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Practical application of visible-induced luminescence and use of parasitic IR reflectance as relative spatial reference in Egyptian artifacts

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Abstract

Egyptian blue ($CaCuSi_4O_{10}$) is one of the most ancient artificial pigments, widely used in ancient times. Its peculiarity is an exceptional infrared emission upon visible excitation, allowing an easy and non-invasive diagnostic through the so-called visible-induced luminescence (VIL) technique. Usually, it requires total absence of infrared parasitic light, highlighting areas in which the pigment is present even in traces. In this report, we propose the introduction of a small portion of IR parasitic light as spatial reference for locating Egyptian blue on analyzed object. In VIL modality, the contemporary reflectance transformation imaging (RTI) and 3D photogrammetric model reconstruction were performed with the final 3D rebuilding of surface, morphology, and pigment distribution. We demonstrated the possibility to perform VIL and 3D photogrammetry without opening the conservation case that is extremely important by a conservation point of view, avoiding any microclimatic alteration, compatibly with the minimum invasiveness (absence of contact and displacement of the object).

Keywords Egyptian blue · Visible-induced luminescence · Infrared emission · Reflectance transformation imaging · Photogrammetry · Egyptian artifacts

Introduction

Egyptian blue is one of the most ancient artificial pigments, first produced during the Egyptian pre-dynastic period (~ 3200 BC, (Corcoran 2016)) and then widely diffuse during the 4th Dynasty (Berke 2007; Hatton et al. 2008). It was used in all Mediterranean basin (Linn et al. 2018), including Ancient Greece (Berke 2002), Etruscan civilization (Alfeld et al. 2018), Roman Empire (Miriello et al. 2018; Piovesan et al. 2011), Spain (Mateos et al. 2018), and also during the Medieval period (Bredal-Jørgensen et al. 2011; Lazzarini 1982; Nicola et al. 2018). Its stoichiometry is $CaCuSi_4O_{10}$ (corresponding to the natural mineral cuprorivaite), obtained by mixing $CaCO_3$, silica sand, a copper mineral (generally malachite or copper metal), and a flux based on potassium or sodium salts (Giménez et al. 2017) and heating at 850–950 °C (Berke 2007). The so-synthesized compound is a powder with a characteristic and intense blue color. The peculiarity of this pigment is that, upon excitation in the visible region of electromagnetic spectrum, it shows a broad emission in the infrared region (centered at ~ 950 nm; full width at half peak ~ 120 nm) (Accorsi et al. 2009; Ajo et al. 1996; Pozza et al. 2000). The emission is high, reaching a quantum yield of ~ 10% (Berdahl et al. 2018), underlining an excellent manufacturing technology of five thousand years ago. These properties allow its identification through photo-induced luminescence that can be applied directly in situ, obtaining a spatially resolved imaging of the pigment onto artifacts (Smith et al. 2009; Verri 2009) even in traces (Verri et al. 2010). The technique, called visible-induced luminescence (VIL), uses a digital camera (to which the IR cut filter has been removed) to acquire Egyptian blue response (Chiari 2018) and common irradiation source, such as photographic flashes or LED lamps, to irradiate the sample: the former sources possess a considerable IR part that should be adequately filtered; on the contrary, LEDs emit in narrower range

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with a considerable less IR component. VIL requires absence of parasitic light for acquiring only infrared luminescence produced by areas characterized by the presence of Egyptian blue, while the rest of the subject remains completely dark and undetectable by the CCD sensor of the modified camera (Fig. 1). Hence, the irradiation source is often shielded by one or more IR cut filters to reduce the parasitic light induced by the experimental setup; as anticipated, the effect is mitigated also using LED's source that have a reduced IR emission (Verri 2009). At the same time, the camera lens mounts a UV–VIS cut filter to prevent the ambient and visible excitation source light to reach the camera sensor. Interestingly, the introduction of infrared parasitic light allows to redefine the spatial description, accepting spurious images as a result (Verri 2009). Indeed, parasitic light can be exploited for 3D reconstruction and reflectance transformation imaging (RTI) (Garstki 2017). RTI constitutes a straightforward technique developed by T. Malzbender et al. (Malzbender et al. 2001) that found immediately application in Cultural Heritage investigation and conservation (Newman 2015). Briefly, RTI consists acquisition of several images with the same framing and distance from the subject at different illumination angles (Mytum and Peterson 2018). A spherical reference, put inside the camera view field, shows the direction of provenance of irradiation. From the comparison between the images, a numerical mapping of the surface normals is processed,

Fig. 1 Visible (left) and visible-induced luminescence (right) images of Ptha-Sokar-Osiris's wooden statue (Ptolemaic era, 332–30 B.C. Cat. N. Provv. 0097, Torino, Museo Egizio). In VIL acquisition, white spots indicate Egyptian blue presence

optimizing the visualization of the morphology and producing customized illuminations based on the mapping itself. This technique is easily adapted to the infrared field, but in the VIL context, it clashes with the difficulty of catching the reflection of the sphere and describing the portions of the surface without Egyptian blue. In this work, we propose the introduction of a portion of infrared parasitic light allowing the contemporary VIL and RTI acquisition. The RTI in VIL mode integrates the morphological data with the spatial localization of Egyptian blue on the artifact. The 2D-VIL image usually does not allow the interpretation and analysis of the brush strokes, e.g., regarding the deposition technique or the morphological aspect of the surface. Different from the common RTI performed using visible light, the high luminescence of Egyptian blue can be exploited for its identification even in traces. Consequently, the use of the RTI in VIL mode allows a better diagnostic study of this pigment because it identifies both its spatial location on the artifacts and allows the identification of the technique used for its deposition. Moreover, the artifact's surface is well identified, especially in the case of a rough surface as wooden statuettes and sarcophaguses are. The amount of infrared parasitic light purposely introduced for the RTI in VIL mode was modulated using from one to three UVIR cut filter in front of the excitation source, and it was quantified basing on RGB value obtained during software elaboration.

In this paper, we described the operative conditions to obtain VIL and RTI or 3D photogrammetry both in VIL mode. The experimental set-up was firstly tested on ancient Egyptian statues (preserved at the Museo Egizio di Torino, Italy) in VIL and RTI acquisition. The contemporary VIL and 3D photogrammetry (Miles et al. 2014) was carried out on Pasherienaset's sarcophagus (preserved at the Ligurian Archeological Museum in Pegli, Genoa, Italy). In this latter case, due to the allocation of the artifact in the center of the exposition room, the analyses were performed "through the glass", i.e., without opening the conservation case, thus, minimizing the diagnostic invasiveness.

Materials and method

Ptha-Sokar-Osiris's statues and Pasherienaset's sarcophagus

The statues represent the divinity of Ptha-Sokar-Osiris, born from the union of three deities: Ptha, god of craftsmanship and Memphis's deity, Seker, god with the head of a hawk, and Osiris, god of death. For this union, the divinity is often represented as a standing mummy, with a horned crown or with the head of falcon. The statues, from different Egyptian periods, are preserved at the Museo Egizio in Turin (Italy): Ptolemaic era, 332–30 BC (Fig. 1); XXV–XXXI Dynasty,

712–332 BC (?) (Fig. 2); XXI Dynasty, 1070–946 BC (from Khaemuaset-QV 44 and Setherkhepshef-QV 43 tomb Fig. 5). To the best of our knowledge, no diagnostic analyses have yet been performed on these artifacts.

Pasherienaset's sarcophagus comes from Efdu (Na gel-Hassaia) and it's preserved in the Ligurian Archeological Museum in Pegli (Genoa, Italy). The sarcophagus is anthropoid, or mummiform, because it reproduces ideally the embalmed body of the dead. The sarcophagus is sumptuously decorated and made up of a bed on which there is an ephemeral reproduction of Egyptian blue and a cover decorated and embellished with several colors. Inside, Pasherienaset's mummy (first half of XXVI Dynasty, 664–525 BC) is preserved. Preliminary X-ray fluorescence (XRF) analyses identified the presence of the Egyptian blue, malachite, orpiment, red ochre, and gypsum in the blue, green, yellow, red, and white spots, respectively (Cortese and Rossi 2008; Franceschi and Locardi 2014).

Acquisition set

Acquisition set is composed by a Nikon D800 UVIR-modified camera equipped with 50-mm AF-S NIKKOR 50-mm f/1.8G objective with a B+W 093 IR mounted filter. Illumination light was provided by a Nikon SB610 Flash shaded with one, two, or three Hoya A-77 UVIR cut filters. For VIL and RTI, the camera was set at zenith at a 1-m height; flash light at 1.5 m. Exposition values were applied as follows: diaphragm f8 sensitivity iso 800, shutter speed 1/125, and flash on 1/1. The subject was a complete gray scale of a standard Xrite Colochart Classic, including white and black swatches, coupled with a tab of Kremer 10060 Egyptian blue

used as a reference for VIL luminance correction. The latter value was used to set the reflectance value in Lightroom equal to 95% (RGB 243, 243, 243) avoiding an over exposure or saturation of the white pixels in the image. A RTI infrared compatible test sphere has been introduced to check the response to parasitic infrared light coming from the flash shaded with an increasing number (from 1 to 3) of Hoya UVIR cut filters. The subject has been disposed on a horizontal plane; the center point of field of view represents the nadir of the set.

Spectroscopic analysis

Emission of the excitation source and the cutting effect of the different filters employed have been checked using a CCS200 Thorlabs CCD spectrometer equipped with an optical fiber. Filters have been located directly in contact with the fiber that has been placed at 30 cm from the excitation source.

Software analysis

Adobe Lightroom software has been used in color correction and sorting tiff and JPEG files from the raw original acquisition image. RTI Builder software by CHI Cultural Heritage Imaging ((CHI) 2018) was applied in PTM fitter mode, processing JPEG image (max quality) files in full dimension (7360 × 4912) at 300 DPI. A 3D model has been produced through Agisoft Photoscan, processing JPEG image (max quality) files in full dimension (5000 × 3337) at 150 DPI. The resolutions of the images used were 20 pixel/mm and 7 pixel/mm for RTI in VIL mode and 3D reconstruction, respectively.

Fig. 2 a Image of statue under ambient illumination. b VIL with parasitic IR light. c DARK acquisition of IR parasitic light. d VIL after image subtraction of dark acquisition of Ptha-Sokar-Osiris's wooden statue (XXV–XXXI Dynasty, 712–332 BC (?). Cat. N. Provv. 0098, Torino, Museo Egizio
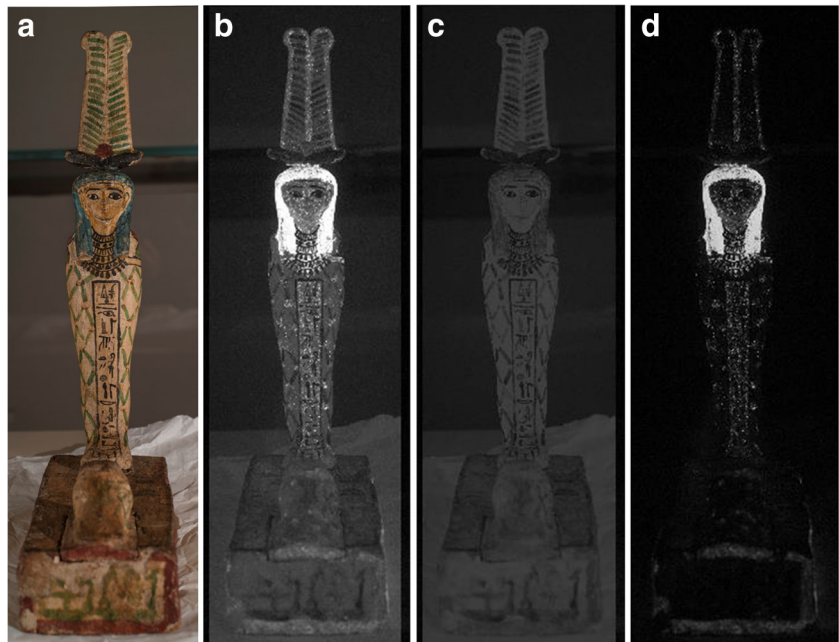
Results and discussion

### Visible-induced luminescence (VIL)

As previously described, traditional VIL implies the reduction of IR ambient and instrumental parasitic light. Indeed, a VIL image can be corrected through the acquisition of a "DARK" image that is acquired with same exposure set excluding an artificial light source (e.g., camera flashes or LEDs). Figure 2a and b show images acquired under ambient illumination and in VIL modality in the presence of IR parasitic light, respectively. The lighter areas indicate Egyptian blue presence that, in this case, was used mainly for the decoration of the hair of divinity. The entire body of the statuette is still visibly illuminated by the IR parasitic light allowing the spatial location of Egyptian blue. To enhance the spots in which Egyptian blue is present, the VIL images are corrected acquiring "dark" photograms (Fig. 2c) and subtracting it to the previous photo. The "dark" image should be taken in the same conditions in which VIL is performed avoiding possible under/overestimation of the real Egyptian blue signal. The resulting image (Fig. 2D) is impoverished in artifact morphology but Egyptian blue is more evident, for example, onto the body and ornament above the head.

Operation is performed using Adobe Lightroom suite. Operatively, a first corrective step of VIL image is based acquiring a shoot of artifact with the presence of Kremer Egyptian blue tab used as reference, assumed as 95% luminance in Lightroom scale. It corresponds to 244/255 of Adobe RGB levels in a Photoshop environment; synchronizing the DARK image with the same criteria, a parasitic light detection is obtained and it can be digitally subtracted to a VIL image as a layer in Photoshop. Finally, the value of the Kremer

reference is re-estimated on the 95% luminance. A similar solution is achieved using non-fluorescent white reference (e.g., Minolta 99% colorimeter tab or white swatch of Macbeth XRite color chart) taking a picture both in visible and IR ranges and producing a virtual DARK, i.e., a uniform level with the same colorimetric characteristics of the reference. The drawback is a limited coherence with the effective distribution of the environmental parasitic light, but it allows to monitor the presence of possible emitting infrared parasitic light. Considering that LED technology-based VIL cannot provide spatial characterization of not Egyptian blue–related areas, the choice of a light source had fallen on conventional flash light filtered with a UVIR cut filter, disposing intentionally, a parasitic IR source, whose infrared component could be modulated according to need.

The conventional flashes used for VIL acquisition mounted a single IRUV cut filter, inducing a conspicuous presence of instrumental parasitic light whose subtraction requires precise measurement on the white reference and subsequent production of a virtual DARK. Consequently, one or even two additional filters can be applied to effectively suppress IR parasitic light coming from the irradiation source. Figure 3 reports pristine and filtered (Hoya A-77 UVIR cut filter) emission spectrum of excitation flash. Dark line evidences pristine source, characterized by a continuous emission from the visible to infrared region; colored signals drawn the emitting behavior after the addition of one (red line), two (blue line), and three (green line) filters. Although infrared emission is dramatically cut already with a single filter, a not negligible portion is still present evidenced by a weak peak around 870 nm (Fig. 3, inset); the latter signal is included in the transmission window of filter mounted (B+W 093 infrared pass filter) in front of the camera generating a consistent parasitic light. Apparently,

Fig. 3 Emission of unfiltered excitation source used for VIL and the same filtered with one, two, or three Hoya A-77 UVIR cut filters. Inset: magnification of figure in the range 700–1000 nm
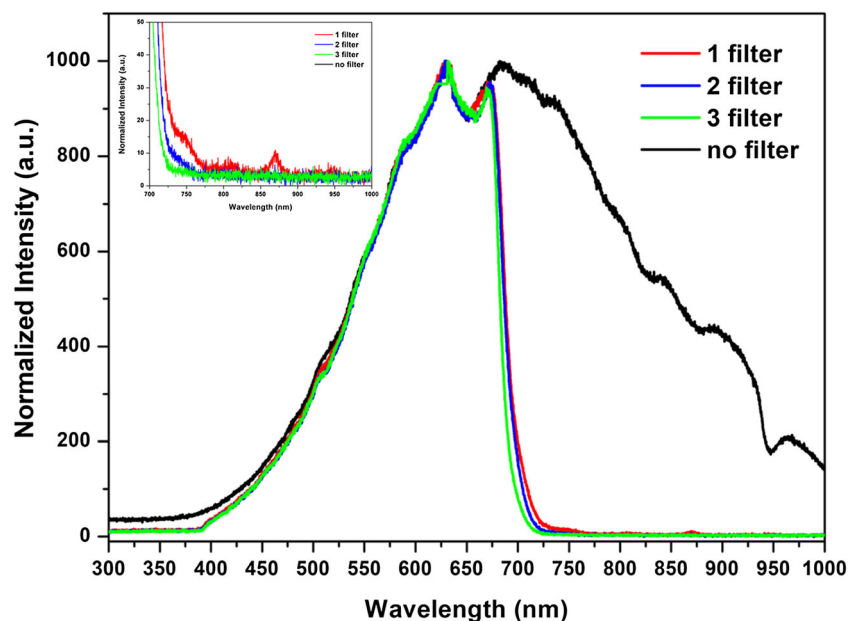
using two filters, infrared parasitic radiation coming from the source is suppressed even if the use of three filters further reduces it (Fig. 3, inset). Obviously, the ambient infrared parasitic light remains and should be considered during postproduction.

A series of practical tests have been performed using a different number of filters for the optimization of infrared parasitic light coming from the excitation source. This constitutes a prerequisite to RTI and tridimensional photomodeling, whereas the standard VIL luminescence conditions do not allow the procedure of computational techniques. The multiple filter system has been tested acquiring the same subject under a homologous set and exposure irradiating with the progressive shading of excitation source by the Hoya UVIR filters. Thus, the amount of infrared luminance acquired by the camera is measured. Figure 4 reports the post-produced images. In every photogram, VIL checker represents the luminance corresponding to the RGB values of 243, 243, 243, respectively (95% of reflectance in Lightroom). The quantity of parasitic light, coming from the excitation source, was directly measured as the RGB value in Photoshop on the white swatch (red highlighted frame in Fig. 4). Increasing values corresponded to reduction of UVIR cut filters; thus, RGB values of 18, 18, 18–30, 30, 30–80, 80, and 80 were measured using three, two, and one filter, respectively. The higher parasitic infrared light using only one filter is clearly visible in Fig. 4a, allowing spatial description required for 3D photogrammetric model reconstruction. The best VIL quality in terms of pure blue Egyptian blue response is obtained using three filters, where the white swatch appears totally black (Fig. 4c). Indeed, although visive results are substantially and practically optimal, the RGB values of 18, 18, and 18 suggest that

a very small amount of parasitic IR light coming from the excitation source is still present. This condition, as just mentioned, is perfect for VIL applications; on the contrary, further elaboration as photogrammetry or RTI is impossible due to low or absence of infrared flash light reflection on RTI control spheres. Differently, using one or two filters make these computational applications feasible: infrared flash light reflection on spherical references is perceivable, as a progressive visive reconstruction of areas characterized by the absence of Egyptian blue that can be itself an improvement to standard bi-dimensional VIL imaging.

Reflectance transformation imaging and photogrammetry

Reflectance transformation imaging (RTI) in the infrared region was performed applying two UVIR cut filters. As for RTI in visible light, a first realignment of each photogram in Photoshop suite is needed. The operation is performed by introducing all the photograms as layers and verifying, manually, the effective alignment of the pixels. After this operation, each image can be locally contrasted (leaving the main subject unchanged) on the light point if the flash spill on the spheres is not enough. This allows an easier shape and reflection quantification by the RTI software and lastly, a better reconstruction of the subject. RTI in VIL has a double impact: it detects pictorial area characterized by Egyptian blue and, by the introduction of the infrared parasitic light, localizes the pigment on the artifact's surface describing also the morphological aspect. Even if obtaining a parasitic infrared light-free RTI VIL is theoretically and practically unavailable, original photograms, after the identification of highlight directions,

Fig. 4 Multiple filter set reference VIL chart: **a** no.1 UVIR cut filter; **b** no.2 UVIR cut filters; **c** no.3 UVIR cut filters. Red square identifies RGB sampling area
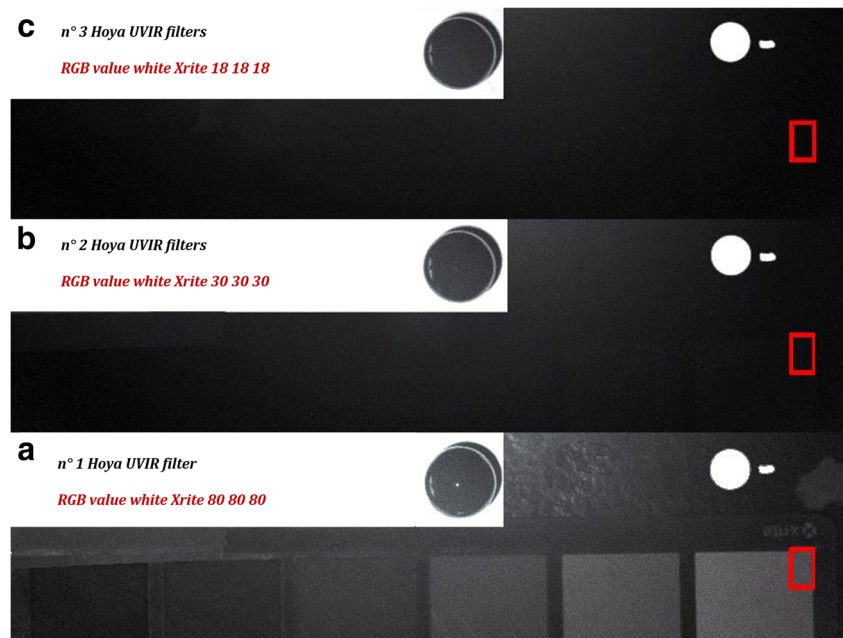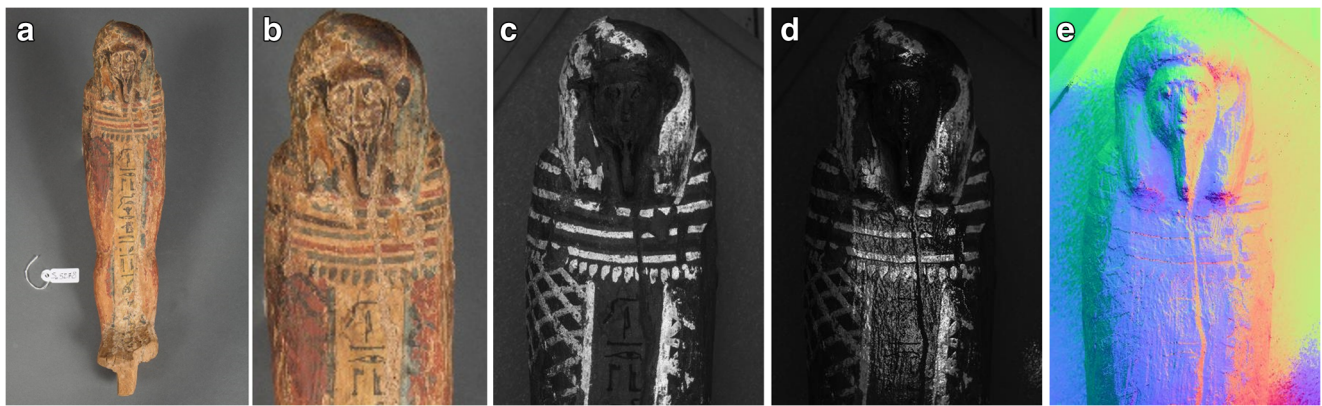
Fig. 5 Statue of Ptha-Sokar-Osiris's wooden statue from Khaemuaset (QV 44) and Setherkhepshef (QV 43) tomb (XXI Dynasty, 1070–946 BC (?). Cat. N. S. 05278, Torino, Museo Egizio) **a, b** Under ambient illumination. **c** RTI VIL in gain mode. **d** RTI VIL in specular enhancement mode **e** RTI VIL in normal visualization mapping. Images in **c**, **d**, and **e** were acquired setting two UVIR cut filters

can be replaced by digital correction through subtractive mask copies (DARK method) or by coherent twin set acquired adding filter.

The wooden statue (Fig. 5) has been examined with RTI VIL (setting two UVIR cut filters), gaining a double result on identification of blue pigment even considering the poor conservative condition of the artifact and Egyptian blue low concentration (Fig. 5a, b). Different postproduction conditions are reported in Fig. 5c, d, and e: morphology of the artifact is visible in the enhancement mode (Fig. 5d) and visualization mapping (Fig. 5e), whereas carbon black hieroglyphs and non-depicted structure are reported in the gain mode (Fig. 5c). It is worth to note that VIL and RTI in VIL mode are two different techniques. The former acquisition identifies the Egyptian blue even in traces (Figs. 1 and 2D); on the contrary, the second modality enhances the surface properties, e.g., roughness and defects (Fig. 5d), while maintaining the spatial location of the pigment on it.

3D-photogrammetric model reconstruction is a tridimensional relief technique based on the acquisition of images which are compared (Miles et al. 2014), resulting in a polygonal model with integrated texture (Fig. 6). Photomodeling in VIL has been performed on Pasherienaset's sarcophagus (Fig. 6a) to build a 3D model of the subject with the contemporary spatial localization of Egyptian blue. As in RTI VIL case, it was mandatory to introduce a certain amount of parasitic light from the irradiation source that lights the artifact's surface allowing the correct processing by Agisoft Photoscan modeling software. Consequently, the set-up using only one UVIR cut filter shading the flash light was used. The acquisition required the use of many flash shots, thus, derogating from the usual photomodeling practice that requires diffused ambient light; it should be noted that the flash lights were set on a wide-angle mode, avoiding artifacts and errors by software PhotoScan. The color correction followed the usual standards for VIL.

Fig. 6 a Pasherienaset's sarcophagus (Ligurian Archeological Museum in Pegli, Genoa, Italy) and 3D model in **b** polygonal view and **c** texturized view
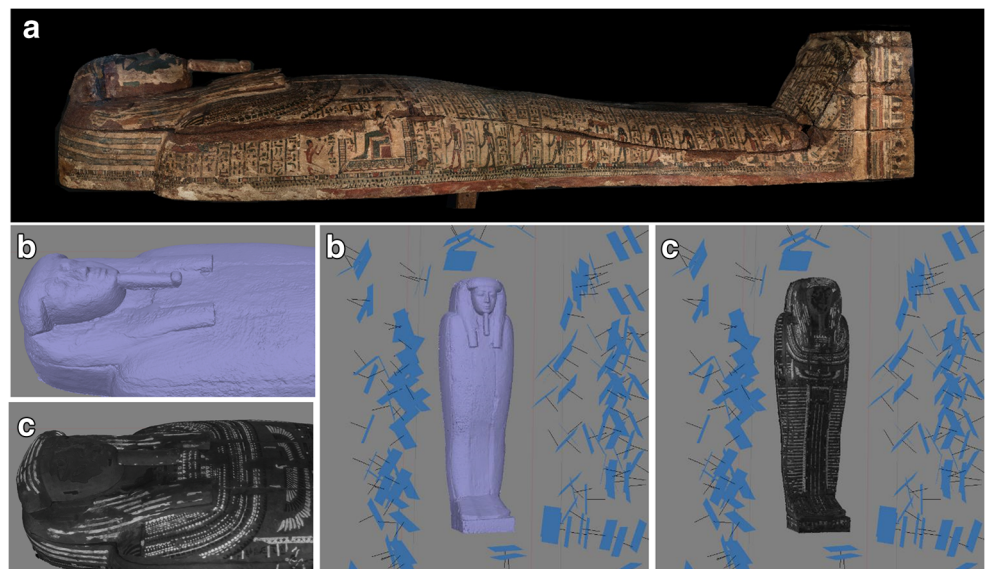
A controlled amount of parasitic IR let the identification both of Egyptian blue–characterized areas and of other pigments or the wooden support, allowing computational processes such as point cloud and mesh build up, but above all, the texturizing process of the 3D model. Different from the laser scan technique, texture is native and it does not require digital image stretching on the polygonal object; thus, the superimposition of the VIL image in the 3D model is immediate. Furthermore, it is always possible to optimize the texture quality by treating it subsequently as a two-dimensional datum, correcting the contrast or applying a subtractive mask for parasitic light. It has been also tested on a secondary set based on coupled acquisition of infrared photograph and co-axial VIL, with the aim of constructing the morphology of the sarcophagus by means of IR reflectography data and subsequently replacing them with VIL images during the texturization process (Fig. 6c). Anyway, a faster and more feasible optimization process of polygonal reconstruction in VIL band has been applied using a "twin" overexposed original VIL images, produced during color correction to perform volume reconstruction. This step is followed by the replacement with the correct VIL files, to obtain a superior yield of the volumetric detail, associated to the best description of the "skin" of the sarcophagus.

It should be underlined that all the acquisitions (VIL and photogrammetry) on sarcophagus were performed without opening the conservation case, thanks to the glass transparency to visible and infrared radiation. The "through the glass" analyses are extremely important by a conservation point of view, avoiding any microclimatic alteration, compatibly with the minimum invasiveness (absence of contact and displacement of the object).

Conclusions

Traditional VIL technique requires the maximum reduction of infrared parasitic light. Indeed, a controlled introduction of a portion of IR radiation allows the possibility to perform also RTI investigation and photogrammetry. Ancient Egyptian artifacts were investigated through VIL–RTI and VIL-photogrammetric techniques were performed contemporary. The portion of IR parasitic light was modulated using a different number of UVIR cut filter in front of the excitation light. Results evidence the possibility of a spatial distribution of the pigment on artifacts with the contemporary RTI or 3D-photogrammetric model reconstruction. Considering the low cost of the set-up used, the quickness of data acquisitions and the possibility to perform analyses in situ, these techniques constitute an excellent diagnostic tool for ancient Egyptian artifacts, useful for planning further analyses using complementary techniques, e.g., X-ray fluorescence and Raman spectroscopy.

Compliance with ethical standards

Conflict of interest   The authors declare that they have no conflict of interest.

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