Multispectral imaging to reveal ancient hieroglyphic text in an Egyptian Stele.

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***Abstract*— In this paper, we discuss the application of Multispectral Imaging combined with statistical algorithms for enhancing hidden patterns to reveal part of the no more readable hieroglyphics in an ancient Egyptian stele. A series of images was taken at different wavelengths of the upper part of the stele S.6145, coming from the archaeological site of Deir El-Medina (Egypt) and currently stored at the Egyptian Museum of Turin (Italy). The analysis of the single images did not allow retrieving the information on the hieroglyphic text. However, the application of Blind Source Separation algorithms allowed to reveal the hidden pattern in a fast and highly efficient way, restoring the correct readability and the value of the artwork itself.**

Keywords — Stele, Multispectral imaging, Blind source separation, Hidden patterns retrieval

I. Introduction

Multispectral Imaging (MSI) is one of the most widespread methodologies for the study of cultural heritage and archaeological findings. One of the main advantages of MSI is that it is a non-invasive technique that requires simple experimental setups, but at the same time allows for high spatial resolution images. In its simplest realization, four images of the subject under study are acquired in the blue, green, red and infrared spectral bands. In particular, thanks to the peculiar capacity of the infrared radiation to penetrate the object surface, it is possible to reveal otherwise invisible details such as underdrawings and *pentimenti* in canvas and panel paintings [1, 2, 3, 4] or to improve the readability of degraded manuscripts [5, 6, 7, 8] using only that band, or a simple false-color image. However, only the combined elaboration of the acquired bands guarantees the maximum result. Among the image processing techniques typically explored using MSI data, statistical analysis and dimension reduction have proven to be powerful tools for further enhancing and detecting hidden patterns in artworks or removing undesired interferences for improving the readability of texts. Dimension reduction can be also unsupervised, as in blind source separation (BSS) techniques [9, 10]. The main principle underlying the enhancement capabilities of dimension reduction techniques is that, while the spectral components of an image are usually spatially correlated, the individual patterns (or classes) superposed onto the image are usually much less correlated. Hence, decorrelating the colour components gives a different representation, where the now orthogonal components of the image could coincide with single classes [11, 12, 13, 14, 15]. In this paper the ability of MSI to reveal apparently invisible information has been tested on the hieroglyphic text of the stele S.6145, created as a decorative relief inside the sanctuary of Meretseger and Ptah in Deir-el Medina and today conserved in the Egyptian Museum of Turin. The rereading of the symbols painted above the figures was obtained through the application of statistical separation methods on the set of multispectral images, using orthogonalization algorithms developed by the CNR of Pisa. With this technique it was possible to interpret the hieroglyphic text painted above the figures.

II. Materials and Methods

A. *The Stele*

The necropolis and the village of Deir el-Medina are located in Upper Egypt, in a valley behind the hill of Qurnet Marrai, on the left bank of the Nile, south-west of Sheikh-abd el-Qurna, facing the city of Thebes, in an area between the two sanctuaries of Karnak and Luxor [16, 17, 18]. The village was active throughout the New Kingdom and hosted the workers responsible for building the tombs of the Valley of the Kings and the Valley of the Queens. Along the path that connects the village of Deir el-Medina to the Valley of the Queens a rock sanctuary is located. Here, the cliff creates a series of natural shelters, which the villagers expanded to make them juxtaposed chapels. The walls of these chapels are decorated with reliefs engraved directly on the surface of the rock, which have been (erroneously) defined as steles for convenience; one of these decorations was detached and brought to Turin, at the Egyptian Museum, and was the subject of the study of this

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work [19]. Inside the tomb, the stele has a very specific function: it constitutes the filter between the world of the living and the deceased, and it is through it that the dead receives the offerings that allow his survival in the afterlife. Beside the funerary steles, there are others realized for commemorative purposes. Their typology is not different from the funeral ones but their location and function are different: they are found inside temples or shrines, dedicated to the main deities of these places of worship. It is within this category that we place the stele object of this study. It is a large fragment (100x100x15 cm) of an Egyptian wall decoration, whose shape simulates a typical Egyptian stone stele. From a typological point of view, the object imitates the arched steles. Only the upper portion of this composition is preserved (Fig. 1.).

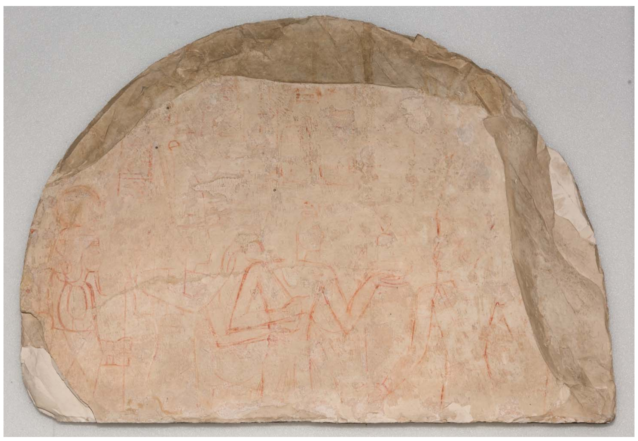

Fig. 1. Picture of the stele S.6145, front, taken after the restoration at the "La Venaria Reale" Conservation and Restoration Center.

The stele is divided into two parts, at the bottom we find human figures, while the hieroglyphics in the upper part were not readable anymore. The main scene is at the centre of the representation: the God Amun is depicted in the act of offering the symbol of the feast Heb-Sed [20] to Pharaoh, Seti II. The latter was one of the rulers of the 19th dynasty and is represented here with the scourge in his right hand and a wig topped by uraeus; behind him we can find two other figures: Khonsu and Mut. Khonsu, Mut and Amon represent the Theban triad and are depicted with their distinctive attributes:

- Khonsu, shown on the left, presents the usual wig with a lateral curl surmounted by the lunar disk;
- Mut, alongside Khonsu, is depicted with the double crown of Upper and Lower Egypt called Pschent;
- Amon, pictured on the right, is portrayed with the usual crown with double feather.

The Pharaoh is depicted in the centre of the deities; this is a particular representation, given that the divinities were usually depicted on one side and the pharaoh, possibly followed by the bride and other family members, on the other. Above are the hieroglyphics, which explain the scene below; unfortunately, the signs are unreadable, and therefore impossible to decipher.

B. The MSI Camera

For the MSI analysis, we used a system equipped with a high-resolution Moravian G2-8300 camera (CCD detector KAF-8300, imaging area 18.1 × 13.7 mm, pixel size 5.4 × 5.4 µm) with a high dynamic range (16 bits). The sensor is cooled for reducing the electronic noise during the acquisition. The spectral resolution is obtained through the use of interferential (±25 nm band pass around the central wavelengths) at 450, 500, 550, 600, 650, in the visible range and 850, 950, 1050 nm in the near infrared. The exposing and focusing characteristics were changed for each band, maintaining the same lighting condition for the visible and infrared image sequence. The diaphragm aperture was set to f/11 for all acquisitions.

C. Image Processing

The MSI system builds the colour image through the combination of the three images acquired sequentially in the fundamental RGB spectral bands (Red, Green and Blue - additive synthesis). The images acquired with the three RGB filters must be balanced to obtain a faithful colour reproduction, for this reason the image of a white object is acquired under the same lighting conditions, and the exposure of the images is corrected (by varying the exposure time) to reproduce a white image.

For the statistical processing of image data, we used BSS techniques. In some cases it may be useful to hypothesize that the multispectral images acquired on an object are the result of an ideally linear combination of individual characteristics, each of which can be recognized by individual spectral "signatures". At this point, a set of multispectral images can be processed to highlight details otherwise not immediately visible or improve the readability of the subject. False IR colour visualization is an 'easy' example of this procedure [21], although in general it provides results of poorer quality with respect to BSS. The idea behind the Separation Methods is to consider the n multispectral images (with n equal to the number of images acquired at different spectral bands) as the superposition of other n 'independent' images, each corresponding to a physical characteristic (in the case of paintings, substrate, pictorial layer, surface damage, 'underdrawing', etc ...). The separation algorithms attempt to extract independent images through a linear combination of the original multispectral images. This allows, if the starting hypothesis is verified, to separate the original image into as many as there are invisible features. In formulas, let (i,j) be a pixel index; if x(i,j) is an n-vector map representing the multispectral image, and s(i,j) is an m-vector map representing the collection of the original patterns, we have:

$$x(i,j)=As(i,j) \tag{1}$$

where the n × m-matrix A is called mixing matrix. Once linearity is assumed, separating the individual patterns is easy if all the relevant spectral signatures are known, that is, if A is known. Unfortunately, the A, the key element for separating the information, is not known a priori; moreover, realistically, the details that are not visible and the corresponding schemes are not combined linearly, and consequently not completely separable. To overcome it, statistical hypotheses are formulated to invert the matrix A, identify the independent components and therefore be able to estimate the individual contributions, assuming that they are mutually uncorrelated. With respect to more advanced separation methods [22], the orthogonalization technique has the advantage of a particularly simple numerical implementation, while providing a straightforward interpretation of the results as linear combinations of the original multispectral series.

III. RESULTS

For the analysis of the stele, two sets of 9 acquisitions were realized for the different available bands (see above): one of them using the visible light as illuminator and the second one with UV leds (10V). In the first case, integration time was set to 1s for the acquisitions from 550 to 950 nm and increased up to 10 s from 400 to 500 nm and to 15 s for 1050 nm band, as reported in table 1.

TABLE I.

Spectral band (nm)	**Experimental parameters**		
	VIS acquisition time (s)	***UV acquisition time (s)***	***Aperture***
400	10	15	11
450	10	15	11
500	10	30	11
550	1	30	11
600	1	45	11
650	1	90	11
850	1	90	11
950	1	120	11
1050	15	400	11

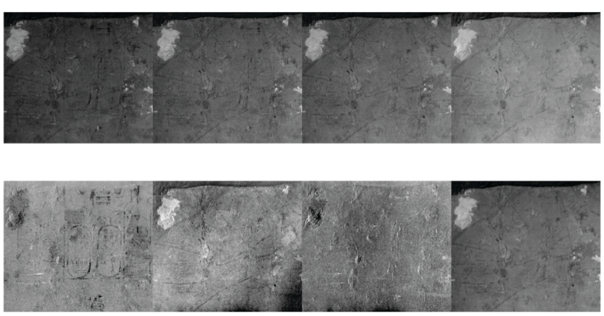

Fig. 2. Detail of the stele. Top: Multispectral images taken at 450 nm, 550 nm, 650 nm, and 1050 nm (from left to right); Bottom: Several outputs of the Blind Separation Technique (the first image recovers the readability of the text).

After the images acquisition, it is necessary to register them to compensate the unavoidable shifts and distortions introduced by the different filters interposed between the objective and the sensor of the CCD camera. To this purpose, a specialized software realized by the Institute of Science and Technologies of Information of CNR was used [14], which guarantees a sub-pixel accuracy in the images' registration. The colour image was reconstructed through the superposition of three images acquired sequentially in the fundamental RGB spectral bands (450 – 550 – 650), and similarly for the false IR colour (550 - 650 – 1050). As expected, these two images didn't improve the readability of the patterns. The rereading of the hieroglyphics painted above the figures was obtained through the application of the statistical separation methods previously described on the all set of 18 multispectral images. Figure 2 shows the three fundamental RGB acquisition and the most significant channels in the near infrared at 1050 nm in the upper part, whereas in the bottom some output channels of BSS algorithm. Figure 3, instead, reported the most significant BSS results: it is worth nothing that the picture is the composition of two different images that were acquired to cover the whole upper surface of the stele. The analysis reveals that the hieroglyphics give the name of the characters depicted in the bottom part; moreover, the presence of the scarab confirms that the central figure represents the pharaoh Seti II. The recovered readability of the Stele is clearly visible in Figure 4. The picture is realized overlapping the RGB image with the pattern obtained with the most significant BSS output. This method enables a sort of

Fig. 3. Output of the BSS algorithm used for enhancing the readability of the hieroglyphic text in the stele S.6145.

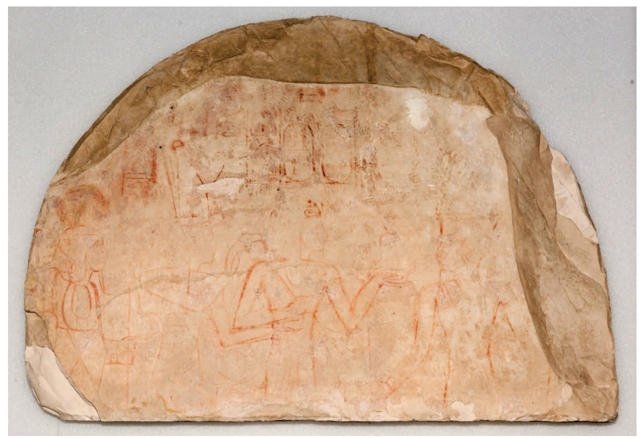

Fig. 4. Recovery of the readability of the hieroglyphics (virtual restoration).

“virtual restoration” of the original heritage object, useful for its promotion and study.

IV. Conclusions

We demonstrated the advantages of using MSI and BSS algorithms for enhancing hidden patterns in archaeological steles, using an approach up to now limited to paintings and ancient manuscripts. The multispectral investigations has allowed the reading of the hieroglyphic text on the top of the stele, above the representation. It was thus possible to confirm the iconography of the characters depicted, including the figure of Pharaoh Seti II, by adding an important element for the complete knowledge of the work. Depending on the spectral response of the materials and their conservation state, sometimes satisfactory results can be obtained even limiting the analysis only to one of the infrared bands, but in the general case, more sophisticated methods must be used, as the one reported in this paper.

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