Multispectral Photogrammetry in Cultural Heritage: Applications and Case Studies

Celine Beier and Renata Miftakhova
Erasmus Mundus Master in Archeological Materials Science
Digital Techniques and Laboratory Practice in Archaeological Materials Science
January 23, 2025

1 Introduction

Multispectral photogrammetry is an innovative technique that merges two well-established methods in cultural heritage research: multispectral imaging and photogrammetry (Rahrig at al., 2023). By integrating these two approaches, it provides new insights into cultural heritage objects and sites, with a wide range of applications.

Multispectral photogrammetry is based on data collected through multispectral imaging, which involves capturing and analyzing images of heritage objects or sites across multiple spectral ranges, including the ultraviolet (UV), visible (VIS), red-edge (RE), and infrared (IR, including near-infrared or NIR) regimes (Rahrig at al., 2023). Each spectral band offers unique and complementary information that can reveal hidden details and improve the understanding of materials, structures, or phenomena. For instance, UV imaging highlights material fluorescence and restorations, RE emphasizes subtle material differences, and IR/NIR can uncover subsurface details (Remondino & Stylianidis, 2016).

In multispectral photogrammetry images taken at different wavelengths are integrated with photogrammetric techniques: The process involves capturing overlapping images in different spectral channels, followed by pre-processing steps like color balancing and denoising. The images are then processed using specialized software to create 3D models through camera alignment, dense cloud generation, mesh creation, texture mapping, and orthorectification (Remondino & Stylianidis, 2016). The resulting orthoimages function as scaled maps, enabling accurate measurements of distances, angles, and areas. Ultimately, the process yields 3D models with precisely aligned spectral data.

This fusion of spatial and spectral information is particularly valuable for the conservation, restoration, and research of cultural heritage objects and sites. It facilitates non-invasive analyses, reveals previously inaccessible information, supports detailed monitoring of changes over time, and contributes to the creation of digital archives for artefacts and sites.

This paper offers an overview of the ongoing research in this emerging technique. It starts with a bibliometric analysis to summarize the published research. Given the broad scope of multispectral photogrammetry, the next chapter provides an overview of its diverse applications in cultural heritage research. In the following, two detailed case studies are presented. These case studies are selected to highlight recent developments and to demonstrate applications of multispectral photogrammetry that can be easily adopted by research institutions in the field of cultural heritage, such as the Hercules laboratory.

2 Bibliometric Analysis

This chapter presents an overview of published research on multispectral imaging through a bibliometric analysis of the past decade. The analysis was conducted using the SCOPUS database, employing various keywords related to the technique ("Multispectral AND Photogrammetry," "Photogrammetry," "Multispectral Images," "Multispectral Imagery," "Digital Photogrammetry," "Close Range Photogrammetry") for the period 2014–2024. The results (Figure 1) indicate a steady growth in research on multispectral photogrammetry since 2014. The sharp increase in publications during 2017–2019 can potentially be attributed to the greater availability of affordable multispectral sensors and unmanned aerial systems (UAS).

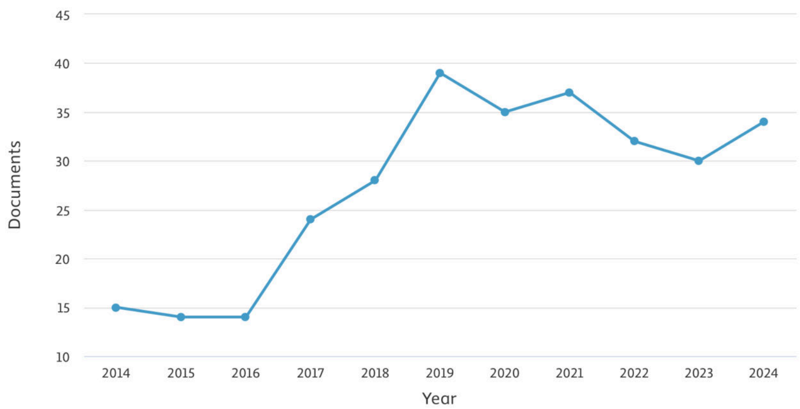

Figure 1: Number of SCOPUS documents related to multispectral photogrammetry by year for 2014–2024. From Elsevier (2025).

Figure 2 illustrates the distribution of publications across various fields. The majority of the papers are concentrated in the earth and environmental sciences, as well as engineering. While publications in the geosciences primarily focus on applying multispectral photogrammetry for research, a significant portion of the papers in engineering and computer science centers on the technical implementation of the technique, which includes advancements in multispectral sensors, image processing and machine learning. This distribution underscores the interdisciplinary nature of multispectral photogrammetry, bridging sensor technology, image analysis, and remote sensing applications.

Key application areas of multispectral photogrammetry include precision agriculture, where it aids in assessing crop health, estimating yields, and managing resources; forestry, where it is used to monitor water quality and track land-use changes; and earth observation, where multispectral imaging supports mapping areas impacted by natural disasters such as floods, landslides, and earthquakes. Another significant area of application for multispectral photogrammetry is the investigation, conservation, and restoration of cultural heritage. Within this field, multispectral photogrammetry has many different applications, which are discussed in detail in the next chapter.

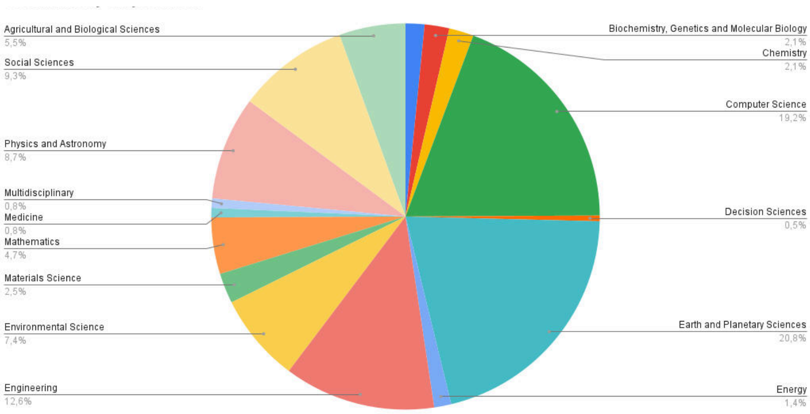

Figure 2: Number of SCOPUS documents related to multispectral photogrammetry by subject area for 2014–2024. Adapted from Elsevier (2025).

The main publication outlets for multispectral photogrammetry research include journals such as *Remote Sensing*, the *ISPRS Journal of Photogrammetry and Remote Sensing*, and conference proceedings from the *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*. This reflects the technical nature of the field and its strong connection to remote sensing research. Additionally, a smaller but significant number of articles are published in interdisciplinary journals spanning environmental monitoring, agricultural sciences, and archaeology, representing the diverse applications of the technique. For instance, journals like *Heritage Science* and the *Journal of Cultural Heritage* feature studies on artwork examination and historic site documentation while analytical chemistry-focused journals also include research where multispectral photogrammetry complements chemical analyses, particularly in non-destructive testing contexts.

The geographical reach of multispectral photogrammetry research is evident in SCOPUS articles and papers, as shown in Figure 3. Institutions from Europe, particularly Italy, Spain, and Germany, and North America dominate the publication landscape. This dominance can be attributed to robust research infrastructures and access to funding for geospatial technologies. Active research groups in China, Japan, and India are also contributing significantly, especially in fields such as precision agriculture and infrastructure monitoring. This distribution indicates that multispectral photogrammetry is garnering growing global interest.

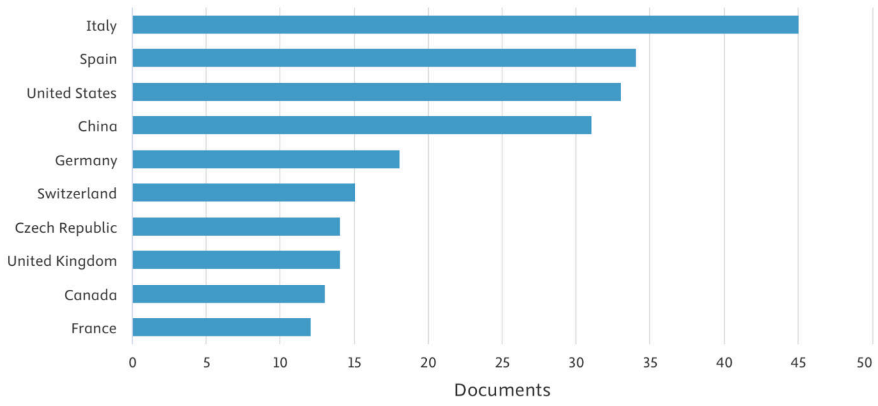

Figure 3: Number of SCOPUS documents related to multispectral photogrammetry by country for 2014–2024. From Elsevier (2025).

The analysis of SCOPUS papers highlights key focuses in multispectral photogrammetry research. One notable trend is the integration of machine learning with multispectral imaging, enabling advanced data analysis and interpretation. Another significant trend is data fusion, where multispectral photogrammetry is combined with tools like thermal cameras or LiDAR sensors to provide more comprehensive information about an object or area. A common challenge across all research areas is ensuring data reliability; variations in lighting conditions and sensor quality necessitate precise calibration of instruments. This is particularly critical in art conservation, where even minor inaccuracies in color representation can result in incorrect conclusions.

In summary, multispectral photogrammetry is a highly interdisciplinary technique with a wide range of applications in fields such as environmental science, agriculture, archaeology, art conservation, and materials chemistry. The bibliometric analysis for the 2014–2024 period highlights the technique's ability to provide detailed spatial and spectral information, supporting both large-scale applications, like geospatial assessments, and small-scale studies, such as art historical research. The steady increase in published studies indicates that multispectral photogrammetry will continue to be a powerful, non-invasive tool with high resolution.

3 Applications in Cultural Heritage

Recent multispectral photogrammetry research in cultural heritage has focused on the investigation, documentation, preservation, and restoration of historical sites and objects. This chapter highlights some recent important studies with the goal of demonstrating the wide range of applications for multispectral photogrammetry.

Multispectral photogrammetry is a valuable tool in the conservation of murals and frescoes. Advanced image analysis techniques enable researchers to detect hidden features in wall paintings, such as underdrawings or degradation patterns, without damaging the artwork. This method provides essential information to restoration experts as the basis for informed decisions about conservation strategies. For example, Rahrig et al. (2023) use multispectral photogrammetry to investigate a wall painting in the Cathedral of Valencia, revealing previously unnoticed artistic elements. This research is discussed in detail below in the second case study. Another example for a study of wall paintings using multispectral photogrammetry is the *Anamorphosis* project by Pamart et al. (2017) which involves using a specialized dual-camera system to simultaneously acquire VIS and IR images. This technique enables the precise alignment and integration of multispectral data and successfully links the artwork's spectral properties, such as underdrawings and material compositions, with its 3D geometry.

Another important research area is the use of multispectral photogrammetry for the condition assessment and monitoring of cultural heritage sites and objects. Studies like De Fino et al. (2023) show how multispectral photogrammetry can help in non-invasive monitoring of the structural integrity of buildings over time: Combining VIS photogrammetric data with thermal infrared images and advanced image analysis techniques allows for the identification of deterioration issues, such as moisture patterns, material loss, or chromatic changes, as well as small-scale defects like cracks, which can be the basis for planning of necessary interventions. Another example is the study on multispectral photogrammetry and change detection algorithms in documenting and monitoring the restoration of an 18th-century Byzantine icon by Abate (2019). It involves periodic imaging using a camera with polarizing filters and generating detailed orthoimages. A simpler 2D change-detection method, enhanced by correlation-based improvements, reveals differences in flat images, while more advanced 3D comparisons detect tiny shape variations of less than a millimeter. The process documents each restoration phase, including varnish removal, cleaning, and retouching, and reveals minimal geometric distortions due to varnish removal and slight deformation of the wooden support. In this study, multispectral photogrammetry provides precise documentation with potential applications in conserving other heritage assets like frescoes and monuments. While multispectral photogrammetry is a highly adaptable technique and can be used to address many different monitoring and diagnostic challenges (De Fino et al., 2023), currently, a significant limitation of the approach lies in automated decay detection. This remains challenging due to "the great heterogeneity in architectural heritage, and often to the little availability/sharing of photogrammetric data belonging to analogous cases, which could be useful to perform comparative analyses or to train machine/deep learning systems" (De Fino et al., p. 7057). De Fino (2023) emphasises that the need for standardized guidelines, more flexible UAV-based surveys, and integrated monitoring data would make studies applying multispectral photogrammetry for condition assessment and monitoring less fragmented.

Multispectral photogrammetry can also be used for the investigation and documentation of large-scale sites. The combination of UAS-based photogrammetry and multispectral analysis enables the creation of detailed 3D models, which help archaeologists discover and interpret archaeological sites (Pena-Villasenín et al., 2024). For example Fiz et al. (2022) employ multispectral photogrammetry for the investigation of the Roman Clunia Sulpicia settlement near the town of Peñalba de Castro, Spain. The project focuses on a section between the theater, forum, and the excavated Roman houses, employing non-invasive remote sensing and multispectral photogrammetry techniques. Despite a seasonal drought, which reduces the visibility of vegetation differences and complicates feature detection, careful georeferencing of multiple sensor bands allows for the creation of vegetation indices (NDVI, ENDVI, ARVI), principal component analysis (PCA) and SPOT and TripleSat multispectral images. These orthoimages reveal subtle anomalies in the site layout and the presence of cropmarks that could be interpreted as indicative of archeological structures from which building walls were supported. This illustrates the value of multispectral photogrammetry for investigating historical sites like Clunia Sulpicia.

Another key research area is the use of multispectral photogrammetry for advanced imaging of archaeological objects. Including other wavelengths, like UV fluorescence, RE and IR, can enhance features of the objects that are not or less visible in classic VIS photogrammetry and therefore aid the understanding of an object (Mathys et al., 2019). An example is given in Mathys et al. (2019), where including the UV and IR regimes in the investigation of engraved ivory horns and antlers enhances the contrast and visibility of engravings on the objects. Additionally, the resulting precise 3D models can serve as a virtual backup for fragile artifacts. Combining 3D reconstruction and multispectral imagery can also help with the photogrammetric digitization of challenging materials: Mathys et. al (2018) addresses that teeth as reflective and partially translucent materials are challenging to digitize with traditional 3D scanning. As methods like laser scanning face problems with enamel, usually an opaque paint is applied to enhance imaging, however, this is not feasible for delicate artifacts. Multispectral photogrammetry involving UV wavelengths offers better surface reconstruction for enamel by capturing reflective and translucent properties more effectively than standard white light or red wavelengths. The researchers applied this technique to Neanderthal and modern human teeth from Belgian archaeological sites, as well as to vertebrate specimens.

4 Case Study 1: UAS-Based Multispectral Photogrammetry for the Detection of Buried Archaeological Remains through Cropmarks

Pena-Villasenín et al. (2024) evaluate the potential of multispectral photogrammetry utilizing UAS for detecting cropmarks linked to buried archaeological structures. The study investigates a range of environmental conditions and experimental methodologies to assess the capabilities and limitations of this emerging technique. Unless stated otherwise, all information in this chapter is derived from Pena-Villasenín et al. (2024).

4.1 Introduction

Cropmark photography is a non-invasive method for detecting archaeological sites by observing vegetation anomalies caused by buried structures interacting with the upper soil layers. This interaction can result in differences in vegetation health or height above the archaeological remains. Changes in crop health are most effectively detected through the analysis of multispectral or hyperspectral images. Historically, such studies have relied on aerial images captured from manned aircrafts or satellites (Aqdus et al., 2012). However, these approaches face significant limitations, including restricted spatial resolution, slow data acquisition, atmospheric interference, and high operational costs. In recent years, UAS have emerged as a promising alternative due to their ability to fly at low altitudes and avoid cloud cover as well as capture images with exceptional spatial and temporal resolution. UAS equipped with multispectral sensors, combined with advanced data processing techniques, can detect a wide range of anomalies that were previously challenging or expensive to identify. However due to the variability in vegetation cover at archaeological sites there are many open questions regarding the universal applicability of this technique. The cropmarks visible above a buried structure depend on the interaction of the archaeological remains with the surrounding environment and are influenced by factors such as environmental conditions, crop type, and the time of year when measurements are taken. This study seeks to address these questions by investigating the use of UAS-based multispectral photogrammetry to detect cropmarks under diverse conditions.

4.2 Materials and Methods

Site Selection: Six archaeological sites located in the northwest of the Iberian Peninsula are chosen for the study to represent a diverse range of contexts and conditions. These sites span different time periods, including the Bronze Age, Iron Age, Roman and Romanized settlements, as well as a medieval castle. The study includes both sites with no prior excavations and those with partial excavations. Additionally, the areas differ in vegetation characteristics, including various types of vegetation and agricultural use. One site has recently experienced a fire, expanding the scope to include areas with post-fire vegetation regeneration.

Materials: The study requires a UAS for image capture, specialized software for photogrammetry and computing hardware capable of managing and processing the collected data. The UAS is a consumer model equipped with one optical sensor for the visible spectrum and five monochrome sensors dedicated to multispectral imaging – blue, green, red, RE and NIR. The use of a commercially available UAS highlights the accessibility of this technique.

Procedure: First, the survey area is recorded using the UAS's five monochrome sensors. The flights for image capture are conducted with an overlap of 70–80% between individual images, which is essential for photogrammetric reconstruction, and at altitudes of 45–110 m above ground level, resulting in a ground sample distance of 3–6 cm. For the photogrammetric processing, the captured images of the different wavelengths are aligned, corrected for distortions and registered to a coordinate reference system. The images are then stitched together to create an orthoimage, a geometrically corrected, scaled image generated from overlapping aerial photographs.

INDEX	FORMULA
NDVI (NORMALIZED DIFFERENCE VEGETATION INDEX)	$(NIR - Red)/(NIR + Red)$
NDVIRE **(NORMALIZED DIFFERENCE VEGETATION INDEX FOR** RED-EDGE)	$(NIR - Red\text{-}Edge)/(NIR + Red\text{-}Edge)$
NDRE (NORMALIZED DIFFERENCE RED-EDGE)	$(NIR - Red\text{-}Edge)/(NIR + Red\text{-}Edge)$
SAVI (SOIL ADJUSTED VEGETATION INDEX)	$(NIR - Red)/(NIR + Red + 0.5) \times (1 + 0.5)$
NLI **(NONLINEAR VEGETATION INDEX)**	$(NIR^2 - Red)/(NIR^2 + Red)$
GEMI (GLOBAL ENVIRONMENT MONITORING INDEX)	$\eta \times (1 - 0.25 \times \eta) - ((Red - 0.125)/(1 - Red))$ $\eta = ((2 \times (NIR^2 - Red^2) + 1.5 \times NIR + 0.5 \times Red)/(NIR + Red + 0.5))$
TVI **(TRIANGULAR VEGETATION INDEX)**	$0.5 \times (120 \times (NIR - Green) - 200 \times (Red - Green))$
MTVI (MODIFIED TRIANGULAR VEGETATION INDEX)	$1.2 \times (1.2 \times (NIR - Green) - 2.5 \times (Red - Green))$
GDVI (GREENNESS DIFFERENCE VEGETATION INDEX)	$(NIR - Green)/(NIR + Green)$
CHLGREEN **(CHLOROPHYLL GREEN)**	$(NIR/Green) - 1$
TCARI (TRANSFORMED CHLOROPHYLL ABSORPTION RATIO INDEX)	$3 \times ((Red\text{-}Edge - Red) - 0.2 \times (Red\text{-}Edge - Green)) \times (Red\text{-}Edge/Red)$
MCARI (MODIFIED CHLOROPHYLL ABSORPTION REFLECTANCE INDEX)	$((Red\text{-}Edge - Red) - 0.2 \times (Red\text{-}Edge - Green)) \times (Red\text{-}Edge/Red)$
ARI **(ANTHOCYANIN REFLECTANCE INDEX)**	$(1/Green) - (1/Red\text{-}Edge)$
NGRDI (NORMALIZED DIFFERENCE GREEN/RED INDEX)	$(Green - Red)/(Green + Red)$

Figure 4: Formulas of the different vegetation indices used for image processing. From Pena-Villasenín et al. (2024).

Through combining the orthoimages captured at different wavelengths, new images can be mathematically generated that facilitate the identification of cropmarks. First, true-color and false-color composite orthoimages are generated using the red, green and blue (RGB) color bands. Additionally, principal component analysis (PCA), a statistical method for data analysis, is applied, which allows for the automatic extraction of patterns in the images. Finally, vegetation health maps are generated by combining the different wavelengths using specific formulas, called vegetation indices. One key index is the normalized difference vegetation index (NDVI). The NDVI formula compares the NIR and visible red (RED) bands and is based on the fact that healthy green vegetation reflects more NIR, while weak, less green vegetation reflects more VIS. By calculating the ratio NDVI=(NIR-RED)/(NIR+RED) an image highlighting vegetation health can be created. In addition to NDVI, several other plant health indices are tested and are summarized in Figure 4.

The cropmarks in the resulting images are then categorized based on their likelihood of being associated with actual structures, using criteria such as their shape and alignment, their intensity, temporal continuity (whether the marks appeared in images from different dates) and spectral continuity (whether the marks remained consistent across various layers). Finally, the cropmarks are vectorized, converting the visible patterns into precise digital outlines for further analysis.

4.3 Results

The study demonstrates that images obtained from multispectral photogrammetry are effective in the identification of cropmarks from buried archaeological structure. Figure 5 presents orthoimages generated using color composition, PCA and vegetation indices for the same archaeological site. Significant differences are evident between the images, some provide better detection of cropmarks, while others are less effective. By comparing the results obtained from different sites and environmental conditions, the study was able to conclude which indices are most suitable for specific scenarios. The NDVI index is found to be particularly effective across a wide range of site conditions, thus making it an effective first step in an investigation.

The study also examines the effect of the time of year at data collection. Figure 6 shows the same site in images taken during spring, summer, and fall. In this scrubland area, spring images provide the best detection of cropmarks, followed by the summer images, where cropmarks can also be identified, though to a lesser degree. The fall image is significantly less effective due to disturbances from recent clearing activities at the site. In general, case studies involving multiple data taking periods suggest that the peak growing season in spring is optimal for detecting cropmarks in scrublands and post-fire regeneration areas, while in grasslands, summer, when vegetation is most stressed, is the best time.

One complication encountered in the study is the detection of both archaeological cropmarks and recent agricultural machinery marks. This overlap complicates the interpretation of the results, as the agricultural marks can easily be mistaken for archaeological cropmarks. This is illustrated in Figure 7.

Finally, it is important to note that all these results represent potential cropmarks and should be validated in the future using other remote sensing techniques and/or excavation.

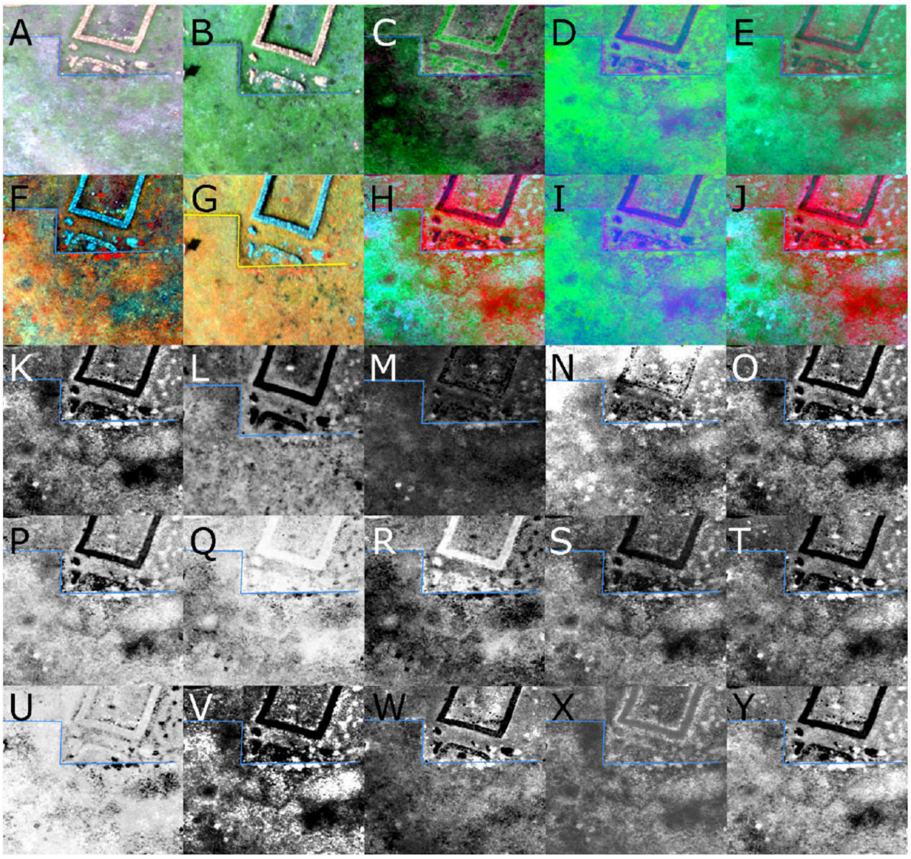

Figure 5: Orthoimages for the same archaeological site obtained through photogrammetry and image processing. The zigzag line visible in all images delineates the boundary between the excavated area (top) and the non-excavated area containing buried archaeological structures (bottom). The individual images are: (A) RGB (B) RGB (C) PCA, composition 123 (D) PCA, composition 147 (E) PCA, composition 159 (F) Color Infrared, composition 521 (G) Color Infrared, composition 521 (H) Combined PCA, composition 149 (I) Combined PCA, composition 147 (J) Combined PCA, composition 159. (K) NDVI (L) NDVI (M) NDVI RE (N) NDRE (O) SAVI (P) NLI (Q) GEMI (R) TVI (S) MTVI (T) ChiGREEN (U) TCARI (V) MCARI (W) ARI (X) NGRDI (Y) GDVI. From Pena-Villasenín et al. (2024).

4.4 Discussion

The study demonstrates that UAS-captured multispectral photogrammetry is a highly effective method for detecting cropmarks and identifying buried archaeological remains across various environments and sites. This technique is non-invasive, cost-effective, enables rapid data acquisition, and offers high spatial and temporal resolution. While its results require verification, it can serve as an excellent initial step in investigating the layout of archaeological sites through cropmark detection.

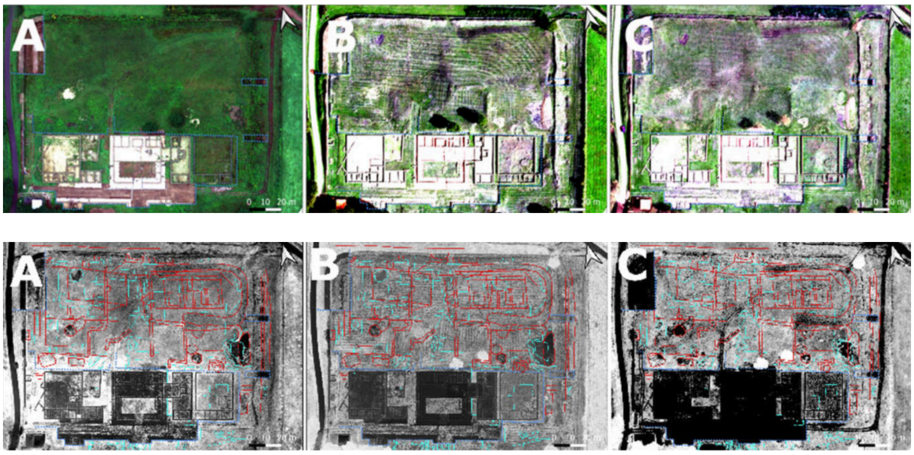

Figure 6: RGB orthoimages (top) and NDVI images (bottom) with detected cropmarks for different data taking periods: (A) summer (B) fall (C) spring. From Pena-Villasenín et al. (2024).

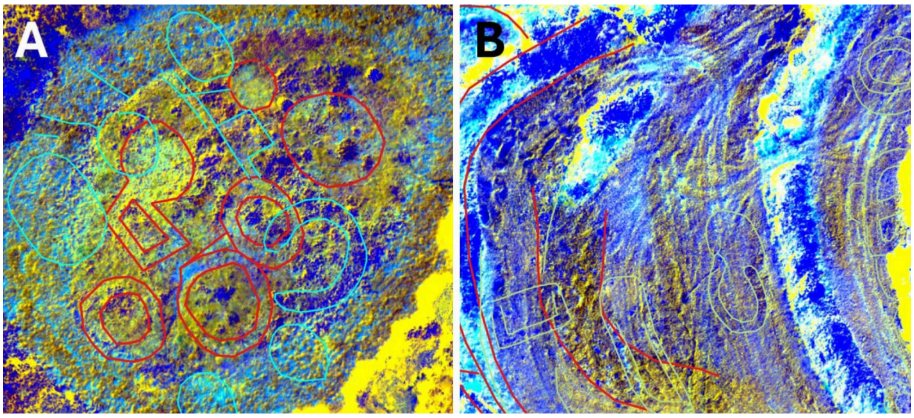

Figure 7: PCA, composition 123 image illustrating the difficulties encountered when investigating pasture areas with marks from agricultural machinery (right) compared to a scrubland zone (left). From Pena-Villasenín et al. (2024).

The comparison with other non-invasive subsurface techniques, including Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR), emphasizes the unique advantages and why researchers should consider incorporating multispectral photogrammetry into their investigations: Compared to ERT and GPR, UAS-based multispectral photogrammetry is a relatively cost-effective technique, with equipment costs starting at approximately €6,000 (Pena-Villasenín et al., 2024). In contrast, the prices for entry-level ERT and GPR systems are around €15,000, with costs increasing significantly depending on system complexity (United States Environmental Protection Agency, n.d.-a; United States Environmental Protection Agency, n.d.-b). UAS-based multispectral photogrammetry is also highly accessible, with experimental materials and software commercially available, a characteristic shared with ERT and GPR. In terms of data acquisition, UAS-based multispectral photogrammetry offers a significant advantage in speed. The process of flying a drone over an area is considerably faster than the labor-intensive task of placing the electrodes required for ERT or moving a GPR sensor across the site. Furthermore, given that this method employs UAS, it is particularly well-suited to challenging topographies where ERT and GPR may be impractical or ineffective. Despite these advantages, the results of UAS-based multispectral photogrammetry may not always be as conclusive as those obtained through ERT and GPR. As demonstrated in this study, the effectiveness of UAS-based multispectral photogrammetry is highly dependent on site-specific conditions. Therefore, for most applications it is an excellent starting point due to its affordability and efficiency, but the results need to be verified with other techniques, such as ERT or GPR. Finally, UAS-based multispectral photogrammetry can address specific research questions that are inaccessible through other non-invasive subsurface techniques. For example, the study by Pena-Villasenín et al. (2024) reveals that earth mounds created during excavations in the 1930s, now removed, continue to influence vegetation patterns at the site. Such temporary alterations to the soil produce features that can be identified only through cropmark analysis. This is a capability unique to UAS-based multispectral photogrammetry, that falls outside the range of both ERT and GPR.

5 Case Study 2: Multispectral Photogrammetry for the Analysis of Mural Paintings

Rahrig et al. (2023) investigate how multispectral imaging techniques, well-established and widely used in the study of mural paintings, can be enhanced through the combination with photogrammetry and advanced image processing methods. This presents another compelling application of multispectral photogrammetry, which is summarized in the following chapter. Unless stated otherwise, all information is from Rahrig et al. (2023).

5.1 Introduction

Multispectral imaging is frequently used in investigating mural paintings. It involves capturing spectra at discrete wavelengths across the UV, VIS and NIR spectral ranges, each providing unique and complementary information. UV images reveal surface details such as varnishes or restorations, the VIS range being perceptible to the human eye serves as the primary reference point for analysis, and NIR images uncover underlying features like charcoal sketches or earlier paintings. This study introduces a new aspect to traditional multispectral imaging as it integrates photogrammetric methods to stitch individual wavelength-specific images into a seamless, high-resolution composite of the entire mural.

5.2 Materials and Methods

Case Study: This study focuses on the *Adoration of the Shepherds*, painted in 1472 by Paolo de San Leocadio and Francesco Pagano in the Cathedral of Valencia. It is an iconic Spanish Renaissance painting and one of the first applications of Italian fresco techniques in Spain. The mural, located within the Cathedral's interior enclosure, was created as a trial piece for the artists to demonstrate their proficiency in fresco painting before being commissioned to work on the altar ceiling. Renowned for its exceptional quality, the mural also provides valuable insights into the working methods of the two artists, particularly because of its unfinished state, which offers unique opportunities for technical and artistic analysis.

Materials: Multispectral images are captured using a commercial camera modified to remove the low-pass filter that blocks IR radiation, making it sensitive to UV, VIS and NIR wavelengths. Additional filters are placed in front of the camera to selectively allow specific wavelengths to pass. Illumination for the mural is provided by two halogen studio lamps for the VIS and IR images and two UV LEDs for the UV images. In addition to the modified camera, a wide-angle commercial camera and a commercial laser scanner are employed to gather supplementary information.

Procedure: The mural is documented in 18 individual sections, with each section captured using four different imaging techniques: UV-induced UV reflectography, VIS-induced VIS reflectography, and IR-induced IR reflectography at 850 nm and 1000 nm. This results in four images per section, along with an additional 19th section used for white correction. To ensure comparability, consistent camera settings are applied for all images. Since the multispectral images are primarily taken from a frontal camera position, which is suboptimal for photogrammetry, additional photos are captured using a wide-angle camera to assist in the photogrammetric processing. A commercial laser scanner is also employed to provide ground truth information as reference for the photogrammetric data and supply details about the orientation and localization of the mural within the cathedral.

The raw images collected from each technique are first pre-processed using their respective software. Then the images are combined through photogrammetry to create high-resolution orthoimages for each wavelength. These orthoimages are processed and combined using techniques similar to those described in the first case study. False-color images are generated, and principal component analysis (PCA) is applied to emphasize specific structures within the images. Additionally, the study develops a normalized difference painting index (NDPI) based on the normalized difference vegetation index (NDVI) that compares the UV and IR bands: NDPI=(UV-IR)/(UV+IR). In the final step, all generated images, including both the raw multispectral orthoimages and the processed images, are standardized to share the same pixel dimensions, size, and orientation. These images are then integrated into a geographic information system (GIS), enabling precise and direct comparisons across all datasets.

5.3 Results

Figure 8 shows the orthoimages obtained at different wavelengths. They are used to create the composite images, such as false-color images, which are effective in classifying and differentiating materials, such as the pigments used in the mural painting. Figure 9 demonstrates how false-color IR images can be used to compare the blue pigments used in the sky and Maria's veil. The identical behavior of both blue areas suggests that the same blue pigment is employed. The transformation of the blue pigment into a strong red in the false-color IR image may indicate the presence of lapis lazuli, however further analysis with complementary methods is required to confirm this hypothesis.

Figure 8: UV, VIS and IR (850 and 1000 nm) orthoimages. From Rahrig et al. (2023).

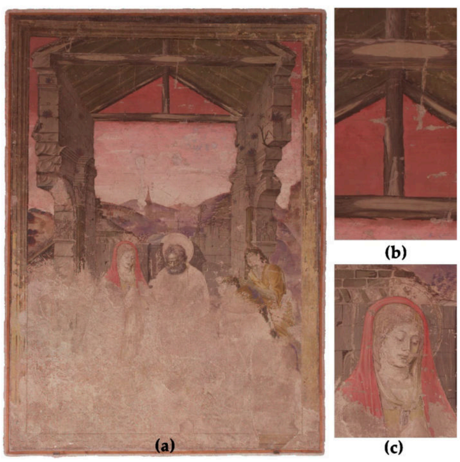

Figure 9: (a) False-colour infrared image created from the red and green VIS spectral bands and the IR image at 850 nm. It can be used to compare the blue pigments in the sky (b) and Maria's veil (c). From Rahrig et al. (2023).

An orthoimage resulting from PCA is shown in Figure 10. It proves particularly useful for examining the unfinished areas in the lower portion of the painting, where it reveals details such as the contour of Maria's veil, the hands of the left shepherd (Figure 10b), and the halo of the undrawn Jesus (Figure 10c). These features are much more apparent in the PCA image than in the traditional IR image shown in Figure 8. Similarly, Figure 11 presents another orthoimage generated through PCA which highlights details more clearly than the individual multispectral images. For example, it shows the extension of Joseph's rod into his lap (Figure 11b), the pentimenti of a shepherd's crook in the background (Figure 11c), and enhanced details in the sky, such as clouds and two distinct damage phenomena (Figure 11d).

The result for the NDPI analysis is shown in Figure 12. The advantage of this image lies in the increased detection of surface damages and surface roughness. It is therefore helpful in identifying the giornata of the mural and offers critical insights into the working process.

Finally, integrating the processed images within a GIS environment provides significant analytical benefits, such as simplified comparison between individual images and tracings which can be overlaid on any file. Figure 13 illustrates this with the VIS image overlaid with tracings of the giornata, underdrawings, and pentimenti extracted from the hybrid images, serving as a comprehensive summary of all information obtained about the painting.

5.4 Discussion

This study demonstrates how multispectral photogrammetry and advanced image processing enhance traditional multispectral imaging for the analysis of the *Adoration of the Shepherds*. Multispectral imaging is a low-cost, non-destructive and straightforward, yet complex method for investigating mural paintings. While the individual spectral images provide valuable information about the materials and condition of a painting, manually comparing these bands is often labor-intensive and time-consuming. Multispectral photogrammetry addresses this challenge by stitching individual spectral images into seamless composites that capture the entire artwork at a high resolution. Furthermore, the integration of the resulting images into a GIS facilitates streamlined comparisons of individual wavelength bands and therefore improves the efficiency of the analysis process. Multispectral photogrammetry also enables advanced image processing techniques, such as the creation of false-color images, PCA orthoimages, and NDVI/NDPI images. These images combine the data from different wavelengths and thereby create additional valuable insights that are otherwise difficult to extract. By enhancing the traditional approach, multispectral photogrammetry provides a more comprehensive analysis and can lead to significant new discoveries in the study of mural paintings.

As multispectral imaging is already widely used and many research institutions, such as the Hercules laboratory, have the necessary equipment, the methods discussed in this study can easily be adopted to become a standard in the analysis of mural paintings. The data collection process requires only minor modifications compared to multispectral imaging to ensure that the results are suitable for photogrammetry and GIS integration. The primary newness lies in the data analysis phase: Additional steps in the image analysis, such as photogrammetry and the generation of false-color images, PCA orthoimages and NDVI/NDPI images may require specific software, computing power and human resources. However, the new results provide significantly more information than traditional multispectral analysis techniques.

6 Conclusion

Multispectral photogrammetry is an emerging technique that combines multispectral imaging with photogrammetry methods. The bibliometric analysis shows that it is a constantly growing, highly interdisciplinary and international field with a wide range of applications from environmental science, agriculture, materials chemistry, to archaeology and art conservation. Within cultural heritage research, multispectral photogrammetry is relevant for the investigation and conservation of murals and frescoes, assessment and monitoring of cultural heritage sites and objects, geophysical investigation of archaeological sites and enhanced imaging of heritage objects (De Fino et al., 2023; Fiz et al., 2022; Mathys et al., 2019; Rahrig et al., 2023). This paper examines two case studies in detail: Pena-Villasenín et al. (2024) demonstrate in their proof-of-concept study how multispectral photogrammetry can detect cropmarks under various conditions and thereby provide a foundation for conducting more detailed geophysical investigations of an archaeological site. Another powerful application is given in Rahrig et al. (2023), where multispectral photogrammetry is able to reveal features and structures in a mural that are not accessible through traditional multispectral imaging and therefore offers improved analytical capabilities. Both case studies highlight the immense potential of multispectral photogrammetry as well as the accessibility of this technique. As many research institutes in the field already have the materials for multispectral imaging, or UAS equipped with the respective sensors can be commercially bought, multispectral photogrammetry can be easily adopted by including additional image processing steps while maintaining a largely similar data acquisition process. It can be anticipated that in the future, a greater number of researchers and research institutions will adopt multispectral photogrammetry as a standard method, resulting in numerous valuable findings in the field of cultural heritage.

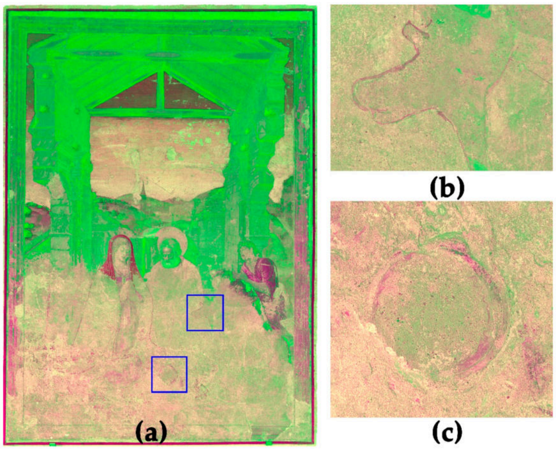

Figure 10: PCA, composition 123 image (a), which reveals details in the unfinished areas in the lower portion of the painting, such as details of the shepherd's hand (b) or the halo of the undrawn Jesus (c). From Rahrig et al. (2023).

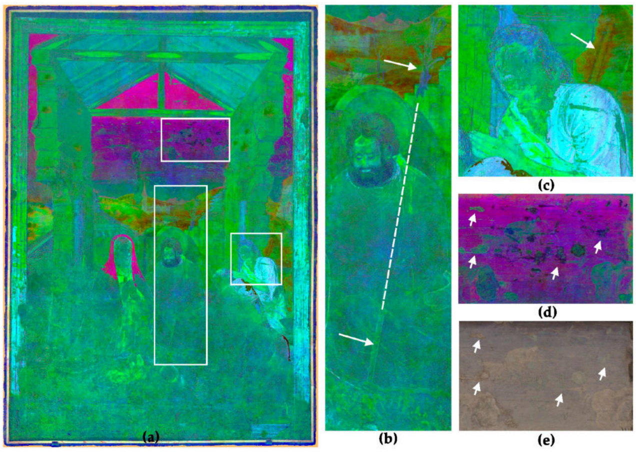

Figure 11: PCA, composition 345 image (a), which identifies covered underdrawings, like the extension of Joseph's rod into his lap (b), the pentimenti of a shepherd's crook in the background (c) and enhanced details in the sky, such as clouds and two distinct damage phenomena (d). The same details are shown in VIS for comparison (e). From Rahrig et al. (2023).

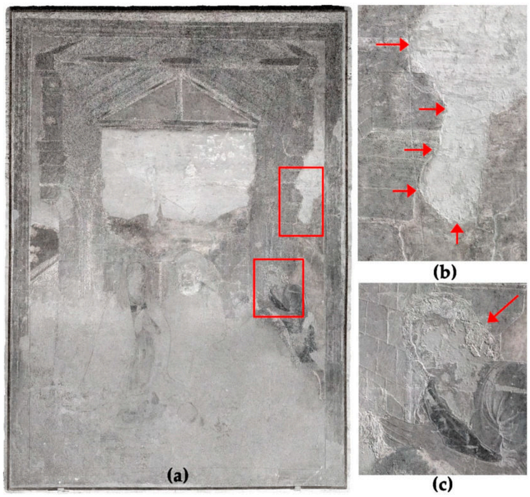

Figure 12: NPDI image (a) highlighting the borders between two giornata (b) and the differences between intact and lost surfaces (c). From Rahrig et al. (2023).

Figure 13: VIS image overlaid with tracings of the giornata (red), underdrawings and pentimenti (blue) and additional details (with and black) extracted from the hybrid images. From Rahrig et al. (2023).

Bibliography

Abate, D. (2019). Documentation of paintings restoration through photogrammetry and change detection algorithms. *Heritage Science, 7*(1), 13. https://doi.org/10.1186/s40494-019-0257-y

Aqdus, S. A., Hanson, W. S., Drummond, J. (2012). The potential of hyperspectral and multi-spectral imagery to enhance archaeological cropmark detection: a comparative study. *Journal of Archaeological Science,* 39 (7), 1915-1924. https://doi.org/10.1016/j.jas.2012.01.034

De Fino, M., Galantucci, R. A., & Fatiguso, F. (2023). Condition assessment of heritage buildings via photogrammetry: A scoping review from the perspective of decision makers. *Heritage*, *6*(11), 7031-7066. https://doi.org/10.3390/heritage6110367

Elsevier (2025). Scopus Database. https://shorturl.at/PEfEs

Fiz, J. I., Martín, P. M., Cuesta, R., Subías, E., Codina, D., & Cartes, A. (2022). Examples and results of aerial photogrammetry in archaeology with UAV: Geometric documentation, high resolution multispectral analysis, models, and 3D printing. *Drones*, 6(3), 59. https://doi.org/10.3390/drones6030059

Mathys, A., Jadinon, R., & Hallot, P. (2019). Exploiting 3D multispectral texture for a better feature identification for cultural heritage. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* IV-2/W6, 91–97. https://doi.org/10.5194/isprs-annals-IV-2-W6-91-2019

Mathys, A., Semal, P., Brecko, J., & Van Den Spiegel, D. (2019). Improving 3D photogrammetry models through spectral imaging: Tooth enamel as a case study. *PLoS ONE*, *14*(8). https://doi.org/10.1371/journal.pone.0220949

Pamart, A., Guillon, O., Faraci, S., Gattet, E., Genevois, M., Vallet, J. M., & De Luca, L. (2017). Multispectral photogrammetric data acquisition and processing for wall paintings studies. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W3,* 559–566. https://doi.org/10.5194/isprs-archives-XLII-2-W3-559-2017

Peña-Villasenín, S., Gil-Docampo, M., & Ortiz-Sanz, J. (2024). Hidden archaeological remains in heterogeneous vegetation: A crop marks study in fortified settlements of northwestern Iberian Peninsula. *Remote Sensing*, 16(21), 3923. https://doi.org/10.3390/rs16213923

Rahrig, M., Herrero Cortell, M. Á., Lerma, J. L. (2023). Multiband Photogrammetry and Hybrid Image Analysis for the Investigation of a Wall Painting by Paolo de San Leocadio and Francesco Pagano in the Cathedral of Valencia. *Sensors*, 23, 2301. https://doi.org/10.3390/s23042301

Remondino, F., & Stylianidis, E. (2016). *3D recording, documentation and management of cultural heritage* (Vol. 2). Dunbeath, UK: Whittles Publishing.

United States Environmental Protection Agency (n.d.- a). Geophysical Methods: Ground Penetrating Radar. Hazardous Waste Clean-Up Information (CLU-IN) On-line. https://clu-in.org/characterization/technologies/default2.focus/sec/Geophysical_Methods/cat/Ground_Penetrating_Radar

United States Environmental Protection Agency (n.d.- b). Geophysical Methods: Electrical Resistivity Tomography. Hazardous Waste Clean-Up Information (CLU-IN) On-line. https://clu-in.org/characterization/technologies/default2.focus/sec/Geophysical_Methods/cat/Electrical_Resistivity_Tomography