Low-cost mobile system for multispectral cultural heritage data acquisition

Jan Blažek, Jindřich Soukup, Barbara Zitová, Jan Flusser
Institute of Information Theory and Automation, ASCR
Academy of Sciences of Czech Republic, Prague, Czech Republic
Email:[blazek—soukupj—zitova—flusser]@utia.cas.cz

Tomáš Tichý and Janka Hradilová
ALMA Laboratory, Academy of Fine Arts
Prague, Czech Republic
Email: tomas.tichy.cz@gmail.com, hradilovaj@volny.cz

***Abstract*—In the paper we propose an alternative approach to the multispectral data acquisition of the cultural heritage artifacts. The demonstrated solution is mobile, affordable, and consists only of commercial off-the-shelf products. It could be used for the data acquisition in-situ without limitations. It was designed for multispectral scanning of cultural heritage artifacts for their first analysis, for multimedia presentations dedicated to public, and, of course, for art conservation studies. The presented solution contains next to the hardware part as well the description of pre-analysis step - two alternative ways of the photometric calibration - to ensure the anticipated precision. The applicability of the framework was demonstrated on the case study, the preliminary spectral analysis. The proposed methodology is successfully used in the art restoration practice.**

***Index Terms*—Multispectral data acquisition, cultural heritage, photometric calibration.**

I. Introduction

Multispectral imaging is nowadays an established technology for an acquisition of cultural heritage data, including paintings [15], large-sized pictorial surfaces such as frescoed halls [2], or even 3D structures like walls or monuments [8]. It is a non-destructive technique for analysis of paintings and other art objects. It provides spectral and colorimetric characterization of the artifact, which helps to document the current state of an artwork, its creation progress, and the restoration interventions, too.

The scanning systems produce datasets representing the studied artifacts in various wavebands (infrared, ultraviolet). The multispectral scans provide information about the art composition, it helps to achieve faithful color reproduction, it can effectively reveal the artwork creation. Such information can create valuable insight into the painting. It could bring near the history of the painting, demonstrate the painter's original intentions and show the tracks of the restoration interventions.

There are many solutions for multispectral cultural heritage data acquisition. They differ in their mobility (in-situ or laboratory-only data acquisition), in their spectral resolution, in their allowed spatial as well as spectral measured extent. The price can differ significantly, too. Today, the topic of the multispectral imaging attracts big attention. The survey of the 3D and multispectral data acquisition for cultural heritage applications was recently published [4]. They present the state of the art and existing registration techniques for creation of 3D models with multispectral texture. There were several large project studying this topic like MARC - Methodology for Art Reproduction in Colour [12], VASARI - Visual Arts System for Archiving and Retrieval of Images [13], or CRISATEL - [6]). In the CRISATEL project the high resolution multispectral image acquisition system was built for digitizing art paintings. The system consists of a multispectral digital camera and of light projectors. They have utilized the developed system to scan famous Mona Lisa painting [9]. The acquired data were used for better understanding of this masterpiece as well as for the attempts to apply virtual restoration. The tutorial on the multispectral imaging where Mona Lisa is used as a case study was published in [16].

Novati et al. [14] proposed the exploitation of the multispectral imaging for the image acquisition in a digital museum. They addressed two approaches to multispectral acquisition using narrow-band and wide-band sensors. They proposed new framework for wideband acquisition, which could be affordable for cultural institutions archives. Paviotti et al. [2] concentrated on multispectral acquisition of large-sized pictorial surfaces. They paid special attention to the practical issues related to the size of the scanned objects as well as to their illumination. Carcagni et al. [5] proposed their multispectral scanning system ($380\,\mathrm{nm}$ up to $800\,\mathrm{nm}$), developed to overcome problems related to the systems based on CCD or Vidicon cameras. They work with the spectrometer for contact-less single-point spectral measurements, moved by two orthogonally mounted translation stages. Bianco et al. [3] studied the multispectral data acquisition, producing already geometrically registered data using the specialized focus control system. They demonstrated the applicability on the document analysis.

Despite listed references the multispectral technology is often still understood as something available only to special cultural laboratories. In our paper we propose multispectral acquisition framework which is mobile and adjustable. We believe that such solution could spread even among the individual specialists and thus the multispectral acquisition could became available for general interested public.

It is composed of commercial off-the-shelf products and it has low purchase price. It is mobile so it could be used for the data acquisition "in situ" without any limitations. We foresee its applicability in the data acquisition for cultural heritage artifacts for first analysis, for multimedia presentations,

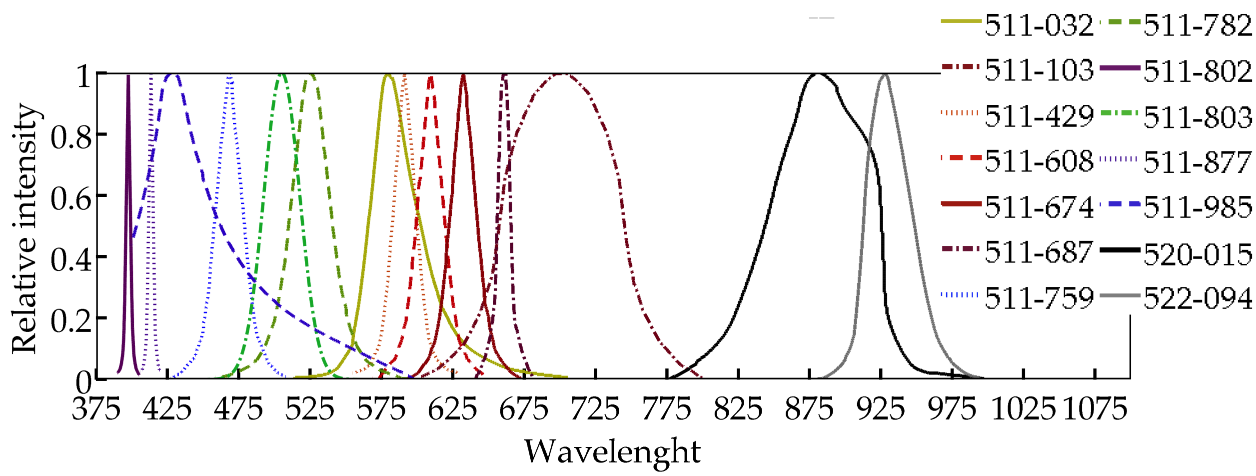

Fig. 1. Spectral relative intensities of used LEDs.

dedicated to public, and, of course, for the art conservation studies. Moreover, the advantage of our approach is that we do not limit the introduced solution to the hardware proposal. We describe the calibration and the evaluation of the system parameters to ensure the anticipated precision, which is very important step if we want to be sure about the meaning of the measured data. We demonstrate the applicability of the framework on the case study.

The proposed paper is organized as follows. The data hardware is described in Section 2. The proposed camera calibration system is described in Section 3. The Section 4 demonstrates the applicability of the method on the real data. Finally, Section 5 concludes our contribution.

II. Hardware for data acquisition

Proposed framework addresses the data acquisition in the interval from $380\,\mathrm{nm}$ up to $1200\,\mathrm{nm}$, covering the narrow part of the ultraviolet light (UV, till $400\,\mathrm{nm}$), visible light (VL, $400\,\mathrm{nm}$ up to $700 nm$) and, finally, the infrared light (IR, $700\,\mathrm{nm}$ up to $1200\,\mathrm{nm}$). The most interesting and as well the most useful in the restorer practice is infrared (IR) band and ultraviolet fluorescence. Unlike the visible light, infrared radiation can pass through certain materials and this property is exploited in the art analysis - beginning stages of the artwork can be studied. First attempts to use the IR features for artwork investigation appeared around 1970 in the work of the Van Asperen De Boer [18]. However usage of the IR photography is still not yet as spread as it could be.

There are successful applications of IR imaging. Cornelis et al. [7] studied Gauguin paintings in thirteen high resolution spectral bands – nine in the visible domain, one in the near ultraviolet and three in the infrared domain. Anith et al. [1] used IR and other modalities to study van Gogh paintings, processing high resolution scans, too.

Usefulness of the visible light is apparent. UV imaging in the proposed system can capture wavelengths from the interval $380\,\mathrm{nm}$ - $400\,\mathrm{nm}$, however capturing of UV sub-bands can be limited by glass optics used on the camera. The UV fluorescence can uncover a condition of the varnish layer. A progress of restoration treatment (retouchings, over-paintings), or an identification of materials used for creation of the artwork can be studied in UV imaging.

In the proposed framework, we suggest a solution, which spectral and spatial resolutions are not as high as in the case of a special dedicated equipment, however our system is mobile, fast, easy to use, cheap, and easy and fast in the data postprocessing. The base unit of the system is a common digital camera (in our case Canon D500 or Canon D50) adjusted for capturing NIR wavelengths. Originally a light sensitive chip from the camera is equipped with IR cut filter (ICF). For our purpose ICF was removed. Such a camera adaptation broke color balance of a light sensitive chip, but its sensitivity is increased up to $1200\,\mathrm{nm}$ in the spectral domain. After this adjustment the camera is prepared for capturing wavelengths from $380\,\mathrm{nm}$ up to $1200\,\mathrm{nm}$. The acquired images are processed using the raw format to avoid mosaicing artifacts.

For filtering particular spectral sub-bands common photographic filters are applied: color filters (we have used red, orange, yellow, green, blue and sepia); IR cut-off filters ($>680\,\mathrm{nm}$, $>720\,\mathrm{nm}$, $>760\,\mathrm{nm}$, $>850\,\mathrm{nm}$, $>950\,\mathrm{nm}$, and $>1090\,\mathrm{nm}$), and an UV cut-off filter ($<400\,\mathrm{nm}$). We have measured the transmittance of the filters to ensure higher precision (see tab. I). We recommend such evaluation for every used filter.

If the camera in use is not equipped with filter holder, instead of the filter application we propose to control light conditions to be able to capture specific spectral sub-bands. For such situation we suggest LEDs as a light source [10]. We have created the LED panel which is able to split the visual part of spectrum into eight sub-bands and two disjunctive IR sub-bands (see fig. 1). Filters and LEDs are shown in fig. 2.

A. Limitations

The proposed solution has many advantages such as its mobility, availability, and the price. However, there are some

TABLE I
SPECTRAL SUB-BANDS ACHIEVABLE BY PROPOSED SOLUTIONS. THEY ARE REALIZED USING FILTERS AND LEDS.

spectral band	GME No.	**used filters/LED diods**
395-401nm	511-802	UV - 330MUV9C (limited with glas optics)
402-408nm	511-877	UV - 530MUV9C
400-470nm	511-985	L-53MBDL - BLUE
450-480nm	511-759	530PB6C - BLUE $3000/40\,\mathrm{deg}$ CREE
470-530nm	511-803	530PG0C - BLUEGREEN
500-550nm	511-782	540PG2C - PURE GREEN
550-580nm	511-032	L-HLMP-3950 - GREEN
560-610nm	511-429	540MY8C - YELLOW $3500/40\,\mathrm{deg}$
580-625nm	511-608	530MO0C - ORANGE
600-650nm	511-674	520MR2C - RED
650-670nm	511-687	L-53SRC-DW - RED
680-720nm		Filters: cut-off $720\,\mathrm{nm}$ minus cut-off $680\,\mathrm{nm}$
670-730nm	511-103	BL-BHG274 REG(GREAN)
720-760nm		Filters: cut-off $760\,\mathrm{nm}$ minus cut-off $620\,\mathrm{nm}$
760-850nm		Filters: cut-off $850\,\mathrm{nm}$ minus cut-off $760\,\mathrm{nm}$
825-925nm	520-015	SFH485-2 - IR
850-950nm		Filters: cut-off $950\,\mathrm{nm}$ minus cut-off $850\,\mathrm{nm}$
930-1000nm	511-094	LD271 - IR
950-1090nm		Filters: cut-off $1090\,\mathrm{nm}$ minus cut-off $950\,\mathrm{nm}$
1090-1200nm		XNite IR cut-off

drawbacks and limitations, which should be mentioned here.

The infrared imaging in the art conservation practice exploits wavelengths up to $2\mu m$[19], however the sensitivity of the standard CCD camera even after the ICF removal is cut off on $1200nm$. The camera optics is geometrically well balanced for the visible part of spectrum. Wavelengths from $700nm$ up to $1200nm$ require different focus setting than images taken in the visible light. The correct focus can be set for the visible or the IR part of the spectrum, respectively, by shifting the camera sensor. Therefore images from different modalities must be first geometrically aligned ([3]). In the proposed solution the geometrical alignment is achieved in the accordant software.

Reflections and light flares are very common defects visible on captured images especially in the IR spectrum, because the antireflection surface of the lens does not compensate these wavelengths. A varnish layer on the artwork makes the reflection problem even worse. An elimination of such reflections should start ”in-situ”, using direct light diffusion or by an exploitation of the polarizing filter on the camera.

Best results of the multispectral data acquisition are achieved with the uniform light source intensity. This is the most problematic part of the capturing ”in-situ”, where often uncontrolled light sources are present, such as windows. We recommend a creation of an auxiliary image for the light intensity balance. It captures a homogeneous color paper/canvas under the same light conditions as in the location of the captured artwork. Light conditions can be then normalized according to this auxiliary image (see Section 4 for more details).

Finally, we strongly recommend to photometrically calibrate the camera before any analysis of the pixel spectral response starts. Without an exact knowledge of the camera spectral response we cannot distinguish underdrawings or a specific paint material using only the captured data. The photometric camera calibration must be done according to the expert knowledge. Then an automatic post-processing and analysis of the acquired data can be realized.

III. PHOTOMETRIC CAMERA CALIBRATION

The goal of our approach is the utilization of the camera as a primitive spectroscope which is able to analyze the whole artwork. We will achieve a partially constant approximation of the spectral response of the artwork. This spectral approximation can be then used for the paint material identification. Knowledge of the camera sensitivity, see fig. 5, is necessary to achieve meaningful artwork representation. This can be find out by means of the photometric camera calibration. The calibration process as well helps to eliminate intensity values mixing due to the presence of CFA (color filter array).

The process of photometric calibration of a camera establishes the relation between pixel values produced by a given camera and photometric quantities such as SI light units. For the camera calibration it is necessary to have a calibrated light source, where we know the output light intensity for each wavelength sub-band, which we want measure. Well known light source is the Sun [17], however we used the calibrated light source HL2000 CAL-EXT (Ocean Optics, calibrated from $360\,\mathrm{nm}$ up to $1500\,\mathrm{nm}$) because of an easier setup for the measurement.

The calibration process will estimate the sensitivity of the camera $s(\lambda)$, where s is partially constant (for our purpose). We assume the same sensitivity function $s(\lambda)$ across the whole sensor.

For the camera calibration we will use the following transmittance model:

$$I = g \int_{\lambda} l(\lambda)s(\lambda)\,\mathrm{d}\lambda, \tag{1}$$

where I is the captured intensity, $l(\lambda)$ represents a light intensity emitted from the light source. Finally, g function describes a nonlinear (in general) dependency between the light and the intensity on the captured photography. The function g is dependent on ISO, a white balance, a gamma correction and on other software intensity compensations. In accordance with our measurements we approximate the function g as

$$g(x) = ax + b, \tag{2}$$

with different a and b for each camera sensor (RGGB). The estimation of $s(\lambda)$ was realized in two ways. The first approach is based on a filter based intensity measurement, while the other makes use of a monochromatic measurement. Both methods are easily repeatable even under limited conditions.

Fig. 2. Constructed LED panel and used filters. All filters have common diameter 77mm.

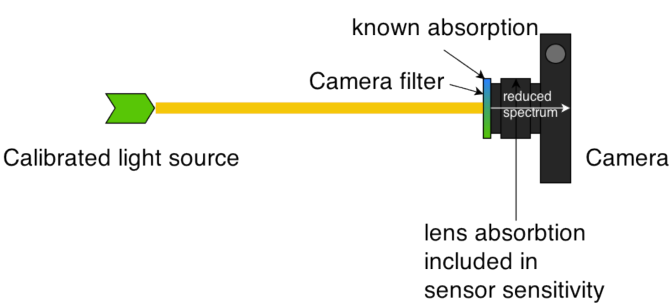

Fig. 3. Proposed scheme of the sub-band intensity measurement and the camera calibration.

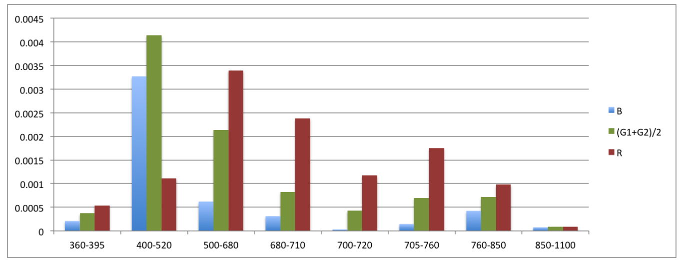

Fig. 4. Measured relative sensitivity of the camera segments (red, blue, green average). Horizontal axis contains 8 wavelength subbands. Vertical axis shows ratio between pixel response (measured intensity) and light intensity from particular subband. The sub-bands were constructed as a linear combination of the used filters.

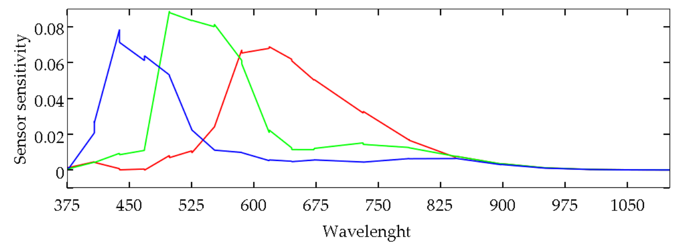

Fig. 5. The estimated sensitivity of camera segments. Values were measured for each 25nm, from 375 to 1050. Each step was captured twice with different camera ISO. The vertical skips in sensitivity curves correspond to multiple measurements in particular subband.

A. Filter based intensity measurement

The first approach to the camera calibration makes use of several filters and known calibrated light source. The light source is aimed directly into the camera. The camera is equipped consecutively with filters, used later for the artwork analysis (see fig. 3).

The formula (1) is now extended with $f_i(\lambda)$, which represents the transmittance of the filter i:

$$I_i = g \int_{\lambda} l(\lambda)f_i(\lambda)s(\lambda)d\lambda, \tag{3}$$

Measurements with different filters f_i and with a piecewise constant function s give us:

$$\begin{aligned} I &= A \times \vec{s} \\ s \approx \vec{s} &= A^{+} \times I, \end{aligned} \tag{4}$$

where A matrix contains in every row i-th values of $l(\lambda_j)f_i(\lambda_j)$. λ_j represents the interval, where s is approximated as a constant. Vector $\vec{s}$ therefore contains the sensitivity of the camera at intervals λ_j.

The discretization of the spectrum from 380 nm to 1200 nm was made according to the used filters. We obtain eight useful sub-bands (see fig. 4) in which we can measure the spectral response. These sub-bands were constructed as linear combinations of available measured filters (blue, green, orange, yellow, red, sepia and cut-off 680, 720, 760, 850).

B. Monochromatic intensity measurement

The second approach uses the same calibrated light source. In this case light spectrum was filtered to narrow sub-bands by a monochromator, the filters were not used. In contrast with the filter based estimation, the function s is measured for several wavelengths and then approximated by a polynomial.

Here, the model (1) must be extended with an extra light absorbance $D(\lambda)$ which reflects the reduction of the light intensity in the monochromator and with the parameter w, which reflects the function of the monochromator. The w function here is approximated by delta function. We neglect variance around filtered wavelength.

$$I = g \int_{\lambda} l(\lambda)s(\lambda)D(\lambda)w(\lambda)d\lambda \tag{5}$$

Then the narrowed light spectra is captured by an optical cable and is measured by the calibrated photodiode. The resulting intensity is evaluated in the camera, too. For each wavelength we evaluate the ratio of the camera-estimated intensity $g^{-1}(I)$ to the photodiode-estimated intensity I_p,

$$\frac{g^{-1}(I)}{I_p}. \tag{6}$$

The measurement was realized for 21 various wavelengths ranging from $317\,\mathrm{nm}$ up to $1103\,\mathrm{nm}$, for each wavelength multiple times with various expositions. Results of the camera calibration process is demonstrated in fig. 5.

IV. Application

The applicability of the proposed solution for multispectral cultural data acquisition and preliminary analysis is demonstrated here. While studying the *Fruit festoon* painting (see fig. 6) we collected 12 spectral sub-bands - ($I_{captured}$) (see fig. 8). Each sub-band was normalized - (I_{norm}) - according to the shutter speed (T) and the LED panel average intensity. Individual spectral sub-bands were mutually aligned using weighted mean method [11] to remove possible geometrical differences, introduced during the acquisition process.

The LED panel intensity was captured separately for further normalization - (I_{canvas}). At the position of an artwork a white canvas was placed and its image was captured. An average intensity for the whole canvas was computed - $E(I_{canvas})$ - and used for the normalization of captured sub-bands

$$I_{norm} = \frac{I_{captured}}{T * E(I_{canvas})}. \tag{7}$$

Problematic scans $605\,\mathrm{nm}$ and $700\,\mathrm{nm}$ were dropped, because the values were out of the range of the camera sensitivity.

To verify realized measurements a virtual coloring was created (see fig. 6). The acquired data were used to evaluate the normalization and to demonstrate the quality of the proposed solution.

Spectral curves in fig. 7 show pixel responses in each subband, values are extracted directly from both the original and the generated image, respectively, in fig. 8. Values are relative to each other (according to shutter speed normalization and LED panel average intensity). Two types of blue were selected for the comparison. A significant dissimilarity appeared only around $500\,\mathrm{nm}$.

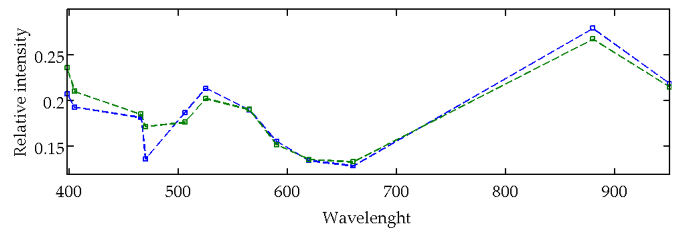

Fig. 7. Comparison of multispectral responses of two areas circled in fig. 6. Subband measurements were made by using LED light and camera RAW format normalized by shutter speed and segment sensitivity (in this case blue segment). Precision of the measurement can be influenced by used LED subbands and by the nonlinearity of the camera sensitivity. More significant dissimilarity appeared around 500nm.

V. Conclusions

We proposed an alternative approach to the multispectral data acquisition of the cultural heritage artifacts. The demonstrated solution is mobile and universal for any size of the artwork. It is based on the IR-modified camera with various filters or, if the camera is not equipped with filter holder, with the the LED panel, splitting the visual part of spectrum into eight sub-bands and two disjunctive IR sub-bands. The proposed solution is affordable and consists of commercial off-the-shelf products. Capturing of images is fast and does not require any special knowledge compared to other common documentation imaging. To ensure the requested accuracy, the photometric camera calibration was described. Two different approaches for the calibration were introduced, which could be chosen depending on the auxiliary tools availability. Both methods are easily repeatable even under limited conditions. Finally, we showed an exploitation of acquired images for the preliminary spectral analysis. The proposed methodology we successfully use in the art restoration practice.

We believe that the proposed system can spread the multispectral data analysis and made it available for general interested public. In the future, we plan to continue in the evaluation of the proposed system and to compare it to high-end systems.. We will concentrate on testing the calibration robustness and on comparison of the achieved spectral information to the results of the common spectrometer. Achieved experience will be utilized in the creation of the database of colors, pigments, and binding materials, where the spectral information will form the key entry in this database.

Acknowledgment

The authors would like to thank to Pavel Kvasnička for help with camera calibration. This work has been supported by Czech Science Fundation, (project no. P103/12/2211).

References

[1] Anila Anitha, Andrei Brasoveanu, Marco Duarte, Shannon Hughes, Ingrid Daubechies, Joris Dik, Koen Janssens, and Matthias Alfeld. Restoration of x-ray fluorescence images of hidden paintings. *Signal Process.*, 93(3):592–604, March 2013.

[2] Luca Poletto, Guido Maria Cortelazzo, Anna Paviotti, Filippo Ratti. Multispectral acquisition of large-sized pictorial surfaces. *EURASIP J. Image and Video Processing*, 2009.

Fig. 6. (left) - Tomáš Tichý (2008), the copy of Fruit Festoon by Nicolaes van Gelder, oil on canvas - $65 \times 50\,\mathrm{cm}$. (right) - the reconstructed image, created from the scanned data in various sub-bands. The blue channel was taken from scans in $405\,\mathrm{nm}$, $466\,\mathrm{nm}$, and $470\,\mathrm{nm}$, respectively, the green one was taken from $506\,\mathrm{nm}$, $525\,\mathrm{nm}$, and $565\,\mathrm{nm}$, and, finally, the red band from $590\,\mathrm{nm}$, $620\,\mathrm{nm}$ and $660\,\mathrm{nm}$. Two circles contain points to be compared with the ground truth, see fig. 7

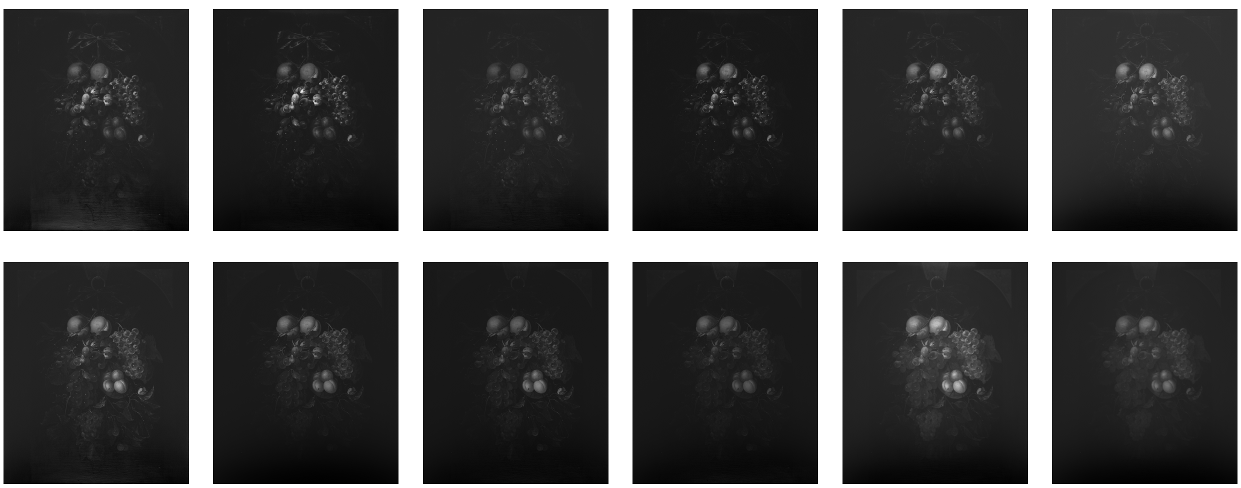

Fig. 8. Spectral responses in $398\,\mathrm{nm}$, $405\,\mathrm{nm}$, $466\,\mathrm{nm}$, $470\,\mathrm{nm}$, $506\,\mathrm{nm}$, $525\,\mathrm{nm}$, $565\,\mathrm{nm}$, $590\,\mathrm{nm}$, $620\,\mathrm{nm}$, $660\,\mathrm{nm}$, $880\,\mathrm{nm}$ and $950\,\mathrm{nm}$ (in the text order). In this case study the LED panel approach was used. Images are captured in camera RAW format, normalized by shutter speed and by segment sensitivity in particular subbands.

[3] Gianfranco Bianco, Fabio Bruno, and Maurizio Muzzupappa. Multispectral data cube acquisition of aligned images for document analysis by means of a filter-wheel camera provided with focus control. *Journal of Cultural Heritage*, 14(3):190 – 200, 2013.

[4] Franck S Marzani, Frank Boochs, Camille Simon Chane, and Alamin Mansouri. Integration of 3d and multispectral data for cultural heritage applications: survey and perspectives. *Image and Vision Computing*, 31:91–102, 2013.

[5] P. Carcagni, A. Della Patria, R. Fontana, M. Greco, M. Mastroianni, M. Materazzi, E. Pampaloni, and L. Pezzati. Multispectral imaging of paintings by optical scanning. *Optics and Lasers in Engineering*, 45:360367, 2007.

[6] R. Lahanier, C. Pitzalis, D. Colantoni, and P. Pillay. Analysis of multispectral images of paintings. *14th EuropeanSignal Processing Conference (EUSIPCO)*, pages 1–5, 2006.

[7] Bruno Cornelis, Ann Dooms, Frederik Leen, Adrian Munteanu, and Peter Schelkens. Multispectral imaging for digital painting analysis: a gauguin case study. pages 77980I–77980I–13, 2010.

[8] M. Caldon, M. Fedel, L. Poletto, N. Brusco, and G. Cortelazzo. Simultaneous acquisition of 3d shape and color texture from large frescoed areas. *Proc. SPIE: Optics for Arts, Architecture, and Archaeology*, (6618 O3A), 2007.

[9] M. Elias and P. Cotte. Multispectral camera and radiative transfer equation used to depict leonardo's sfumato in mona lisa. *Appl. Opt.*, (47):2146–2154, 2008.

[10] Laure Fauch. *Acquisition of Multispectral Color Images Using Light-Emitting Diodes*. PhD thesis, University of Eastern Finland, 2012.

[11] A. Ardeshir Goshtasby. *2-D and 3-D Image Registration: for Medical, Remote Sensing, and Industrial Applications*. Wiley-Interscience, 2005.

[12] K. Martinez, J. Cupitt, and D. Saunders. Methodology for art repro-

duction in colour: the marc project. *Computers and the History of Art Journal*, 6(2):1–20, 1996.

[13] K. Martinez. High resolution digital imaging of paintings. the vasari project. *Microcomputers for Information Management*, 8(4):277283, 1991.

[14] Gianluca Novati, Paolo Pellegri, and Raimondo Schettini. An affordable multispectral imaging system for the digital museum. *International Journal on Digital Libraries*, 5(3):167–178, 2005.

[15] A. Pelagotti, A.D. Mastio, A.D. Rosa, and A. Piva. Multispectral imaging of paintings. *IEEE Signal Processing Magazine*, 25(4):27–36, 2008.

[16] A. Ribes, R. Pillay, F. Schmitt, and C. Lahanier. Studying that smile. *Signal Processing Magazine, IEEE*, 25(4):14–26, 2008.

[17] C. Riordan, D. Myers, M. Rymes, R. Hulstrom, W. Marion, C. Jennings, and C. Whitaker. Spectral solar radiation data base at {SERI}. *Solar Energy*, 42(1):67 – 79, 1989.

[18] J.R.J. van Asperen de Boer. Reflectography of paintings using an infrared vidicon television system. *Studies in Conservation*, 14:96–118, 1969.

[19] Elizabeth Walmsley, Catherine Metzger, John K. Delaney, and Colin Fletcher. Improved visualization of underdrawings with solid-state detectors operating in the infrared. *Studies in Conservation*, 39(4):pp. 217–231, 1994.