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Potential and Challenges of Spectral Imaging for Documentation and Analysis of Stained-Glass Windows

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Abstract

Stained-glass windows are very particular artifacts; they not only have an intrinsic artistic and historical meanings, but also a functional role, strictly connected to the buildings where they were originally placed. The investigation of these artifacts is a challenging research opportunity, due to their optical, chemical and physical characteristics. However, these properties could change with time, depending on the raw materials used, or due to exposure in a very aggressive environment. For this reason, developing imaging techniques that could both digitize and document the morphological/chemical changes of these objects, would solve two important issues: first, it would be possible to obtain a digital model of the object, ensuring the preservation of the objects for the future; second, it would be possible to get information on the materials employed, the ways they change with time, and how these changes modify the final appearance of the artwork.. In this paper a proposal for a more systematic application of spectral imaging to stained glass is presented, discussing challenges and potential of the technique.

Introduction

Stained-glass windows are very particular artifacts; they not only have an intrinsic artistic and historical meanings, but also a functional role. They were built to close gaps in the architecture and at the same time the images, as well the chosen color palette, were designed to communicate stories or represent themes closely connected to the buildings where they were originally placed. The context in which stained glass are found is extremely important: the mounting technique, the materials and technologies employed to produce and color the glass can give many information on the resources and knowledge available in a certain historical period or geographical region [1-4].

From the material point of view, the investigation of these artifacts is a challenging research opportunity, due to their optical, chemical and physical characteristics. Stained-glass windows are made of many components, which together influence their general appearance: their integration in the building structure is guaranteed by a wooden or metallic frame; supporting bars (ferramenta) are added on the external side to give stability to the panels; the lead cames form the constructive framework that connects the glass pieces together in a firm but elastic way, and constitute the outlines of the depicted images; the colored glass, lastly, allows the light to enter the building and creates fascinating effects depending on the color palette and the external and internal illumination conditions. The coloration of glass pieces could be obtained in many ways, to create a variety of artistic effects: exploiting impurities (naturally-colored glass) or adding oxides (pot-colored glass), and then controlling temperature and atmosphere in the furnace to change the oxidation state of the chromophores, and get the desired color; using metallic nanoparticles; fusing thin layer of colored glass on the surface of a transparent glass (flashed glass); painting the surface with vitreous paint or enamels. Grisaille, a brown/black vitreous paint, was often applied on the glass surface to add fine details in the scene represented [1, 5-8].

Stained glass, however, can be very fragile, and their appearance could change with time, depending on the raw material used and/or due to exposure in a very aggressive environment. The presence of pollutants and strong variation in temperature and humidity, favors the development of weathering crusts on the surface, which modifies the transparency of the glass. Consequently, the optical properties are affected, and it becomes difficult to understand the image represented, if the weathering layer is highly developed [7, 8]. For this reason, developing imaging techniques that could both digitize and document the morphological/chemical changes of these objects, would solve two important issues: first, it would be possible to obtain a digital model of the object, ensuring the preservation of the objects for the future; second, it would be possible to get information on the materials employed, the ways they change with time, and how these changes modify the final appearance of the artwork.

In this sense, spectral imaging could be a valuable tool: this technique allows obtaining spatial and spectral information simultaneously. The spectral data, by means of suitable algorithms, allows the visualization of the distribution of the materials in the object [9]. However, the reported use of this technique for stained-glass windows is quite limited, probably due to difficulties in finding proper acquisition methodologies to deal with the transparency of these artifacts. Here, a proposal for a more systematic application of spectral imaging to stained glass is presented, discussing its challenges and potentials.

The paper is organized as follows: first, a review of past works made in the field of imaging and image processing is presented. Then a brief overview of the most common analytical techniques employed in the field of Cultural Heritage for analysis of stained-glass windows is showed. The objectives of the project are stated, comparing the possible outcomes from spectral imaging vs. traditional analysis and discussing potential and challenges of the research presented. Lastly, a small section is dedicated to the presentation of preliminary works carried out on commercial and historical case studies.

Imaging techniques: a review

In this section, image acquisition and processing methodologies applied to stained-glass windows are presented, including both traditional RGB photography and spectral imaging.

RGB photography acquisition and processing

Documentation of stained-glass windows has traditionally been performed with analog cameras and, more recently, with digital cameras. Photographic documentation is a fundamental step in every conservation campaign and must be done before and after any treatment, to document any change happened or happening on the artifact. Suggestions for accurate technical documentation were proposed in [10]. The paper describes the most common issues in photographing stained glass, and presents a methodology developed specifically to deal with these issues and obtain high quality pictures. For example, the paper proposed an innovative way to control the external light, by using an illuminated panel based on a commercial photographic 'soft box' place outside the window to be scanned. The selected illumination source was a 500-watt tungsten-halogen flood light. A methodology for camera characterization specific for photography of stained-glass window has been proposed in the same paper and more details are provided in [11]. A pair of custom glass color checkers (a test and a training set) were built and employed for the purpose; the checkers are built including a large number of colored glass used in medieval times, with colors ranging from very dark to very light, to mimic the high dynamic range of a real stained glass. A way to control the illumination during the acquisition was proposed within the digitization campaign at Fairford Church. Other works have been done to improve the quality of acquisition and archival procedures; the research of the European project VITRA (Veridical Imaging of Transmissive and Reflective Artefacts), carried out from 2002 to 2004, was focused on "developing a practical method for the acquisition, storage and visualization of high-quality images of architectural details in historic buildings", including stained-glass windows. The acquisitions were carried out by means of a robotic arm remotely controlled, which allowed to reach higher areas (up to 15 m). In this way, it was possible to obtain high resolution images of those areas usually difficult to capture from the ground, avoiding loss of details and image distortions. The imaging of stained-glass windows was performed in transmittance using natural light, and many pictures were collected in different exposures to deal with the high dynamic range of the stained glass [12]. On the image processing side, investigations have been conducted to highlight relevant features [13], to correct defects [14] and to remove unwanted features such as shadows coming from the background or from the supporting bars [6], as well as to perform rendering, relighting and virtual restoration [15, 16].

Spectral imaging applications

Compared to RGB photography, application of spectral imaging on stained-glass windows is very limited. At the best of the authors' knowledge, only two papers exist in literature on this specific topic. The first one involved the analysis of the stained-glass windows of the Scrovegni Chapel (Padua); the panels were removed from their original place and acquired in laboratory under controlled illumination, namely transmission and double transmission mode [17]. In the transmission mode, the light sources were simply placed at the opposite side of the camera, while in double transmittance the camera and the lights were placed at the same side, and a scattering white support was placed below the stained glass to be scanned. The latter solution was proposed for stained-glass panels which could not be acquired vertically, and actually yielded better results for light-colored glass pieces. While spectral images are not available in the paper, they showed that results from the two methodologies were complementary and they were able to identify most of the chromophores [17]. The second paper, published in 2019, presented the first hyperspectral acquisition of stained-glass windows in situ [18] . In this case, the window was kept in its place and the analysis was performed in passive mode, using the solar radiation coming through the window as light source. The mapping of the colorants used for the glass pieces in the windows was then performed using Spectral Angle Mapper, a classification algorithm widely used for hyperspectral applications in the field of Cultural Heritage. Despite some limitation due to changing in the light conditions during the day and effect of external background (i.e trees) on the lighter colored glass, the analysis showed promising results, especially when comparing and mapping the spectral results of glass with same color and composition but with different transparency [18].

Another imaging technique worthy of mention is Macro X-Ray Fluorescence (MA-XRF); it is also called "chemical imaging", as the image obtained is made of many points collected with an X-ray fluorescence spectrometer which is connected to a moving stage and scanned over the surface of the painting at a given step size. The result is a datacube, like the hyperspectral one, where every pixel contains information regarding the elemental composition of the material under study. The datacube can then be treated with a suitable software which allows to create maps of elements (or combination of elements) to estimate which kind of material (i.e pigments or colorants) was employed by the artist. While MA-XRF is very popular for the study of paintings, it is still quite limited for the study of stained glass. Only two paper have been published so far, in 2016 and 2019 [19, 20]. In both cases the analysis was carried out in laboratory. Despite the few applications on stained-glass windows, the results obtained are very interesting, especially to distinguish ancient glass pieces from modern ones, to understand how the color in glass was reached, and to detect glass alteration. An interesting result highlighted in the first paper is worthy of mention: the possibility of understanding how the color was obtained in the glass, by scanning both surfaces and comparing them. If a specific chromophore element appears on only one side, then it is possible to guess that the colorant was painted on the back of the glass panels, instead of being added during the glass production.

Scientific analysis of stained-glass windows: a brief review

Regarding the determination of the conservation state of stained-glass windows, scientific analysis usually involves a combination of invasive and non-invasive techniques. Invasive techniques are called as such because they require the collection of small samples from the surface of the artifact, which may be kept for further analysis or destroyed in the process, depending on the kind of technique employed. Most of these analyses must be performed in laboratory, and sometimes they require very specific facilities (i.e XANES, which requires the access to a synchrotron) [3].

Non-invasive techniques, on the other hand, do not require samples and are sometimes portable, which allow to perform analysis in situ. They have become very popular in the last years, especially for preliminary investigation of composition and conservation state of the stained glass and are often enough to get the necessary information without requiring further invasive techniques [21].

In the table below the most used scientific techniques employed for the analysis of stained-glass windows are listed; for each technique, a brief description is given regarding the kind of information obtainable and the level of invasiveness is specified.

Table 1: List of scientific techniques

Analytical technique	Invasive	Information given
Fourier Transform IR spectroscopy (FTIR)	Yes/no (depending on the analysis mode)	Molecular; degradation products. [22, 23]
Particle induced X-ray emission (PIXE)	No	Elements; quantitative information of major, minor and trace elements. [22-25]
RAMAN spectroscopy	Yes/no (depending on size of the object); can be portable	Molecular; colorants and glass components; degradation products (results may vary from lab instrument to portable ones). [26, 27]
Scanning Electron Microscope (SEM); sometimes coupled with electron microprobe (EPMA)	Yes	Elemental; quantitative information on major, minor and trace elements; microscopic observation of the topography of the surface; semi-quantitative information on the distribution of elements on the surface. [28, 29]
UV-VIS-NIR spectroscopy (absorption/ reflectance) ; Fiber Optic Reflectance Spectroscopy (FORS) *	No; can be portable	Molecular; information on oxidation states and coordination of colorants (UV-VIS-NIR) and degradation mechanisms (NIR). [3, 25, 30-32]
X-ray Absorption Spectroscopy (XAS/XANES)	Yes	Elemental; oxidation state of chromophore elements in glass. [3, 30, 33, 34]
X-Ray Fluorescence spectroscopy (XRF)	No; can be portable	Elemental; qualitative information on major, minor and sometimes trace elements (results may vary from the lab instrument to the portable one) [35, 36]; possibility of element mapping in MA-XRF configuration.
X-Ray Diffraction (XRD)	Yes	Molecular; identification of corrosion products [37, 38].

The proposed methodology

The methodology presented here will aim at extending the use of hyperspectral (and multispectral) imaging for the documentation of stained-glass window. Since hyperspectral imaging can be considered a combination of spectroscopy (see table 1*) and imaging, the purpose of the research will be to investigate advantages and disadvantages of employing these techniques to acquire simultaneously spectral and spatial information. At the moment, the project has two main objectives: firstly, improve the acquisition and image processing methodology; applying spectral unmixing techniques to obtain maps of the different glass components, validated using other non-invasive techniques (i.e. XRF). In a later stage, integration of the data obtained, and virtual restoration will be also considered. These objectives will aim to answer different research questions, discussed in detail in the following paragraphs, and developed from this literature review.

Acquisition methodology

As discussed in the previous section on imaging techniques, many works have been done in studying the correct acquisition conditions for RGB cameras, but little has been done for hyperspectral imaging; one of the purpose of this research, within the framework of the CHANGE-ITN project, will be then to study the different situations in which the stained glass are either exhibited, in a museum, in situ (either in high or low places) or in laboratories and restoration workshops. Depending on the location of the stained glass, it is expected that the lighting condition will be more or less controlled; this aspect will be taken into consideration to understand how much it will be possible to control the illumination directly in situ, like in [10], and how much it will be necessary to correct afterwards during the image processing stage. Once the methodology has been defined, then it could be possible to apply it to similar objects, such as reverse glass painting.

Image processing and validation with scientific analysis

One of the main purposes of the project is also to determine the materials and the techniques employed to produce the stained-glass windows.

To fulfill this objective, employing spectral imaging has a great advantage; with hyperspectral imaging, the possibility of getting a spectrum in each pixel of the image will allow the detection and mapping of colorants and alteration products distribution. This information can be extremely useful to highlights the use of different colorants to obtain certain shades of the same color, or to identify areas where original pieces have been substituted during restoration with modern glass. Also, it will be possible to detect areas more prone to degradation or more exposed to pollutants or strong variation of atmospheric conditions. While multispectral imaging does not always allow to obtain a complete spectrum (depending on the spectral bands available in the camera), this technique has the advantage of being easier to carry and cheaper than a hyperspectral system. For this reason, it could be a valuable instrument for a preliminary investigation, especially in situ. In order to extract information from the datacube several algorithms will be investigated to understand which one could be more suitable for the purpose. For example, one of the tasks of the project will be to compare the performance between classification methods (such as Spectral Angle Mapper) and the less known, at least in the field of Cultural Heritage, unmixing algorithms. Hopefully, using unmixing algorithms will allow, not only to understand an eventual superimposition of colored glass and vitreous paint, but also it will help to deal with unwanted features in the image such as shadows from ferramenta or background.

Potential and limitations of spectral imaging

As already mentioned, one of the main advantages of using spectral imaging is the possibility to obtain at the same time, spatial and spectral information. Also, the technique is totally non-invasive and the possibility to be carried in situ is surely an added value.

The possibility to map the different typologies of glass and the presence of degradation products, could be certainly useful to conservators, especially for windows still in situ that cannot be removed, or that are difficult to reach. For example, with spectral imaging it could be possible to highlight areas restored with new glass, filled fractures, as well as to determine the areas more sensitive to weathering, distinguish between different alterations, and understand how those degradation products are distributed on the surface. The maps obtained then could be used to help the establishment of a condition report before carrying out a new restoration campaign.

However, some limitations are to be taken into consideration; first, with respect to RGB images, spectral datacubes (especially the hyperspectral ones) are way more complex to analyze, due to their high dimensionality (both spatial and spectral). For this reason, it is expected that pre-processing and processing of data will not be as straightforward as for RGB images[39].

Regarding chemical information, it is clear that the use of spectral imaging alone will not be able to answer all the research questions posed by conservators. For this reason, the use of other non-invasive techniques is already considered to validate the spectral imaging results. However, employing only non-invasive techniques may be another limitation itself; while it has been demonstrated that UV-VIS-NIR spectroscopy is able to substitute destructive techniques like XANES to identify chromophores by their oxidation state [30], some other information are obtainable only by taking samples, as most of the portable instruments proposed for validation can give only surface information. This may be a limitation, for instance, when trying to understand the colorant distribution within the glass or to determine glass composition, which very often vary between the surface and the deeper part of the glass, depending on the presence of weathering layer and its thickness.

Nonetheless, spectral imaging represents a valid non-invasive solution to have a general understanding of the work of art. In addition, the spectral maps themselves could be useful for a correct identification of sampling areas, by showing the points where the collection of samples could be more significant.

Preliminary works

Preliminary studies have been performed both on commercial (modern) and historical stained-glass panels. The panels were scanned with a HySpex VNIR-1600 pushbroom hyperspectral camera. The camera works in the visible and infrared region, in the range between 400 and 1000 nm. The image is built line by line keeping the camera and the light source fixed, while a translational stage moves beneath. The acquisitions were performed in transmittance as well as in reflectance, in order to understand whether it was possible to obtain complementary information (i.e glass composition and deposition of degradation products on both surfaces). In reflectance mode, the glass panels were acquired placing a white diffuser sheet under the stained glass and keeping the traditional lighting system for reflectance (two light sources at 0-45), similarly to [17]. On the other hand, in transmittance mode the stained-glass panels were positioned above a white diffuser panel large enough to cover the field of view of the camera, and located in the middle of the translational stage; in this set-up, a halogen lamp was positioned under the stage, in correspondence with the diffuser panel, so that the light could shine through it and the stained glass. Despite some difficulties, these preliminary tests showed promising results and were extremely useful to understand some of the challenges that need to be addressed in the future. For example, modification of the lighting set-up for the transmission mode is planned, in order to improve the spatial distribution of the light over the diffuser panel and decrease the heat coming from the halogen lamp, while trying to improve the obtainable spectral signal even for very dark stained-glass windows.

Publication of complete results on the historical stained glass is planned in the near future.

Conclusion

The aim of this paper was to present a proposal of a research project with the aim of exploring the use of spectral imaging for the documentation of stained-glass windows. To clarify the purpose of the project, a review of existing literature regarding application of imaging techniques (RGB and spectral) on stained-glass windows has been shown. In addition, scientific techniques used for the analysis of stained glass have been described to show which kind of information can be retrieved with invasive and non-invasive techniques. Lastly, potential and limitation of these techniques have been presented, explaining in which way spectral imaging could add information or substitute destructive analysis for some specific tasks.

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