various types of artworks and underlying materials. By our multiple acquisition experiments both in laboratory and on-site, we have proved that our system is highly portable and this is thanks to the integrated hardware components that can be controlled by a single tool. Apart from the all-in-one controlling software, we have showed how the image stack delivered by the dome is easily compatible with image calibration and visualization tools developed in previous work for different RTI setups, by adding only minor tweaks. Above all, we



(a) (b)

Figure 11. Lamina images relighted from top center position (lx, ly) = (0,0) and with raking light from right (lx, ly) = (0,0.85) using Radial Basis Function interpolaton.

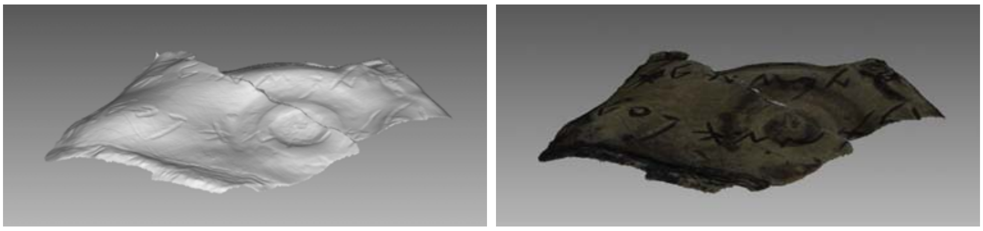


Figure 12. Shaded (left) and textured (right) rendering of the 3D model of the lamina obtained with 3D stitching of the two meshes recovered by normal map integration.

have seen that the multispectral dome in combination with reflectance fitting algorithms leads to revealing results for artworks, from detail visibility enhancement to 3D reconstruction and fragment reassembly.

As future work, we intend to enlarge the portfolio of acquisitions with the dome, by testing it on more artworks, with other properties than what was covered so far. At the same time, we are planning to continuously improve the supporting image processing tools, according to new challenges that may arise, and to extract more visual information based on the multi-light image stacks captured by the dome.

Acknowledgments

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