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Multispectral imaging for the documentation of graffiti in an urban environment

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ABSTRACT

Multispectral imaging (MSI) is increasingly used for the documentation and analysis of cultural heritage. It provides conservators a powerful non-destructive technique (NDT) and non-contact tool for detecting damage, hidden features and material-specific characteristics. Hereby multispectral documentation of wall paintings in an urban environment poses special challenges for the art expert. For example, these are often large works of art located outdoors on building façades. Excitation with artificial light in well-defined spectral ranges, as should ideally be the case in MSI, is therefore often not possible. In the following, low-cost variants of MSI (ultraviolet reflectography, visible light imaging and infrared reflectography) in combination with 3D photogrammetry and statistical methods for analysing image data are tested and discussed. Hereby, a metrically correct, large-scale documentation of wall paintings with accurate superimposed images of different spectral ranges will be generated by linking the MSI data in a photogrammetric image cluster to create individual texture maps for each spectral band. Furthermore, Principal Component Analysis (PCA) is used to extract additional information from the MSI data. The case studies are located on the campus of the Universitat Politècnica de València.

I. INTRODUCTION

A large variety of imaging techniques are used to examine cultural heritage objects. Multispectral (MSI) and hyperspectral imaging (HIS) find increasingly vast fields of application. Spectral imaging is a broad field of optical metrology, were different wavelengths of electromagnetic radiation are used to capture image data of an object (Cucci and Casini, 2020). The spectrum of wavelengths that human eyes can observe as visible light represents only a small range of those wavelengths usable for multispectral imaging. It starts with very short and thus high-frequency and high-energy wavelengths, such as gamma and X-rays, and ends with long-wave, low-energy radiation, the micro and radio waves. In between are the ultraviolet (UV), visible (VIS) and infrared (IR) light spectra. The best-known imaging variants include, for example, UV fluorescence photography and infrared reflectography. For many years, both have been used to document polychrome surfaces, such as frescos, panel and canvas paintings, as common standard methods for detecting preliminary drawings, damage, and material differentiation. Most standard multispectral and hyperspectral imaging techniques are non-contact and non-destructive methods and will not course any risk or harm to historical objects during the examination.

The difference between multispectral and hyperspectral imaging is related to the number of images taken. For multispectral images, each spectral band is captured separately by using different filters or detectors, while in hyperspectral imaging, an entire spectral range is captured simultaneously (Amigo, 2020; Amigo and Grassi, 2020). For the documentation of cultural heritage MSI is more often used. The most common examination methods cover the spectral ranges in the vicinity of visible light: visible light (VIS: 400-700 nm), ultraviolet (UV-A: 315-400 nm) and near-infrared (NIR: 700-1,400 nm). However, longer wavelengths are also used; here, special consideration should be given to the different areas of the infrared. In addition to the NIR, infrared is divided into short-wavelength infrared (SWIR: 1,400-3,000 nm), mid-wavelength infrared (MWIR: 3000-8000 nm) and long-wavelength infrared (LWIR: 8,000-15,000 nm). The last is well known used in Thermography. In addition, terahertz (THz), X-rays or radar, for example, are also used to examine cultural heritage (Dyer *et al.*, 2013; Badea *et al.*, 2008; Picollo *et al.*, 2019; Privitera *et al.*, 2021; Cosentino, 2015a; Alberghina *et al.*, 2019).

A consensus is that using a single spectral band usually produces only limited information about an object. Only a combined use of a range of methods can provide valuable results (Cavallo *et al.*, 2020; Keller *et al.*, 2019). Investigations in the UV-VIS-NIR can be made with a modified camera and different filters in front of the lens (Cosentino, 2014, Verhoeven, 2012; Dyer *et al.*, 2013; Webb *et al.*, 2018). In this case, referencing the individual images to each other is relatively simple, as the camera does not have to be moved between the single pictures. The photos overlap almost precisely. In other spectral ranges, however, very different devices are used. The resolution of the image sensors varies greatly, making correct superimposition and thus comparability of the data more difficult. Furthermore, it is often impossible to image an entirely cultural heritage object with a single image section. Therefore, for a comprehensive examination, various image positions are needed. Alternatively, exemplary examination areas must be defined to represent the entire object. This creates particular challenges for the user, especially when investigating complex, three-dimensional objects.

Monitoring and damage assessment are other essential fields for using MSI in cultural heritage. However, evaluating a large number of different spectral bands and sensor data can be very challenging. Nevertheless, the superimposed image data of several monitoring campaigns can provide important information about the condition and the course of damage processes of an object. Principal Component Analysis (PCA) can make an important contribution to the interpretation of the data. This multivariate statistical approach makes it possible to analyse an almost unlimited number of image data and detect differences (Marengo *et al.*, 2011). A correct overlay of the image data and a complete protocol of all acquisition parameters is essential to ensure that the images are not affected by varying external conditions (Jones *et al.*, 2020).

In the following, different spectral imaging methods and their application in the documentation and examination of modern wall paintings will be presented. This includes a description of the methodology and an overview of the current state of research. Based on case studies, methods of combining and linking spectral images, including computer-assisted analysis, will be presented and discussed.

II. METHODOLOGY

A. *UV-VIS-IR imaging*

UV-VIS-IR photography uses the phenomenon that different materials react characteristically to varying wavelengths of light (Cosentino, 2014; Webb *et al.*, 2018). If an object is exposed to electromagnetic waves, such as irradiated with a light bulb, the surface can react differently. The material may appear translucent to the wavelength. In this case, electromagnetic waves can pass through the material. For example, this is known from X-rays and window panels. The electromagnetic radiation can also be absorbed completely or reflected by the material, like a mirror. The reflection occurs in the same wavelength as the excitation. Furthermore, some materials can react fluorescently to excitation with electromagnetic radiation. Part of the radiation is absorbed, and electromagnetic radiation is emitted in a longer wavelength. This happens especially with certain pigments and living organisms that glow colourfully in the visible spectral range during excitation with UV light (blacklight) (Dyer *et al.*, 2013; Cosentino, 2015a; Webb, 2019).

A CMOS image sensor of a commercially available digital camera can capture the spectral range from about 350 to 1,050 nm. However, this requires removing the IR cut filter, which is usually placed in front of the image sensor and replacing it with protective glass, allowing the entire spectral range to pass through, *e.g.* Schott N-WG280. Such cameras are called modified cameras. Some manufacturers also offer cameras without IR cut filters ex-works. To reduce the incoming light to a specific wavelength requires special filters placed in front of the camera lens (Cosentino, 2014, Verhoeven, 2012; Dyer *et al.*, 2013; Webb *et al.*, 2018).

If the outgoing wavelengths of the light source are controlled, and its reflections or emission are recorded in a deliberately selected spectrum, characteristic features of individual materials can be identified. For example, this can be used as a non-contact and non-destructive examination method in cultural heritage research to determine the pigments used in a painting (Cosentino, 2014; Dyer *et al.*, 2013; Webb *et al.*, 2018). Table 1 gives an overview of combinations of induced (emitted) and detected spectral range commonly used for UV-VIS-IR imaging (Keller *et al.*, 2019; Bläuer and Keller, 2020; Sfarra *et al.*, 2014; Dyer *et al.*, 2013; Cosentino, 2014; Lang and Lenz, 2017; Keller and Lenz, 2021).

B. *Combination of the techniques*

Linking the MSI variants is a significant challenge and is particularly important for a detailed examination of objects. In addition, the image file of a single spectral band provides only limited information; only the comparison with other bandwidths enables a well-founded analysis (Keller *et al.*, 2019). The image series of different bandwidths of a modified camera can be combined relatively easily. The viewpoint does not have to be changed between the single images; only the light source and the filters on the camera have to be changed. So the individual image data are already almost pixel-precise superimposed onto each other; otherwise, warping will be required to avoid parallax. There are also open-source solutions for processing and overlaying the images of MSI (Dyer *et al.*, 2013). However, to link additional MSI data, for example thermography images, a correct superimposition already poses specific challenges to the user since both the sections and the resolution of the images vary greatly. Usually, it is impossible to capture an entire object with a single image section. Depending on the size and geometry, many different image viewpoints are required. In the case of flat objects, such as paintings and murals, stitching is often used to link overlapping images (Keller and Lenz, 2021). Such photo mosaic generated by image stitching can provide high resolutions over a large area. However, these images are not metrically correct and can only be used to a limited extent for mapping purposes. Three-dimensional objects, such as sculptures or vaulted ceilings, cannot be captured in this way.

Table 1. Different methods of UV-VIS-IR imaging

Name	Imaging Method	Also known as	Radiation Source	Filter sensitivity
UVR	UV-induced UV-reflectography	UV-reflectance imaging	UV (~365 nm), UV-LED, Wood's Lamp	UV band-pass filter (320-390 nm)
UVF/UVL	UV-induced VIS-luminescence	UV-fluorescence imaging	UV (~365 nm), UV-LED, Wood's Lamp	UV/IR-cut filter (380-750 nm)
VIS	Visible-reflected imaging	VIS-reflected images, Colour photography	LED, Tungsten, Flash	UV/IR-cut filter (380-750 nm)
IRF/VIL	VIS-induced IR-luminescence	IR-fluorescence	VIS 380-750 nm	IR long-pass filter (starting at 830 nm or 1000 nm)
IRR	IR-induced IR-reflectography	IR-reflectography	IR (700-1050 nm), LED	IR long-pass filter (starting at 830 nm or 1000 nm)
IRR	VIS-IR-induced IR-Reflectography	Variant of IRR with undefined light-source	Tungsten, Flash, Halogen lamp (VIS-IR 400-1050 nm)	IR long-pass filter (starting at 830 nm or 1000 nm)

Photogrammetry can offer a solution. Some applications to generate 3D models from MSI image series were already made in recent years. Rahrig *et al.* (2018) rectified individual multispectral images from different documentation campaigns using 3D data and superimposed them as orthophotos in CAD, enabling close monitoring of surfaces across several campaigns Mathys *et al.* (2019), Zainuddin *et al.* (2019), Webb (2015; 2017; 2019) have compared the quality of point clouds from different spectral images. An overlay of different spectral bands as textures for the 3D model was also tested for VIS and UVL by Nocerino *et al.* (2018) and for 17 spectral bands between UV and NIR by Mathys *et al.* (2019). Mathys used a modified camera and only changed the filters in front of the lens and the light source for changing spectral bands. In post-processing, she then calculated the alignment of the imaging positions and the basic 3D model based on a series of VIS photos (RGB colour photos). She then exchanged the individual images according to the spectral band and recalculated only the texture map using the orientation of the VIS images also for the other spectral ranges. Nocerino, on the other hand aligned each spectral band separately and combined the results via one uniform coordinate system.

Both variants offer certain advantages. Exchanging the photos and only recalculating the texture map reduces the time required significantly, especially when processing multiple spectral ranges in the VIS. Away from the VIS, however, a slight shift of the focal point takes place so that a recalculation of the image orientation could be helpful to improve the quality of the results. If image data from different sensors are to be linked, the individual clusters must generally be aligned separately and connected via one uniform coordinate system for all spectral bands.

III. CASE STUDIES

A. *Case Study 1: Hand*

Exemplary image series of modern murals were produced outdoors in UVR, VIS and IRR to test the superimposition and analysis of variable spectral bands. The murals were created in the context of the 16th urban art festival "Poliniza Dos x Hyuro" 2021 and are easily accessible on the campus of the Universitat Politècnica de València. A section of a graffito made by students of Painting and Environment (Figure 1) was captured from different camera positions to document the surface in high resolution in a larger area and in 3D.

Figure 1. Overview of the wall painting. Case study 1 is highlighted in red.

Three photographs (UVR, VIS and IRR) were taken at each of nine camera locations using a Fujifilm IS Pro camera. The camera is produced ex-works as a modified camera and has a Super CCD Pro image sensor (APS-C: 23 x 15.5 mm) with a resolution of 4256 x 2848 pixels. The lens used was a 60mm UV-VIS-IR Apo Macro by CostalOpt. The excitation of the surface was done by direct sunlight, so there was enough energy from UV to NIR. For the VIS images, a UV/IR blocking filter was used (BP550 Near-IR/UV Block Visible Bandpass Filter, by MIDOPT®. Range: 405-690 nm). IRR images were taken with a long-pass filter that filters all spectral regions shorter than 930 nm (LP920 Short-Wave Infrared Longpass Filter, by MIDOPT®, Range 930-2300 nm). The UVR images were made with a UV band-pass filter, and an IR cut filter (BP365 Near-UV Bandpass Filter, by MIDOPT®. Range: 335-400 nm + 830-1100 nm. Combined with SP730 Near-IR Shortpass Filter by MIDOPT®. Range: 320-730 nm). The UV band-pass filter has a peak in the NIR, so the additional IR cut filter is necessary to avoid interference in the IR. The image sections of the nine camera positions have an overlap of about 80%, so sufficient data for a photogrammetric alignment was available.

The photographs were taken in manual mode with constant settings in RAW format. For this purpose, the ideal settings were tested at the first camera position. The pictures were taken at ISO 100 and f-number 8 to achieve good images. So only the exposure time had to be changed on-site: 1/500 sec for the VIS images, 1/10 sec for the UVR and 1/20 sec for the IRR 1/20 sec. The exposure time was controlled via the RGB histogram, whereby all channels (R, G, B) were checked, and uniform distribution of the colour values was ensured. The white balance of the photos was also done manually using a reflection target with a medium grey value. Two image sets were taken at the first camera position—the first with the target in the image centre, the second without the target. The settings were applied consistently to all camera positions. White balance was adjusted in the software RawTherapee, which allows batch processing of the image series. The tone curve was also set to "linear" to eliminate automated, camera-specific colour manipulations. Furthermore, the UVR and IRR images were converted into monochrome images. For this purpose, the UVR images were reduced to the blue channel and the IRR images to the red channel. Processing the photos follows the recommendations of Dyer *et al.*, 2013, which were developed within the framework of the EU project CHARISMA.

In addition to the monochrome UVR and IRR photos, false colour images were created. For UV false colour photos (UVR-FC), the monochrome UVR was combined with the green and blue channels of the VIS to create a new image. In this image file, the R/G/B channel corresponds to the G/B/UV band of the original data. For the IR false colour images (IRR-FC), the monochrome IRR images were combined with the red and green channel of the VIS to form a new image file. Here, the R/G/B channels of the new image data correspond to the IR/R/G bands of the initial data.

After processing the individual images was completed, the images were combined in 3D using photogrammetry. For this purpose, the image series were imported into Agisoft Metashape and divided into separate chunks according to their acquisition technique (VIS, UVR, UVR-FC, IRR and IRR-FC). The spectral bands were aligned separately, and dense point clouds were calculated. The point clouds served as an additional optical check to improve the alignment. Using natural control points, which could be clearly identified on the single photos, the alignment of the image chunks to each other was carried out. Scaling was also done using natural control points; the distance was measured on a flat surface of the object by using a ruler (Figure 2). For proper scaling the use of scale bars is recommended, to guarantee a higher accuracy of the scaling.

The 3D surface model was only processed for one image group (VIS) and then copied to the other groups. After that, a high-resolution texture map was generated for each image band (VIS, UVR, UVR-FC, IRR and IRR-FC). Superimposed high-resolution orthophotos can now be generated directly in the Metashape software for further evaluation and comparison between the spectral bands. This allows a fast visualisation and observation in 2D, with a correct metric representation (Figure 3).

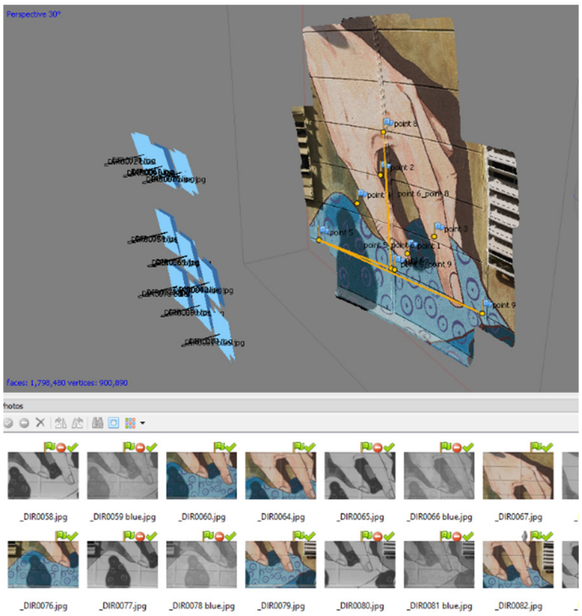

Figure 2. 3D point cloud of the MSI image set. The reference points for orientation and scaling are shown on the wall painting.

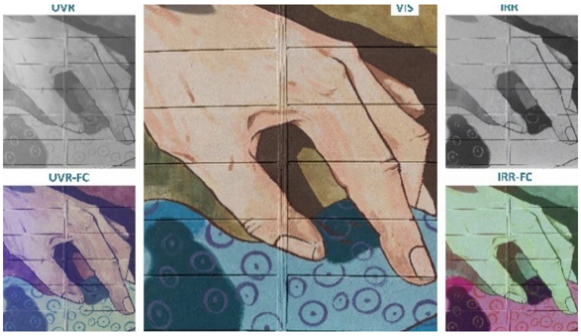

Figure 3. FMSI orthoimages of the different spectral bands.

In this way it is also possible to compare the spectral bands directly on the 3D model. Especially with complex surface geometries, this allows a dynamic inspection and offers particular advantages in observing areas that would be hidden in a 2D orthophoto. Linking spectral bands with a single 3D model were tested in the software Blender. First, the geometry, *i.e.* the surface model, is imported. Then the different texture maps of the spectral bands can be imported and linked to the 3D model as materials. When observing in Blender, it is now possible to switch dynamically between the materials, allowing the spectral bands and false colour images to be compared with pinpoint accuracy (Figure 4).

Figure 4. Detail of the multi textured 3D Modell in Blender. Left: VIS texture, right IRR texture. The pigment used for the purple circles has the same characteristics as the blue background under IR.

B. *Case study 2: Vase*

The second wall painting discussed here was created by the artist JAZ. The graffito is located on the northwest façade of the Directorate building; it covers a width of approx. 7 m over a height of 3 floors (Figure 5). Due to its location in a corner situation, it is never entirely exposed to the sun. For image acquisition, a time was chosen when the graffito was completely in shadow to ensure uniform illumination. It was documented exemplarily from one point of view using UVR, VIS, and IRR to test whether the passive illumination was sufficient for the MSI images. Furthermore, the application of statistical methods for the evaluation of MSI images was tested.

Figure 5. Overview of the wall painting of case study 2.

The pictures were taken with the same setup (camera, lens and filter). The exposure times varied from 1/60 s for VIS, 1/3 s for IRR and 1/2 s for UVR. Processing of the RAW data is also analogous to the previous steps. Figure 6 shows a compilation of the results. While the UVR image does not show any significant features, the IRR image reveals some details. Especially in the three whitish rose blooms, horizontal and vertical structures show up, which remain hidden in the VIS. The colours used for the rose blooms behave translucent in the NIR and allow viewing underneath the top layer of paint. This phenomenon can also be observed very vaguely at the left of the vase. Therefore, a possibility was needed to highlight the hidden details more and visualise them better. For this purpose, a Principal Component Analysis (PCA) of the images was carried out using the free available software HyperCube.

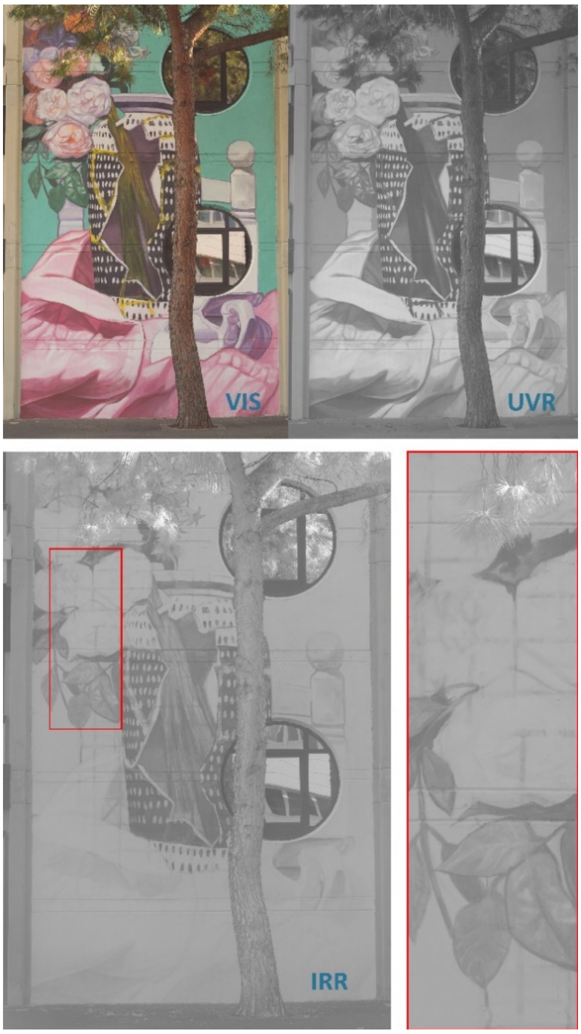

Figure 6. Compilation of the MSI images of case study 2. The IRR shows covered pattern (highlighted in the detail).

PCA is a method for the statistical analysis of data. Applied to image data, it enables an unsupervised extraction of qualitative information of compounds. For example, a standard RGB colour photo can serve as the data basis. The three colour channels represent different spectral bands (red, green and blue) and are superimposed with pixel accuracy. Varying material characteristics in the different spectral ranges can be compared and analysed pixel by pixel using PCA. Principal Component 1 (PC1) shows the matrix of the maximum variance between the initial data. The values calculated in this way can then be visualised in a greyscale image. Principal Component 2 (PC2) corresponds to a differentiated matrix, where PC1 has been subtracted from the original matrix. In this continuation, any number of PCs can be calculated. Details and differences in the material composition can be filtered and represented in this way in continuous PCs (Domingo *et al.*, 2020; Marini and Amigo, 2020). The advantage of PCA is the comparatively simple evaluation of an unlimited number of spectral bands, as long the individual image bands are correctly superimposed (Salerno *et al.*, 2014).

Figure 7 shows PC1 to PC5 of the MSI recording of the wall painting. In PC2, the horizontal and vertical structures are already better visible compared to the IRR image. The structure can now be detected below the rose blooms and in parts of the vase. However, visualisation of the variances is limited to 256 grey levels in one PC. That means the total variance of material differences must be represented in these 256 grey values. In the case of the wall painting discussed here, a tree standing in the foreground of the picture significantly influences the differentiated visualisation of the painting. The application of PCA to a partial area of the image allows the use of the entire greyscale for a differentiated representation of the wall painting. In this case, the hidden structures were revealed most clearly in PC4 (Figure 8).

Thanks to PCA, it was possible to detect the horizontal and vertical structures distribution over the entire area of the rose blooms and the vase. They are thus directly related to the detailed central motif and end precisely at its borders. The comparatively simple realised picture components, such as the pink cloth in the lower quarter of the picture, the turquoise background and the back of the chair, on the other hand, do not show any comparable structures. Therefore, it can be assumed that the covered patterns are a preliminary drawing in the sense of a raster. It probably served the artist as orientation for the execution of his work. In consideration of the size of the graffito, it had to be painted from scaffolding or a hydraulic lift, so such a raster helps immensely in orientation and in keeping proportions and dimensions of the individual elements of the picture.

IV. DISCUSSION AND CONCLUSION

MSI is fast, easy-to-execute tool that can be essential for non-destructive and non-contact cultural heritage inspection. Especially in recent years, various research groups have been working on characterising and identifying historical pigments using MSI. Also the interaction of pigment and binding material is being studied more and more, which strongly influences the spectral properties of the pigments (Cosentino, 2015b; Keller *et al.*, 2019). Many exciting results and new developments can be expected in the coming years.

The case studies presented here to document modern wall paintings in an urban environment showed that it is possible to combine different camera positions and spectral bands using photogrammetry. The field study enabled the correlation of VIS, UVR, UVR-FC, IRR and IRR-FC on a combined high-resolution 3D model. This offers new possibilities for investigation, especially for overall multispectral documentation of large wall paintings and complex, three-dimensional objects.

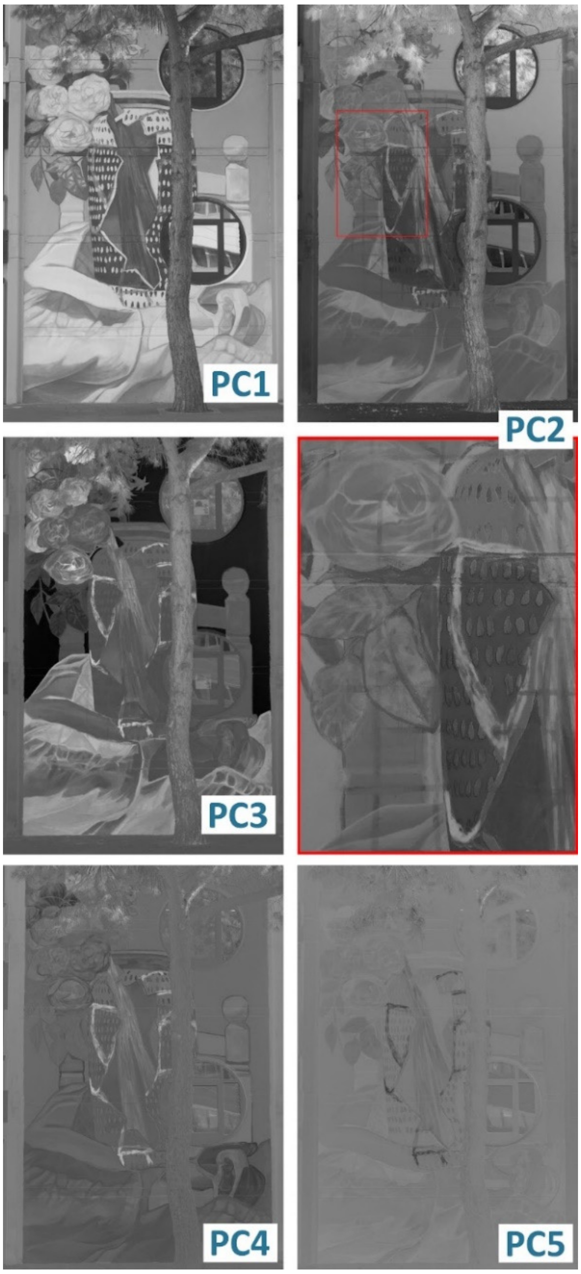

Figure 7. Principal Component Analysis of the wall painting. The image shows PC1 to PC5 analysing the UVR/B/G/R/IRR bands of the MSI. A detail of PC2 is highlighted in red, it shows the covered pattern better than the IRR.

Figure 8. To higher the differentiation a second PCA was processed on a image section without interfering environment (tree, floor, windows). Now PC4 revealed the underdrawn raster entirely.

The advantages of PCA were presented using the example of the second wall painting. For this purpose, a low-cost method consisting of UVR, VIS and IRR was used, and active excitation of the surfaces in specific spectral ranges was dispensed with. This limits the investigation, but it should be considered that the murals are exposed outdoors and in an urban environment. Artificial illumination under ideal conditions without parasitic stray light was impossible or can only be realised with great effort. Nevertheless, thanks to PCA, new findings and insights into the graffito were obtained. The detection of the covered raster provides information about the artist's working process.

It was shown that MSI could also be used in an urban environment. Despite the resulting limitations of the recording technique, it can provide new insights for investigating modern wall paintings such as graffiti. In the future, it will be necessary to test the combination of image series on a wider spectral range, integrating different imaging sensors with photogrammetry even at different times. Due to the congruent metric superimposition of different temporal image data, this offers further interesting PCA applications for monitoring cultural heritage.

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