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An affordable multispectral imaging system for the digital museum

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Abstract. The use of multispectral imaging for the acquisition of the image content of a digital museum is proposed. The advantages of multispectral imaging over "traditional" RGB imaging are explained, and the two existing approaches to multispectral acquisition, based on narrowband and wideband sensors respectively, are detailed. The characteristics of wideband multispectral acquisition systems in view of their possible large-scale use for digital museum content acquisition are then discussed, and an example system assembled by the authors and tested in acquisitions of real artifacts is introduced. Finally, it is shown that multispectral representations collected with such systems can be used for several purposes, including reproduction with current and future devices and support for monitoring and restoration, making them a natural choice for master copies in cultural institutions' archives.

Keywords: Multispectral imaging – Multispectral acquisition – Content acquisition – Content reproduction

Introduction

In recent years, digital libraries have emerged as increasingly important systems to provide users with access to large, organized repositories of information and knowledge [1]. To fulfill this role, a digital library must be designed taking into account several technical issues, including useful and easily searchable descriptions for its digital objects, efficient management and organization of collections and their evolution, interfacing to the hardware/software infrastructure, effective and user-friendly presentation of content, and proper handling of related economic and legal matters [1]. However, the most basic and most important issue is the creation and/or acquisition of the library content, which must be adequate to the required quality standards and actually usable for a number of purposes. Also, as content creation/acquisition may be a very costly process, the ability to use the same content in new and yet unconceived scenarios with only a minimal effort would be a great plus.

If we narrow our view to digital museums, we can expect that content will be mainly acquired and made available under the form of images, so that image acquisition becomes a crucial topic. This is true for typical hanging paintings as well as for other artifacts, such as archaeological objects, ancient books and other written material, frescoes and wall paintings, and fully three-dimensional objects such as statues. Also, in view of presenting such content, image reproduction becomes another obvious issue.

Ideally, the image content of a digital museum should be acquired with a high degree of precision, meaning that the stored data should be a "faithful" and consistent representation of the original artifacts. This implies that such representation should not depend on local conditions, including both the environment and acquisition devices employed, and that if different representations are used for convenience, then there must be a known way to pass from one representation to another. Also, the representation should be chosen so that reproduction is as straightforward as possible; the ability to use the same stored data for routine heritage monitoring as well as for guidance in any needed restoration attempts would be a great plus, too, since the amount of data that cultural institutions have to store and manage would be reduced. However, achieving all these goals is not straightforward.

We propose here the use of multispectral imaging for the acquisition of the image content of a digital museum and introduce an affordable multispectral acquisition system that can be used for this purpose. Multispectral imaging is a recent technology that allows the acquisition of color (and thus images) with a superior quality compared to "traditional" RGB imaging [2]. A number of studies have already been published that outline the general framework of multispectral imaging [3–6] as well as more specific technical issues [3, 7]. Some pioneer applications to the cultural heritage field have also been investigated [8–11], and multispectral acquisiton systems like the VASARI [12] and MARC projects [13] have been assembled and employed in several studies. However, so far multispectral imaging has generally been seen as a cutting-edge technology that yields results of an extremely high quality but is accessible only to the most important and resourceful cultural institutions.

In the following, we first outline the theory behind color acquisition, stressing the advantages that multispectral imaging enjoys over RGB imaging. We then detail the multispectral approach to image acquisition and introduce a multispectral acquisition system that was assembled by the authors, discussing its suitability for large-scale use in digital content acquisition. Finally, we show how multispectral images can be advantageously used as master copies in digital museums and cultural institutions' archives.

Image acquisition with an RGB device

It is reasonable to expect that the content of a digital museum will be of higher or lower quality depending on which technology was employed to acquire the content images. Currently, the "traditional" approach that uses RGB acquisition devices is finding an alternative in the still developing approach based on multispectral imaging; also, both technologies can be implemented with different degrees of precision.

RGB imaging is based on the theoretical framework of colorimetry [14], which in turn was directly inspired by the human vision system. An RGB acquisition device has three sensors that show different sensitivity to light, so that each sensor may be regarded as if it were able to see a specific color, namely, red, green, or blue: the result of an RGB acquisition is therefore a triple of numbers that may be interpreted as the "amounts" of red, green, and blue necessary to "obtain" the acquired color [15]. This system has an obvious parallel in the three types of cells ("cones") that are responsible for color vision in the human eye [16].

However, RGB imaging also suffers from three main drawbacks. First, the RGB representation is not unique, but rather each RGB device uses its own representation, which is generally different from those of other devices. This means that the same RGB triplet does not necessarily indicate the same "physical" color on all RGB devices [2]. Second, the RGB representation of a color depends on the environmental conditions (lighting in particular) under which the color was acquired, so that the same color acquired under different conditions by the same device will generally have different representations [2, 14]. Lastly, the technical characteristics of RGB devices, especially the sensitivity of the sensors they employ, may prevent them from achieving a complete accuracy in the capture of colorimetric data [17, 18].

The fact that RGB representations depend on devices makes such representations inconsistent with one another and poses a difficult challenge when performing cross-media reproduction even in simple situations such as "properly" displaying on a monitor an image that was acquired with a scanner. However, colorimetry offers a way to overcome inconsistency through the use of device-independent color representations ("color spaces") [14, 19]. A device-independent color space represents colors as they appear when viewed under a chosen illuminant by a standardized observer: if a link between a device representation and a device-independent color space can be established (a process known as the "colorimetric characterization" of a device [7]), then it is possible to obtain consistent color representations.

As for cross-media reproduction and the use of different devices, some international standards are available that ease the task of keeping the colors as close as possible to the original acquisition. The ICC standard [20] defines "profiles" that include the needed information to link a device color representation to a device-independent representation (called "profile connection space"), and widely supported device-independent representations such as the sRGB standard (see `http://www.microsoft.com/whdc/hwdev/tech/color/sRGB.mspx` and `http://www.srgb.com`), albeit not primarily intended for high-quality imaging, can be leveraged to simplify moving images across the profiles of different devices as well as to ease content distribution on the Internet.

Achieving this degree of precision already requires the work of specialized personnel as well as the availability of specific instruments and software; also, depending on the desired quality of the digital museum content, which is often very high, expensive devices are possibly needed. Still, the acquisitions performed in the context of RGB imaging will generally depend on the environmental conditions, which may change from one acquisition to another: given the long times needed to acquire entire collections, this may again make archives inconsistent.

Multispectral acquisition

To achieve independence from the environment, a multispectral imaging system must be used. Such a system works in a way similar to an RGB device but uses a greater number of sensors, resulting in a color representation that uses more than three parameters [3]. The reason this is done can be understood by looking at the phenomenon called "metamerism," that is, the fact that two physical samples sometimes appear to be the same color under a certain light but "turn different" under a different light [2, 14]. This fact indicates that there exist different "physical" colors (or "spectra," see below) that sometimes (i.e., when using a certain illuminant and viewed by a certain observer) get the same colorimetric representation, which means that there are more spectra than colorimetric representations. In mathematical terms, this means that more than three parameters are needed to unambiguously identify a color, and this is why more than three sensors are employed in multispectral acquisition.

However, raising the number of sensors is not sufficient: since the problem with colorimetry lies in the fact that environment and observer are taken into account, "eliminating" this dependence from a color representation requires a different approach. In fact, color representations in RGB imaging and colorimetry use parameters whose ultimate physical significance is that of measuring the amount of light energy that is "registered" by the device sensors (or human observer's cells). Formally, the value a_i of the parameter associated to a certain sensor (identified by an index i) is given by the following equation:

$$a_i = \int E(\lambda)R(\lambda)S_i(\lambda)d\lambda\,, \qquad (1)$$

where λ is the wavelength, E is the energy that reaches the physical sample observed, R is the color reflectance (see below) of the sample, and S_i is the "sensitivity" of sensor i. The integration, which in practice is usually replaced by a summation, is performed in the range of the visible light spectrum. Typically, RGB representations from different devices differ in the S_i functions that describe the device sensors, while device-independent representations usually differ in the E function that describes the illuminant considered; however, in all cases illuminant and sensor/observer are still part of the representation.

To avoid this, multispectral imaging tries to estimate the reflectance function R, which describes how much light energy is reflected at the different wavelengths by the physical sample considered [16]. In fact, opaque objects appear to be colored because they reflect the light that is cast on them (similar considerations apply to translucent objects). Other sources of images try to simulate this phenomenon: monitors emit light trying to excite our eye sensors so that the same nervous signal occurs as with real objects' reflections, while prints and projections try to directly simulate those reflections. The amount of light actually reflected usually varies with the wavelength, so that some objects reflect more blue light, others reflect more red light, and so on; therefore, the reflectance R is a function of the wavelength and can be represented as a continuous curve called a "spectrum." Sometimes objects absorb energy in the ultraviolet range and re-emit it in the visible range: this energy then appears to be reflected at some visible wavelength, so that reflectance actually seems greater at that wavelength. This phenomenon is called fluorescence, and is widely exploited for whitening objects; however, it is also a potential problem in multispectral acquisitions, and it must be somehow corrected or avoided altogether.

Reflectance may be seen as an object's own contribution to how its color will be perceived. This contribution depends only on the physical properties of the object observed and does not change as long as these properties are not changed; function R is then the only invariant term in (1). Both devices' and device-independent colorimetric representations do not try to determine function R but rather concentrate on the final color appearance, so they are not generally able to discriminate between, for example, a white object seen under a green light and a green object seen under a white light.

The obvious issue with multispectral imaging is, then, how many parameters are needed to unambiguously describe a reflectance curve and how to obtain them. A spectrum could theoretically be described by telling how much light is reflected at each wavelength, but since the range of visible light is continuous, it would be impossible to do this wavelength by wavelength. Therefore, either a reasonable number of these values must be given, so that the other values can be obtained from the known ones using some approximation technique, or a mathematical represention of the curve in terms of a suitable number of variables must be provided. Both approaches are employed in current multispectral acquisition systems, and the known reflectance values or variables respectively become the parameters used to describe spectra. Many studies have been published in which the minimum number of parameters needed was investigated [21–25], but no agreement on this subject has been reached yet. Although most studies indicate that less than 10 parameters are sufficient, the official recommendations from CIE (Commission Internationale de l'Eclairage, the international authority on this matter (http://www.cie.co.at/cie/) suggest that at least 31 parameters corresponding to the value of the reflectance function in the range from 400 nm to 700 nm at 10-nm steps be used. In this way, function R is sampled at a reasonable density in the most significative subrange of the visible light spectrum.

The "narrowband" approach

The parameters corresponding to a color representation can be obtained using two different approaches [26]. On the one hand, direct measures of these values can be attempted if the device's sensors show a very specific sensitivity, that is, if each sensor can only register the light energy associated to a very narrow wavelength interval. In fact, if this interval is 10 nm or less, the value a_i obtained from the acquisition performed using the ith sensor can usually be interpreted as the value of function $E(\lambda)R(\lambda)S_i(\lambda)$ at a specific wavelength, with just a negligible error. Using the notation of (1), this can be expressed as

$$a_i = E(\lambda_i)R(\lambda_i)S_i(\lambda_i)\,, \tag{2}$$

where λ_i is the wavelength associated to sensor i; usually, wavelength λ_i is the center of the interval in which the ith sensor can register light. Once the a_i values have been obtained, the contribution of both illuminant and device must be eliminated; this can be done by using a known illuminant and estimating sensors' sensitivity by means of proper measurement instruments, so that the values $E(\lambda_i)$ and $S_i(\lambda_i)$ are known and $R(\lambda_i)$ can be computed. However, as this approach requires that the acquisition setup be properly and strictly controlled, and that additional instruments be available, it may not always be feasible. An alternative is that of comparing the output values a_i with the corresponding values previously obtained from the acquisition of a reference physical sample whose reflectance is known. If the result of this previous acquisition for sensor i is indicated by a'_i, then it is easy to see that

$$\frac{a_i}{a'_i} = \frac{E(\lambda_i)R(\lambda_i)S_i(\lambda_i)}{E(\lambda_i)R'(\lambda_i)S_i(\lambda_i)} = \frac{R(\lambda_i)}{R'(\lambda_i)}\,, \tag{3}$$

where R' is the (known) reflectance of the reference sample. The value of $R(\lambda_i)$ can then be computed using the following equation:

$$R(\lambda_i) = \frac{a_i}{a'_i}R'(\lambda_i)\,. \tag{4}$$

Multispectral acquisition systems that use this approach are often extremely precise, sometimes even sampling function R at 1-nm steps or more densely; however, they also suffer from a number of drawbacks. First of all, they are usually very expensive and require specialized personnel to handle them. Second, the machinery of which the whole system is composed is often bulky and unwieldy, making it difficult to deploy and redeploy them within museums. Third, acquisition is often performed "line by line," so that misalignment problems may arise. Lastly, most of these systems are conceived with hanging paintings as their main target, and so it is difficult or even impossible to use them for objects that must typically be acquired from above, like most written material.

The "wideband" approach

The second approach to multispectral acquisition is based on wideband sensors. In this case, each sensor is sensitive to light energy in a sufficiently large wavelength interval, so that the values a_i obtained from the acquisition cannot be associated to specific wavelengths; the relationship between these values and the actual reflectance values must then be somehow established to estimate the reflectance function R. In mathematical terms, this can be seen as a "deconvolution" problem, and the general theory of deconvolution can be applied to it.

If we want to know the value of R at N different wavelengths values λ_j, then the discrete form of (1) will be written as

$$a_i = \sum_{j=1}^{N} E(\lambda_j)R(\lambda_j)S_i(\lambda_j)\Delta\lambda j\,, \tag{5}$$

with $\Delta\lambda_j$ being the width of the wavelength interval in which the value of function $E(\lambda)R(\lambda)S_i(\lambda)$ is considered to be constant and equal to $E(\lambda_j)R(\lambda_j)S_i(\lambda_j)$. If M sensors are used, with M not necessarily equal to N, then M such equations can be written as i varies from 1 to M; these equations form a linear system that can be rewritten in algebraic notation as

$$\mathbf{a} = \mathbf{Dr}\,, \tag{6}$$

with

$$\mathbf{a} = [a_i],\ \mathbf{D} = [d_{ij}] = [E(\lambda_j)S_i(\lambda_j)\Delta\lambda_j],\ \mathbf{r} = [R(\lambda_j)]\,. \tag{7}$$

If matrix $\mathbf{D}$ were known, then (6) could be solved with respect to $\mathbf{r}$ by means of some system inversion technique. However, this is seldom the case, as a direct estimation of the illuminant E (assuming that sensitivity S_i is known for each value of i, which is not straightforward) requires advanced measurement instruments and, in the case of a complex illumination geometry (such as multiple and possibly different light sources used together from different angles), costly computations as well.

For these reasons, it is customary to estimate the relationship between the acquisition output $\mathbf{a}$ and the sampled reflectance function $\mathbf{r}$ by means of an empirical model. In fact, if $\mathbf{r}$ is measured with a proper instrument (like a spectrophotometer) for a "sufficiently representative" set of sample colors, then the relationship between the measured reflectance $\mathbf{r}$ and the corresponding acquisition output $\mathbf{a}$ obtained from an acquisition of the same colors can be identified and extended to all colors. Specifically, following (6), for a generic color of reflectance $\mathbf{r}$ and corresponding output $\mathbf{a}$ we can write

$$\mathbf{r} = \mathbf{D}^{-}\mathbf{a}\,, \tag{8}$$

where $\mathbf{D}^{-}$ is the (pseudo-)inverse of matrix $\mathbf{D}$. The function that links an acquisition output vector $\mathbf{a}$ to its corresponding reflectance $\mathbf{r}$ is therefore linear and can be approximated using a linear model. This model can be built from the chosen sample colors: if P sample colors are available, and their corresponding a_k and r_k vectors (with k ranging from 1 to P) are considered, then it must be that

$$\mathbf{R}_S = \mathbf{D}^{-}\mathbf{A}_S\,, \tag{9}$$

with

$$\mathbf{R}_S = [\mathbf{r}_1|\ldots|\mathbf{r}_P] \text{ and } \mathbf{A}_S = [\mathbf{a}_1|\ldots|\mathbf{a}_P]\,. \tag{10}$$

The matrix $\mathbf{D}^-$ can then be computed by inverting (9) with some chosen inversion technique, giving

$$\mathbf{D}^- = \mathbf{R}_S * \mathbf{A}_S^- \,. \tag{11}$$

As can be seen, when following the wideband approach the contributions of the environment (function E) and acquisition device (function S_i) are considered as a whole and are treated as a black box. This does not pose any difficulties for the device sensitivity S_i, which can be assumed to be constant and independent of the environment, but makes the model represented by matrix $\mathbf{D}^-$ dependent on the illumination. This means that in general a new model will be needed every time the illumination conditions change. Also, the acquisition output values a_i must be properly corrected to discount the geometry of the illumination before they can be used to compute the corresponding reflectance $\mathbf{r}$. In fact, achieving a uniform illumination on the whole scene to be acquired is usually very difficult; different parts of the scene will typically receive different amounts of light energy, so that the illuminant function E will actually vary depending on the point being considered within the scene. This would in turn make matrix $\mathbf{D}^-$ and the resulting empirical model dependent on the position within the scene, so that a different model would have to be computed for each point in the scene, which is impractical. However, it is possible to correct the acquisition output values to make them independent of the position in the scene; such correction is usually performed by acquiring a reference physical sample as in the narrowband approach, although the result has in this case a different meaning [3]. The corrected output values can then be used in (8)–(11) to compute a single model that is valid for the whole scene.

Another obvious issue is the choice of the "training set," that is, the set of colors used to build the empirical model. As stated above, this set must be "sufficiently representative" of the whole range of possible colors, which intuitively means that the resulting model can actually be extended to any other color. This is not a clear-cut notion, but specific targets that include a good selection of sample colors, such as the Macbeth ColorChecker and ColorChecker DC (`http://www.gretagmacbeth.com/files/products/ColorCheckerDC_new_EN.pdf`), are available. Also, some studies that outline the theoretical bases of this subject and propose working methods to select sample colors have been published in recent years [27, 28].

A multispectral acquisition system

While research on advanced topics in multispectral imaging is still going on, operational prototype multispectral acquisition systems are already available. This is true of systems that employ the narrowband approach as well as systems based on the wideband approach [3–5, 29]; however, wideband systems show some practical advantages that make them more interesting for large-scale use.

The typical wideband acquisition system uses optical filters coupled with a monochrome digital camera to simulate sensors of different sensitivity. While in an RGB device the sensors for the red, green, and blue colors are physically distinct, in a wideband multispectral acquisition system the same sensors are typically used for all bands, but their sensitivity is modified each time by putting different optical filters before them. One acquisiton is then performed for each simulated sensor to retrieve the acquisition output vectors a_i. The optical filters are the heart of the system; currently, either traditional filters like those used in standard photography or a tunable filter is employed. A tunable filter has the ability to change its sensitivity to light by means of an internal magnetic field that can be controlled by the user [30–32], so that the same filter may be used to replace a whole set of traditional filters. The main problem with traditional filters is that they must be changed once for each sensor that must be simulated, which is time consuming; for this reason, traditional filters are sometimes mounted on a semiautomated filter wheel to speed up operations [6]. However, filter wheels may be somewhat unwieldy and can generate some technical issues that may complicate the operating setup; on the other hand, avoiding a filter wheel means that a manual intervention will be necessary each time to change the current filter, and this may easily lead to misalignments in the acquisitions corresponding to different sensors. Compared to traditional filters, the current configuration of a tunable filter may be tuned electronically in real time by the controlling computer, so there is no need for a manual intervention and no time is wasted; this is why the use of tunable filters is rapidly spreading.

As an example, we introduce here a wideband acquisition system that was assembled by the authors [3, 33]; compared to other similar applications that were based mainly on simulated data, this system was conceived to be used "in the field" and was tested in acquisitions of real artifacts and scenes. This system is built around a monochrome digital camera with a resolution of 1392×1040 pixels; this camera has a dynamic range of 12 bits, which allows a much more precise tone discrimination compared to the usual 8 bits of RGB devices. The rest of the system consists of a high-quality lens that shows no geometrical distorsions, a tunable filter, and a cut-off optical filter for infrared and ultraviolet radiations, which limits the sensors' sensitivity to the visible light spectrum (Fig. 1). If need be, the system is used with professional light sources that emit no ultraviolet radiation, so as to avoid any fluorescence. Following CIE recommendations, we use 31 different configurations of the tunable filter; these configurations were chosen so that the peak in the resulting sensor sensitivity varies between 400 nm and 700 nm with steps of 10 nm.

An acquisition system like this has a number of strengths that make it particularly suitable for large-scale use. First, it has the same encumbrance of a typical video

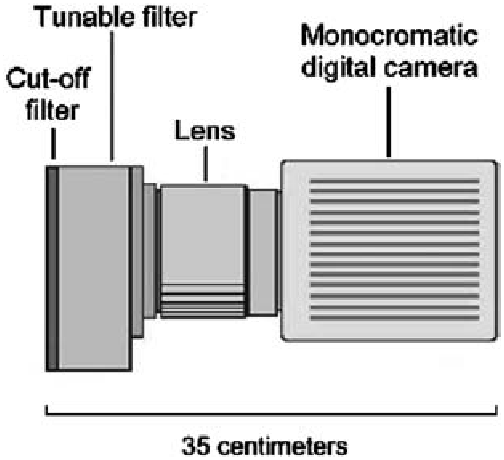

Fig. 1. A scheme of the wideband multispectral acquisition system assembled by the authors

camera plus the computer needed to control it (a laptop computer will do) and can therefore be deployed and redeployed very easily. Also, it can be mounted on a tripod as well as hanged from above using a simple frame (Fig. 2), allowing the acquisition of hanging paintings and wall paintings, as well as of written material and other objects that are typically kept on tables or stands. Second,

Fig. 2. Wideband multispectral acquisition systems can be mounted on a tripod but also hanged from above using a simple frame like this one

the time required for acquisition is considerably shorter compared to both wideband acquisition systems which use traditional optical filters, and narrowband systems, which usually acquire a scene line by line. Lastly, a wideband system is more affordable compared to narrowband acquisition systems because the hardware cost is smaller (around US $ 20,000, while wideband systems can easily cost two to five times as much or even more), and only minimal training is required to operate it, so that no highly specialized personnel is needed. Also, the system is easily assembled as its hardware components are reasonably widely available, and their handling does not require any particular care other than that used with standard photography hardware.

However, as the ultimate aim is to acquire adequate content for a digital museum, these advantages must be considered in light of the quality of the results obtained. In general, the quality will depend on the hardware used, which is scalable to some extent, and the related tradeoff between costs and results, which depends on the specific application, must be considered. Also, deriving the actual multispectral data from the acquisition output requires a significant amount of processing (which was partially outlined above), which in turn requires the developement of suitable techniques and their implementation in a support software, without which the hardware is not sufficient. A proper calibration for the hardware may also be needed [3, 34]. Anyway, systems like the one introduced above have been set up and tested by several authors, who were able to obtain good results [35]; this suggests that wideband acquisition systems based on tunable filters can actually be used for content acquisition even when quality requirements are high. As a reference, Fig. 3 shows results obtained by the authors for a few different colors. Usually, results are judged by comparing the estimated reflectance curves obtained from the acquisition system with the corresponding curves measured by some high-precision (although typically unwieldy) reference instrument. In this case, we show a comparison between the curves estimated from a real acquisition and the corresponding measurements obtained using a spectrophotometer. As can be seen, although the estimated values are very close to the measured ones, some slight errors (mostly due to the unavoidable noise in the acquisition data) are apparent. Errors of such magnitude do not usually result in any noticeable perceptive difference; however, if a still higher quality is desired, narrowband acquisition systems may be considered, provided that the necessary resources are available.

On the other hand, if scalability and the fast acquisition of a great number of images are the main concerns, then lowering the number of sensors may be an option. As we stated above, some evidence has been given by different authors, indicating that much fewer than 31 parameters are sufficient to unambiguously describe colors and their reflectance functions; if this were finally proved, then some strategy to build or select an equally small

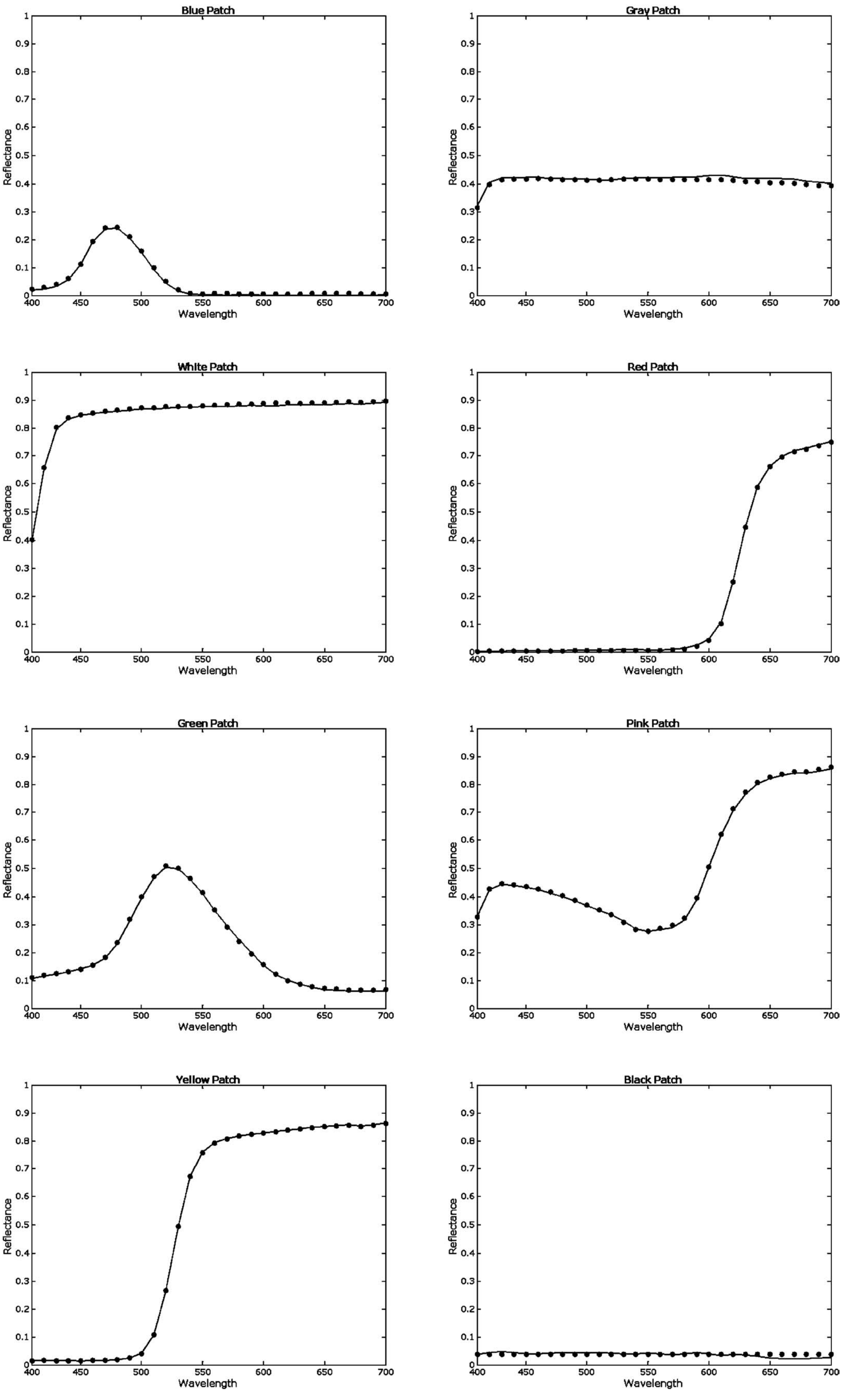

Fig. 3. Some results obtained by the authors for a few different colors. Reflectance curves measured using a spectrophotometer are shown as *dotted lines*, while the corresponding curves estimated from a real acquisition are shown as *continuous lines*

but sufficient number of sensors would probably become available, too. While this is still an open issue, a few studies have been conducted that propose and investigate some practical strategies. In particular, for wideband acquisition systems, lowering the number of sensors usually means using only a subset of the available filters (or filter configurations in case a tunable filter is employed) while trying to keep the quality of the results as high as possible. This may be done by experimenting with different subsets and determining the best one [36, 37], in which case the choice will usually depend on the environmental setup, as well as by applying some theoretical considerations and directly choosing which filters should be employed or even designing them [38].

Acquiring real artifacts

The hardware employed is only a part of the acquisition system, and while hardware issues are crucial to obtain correct multispectral images, such images do not necessarily provide complete representations of any suitable real artifacts.

The main gap to be filled is the need for image mosaicking. One important feature of a wideband acquisition system like the one introduced above is its capability of acquiring images at different resolutions and fields of view by simply changing the lens. However, whenever large artifacts or scenes must be acquired, and/or a high image resolution is desired (for instance, for a hard-copy reproduction), it is unlikely that a single acquired image will be sufficient; most of the time, several images (called "tessels") covering different parts of the scene will have to be taken and then "stitched together" to form an image of the whole. This operation, which is called mosaicking, consists in finding corresponding details in overlapping tessels that cover adjacent areas of the scene and then stitching those tessels together so that the corresponding details perfectly overlap and the resulting composite image does not show any geometrical or color artifact, especially where the edges of the tessels were placed.

Mosaicking has been extensively studied for wide-angle images like those obtained from aerial and satellite photography or panoramas taken with standard cameras (see, for instance, [39–41]). In these cases, tessels often show great geometrical distortions because of the lens characteristics, while the level of detail is sufficiently small, so that correcting large distortions can give good results even if some small-scale artifacts are still present. However, when mosaicking is applied to the acquisition of content for a digital museum, the situation is likely to be very different, with tessels that show very little to no geometrical distortions and that are taken from slightly different view angles or slightly misaligned positions, especially on the vertical axis. On the other hand, the final mosaicked images are usually very sensitive to even small-scale artifacts.

A typical approach in mosaicking is to let the user/operator indicate the overlapping details of two or more tessels and have the mosaicking software compute the corresponding mathematical transformations and produce the mosaicked image. Image understanding and applied artificial intelligence techniques have also been used in an attempt to develop automated procedures that should be capable of choosing the right transformations without any intervention by the user. Anyway, an acquisition system (based on traditional or multispectral imaging) for the digital museum should include mosaicking capabilities, as large artifacts are common and high-resolution content is likely to be required. In the case of the system introduced above, the authors developed a semiautomatic procedure [33] that gets input from the user in the form of corresponding areas and then applies image analysis techniques to find the precise match to be used for computing image transformations (Fig. 4). Compared to other procedures that require single corresponding points to be indicated, this approach reduces the impact of any errors caused by the limitations of the user inspection, which is performed by the naked eye.

Another important step toward obtaining complete representations for cultural heritage artifacts is the integration of color data with shape data. On the one hand, shape data are sometimes needed even to obtain images of the artifacts involved. For instance, in the case of a book it may be impossible to open pages wide because of the risk of damaging the binding; pages will then be partly bent when they are acquired, resulting in a geometric distortion of the page content. Some technique will therefore have to be applied to measure or estimate the bending and correct the acquired images to discount its effect. Similar (although often greater) difficulties must be overcome when acquiring frescoes and paintings that were made on markedly nonplanar walls, such as church vaults; if a linear representation is desired, that is, a representation in which the paintings are viewed as if the walls had been "unfolded" onto a plane, then the effect of the wall-surface curvature must be corrected.

On the other hand, some artifacts have a strong three-dimensional component that contributes to their nature and appearance at least as much as their color. Such artifacts range from low reliefs, and possibly even some kind of paintings, to fully three-dimensional objects such as archaeological material or statues. In all these cases, an image of the artifact (or even several images from different viewpoints) can only be a partial representation, although it can be enough for many purposes. However, the setup flexibility of wideband multispectral acquisition systems makes it conceivable to couple them with shape data acquisition systems [42], such as 3D laser range scanners; color and shape data can then be combined to obtain more realistic representations. All these applications are current research topics for the authors.

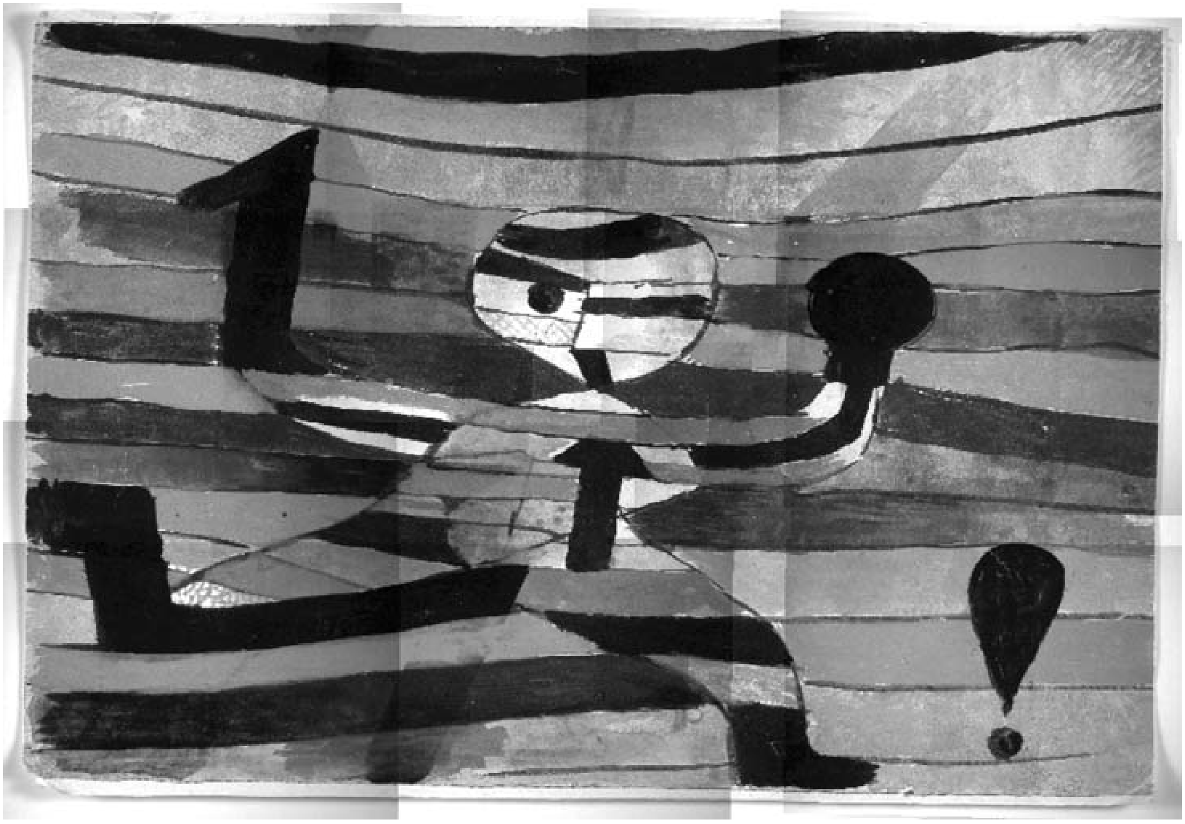

Fig. 4. A mosaicked image obtained from 16 tessels using the semiautomated method implemented by the authors

Using multispectral data for the digital museum

Once multispectral representations have been obtained, a final topic to be discussed is what they can be used for and whether they can be adopted as a "master copy" to derive any useful specialized representations for specific purposes. A number of possible uses for digital representations of museums' artifacts can be enumerated, including those that are typical of digital museums (Fig. 5).

As most cultural institutions have more artifacts than available exhibit space, a first obvious use would be that of setting up stations to display those artifacts that are not currently shown; this would also be useful for objects that have been temporarily lent to other institutions, that are being studied or restored, or that cannot be shown to the public for security reasons. Such stations can be set up using standard displays or projectors, which currently require colorimetric representations, but this is no problem as these representations can be easily obtained from multispectral data by means of standard colorimetric formulas [14]. Also, the current industrial trends suggest that in a few years true multispectral devices will likely be available, so that it will be possible to use multispectral data directly.

Another basic use in terms of guaranteeing the widest accessibility to the institution's holdings is the production of printed material, ranging from simple brochures to full catalogs or (text-)books. Again, passing through a colorimetric representation allows one to obtain ICC-compliant data to be used for devices that support this standard or other equivalent suitable representations that can be leveraged to obtain a faithful reproduction; also, representations that comply with industrial standards for large-scale printing can easily be obtained. Similar considerations would apply for online content accessible through the Internet; in this case, dedicated image formats such as JPG, JPG2000 (`http://www.jpeg.org`), or PNG (`http://www.w3.org/Graphics/PNG/`), coupled with representations that comply with sRGB or other suitable standards, may be exploited to ease both accessibility and faithful reproduction.

The need to transform multispectral data to colorimetric data before using them for reproduction may seem to indicate that faithful colorimetric data would be enough for all these purposes. However, besides recalling what was said above about the limitations and inconsistencies of colorimetric images acquired with an RGB device, the impact of the evolution of standards and technologies must be evaluated, too. In fact, given the costs that a cultural institution must sustain for a large-scale content acquisition campaign, it is important to invest in a technology that is less volatile and more likely to comply with industrial trends. In this sense, while it may be reasonably expected that multispectral imaging will be around 20 years from now, the same cannot be said of colorimetry-related standards and representations, which

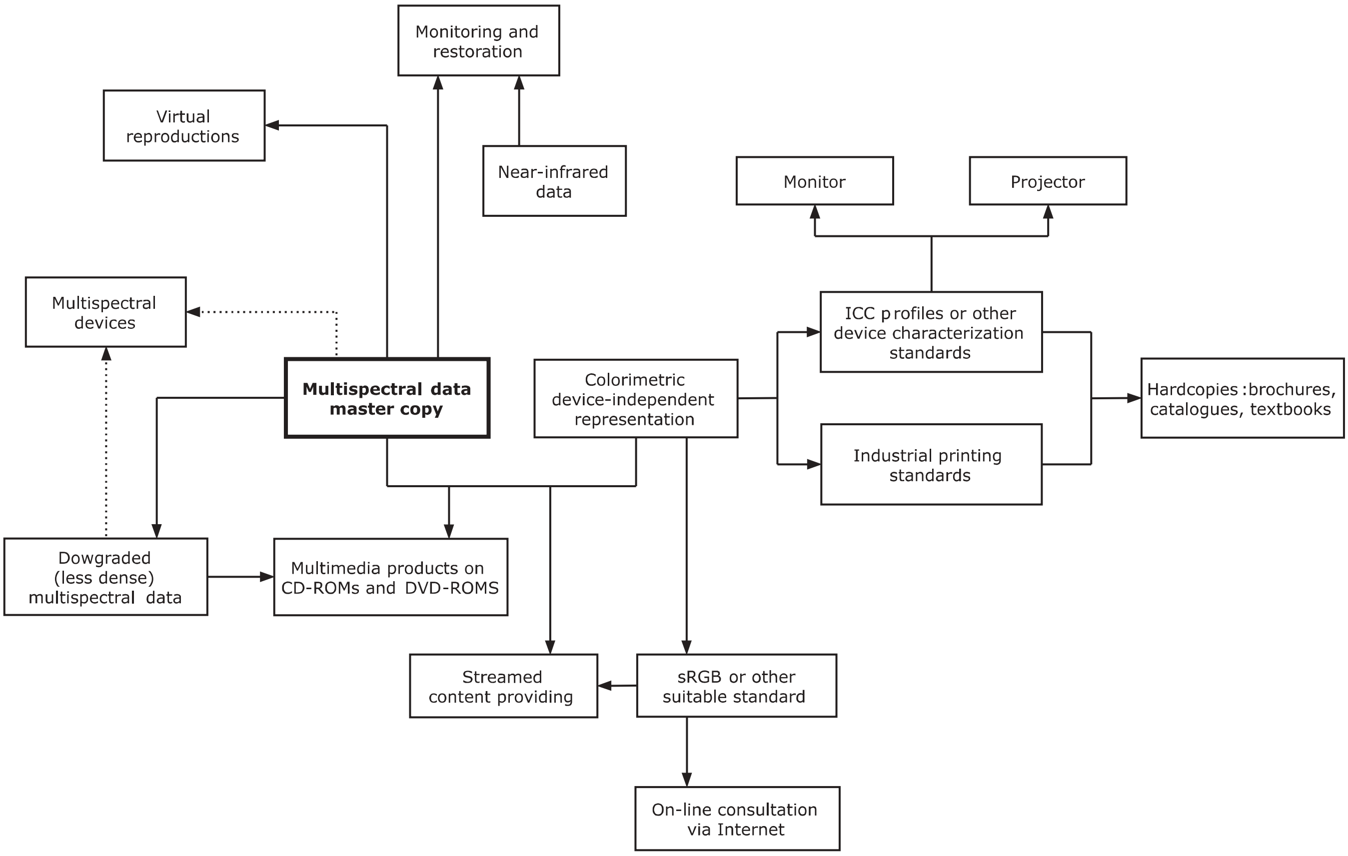

Fig. 5. Multispectral representations can be adopted as "master copies" to derive many specialized representations for specific purposes

are mostly tied to current devices and could easily become obsolete in a few years.

Multispectral representations have more technical advantages, too. For starters, as they are independent of the environmental conditions and the acquisition system, they can advantageously be used for virtual representations (which is not true for colorimetric representations). An interesting application of this feature would be, for instance, that of "correctly" visualizing those works of art that must be seen in dim light when on exhibition because full light would spoil them. When these works were made, usually they were conceived to be seen in full light; if a multispectral representation of these artifacts were available, it would then be possible to show a reproduction of these works seen as if they were in full light simply by choosing a corresponding illuminant when the colorimetric representation to be passed to the visualizing device is derived. It is probably easier to see the potential impact of this possibility when considering multimedia content distributed on digital supports (CD-ROMs, DVD-ROMs) or via streamed content; in fact, in these cases the use of customized viewing software could allow multiple views of the same artifacts and could even let the user modifiy the reproduction interactively. This same ability could be exploited in the educational field as well as in specialized tools used for the design of exhibition space and infrastructure.

Multispectral representations also constitute valuable information for scholarly research in general and are needed for an efficient support to the monitoring and restoration of artifacts, as in this case environmental effects and specific characteristics of observers and acquisition devices must absolutely be discounted for the data to be truly useful and reliable. Given the current standards of precision for the preservation of cultural heritage, simple colorimetric data would be almost useless in this field, while multispectral data, possibly integrated by similar data captured in the near-infrared band, already offer the required information. If the proper hardware components were chosen, wideband multispectral acquisition systems could be modified to also retrieve any needed data in the infrared band, so that no other devices would actually be required. In some cases, multispectral images may even reveal features that are not easily identifiable to the human eye or through traditional RGB imaging.

The only drawback associated with the use of multispectral master images is actually connected to the encoding and storage of the data needed to represent such images. Compared to colorimetric representations, multispectral images using 31 parameters raise the quantity of associated data, and thus required storage space, by one order of magnitude; for instance, a 60×40-cm painting acquired at a resolution of five pixels per millimeter would require more than 350 MB of storage space. However, given the rate at which new advancements in typical storage and processing hardware are announced, it can be expected that in a short time this will not be a problem anymore. Anyway, the issue is being actively addressed by the research community, and some studies that investigate techniques for the compression of multispectral data have already appeared [43, 44]. Also, ongoing research to determine the minimum number of parameters needed for multispectral representations (see above) will likely be of help and lead to more compact, yet complete, representations. On the other hand, the recently launched CIE Technical Committee 8-07 on Multispectral Imaging is working toward a definition of encoding standards to ease the management of multispectral representations and allow the integration of multispectral content archives with established infrastructure technologies on a wide scale.

Conclusions

We proposed the use of multispectral imaging for the acquisition of the image content of a digital museum. Compared to traditional RGB imaging, multispectral imaging guarantees a higher image quality in terms of faithful color storage and reproduction and is much less volatile with respect to the evolution of standards and technologies in the digital imaging field. We then detailed the two existing approaches to multispectral acquisition, based on narrowband and wideband sensors, and showed that the characteristics of a wideband multispectral acquisition system make it particularly suitable for large-scale use in acquiring high-quality images for a digital museum. A wideband acquisition system that was assembled by the authors and tested in acquisitions of real artifacts was also introduced, and it was shown that the multispectral representations collected with such a system can be used for several purposes, including reproduction with current and future devices and support to monitoring and restoration, making them a natural choice for master copies in cultural institutions' archives.

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