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Integrated Method for Three-Dimensional Shape and Multispectral Color Measurement

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Abstract. *This article presents a measurement method for integrated three-dimensional shape and multispectral color measurement with the use of a single detector for data acquisition. Its implementation comprises a shape measurement system using structured light projection combined with a custom developed multispectral camera. Both devices are controlled by dedicated software which enables the estimation of spectral reflection in every point registered on the surface of the measured object. The main application of this research is the digitization of cultural heritage objects for storage, visualization, and copying purposes. Examples of measurement results are presented as well as discussion of measurement uncertainty and directions of further research.* **© 2011 Society for Imaging Science and Technology.**
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INTRODUCTION

In an age where information systems are rapidly being developed with the advent of the internet and the formation of an information society, there is a growing need for a digital remote access to historical objects of cultural significance. The still growing computational power of personal computers (PCs) offers a new approach to preserve, measure, and visualize monuments.

Moreover, it is very important for art conservators to be able to monitor the state of artifacts under varying environmental conditions, for example, monitoring deterioration due to atmospheric factors. A series of measurements taken over a period of time would allow them to estimate the optimal conditions for the storage and exhibition of the artifacts in order to preserve them as much as possible. There are also new methods of displaying cultural heritage artifacts through virtual museums, accessible via the Internet, which show precise reproductions and allow people to visit famous places in virtual reality.

However, in order to use information technology to digitize items of cultural significance, it is very important to cooperate closely with art conservators and art historians and use their knowledge to raise the quality of the said digitization results. It benefits both scientists and artists because the former gain professional guidance on the applications of their research and the latter receive new interesting methods for preserving art. For example, the traditional technique of sculpture reconstruction is a tedious process in which the object first has its missing parts restored by the art conservator, after which a mold is created based on the reconstructed object, and finally the copy can be cast from the mold which even then can usually be used only once. The digitization of the reconstructed object in terms of shape and color allows a virtual model to be created which can be further refined or displayed in different conditions. It also allows us to create a copy of the measured object using three-dimensional (3D) printing technology.

Another issue under investigation by art conservators is how to measure and best maintain the state of an object that is exposed to damaging conditions. Digitization allows periodic measurements to be performed and compared to each other in order to predict the future deterioration of the object by known environmental factors.

These example applications show that digitization technology gives art conservators many new options for the preservation and display of monuments and artifacts. The purpose of the research described in this article is to develop a digitization system specifically for objects of cultural significance, capable of measuring the shape and multispectral color of historical artifacts. This research attempts to combine a shape measurement system using structured light projection and a multispectral color measurement system to create a single integrated setup dedicated to the measurement of 3D shape and color in order to create complete virtual models that can be used in monument conservation and measuring and rendering objects as well as storing or copying them.

There are existing systems developed to measure shape and color. Tonsho et al. proposed a system with a multispectral camera, a laser scanner, and a gonioreflectometer. They obtained a model of 3D shape with additional information about angular spectral reflectance; however, the data came from different devices and they had to be merged after measurement. Additionally their approach was focused on display only, without verification of results by reference measurement.[1]

Imai et al. at Munsell Laboratories developed a system for digitizing oil paintings[2] which was used in the National Gallery of Art in Washington, DC. They tested different approaches to data processing which allowed for the calcula-

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tion of spectral reflectance directly and with some prior knowledge about the examined surface, but with a reduced number of spectral bands.[3] They did not perform any 3D shape measurements.

Conde et al. used a multispectral color measurement system to digitize Mexican codices from the National Library of Anthropology and History (Biblioteca Nacional de Antropología e Historia) in Mexico City. They managed to calculate the colors of codices independent of lighting conditions and simulate their appearance under different illumination conditions.[4]

Another approach has been presented by Mansouri et al. who proposed a combination of a seven channel multispectral camera with a digital projector. It performs integrated measurement of shape and color and allows for reconstruction of an object's shape as well as its color under different illumination conditions.[5] Additionally, Simon et al. described the use of a multispectral camera combined with a structured light projection scanning system applied to shape and color measurement of sandstone sarcophagi.[6] Because of the two separate measurement systems used they had to provide a method for manual fitting the color texture on the clouds of points representing shape.

Most of the research, except for the work described in Ref. 3, focuses on either shape or color properties separately. Moreover, the data are used mainly for display without an assessment of achieved results. Our method, similar to that of Mansouri et al.,[5] is to combine these two functionalities into an integrated system that is capable of digitizing both the shape and color of 3D objects at once; however, we use a different approach to calibration and data processing. The two components of the system share the same hardware and are calibrated together so that the result is a concise model of the surface of the object under investigation. After measurement, each point on the examined surface has specific (x, y, z) coordinates assigned as well as spectral reflectance characteristics and color. Our main application is the documentation of the 3D surface of cultural heritage objects, and thus the measurement uncertainties of the (x, y, z) and color components have to be assessed for the developed method. Additionally, the method for merging measurements made from different directions was proposed with respect to proper color estimation on a curved surface to create a full 3D shape representation.

THE CONCEPT OF INTEGRATED SHAPE AND MULTISPECTRAL COLOR MEASUREMENT SYSTEM

Shape Measurement System Using Structured Light Projection

This section presents ideas of shape measurement and color measurement methods consecutively and then focus on their integration into a single process.

To achieve a complete functionality of 3D shape measurement connected with the extension in the direction of multispectral measurement, the 3D measurement with algorithms of directional merging and conversion (3DMADMAC) system[7] has been used (Figure 1). This

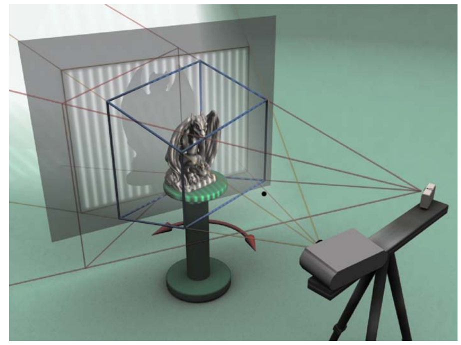

Figure 1. Scheme of 3DMADMAC system with the display of measurement volume indicated as a frustum around the measured object.

method of measurement is based on a structured light technique with digital sine patterns and Gray code projection.[8] This system consists of a digital light projector (DLP) and a matrix detector [an industrial charged-coupled device (CCD) camera or a digital camera]. The 3DMADMAC system can be customized depending on end user requirements connected with the measurement volume size, number of measurement points, and duration of a single measurement. It also consists of a set of software development kit tools which extend its functionality and automate all required measurement and data analysis algorithms.

Multispectral Color Measurement System

The most widely used methods of registering color rely on capturing an image using three wide spectral bands that are meant to resemble human vision, insofar as there are three kinds of cones in the retina with different spectral sensitivities. This fact led to the principles of the International Commission on Illumination (CIE) trichromatic theory.[9] Unfortunately, this approach has some limitations due to the influence of illumination conditions on the color appearance.[10] On the other hand, the direct measurement of the reflectance spectrum gives objective information on material's characteristics. Unfortunately, spectrophotometers are expensive and usually adequate for spot measurements only, because they integrate data only from the area of the aperture. Additionally, spectrophotometric measurements require specified viewing geometry that is difficult to achieve in field measurements. Moreover, stationary spectrophotometers require laboratory conditions in order to take reliable measurements.

However, the trichromatic theory provides a model of transformation from spectral reflectance to color coordinates in the so-called independent color space. It is widely used in color measurement and comparison, despite some of theory's limitations.[9] It also allows the creation of a multispectral color measurement system that uses multiple spectral bands to estimate the reflectance spectrum and then calculate color in independent color space. It can be recalculated to printing or imaging device dependent color space with an arbitrarily chosen illuminant. When using bandpass spectral filters and a matrix detector, it is possible to create a field measurement system that gives a response of the reflectance spectrum in

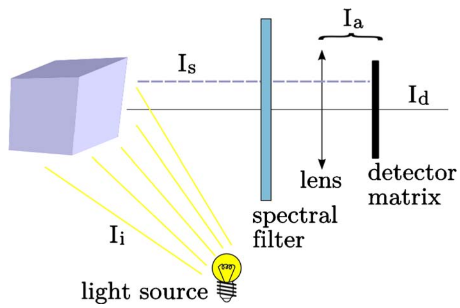

Figure 2. Color measurement system concept.

each pixel of the matrix detector. Such multispectral cameras are already in use in color measurement applications[2,11] and can incorporate different data analyses based on color calculation directly from the reflectance spectrum, or with some *a priori* information on surface colorants as well.[3]

In this work the decision was made to use the direct approach with a few reservations on the type of measured surface. First, the target objects for measurement are cultural heritage objects with a scattering surface (nonmetallic reflection model[12]) and ones which do not have fluorescent properties, because the system is unable to distinguish between radiation reflected and radiation emitted by the surface that is being investigated. Second, the measured surface ought to have isotropic angular reflection characteristics, so that the angle of observation does not influence spectral reflectance characteristics. Third, the assumption was made that there is no *a priori* information on the object under investigation, so that the proposed method should be independent of the type of surface being measured.

The diagram in Figure 2 shows the main components of the multispectral color measurement system. In the proposed model the surface under investigation is illuminated by a light source with a continuous spectrum (I_i) within the visible range. The spectrum of light scattered from the measured surface (I_s) propagates through the optical setup that consists of cycling selective spectral filters, an objective lens, and a matrix detector. The optical setup introduces attenuation (I_a) due to absorption and the spectral sensitivity of the detector. Different filters are used to quantize the reflectance spectrum, and their energetic variations are taken into consideration separately as $T(\lambda)$ in Eq. (1). The function $T(\lambda)$ is a vector with maximum transmission values from spectral filters used to sample spectral reflectance. The sampling of the spectral filters is indicated in the notation of intensities as a function of λ. The spectral characteristic registered by the detector with the use of the whole sequence of spectral filters is described as I_d. Therefore, the system can be described as a set of serial attenuators affecting the spectrum of the source. The spectrum registered by a detector is filtered first by the measured surface, and then by the attenuation characteristic of the detector, i.e., the influence of the lens and spectral sensitivity of the detector matrix,

$$I_d(\lambda) = I_i(\lambda) I_a(\lambda) T(\lambda) I_s(\lambda), \tag{1}$$

where $I_d(\lambda)$ is the light intensity registered by the detector, $I_i(\lambda)$ is the light intensity emitted by the light source, $I_a(\lambda)$ is the spectral sensitivity of the detector and optical system attenuation (filter 1), $T(\lambda)$ is the transmission extremes of spectral filters (spectrum sampling function) [%], and $I_s(\lambda)$ is the spectral characteristic of the measured surface (filter 2).

The spectral characteristic of the measured surface (I_s) is the desired quantity and will be determined through measurement. In order to find it, the spectral characteristic of the light source and the detector's sensitivity characteristics should be compensated. The proposed system does not distinguish between these two factors and is able to compensate for them together through calibration using a photographic white reference plate. A detailed method of CCD detector calibration can be found in Ref. 13. The reference plate scatters all wavelengths within the visible spectrum uniformly, so its spectral reflectance can be assumed constant, as is possible to prove through measurement with a spectrophotometer. This makes possible the derivation of the compensation function from the measured characteristic of the reference plate, as in Eq. (2):

$$I_{dr}(\lambda) = I_i(\lambda) I_a(\lambda) T(\lambda) C, \tag{2}$$

where C is a constant corresponding to the white reference plate's spectral characteristic.

This equation allows us to establish the product $I_i(\lambda)I_a(\lambda)$, which can be substituted into Eq. (1). After that it is easy to calculate (I_s), as indicated in Eq. (3). The parameters (i,j) refer to spatial coordinates of pixels in the recorded image. Additionally, we introduce a normalization factor $I_{s\,\max}$ which allows us to determine the spectral reflectance relative to the level of white reference plate,

$$I_s(i,j,\lambda) = I_d(i,j,\lambda) \frac{C}{I_{s\,\max}} \frac{1}{I_{dr}(i,j,\lambda)}, \tag{3}$$

where $I_{s\,\max}$ is the average maximum intensity from all spectral channels (normalization factor),

The function $I_{dr}(i,j,\lambda)$ is established in a calibration procedure, and it compensates for the influence of the measurement setup (light source and detector spectral characteristics) and energetic characteristic of the filters separating spectral channels. The energetic normalization of the filters' transmission is necessary, because in different spectral ranges their transmission differs significantly. Figure 3 illustrates a sample characteristic of an interference filter appropriate for use in the experiment, as measured by a spectrophotometer.

The energetic differences between spectral filters can be compensated for by integrating the energy transmitted by every single filter and calculating correction factors which equalize the energy of each spectral channel according to Eq. (4),

$$I(x,y,z) = \frac{I_d(x,y,z)}{t}, \tag{4}$$

where $I_d(x,y,z)$ is the intensity recorded by a detector for the point (x,y,z) for a single spectral channel. The energy

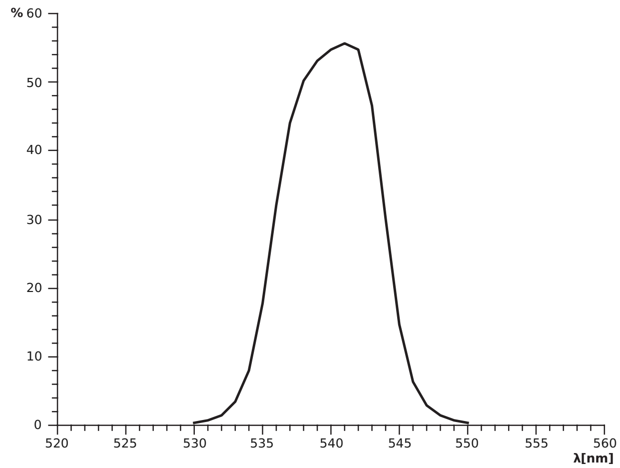

Figure 3. Representative transmission of an interference filter.

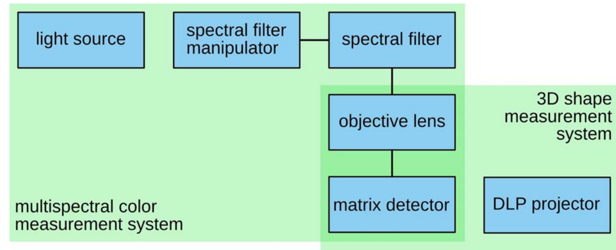

Figure 4. Block diagram of integrated 3D shape and color measurement system.

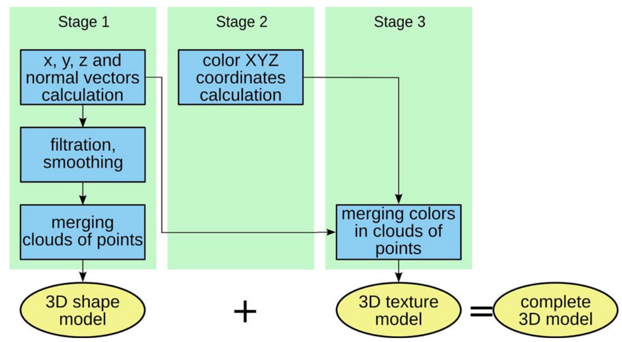

Figure 5. Block diagram of data processing path.

conservation coefficient that describes the ratio of energies transmitted by the reference filter to the ideal filter with 100% transmission is described by Eq. (5):

$$t = \frac{\displaystyle\int_{\lambda_i-\Delta\lambda/2}^{\lambda_i+\Delta\lambda/2} T(\lambda)d\lambda}{\Delta\lambda \times 100\%}, \tag{5}$$

where λ_i is the central wavelength of the ith filter and $\Delta\lambda$ is the spectral resolution of the measured reflectance characteristic.

The approach presented here gives a good estimation of the spectral reflectance for flat surfaces that are located perpendicular to the detector's optical axis; however, this is rarely the case, especially when measuring a curved surface. Therefore, a more precise way of determining spectral reflectance based on angular relations between lighting direction, surface normal, and observation direction is needed for taking precise measurements of 3D surfaces. If geometry is not taken into consideration, the result will vary according to the amount of energy reflected in the direction of the detector. Additionally the signal-to-noise ratio of the measurement result decreases if the surface is observed from a small angle owing to the smaller amount of energy that reaches the detector. Currently, with awareness of these limitations, the main purpose of this research was to calculate color from the estimated spectral reflectance by means of the CIE color theory. After assuming the standard illuminant and standard observer it is possible to calculate color coordinates in the XYZ color space and then in the $L^*a^*b^*$ color space.[10]

Integration of Shape and Color Measurement Systems

In this study, two measurement systems were integrated into a single setup. Figure 4 illustrates its main components.

The 3D shape measurement system and color measurement system share the same detector, which is a grayscale camera. The setup requires an automatic manipulator to change spectral bands by setting an appropriate spectral filter before the camera lens. The manipulator is also capable of removing the filter completely, which is necessary for shape measurement. The system is calibrated in order to measure the object put in the estimated measurement volume. During the shape measurement sequence the projector displays a series of fringe patterns which are registered by the camera, and the additional illuminator is turned off. During the color measurement sequence, filters are placed consecutively in front of the detector, and a series of images is captured while the scene is illuminated by the additional illuminator. Meanwhile, the DLP is turned off. In the single measurement sequence, information about the shape and color from one's perspective is acquired. In order to scan the whole object it is necessary to repeat the measurement sequence for multiple object orientations, so that its whole surface is measured.

The system is controlled by a PC with dedicated software which performs the measurement sequence automatically and independently processes the data. The data processing procedure can be divided into three stages illustrated in Figure 5. First, the coordinates and normal vectors are calculated for every point. After that the directional cloud of points is filtered, smoothed, and merged into a 3D model of the measured object's shape. Then the XYZ color coordinates are calculated independent of the shape for every point in the directional cloud of points. The third part of calculation needs both the shape and color data to merge the clouds of points and their colors to obtain the complete model.

The normal vectors from the shape measurement data are used to calculate color regardless of lighting conditions. When a curved surface with a complicated shape is illuminated, it is extremely difficult to uniformly illuminate every point of the surface, because light scattered from one part of

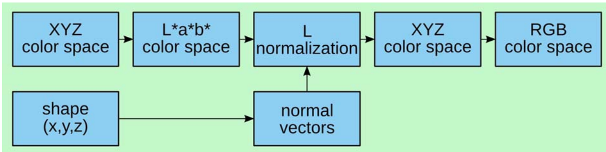

Figure 6. Block diagram of color space calculation process.

the surface may illuminate other parts. Even if the object is put in a light tent, so that diffuse illumination is simulated, some parts of its surface may be illuminated better than others, because a nonuniform surface's shape can partially obscure itself. Moreover, if the detector is placed in any one specific position, then the part of the surface oriented perpendicularly to detector's optical axis will seem brighter than the part that is viewed from a small angle, because the perpendicular surface will scatter more energy in detector's direction. The result of this behavior is that textures from adjacent measurements taken from two different directions may have different average intensities and different illumination patterns. When creating a 3D model of an object it is undesirable to have the illumination pattern fixed for the texture, because a fixed texture does not accurately model reality.

To solve this problem, a method for accurately displaying surface's appearance is proposed here. The method is based on texture creation using the color space $L^*a^*b^*$, which has separate intensity and color coordinates, so that texture's intensity, measured from single direction, can be normalized to results from other directions and kept constant. In the end it is possible to obtain a uniformly colored texture that can be added to a virtual model of the measured object and used to simulate different illumination patterns. Figure 6 shows the principle of normalizing and merging texture colors from adjacent directional clouds of points.

Every point in the cloud of points has CIE XYZ color coordinates calculated from the spectral reflectance. They are recalculated into the $L^*a^*b^*$ color space, so that the intensity component is separated from color coordinates. First, the histograms of the L^* value in overlapping clouds of points are calculated and shifted with respect to one reference cloud of points, so that the cross correlation function between them is maximized. This operation equalizes the mean intensity for every cloud of points. The measured object usually has a uniform texture in the sense that it does not consist of large patches of different colors, but rather small multicolored grains. Therefore, the distribution of intensities for each cloud of points is similar. It may only be shifted because of uneven lighting conditions.

Based on the shape measurements every point is assigned a normal vector, so that it is possible to calculate the angle between this vector and the observation direction (Figure 7). It is assumed that the smaller the angle (converging to surface perpendicular to the detector's optical axis), the better the surface illumination. The proposed algorithm for merging colors from adjacent clouds of points normalizes the L^* coordinate in the points where clouds of points overlap by calculating the weighted average with the cosine of the

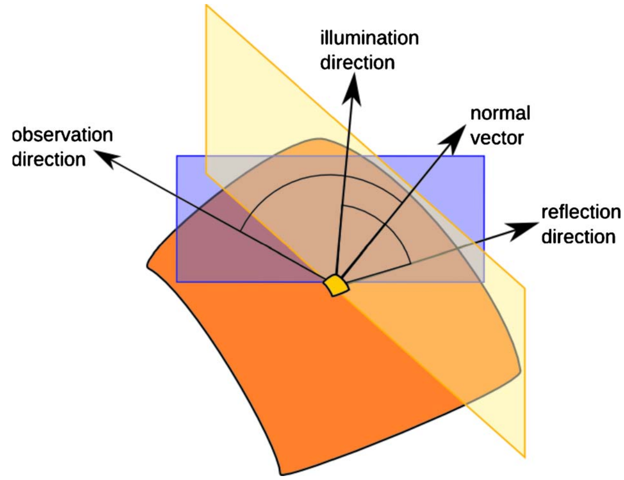

Figure 7. Illustration of illumination and observation directions in relation to surface position.

angle between the normal vector and the observation direction as the weight, as is illustrated in Eq. (6):

$$L_{\mathrm{norm}}(x,y,z) = \frac{\sum_{i=1}^{N} L_i(x,y,z)\cos(\angle \vec{n}\cdot\vec{o})}{\sum_{i=1}^{N}\cos(\angle \vec{n}\cdot\vec{o})}, \qquad (6)$$

where $L_i(x,y,z)$ is the L^* coordinate value in the (x,y,z) point from the cloud of points, $\vec{n}$ is the normal vector in the (x,y,z) point, $\vec{o}$ is the vector indicating the observation direction, and N is the number of clouds of points overlapping at the (x,y,z) point. After this operation the new $L^*a^*b^*$ coordinates are recalculated back to XYZ, so that other dependent color spaces can be derived, for example, the $sRGB$ color space as a texture for display purposes.

IMPLEMENTATION OF THE PROPOSED SYSTEM

The main assumption in the system design was using a single matrix detector in connection with devices specific for shape measurement, as well as for multispectral color measurement. This approach enabled the creation of a single integrated mechanical setup that can be controlled by a PC. The experimental setup built for measurement consists of a grayscale CCD camera (8 bits, 1024×768 PointGrey Flea II), with an 8 mm objective lens, and an off-the-shelf DLP (based on a digital mirror device chip with a resolution equal to 1024×768 pixels) for shape measurement.[7] A Canon SpeedLite 580ex flash was employed for illumination along with a especially designed setup for switching spectral filters responsible for distinguishing between spectral channels in multispectral color measurement. The PC with dedicated software controls the external devices.

Multispectral Color Measurement System

In order to estimate the spectral reflectance characteristic a set of 20 interference filters with a full width at half-maximum of 10 nm and uniformly distributed central wavelengths within the visual range (400–780 nm) were used.

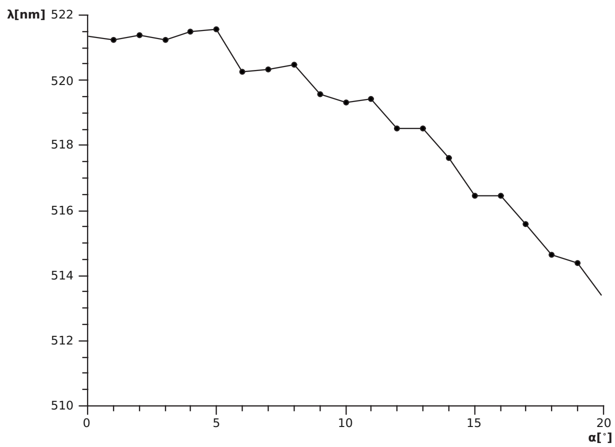

Figure 8. Measured angular characteristic of the interference filter.

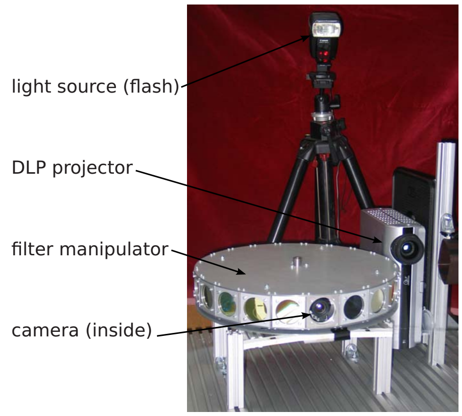

Figure 9. Photograph of the system as built.

The obtained spectral characteristics were smoothed using B-spline interpolation[14] on the discrete measurement data from the spectral channels. Additionally, differences in energetic characteristics between the used filters were compensated with the algorithm described above which calculates energy compensation coefficients relative to the ideal filter with 100% transmission within the interval of interest.

The maximum transmission of the interference filter depends on light's angle of incidence[15] which is a drawback in this application, because rays of light which propagate through the objective lens to the detector matrix are incident into the filter at different angles, and it is impossible to distinguish them in order to compensate for the maximum transmission shift. In order to estimate the scale of error that may occur because of this fact, the angular characteristic of the interference filter was measured using a Perkin Elmer Lambda 40 spectrophotometer; it showed that within the range $\pm 10°$ the shift in the maximum transmitted wavelength is relatively small (Figure 8). This observation leads to the decision that its influence on the measurement is negligible.

The spectral filters change positions in front of the camera lens through a special automatic setup. Two solutions for automatic filter switching are known: one where the filter passes between the lens and the camera and the other where the filter passes in front of the lens.[16] The first solution is more resistant to vignetting, but it also makes the setup more complicated. Therefore, in the proposed experimental setup the decision was made to use the second simpler solution, being aware of its imperfections. Figure 9 depicts the filter manipulator as was used in the experiment. The camera is located under the circular plate, which has holders for interference filters mounted uniformly on the circumference. One of the holders is left empty for capturing the image without a filter.

The plate with the interference filters is driven by a stepper motor with interlocking gears which allows for the positioning of the proper interference filter in front of the camera lens. The filter positioning system introduces deviations between adjacent filter positions estimated as about 0.5°, which results in shifts between images from different spectral channels.[17] These shifts are calculated and compensated for by capturing an image with a set of circular markers for each spectral channel and calculating their shifts by means of simple image processing, which gives coefficients for correcting the transverse location of the object in the field of view of the camera. Apart from this, the longitudinal chromatic aberration of the camera lens and differences in filters' thicknesses and refractive indices result in a slight defocus of images between filters.[17,18] These factors lead to a small decrease of the actual color resolution of the measurements.

The light source proposed for the color measurement should have continuous characteristics within the investigated spectral range. There were several tests conducted with an incandescent light source as well as with a metal-halide lamp. The first source has little emission in the blue region of the spectrum and was therefore insufficiently sensitive in that range. The metal-halide lamp has several separated emission lines, which resulted in many extremes in the emission spectrum. It creates a large amount of uncertainty in the spectrum between points sampled by interference filters. In the end the use of a xenon light source was investigated, and it proved adequate because it has a lot of densely distributed spectral emission lines whose envelope resembles the standard illuminant D65. The emission spectrum as well as the repeatability of this light source was measured with the constructed setup. The repeatability of flash intensity between shots stays within a 5% variation. The measured emission spectrum combined with the optical setup attenuation is shown in Figure 10.

The selection of the light source is connected with establishing the illumination geometry. The most widely used and approved illumination geometries are 45/0, 0/0, D/0, and D/8.[9] These geometries are usually used in spectrophotometers or colorimeters which perform spot metering, whereas in the present setup surface metering is implemented, which makes it difficult to fulfill the requirements of these geometries for every point of the examined surface simultaneously. Therefore, the decision was made to choose diffuse illumination that theoretically gives the same results with a perfect diffusive surface regardless of the observation direction. This concept was put into practice using a light

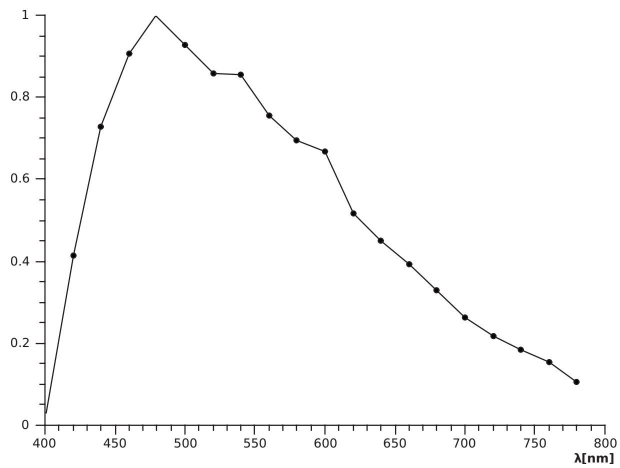

Figure 10. Measured spectral characteristic of xenon light source and optical system attenuation.

Figure 11. The light tent used for diffuse illumination of the measurement volume.

tent covering the measured object and illuminated from the outside (Figure 11).

Integrated Shape and Color Measurement System

Fig. 9 shows the whole measurement system setup ready for shape and color measurement. The whole mechanical unit is controlled by a PC with dedicated software via a universal serial bus interface. The software is capable of calibrating the system and automatic measurement. In the calibration process, the calibration for shape measurement is performed first. It relies on acquiring a set of images of a calibration reference plane in different positions within measurement volume and calculating the phase distribution within this volume.[7,19] Second, during the color calibration, three sequences of measurement procedure are performed: one with the reference plane with markers to compensate for deviations in spectral filter positioning, one with a white reference plate put in the measurement volume for light source spectrum compensation, and one with a uniformly colored background to eliminate uneven illumination in the scene. Ideally, a calibration process could rely on capturing an image of white reference plate which covers the whole field of view of the detector for each spectral channel. Usually, the white reference plate is not big enough, so we decided to put it in the center of the field of view while capturing its image.

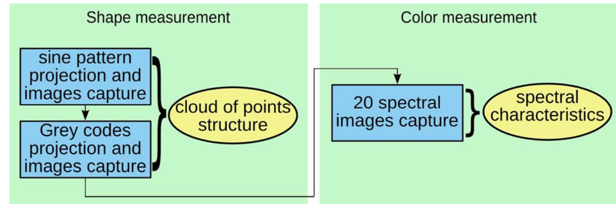

Figure 12. 3D shape and multispectral color measurement sequence.

Separately, we captured the image with a uniform white background which can be normalized to reflect white reference values.

The measurement process is sequential for every direction: First, the system measures shapes by projecting and capturing images with sine patterns which shift in phase and a series of Gray codes for phase hierarchical unwrapping.[8] These create a cloud of points. Then it performs multispectral color measurement by capturing a series of 20 spectral images. They give information about the estimated spectral reflectance for every point in the cloud of points after compensation conducted with the aid of calibration data. Figure 12 illustrates the measurement sequence.

The output data are ready for additional data processing which includes merging data from different directions, simplifying the model, and calculating color coordinates. To fulfill the needs of data processing and storage, a new data format was proposed which describes results from shape measurement and is capable of storing additional information, such as spectral characteristics. The cloud of points obtained from shape measurement may contain additional data layers which in the case of color measurement correspond to estimated spectral reflectance values for specific wavelengths. Consecutively, each point in the cloud of points of the structure has assigned a vector that includes additional information relevant to its properties. In this way the XYZ and $L^*a^*b^*$ color coordinates can also be assigned to every single point. It is also possible to define other data layers during the data processing stage which can contain processed data, such as output color space coordinates.

The software responsible for data processing utilizes the 3DMADMAC calculation environment which implements the processing of large data sets. The data processing engine loads DLL libraries that are responsible for performing a specific part of the calculation process. They can be chosen manually, which allows the user to monitor every stage of data processing, as well as run automatically from a previously defined pattern which enables a fully automatic calculation process. The output data consist of clouds of points merged to the single coordinate system with color in every point calculated in the XYZ, $L^*a^*b^*$, and RGB color spaces. In addition, it is possible to create a triangle mesh and fill it with texture for visualization.

VERIFICATION OF MEASUREMENT RESULTS

Verification of the correctness of measurements' results includes two aspects. The quality of color measurement data is investigated first, and then the repeatability of color estimation is investigated in consecutive measurements. The measurement uncertainty of 3D shape determination of the method used is less than 0.001 with respect to the measurement volume size.[19]

Measurement of the 3D surface lies beyond the scope of the CIE theory, where the $L^*a^*b^*$ color space is used to calculate color differences, because the theory requires the sample to have a well defined measurement geometry and lighting condition. Therefore, it is very difficult to propose an objective method to evaluate the results from a multispectral color measurement system. In our approach we decided to use a reference measurement system for comparison with the multispectral camera. The reflectance spectra obtained from both devices were compared directly rather than in the $L^*a^*b^*$ coordinates; however, both cases were investigated. The reference measurement device was a Minolta CM-2600d spectrophotometer, which uses a xenon light source and has D/8 geometry thanks to the integrating sphere. It was used to measure the spectral reflectance of GretagMacbeth Color Checker patches. The same patches were measured using the multispectral camera, and their reflectance spectrum was independently estimated. They were placed in the field of view of the camera in several different angular positions against the camera's optical axis to evaluate the change in results due to the target's orientation. The procedure demonstrated that the influence of this factor stays within the general variance of measurement, so it does not have to be accounted for. After that it was possible to compare every two measured spectra and make inferences about the quality of the color measurement system. Representative characteristics of the color patches measured by both devices are shown in Figure 13, whereas numerical values of goodness-of-fit coefficients (GFC) and root mean square (RMS) deviations from reference values for chosen color patches are collected in Table I.

Apart from the spectral reflectance, the $L^*a^*b^*$ coordinates for every color patch were calculated for both devices, for the D65 standard illuminant, as well as the corresponding ΔC color differences.[10] The estimated standard deviation of color coordinates in the $L^*a^*b^*$ color space is approximately $s=5.28$. The mean color difference between color patches was calculated with the use of ΔC, because the main goal was to estimate the accuracy of chromaticity regardless of the level of signal which may differ in consecutive measurements, as was described above. Sample results are summarized in Table II. All reference values come from measurements obtained with a Minolta CM-2600d spectrophotometer.

The second aspect of color measurement accuracy verification is the repeatability of measurement results. To achieve this, the GretagMacbeth Color Checker target was measured ten times to prove that the measurement results do not depend on system setup, and that independent measurements of the same objects can be compared objectively. The mean standard deviation of color coordinates for all color patches equals 1.15. More specific results for chosen

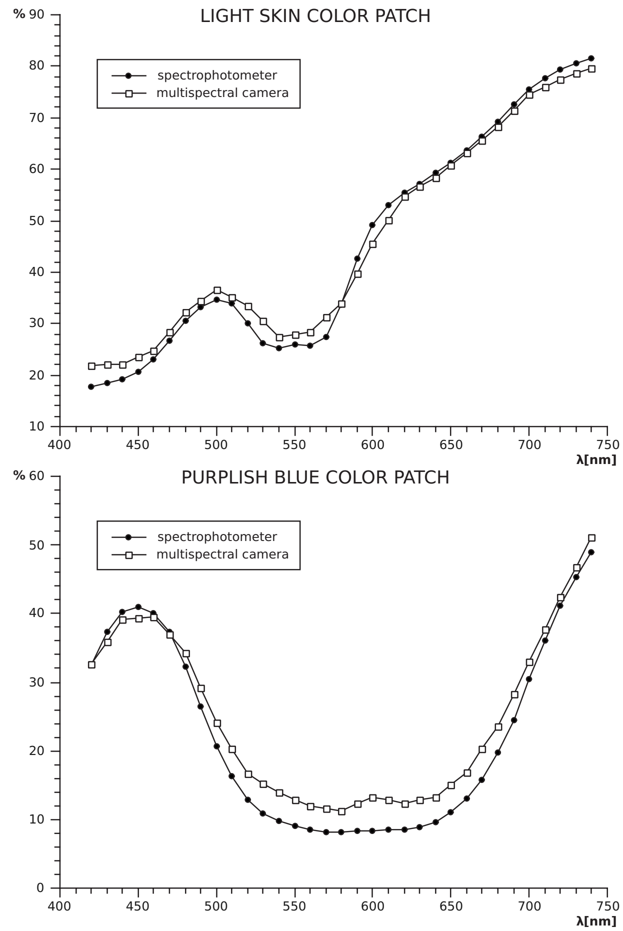

Figure 13. Representative spectral characteristics of GretagMacbeth Color Checker reference plates.

Table I. Comparison between spectral reflectance measurement using multispectral camera and measurement with a spectrophotometer as a reference. Values of goodness-of-fit coefficient (GFC) and root mean square (RMS) are shown.

Color patch	GFC	Relative rms (%)
Blue	0.989	0.38
Green	0.992	0.39
Red	0.998	1.28
Yellow	0.998	2.84
Magenta	0.999	2.19
Cyan	0.996	0.87

color patches of the color checker target are presented in Table III.

These results show the estimated accuracy of the measurement system and prove the correctness of the developed methodology. The errors in color estimation are considerable, because additional factors such as illumination distribution on a curved surface, variable reflectance of the measured surface, and poor repeatability of the light source are involved. Future plans assume further integration with re-

Table II. Representative color differences obtained from GretagMacbeth Color Checker evaluation.

Color patch	Reference a^*	Measured a^*	Reference b^*	Measured b^*	ΔC
Light skin	16.82	13.75	16.71	18.92	3.78
Blue sky	−1.38	−4.90	−21.08	−16.17	6.05
Moderate red	45.87	43.49	15.75	15.30	2.42
Green	−41.15	−36.73	30.67	28.39	4.98

Table III. Results of the evaluation of measurement system repeatability.

Color patch	$S_d L^*$	$S_d a^*$	$S_d b^*$
Dark skin	1.00	0.46	1.32
Light skin	1.25	0.68	1.52
Blue sky	1.03	0.74	1.53
Orange	1.27	0.76	1.61
Purplish blue	0.96	0.77	1.50
Moderate red	1.08	0.80	1.54
Blue	0.84	0.84	1.37
Green	1.12	0.63	1.23
Red	0.98	0.89	1.40
White 9.5	1.69	0.73	2.23
Neutral 8	1.45	0.63	1.95
Neutral 6.5	1.27	0.56	1.70

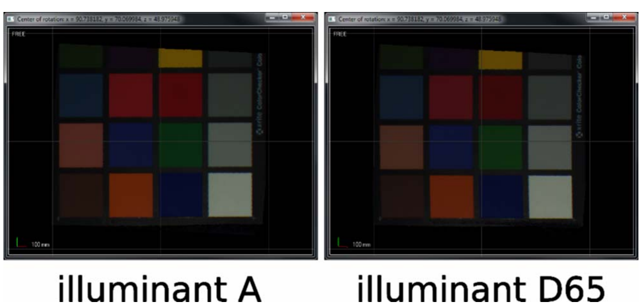

Figure 14. Visualization of the GretagMacbeth Color Checker target measurement result reconstructed under a different standard illuminant.

flectance characteristic measurement and hardware improvements in order to achieve better results.

SAMPLE MEASUREMENT RESULTS

Several different measurements were performed during the described research. The results of some of them are presented below. First, the reconstruction of the GretagMacbeth Color Checker plate as a cloud of points is shown in Figure 14, reconstructed in the *sRGB* color space, under illuminants A and D65. No apparent difference in hue is visible for both images. Its average numerical value stays within 1.03%.

Another measurement result visualization is a full 3D model of a painted plaster figure of a dog, which was measured from ten directions (Figure 15). The clouds of points obtained were merged, and the texture covering the triangle mesh was equalized by means of the described algorithm. The model consists of 1×10^6 points, which were used to create a triangle mesh of 40,500 triangles after simplification. The colors were calculated in the *sRGB* color space with the D65 standard illuminant.

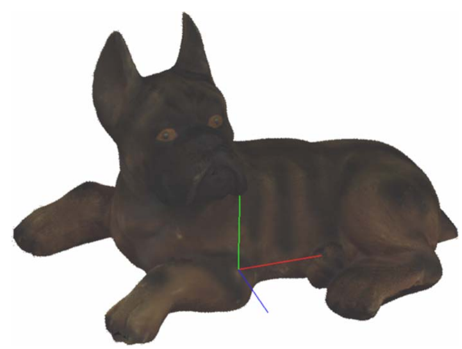

Figure 15. Visualization of measured object.

CONCLUSIONS

The purpose of the research described in this article was to develop a method of shape and color measurement for the digitization of cultural heritage objects mainly for documentation purposes. In this article the concept of the measurement system's acquisition of information about shape and color was presented. The emphasis was put on the method of shape and color acquisition and calibration procedure for the measurement system.

The system employs shape measurement using structured light projection and multispectral color measurement from different directions and is capable of merging the data together, so that a complete virtual model of the real object is obtained. We propose a method for merging spectral information for points measured from different directions, so that the calculated texture is independent of the lighting conditions during measurement, making it possible to model arbitrary illumination for visualization. Sample color values from the color checker target measurement were presented in Table II and compared to values obtained by a spectrophotometer.

The present system realizes its basic foundations, but also reveals directions for further research. Most of all, the accuracy of color measurement is below expectations compared with results from other research groups.[2,4,16] An attempt of measuring color of 3D curved surfaces brings difficulties in verification through comparison to known methods of color measurement. The proposed method uses the CIE color theory that was originally developed for flat specimen measurements, so there are significant assumptions made to fit the model to the new application. A more precise approach would be to use a bidirectional spectral reflectance distribution function (BRDF) model on every point on the surface to calculate the BRDF that can be used for color calculation afterward. It is possible to develop such a method by integrating color measurement system with a shape measurement system to work as a gonioreflectometer. This will be the subject for further investigation.

Moreover, the ongoing research showed several issues influencing the accuracy of the measurement. We conclude that in order to get more precise results there should be feedback implemented in the light source setup, so that its intensity would be better stabilized. Additionally, the placement of light sources can be improved to provide a more even illumination in the measurement volume. Apart from this, the precision of the mechanical setup in filter positioning can be enhanced in order to create better repeatability in the measurement results. Nonetheless, the presented results prove the correctness of the proposed method in applications.

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REFERENCES

[1] K. Tonsho, Y. Akao, N. Tsumura, and Y. Miyake, "Development of gonio-photometric imaging system for recording reflectance spectra of 3D objects", Proc. SPIE **4663**, 370 (2001).
[2] F. H. Imai, M. R. Rosen, and R. S. Berns, "Multi-spectral imaging of Van Gogh's self-portrait at the National Gallery of Art, Washington, D.C.", *Proc. IS&T's PICS Conference* (IS&T, Springfield, VA, 2001) p. 185.
[3] F. H. Imai, M. R. Rosen, and R. S. Berns, "Comparison of spectrally narrow-band capture versus wide-band with a priori sample analysis for spectral reflectance estimation", *Proc. IS&T/SID Eighth Color Imaging Conference* (IS&T, Springfield, VA, 2000) p. 234.
[4] J. Conde, H. Haneishi, M. Yamaguchi, N. Ohyama, and J. Baez, "Spectral reflectance estimation of ancient Mexican codices, multispectral images approach", Rev. Mex. Fis. **50**, 484 (2004).
[5] A. Mansouri, A. Lathuilière, F. Marzani, Y. Voisin, and P. Gouton, "Toward a 3D multispectral scanner, an application to multimedia", IEEE Multimedia **14**, 40 (2007).
[6] C. Simon, U. Huxhagen, A. Mansouri, A. Heritage, F. Boochs, and F. Marzani, "Integration of high resolution spatial and spectral data acquisition systems to provide complementary datasets for cultural heritage applications", Proc. SPIE **7531**, 1 (2010).
[7] R. Sitnik, M. Kujawińska, and J. Woźnicki, "Digital fringe projection system for large-volume 360-deg shape measurement", Opt. Eng. (Bellingham) **41**, 443 (2002).
[8] W. Osten, W. Nadeborn, and P. Andrae, "General hierarchical approach in absolute phase measurement", Proc. SPIE **2860**, 2 (1996).
[9] G. Wyszecki and W. S. Stiles, *Color Science, Concepts and Methods. Quantitative Data and Formulae* (Wiley, New York, 2000), pp. 117–174.
[10] D. Malacara, *Color Vision and Colorimetry: Theory and Applications* (SPIE, Washington, 2002), pp. 77–100, 119–130.
[11] F. H. Imai, M. Rosen, D. Wyble, and D. T. R. Berns, "Spectral reproduction from scene to hardcopy I. Input and output", Proc. SPIE **4306**, 346 (2001).
[12] L. C. Lee, *Introduction to Color Imaging Science* (Cambridge University Press, New York, 2005), pp. 78–85, 145–190.
[13] A. Mansouri, F. Marzani, and P. Gouton, "Development of a protocol for CCD calibration, application to a multispectral imaging system", International Journal of Robotics and Automation **20**, 94 (2005).
[14] W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Wetterling, *Numerical Recipes in C: The Art of Scientific Computing* (Cambridge University Press, New York, 1992), pp. 113–116.
[15] K. Iizuka, *Free Space and Special Media*, Elements of Photonics (Wiley, New York, 2002), Vol. 1, pp. 166–176.
[16] M. Yamaguchi, T. Teraji, K. Ohsawa, T. Uchiyama, H. Motomura, Y. Murakami, and N. Ohyama, "Color image reproduction based on the multispectral and multiprimary imaging: Experimental evaluation", Proc. SPIE **4663**, 15 (2001).
[17] J. Brauers, N. Schulte, and T. Aach, "Multispectral filter-wheel cameras: Geometric distortion model and compensation algorithms", IEEE Trans. Image Process. **17**, 2368 (2008).
[18] A. Mansouri, F. Marzani, J. Harderberg, and P. Gouton, "Optical calibration of a multispectral imaging system based on interference filters", Opt. Eng. (Bellingham) **44**, 027004 (2005).
[19] R. Sitnik, "New method of structure light measurement system calibration based on adaptive and effective evaluation of 3D-phase distribution", Proc. SPIE **5856**, 109 (2005).