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Calibration of commercially-available RGB colorimeters using a spectrometer

Visually accurate color reproduction is crucial in many areas ranging from art and fashion to cultural heritage restoration. For this reason, colorimetric probes are routinely used by color professionals. Colorimeters, however, need to be recalibrated at regular intervals in order to maintain their accuracy. We have developed a calibration method for commercially available colorimeters to improve their function and even fix some unusable devices. Our method uses a scientific-grade spectrometer as an etalon and a numerical procedure to propagate calibration up to target devices. Calibration of the colorimeter significantly increases its lifetime and precision, thus, decrease expenses and unnecessary waste.
Keywords: colorimeter, calibration, spectrometer, color reproduction

1. INTRODUCTION

Data is routinely processed, modeled, and simulated using computers in modern society. Digitalized color data are the main focus in many areas and professions. In the fields such as art, fashion, cultural heritage restoration, and designing, colors play an essential role (1; 2; 3). Although colors are well defined and machines can process them efficiently, human visual inspection is often required in some stages of the color processing workflow. Computer screens are usually used as test subjects for such testing. That is why it is paramount to achieve the most precise reproduction of colors on monitors to display colors as faithfully as possible. However, monitors wear off over time, and hence color representation becomes less reliable, and calibration is needed (4). Correct calibration also ensures constant and reproducible working conditions for different devices and users.

The most common way how to calibrate monitors is employing a colorimeter (5; 6). There are many different types of commercially available colorimeters. Their working principle can differ: either they measure a spectrum of incident light or, more commonly, they directly measure color coordinates using spectral filters of suitable shapes (6). The second principle allows manufacturers to reduce their prices considerably, making colorimeters widely accessible to color professionals. Colorimeters are initially calibrated by manufacturers. However, as time passes, they wear off, reducing the precision. In such a case, recalibration is needed.

This paper proposes and tests a calibration method based on using a scientific-grade spectrometer as an etalon. Our calibration method leads to a significant improvement of degraded colorimeters and, in some cases, even fix already unusable ones. Moreover, this method does not require any particular or calibrated monitor, and just a spectrometer is needed. When calibrated, the colorimeter works for all other monitors without limitations. We used two commercially available colorimeters to present our calibration method. The first one (Colormunki) seams to be only slightly miscalibrated while the second one (I1) suffers from noticeable hardware degradation.

2. THEORETICAL BACKGROUND

Since 1931 three coordinates color notation known as CIE XYZ is used (7). These color coordinates are defined so that all visible colors can be represented by positive coordinate values. Moreover, these coordinates are suitably selected so that the Y coordinate value is proportional to luminance. CIE XYZ coordinates are calculated from spectral power density using equations

$$\begin{aligned} X &= \sum_{\lambda=380\,\mathrm{nm}}^{780\,\mathrm{nm}} S(\lambda)\bar{x}(\lambda), \\ Y &= \sum_{\lambda=380\,\mathrm{nm}}^{780\,\mathrm{nm}} S(\lambda)\bar{y}(\lambda), \\ Z &= \sum_{\lambda=380\,\mathrm{nm}}^{780\,\mathrm{nm}} S(\lambda)\bar{z}(\lambda). \end{aligned} \tag{1}$$

In these equations $S(\lambda)$ stands for spectral power density of observed radiation (either directly emitted or reflected from studied object), and $\{\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)\}$ are the tabulated values of the CIE color matching functions, see Fig. 1, (8; 9).

2.1 Spectrometer

Spectrometers allow examining the spectrum of light. They can be used both on objects that emit their own light and those who merely reflect it. The principle of a typical compact USB spectrometer operation is depicted in Fig. 2 (6): Light enters the spectrometer through an optical fiber, which acts as a point light source. The divergent light beam is collimated by a concave mirror and hits the diffraction grating. Due to the angular dispersion, distinct colors of light are diffracted to different directions. The second concave mirror focuses every individual collimated color beam to a spot on a linear CCD detector. The spectrometer has a finite resolution due to pixel size, grid density, and slit thickness. All the properties mentioned above are characterized by the instrument function, which represents the instrument's response to a perfect monochromatic input. Up to the resolution limit given by the instrumental function, a spectrometer directly measures the spectral density $S(\lambda)$ from which color coordinates are calculated using Eqs. (1), see (6).

We chose the spectrometer as etalon mainly because of its efficient and precise calibration. Various discharge lamps with well-known wavelength peaks (Hg, Ne, Ar) were used to precisely calibrate the spectrometer wavelength axis. We used calibrated white-light source (Ocean Optics LS-1CAL) with tabularized irradiance values for different wavelengths for precise calibration of spectral power sensitivity. These two calibrations ensure that results obtained by the spectrometer are reliable.

2.2 XYZ colorimeters

XYZ colorimeters quantify colors by directly measuring the CIE XYZ coordinates. The XYZ colorimeters are equipped with three or four sensors (10). Each of these sensors contains a filter, which, by its spectral transmittance, copies one of the CIE XYZ color matching functions. For convenience, there might be two sensors for the X coordinate, one capturing lower and the second higher wavelengths, see Fig. 1. Note that there are colorimeters capable of measuring light spectrum and calculating CIE XYZ coordinates. However, their cost is significantly higher than those which merely measure the XYZ values using spectral filters. Therefore we selected two commercially available X-Rite colorimeters: Colormunki and I1, which represent a suitable choice for many color professionals due to their relatively low cost and user-friendly manipulation (6).

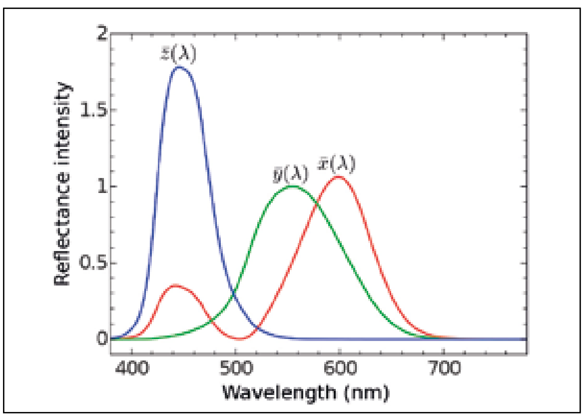

Figure 1: Depiction of CIE 1931 $\bar{x}, \bar{y}$ and $\bar{z}$ color matching functions as defined by CIE (6).

3. CALIBRATION SETUP

Our calibration method relies on a scientific-grade spectrometer (Flame by Ocean Optics) used as an etalon. Spectrometer calibration must be tested before the calibration of colorimeters can begin. As indicated in the previous paragraph, spectra of several discharge lamps were measured, and registered positions of emission peaks were crosschecked with tabularized values. Typically, the spectrometer shows the peak position with a precision of 0.6 nm which is sufficient for our purposes. Also, note that the instrument function of our spectrometer is about 2.0 nm (11). Subsequently, the frequency-dependent detection efficiency of the spectrometer is compensated by measuring its response to the calibrated source of white light (Ocean Optics LS1-CAL). The registered spectral density is $D_w(\lambda)$ whereas the true spectral density of the light source is $S_w(\lambda)$.

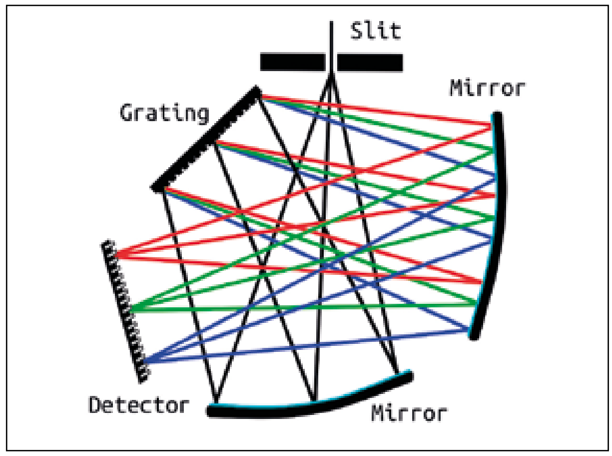

Figure 2: Schematic depiction of the principle of operation of the Czerny-Turner type spectrometer (12).

Once the spectrometer testing is finished, it is mounted into a simple setup depicted in Fig. 3. An uncalibrated screen is used to produce color patches that are simultaneously captured by the spectrometer and the to-be-calibrated colorimeter.

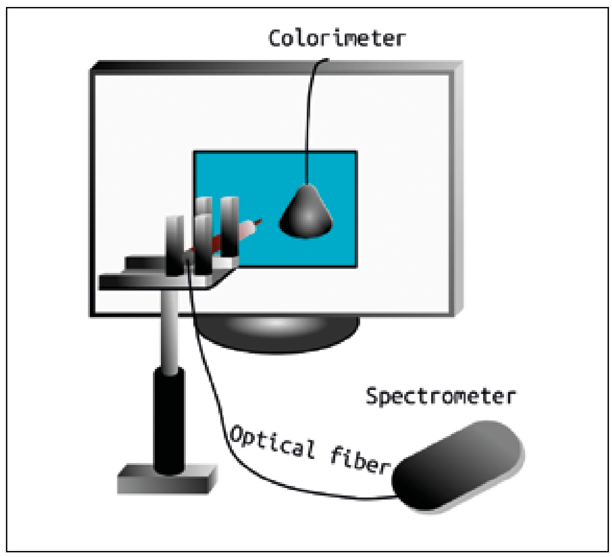

Figure 3: Schematic depiction of the experimental setup.

The Argyll CMS software suite was used to generate a representative set of $N = 175$ color patches via `targen` command (Note that Algyll CMS is actually a bundle of multiple single-purpose executables.)

```
targen -f 175 -r patches
```

The obtained patches.ti1 file stores information about the patches coordinates in CIE RGB color space. The computer screen projected the patches, and Argyll's `dispread` measured responses of the colorimeter.

```
dispread patches
```

Resulting XYZ coordinates of all the patches labeled $XYZ_i^{(c)}$ for $i = 1 \cdots N$ were saved into patches.ti3 file.

To measure the same color patches with the spectrometer, we programmed our software that displays the patches stored in the patches.ti1 file and measures the corresponding spectrum $D_i(\lambda)$ (i iterates over patches). The true spectral density of the i-th patch is then calculated as

$$S_i(\lambda) = D_i(\lambda)\frac{S_w(\lambda)}{D_w(\lambda)}, \tag{2}$$

for all wavelengths λ. Equation (1) provides a direct way for obtaining $XYZ_i^{(s)}$ color coordinates of the patches measured by the spectrometer. The calculated values were stored in spec.ti3 file. Coordinates obtained by both devices should ideally match. In reality $XYZ_i^{(c)} \neq XYZ_i^{(s)}$. To find a correction for the colorimeter measurements, one searches for a function $f(XYZ_i^{(c)}) = XYZ_i^{(s)}$ for all i. Nevertheless, even if such a function exists, it would not be easily implemented in end-user software and is generally prone to overfitting. Therefore we have limited ourselves to a first-order approximate correction provided by a 3×3 matrix M. The goal is to find a matrix that minimizes differences between color coordinates obtained by spectrometer and probe, respectively

$$\min_M \sum_{i=1}^{N} \Delta(XYZ_i^{(s)}; M\ XYZ_i^{(c)}), \tag{3}$$

Where Δ stands for a suitable color difference estimation function. For this task, one can directly use Argyll's function `cxxmake`, as shown in the following command line.

```
ccxxmake -t l -Y r -f spec.ti3,patches.ti3 mat
```

to search for the matrix M fulfilling Eq. (3). In principle, higher-order calibration can be achieved by using a more complex transform, but we found out that the linear matrix transformation is sufficient and more stable. In addition, Argyll also supports the application of such calibration matrix M. Therefore, even end users can easily implement a calibration matrix for the next measurements.

4. CALIBRATION TESTING

For testing, we generated another file (test.ti1) containing 175 new random patches via `targen` command.

```
targen -f 175 -q test
```

Once again, we measured these patches with spectrometer and colorimeter via `dispread` function, but this time we also used the obtained `mat.ccmx` calibration file.

```
dispread -X mat.ccmx
```

To evaluate the improvement after calibration, we analyzed two color properties (lightness and chroma) which are based on CIE $L^*a^*b^*$ and CIE $u'v'$ coordinates, respectively (5). Precision in lightness measurement by the colorimeter translates into the linearity of its detectors and can not, apart from a constant shift, be calibrated by a linear matrix transformation M. Measured chroma and saturation, on the other hand, depend strongly on the imposed matrix correction. This is why lightness on one hand and chroma and saturation on the other are analyzed independently. We also chose these quantities for their homogeneous distance between colors in their color spaces. All XYZ_i coordinates measured by the spectrometer and the colorimeter, respectively, were translated into L^*, u' and v' coordinates using

$$u' = \frac{4X}{X + 15Y + 3Z}, \quad v' = \frac{9Y}{X + 15Y + 3Z}, \tag{4}$$

$$L^* = \begin{cases} \left(\frac{29}{3}\right)^3 \frac{Y}{Y_n}, & \text{if } \frac{Y}{Y_n} \leq \left(\frac{6}{29}\right)^3 \\ 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16, & \text{else} \end{cases}, \tag{5}$$

$$a^* = 500\left(\frac{X}{X_n} - \frac{Y}{Y_n}\right), \tag{6}$$

$$b^* = 200\left(\frac{Y}{Y_n} - \frac{Z}{Z_n}\right), \tag{7}$$

where X_n, Y_n, Z_n are normalization coefficients. Chromatic distances between colors measured by the colorimeter and spectrometer can be calculated using Euclidean distance in CIE $u'v'$ coordinates

$$D = \sqrt{(\Delta u_i')^2 + (\Delta v_i')^2}, \tag{8}$$

where $\Delta u_i' = u_i'^{(s)} - u_i'^{(c)}$ and $\Delta v_i' = v_i'^{(s)} - v_i'^{(c)}$ represent the difference between coordinates measured by the spectrometer and colorimeter, respectively. We also denote $\Delta L_i = |L_i^{*(s)} - L_i^{*(c)}|$ the distance between lightness measured by the spectrometer and colorimeter, respectively. As overall quantifiers of calibration performance, we use the mean values over all test patches

$$\bar{L} = \frac{1}{N}\sum_{i=1}^{N} \Delta L_i, \quad \bar{D} = \frac{1}{N}\sum_{i=1}^{N} \Delta D_i. \tag{9}$$

To quantify improvement ratio of the calibration, we first had to calculate L^*, u', v' coordinates using (4) and (5). Then we were able to use Eq. (8) to calculate D and finally obtain mean $\bar{L}$ and $\bar{D}$ values from (9). Examples of the obtained results are shown in Tab. (1) and (2). Note that the first patch corresponds to the white standard used for power calibration. Hence the difference ΔL is 0 by definition. All quantities were calculated with and without the established correction matrix M. Hence the left column corresponds to colorimeter performance before calibration and the right column after calibration.

If we look at the results obtained by the Colormunki probe, we can see that our calibration method reduced mean Euclidean distance $\bar{D}$ in CIE UV color space from 0.025 to 0.012. Mean lightness $\bar{L}$ is also slightly decreased from 0.877 to 0.793, which was also desirable. In the case of the I1 probe, we can see also significant improvement of $\bar{D}$ from 0.035 to 0.024 and $\bar{L}$ from 0.924 to 0.787. This correction is so significant that the difference between the color profile established by the I1 probe before and after calibration was clearly visible by the naked eye, see

Fig. 4. As expected, the chroma difference $\bar{D}$ was reduced by a factor of 2.1 and 1.4 while lightness difference $\bar{L}$ was only improved by factor 1.1 and 1.2 for the two colorimeters respectively.

	ΔD		ΔL	
N	Before cal.	After cal.	Before cal.	After cal.
1	0.018 7	0.003 2	0	0
2	0.024 4	0.004 9	0.078 1	0.001 0
3	0.018 7	0.003 2	0.036 7	0.049 7
4	0.018 9	0.003 4	0.031 5	0.031 5
5	0.047 1	0.032 0	2.349 8	2.345 6
6	0.056 8	0.050 5	0.039 9	0.194 6
7	0.013 1	0.008 0	0.614 3	0.341 9
8	0.007 4	0.002 4	0.644 4	0.257 3
9	0.016 7	0.004 4	0.531 8	0.217 4
10	0.014 0	0.003 7	0.460 9	0.183 1
⋮	⋮	⋮	⋮	⋮
	$\bar{D}$		$\bar{L}$	
Results	0.024 9	0.012 1	0.877 1	0.792 5

Table 1: Comparison of measurement results obtained by the Colormunki probe before and after calibration.

	ΔD		ΔL	
N	Before cal.	After cal.	Before cal.	After cal.
1	0.026 5	0.010 5	0	0
2	0.034 5	0.009 7	0.243 5	0.382 2
3	0.025 2	0.008 8	0.242 4	0.026 9
4	0.026 4	0.010 4	0.227 0	0.031 5
5	0.281 2	0.273 5	2.063 2	1.945 9
6	0.057 5	0.073 3	0.943 9	0.265 0
7	0.014 9	0.044 4	1.868 2	0.338 5
8	0.008 0	0.039 9	1.735 7	1.480 5
9	0.022 7	0.032 7	1.567 0	1.373 1
10	0.020 5	0.023 5	1.207 7	1.004 0
⋮	⋮	⋮	⋮	⋮
	$\bar{D}$		$\bar{L}$	
Results	0.034 7	0.024 0	0.924 3	0.786 6

Table 2: Comparison of measurement results obtained by the I1 probe before and after calibration.

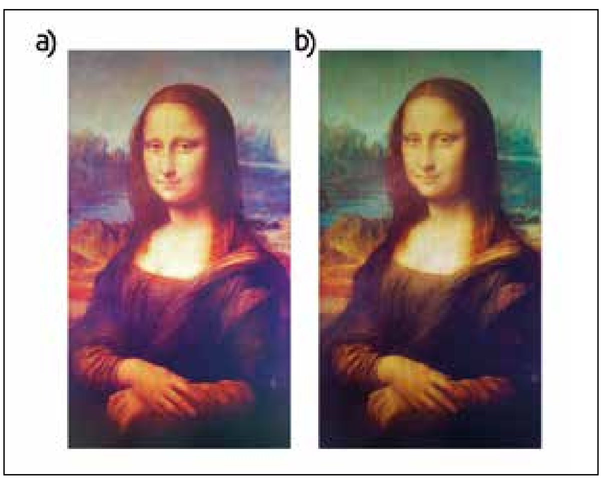

Figure 4: Two-color profiles used on the famous Mona Lisa painting by Leonardo da Vinci (taken from (13)) established by I1 probe a) before calibration and b) after calibration.

5. CONCLUSION

Our goal was to develop a calibration method that uses a scientific-grade spectrometer as an etalon. The proposed method provides a fast and reliable way to calibrate commercially available colorimetric probes. We support our result by comparing the actual results obtained by two colorimetric probes before and after calibration. Moreover, we showed that the improvement in case of the damaged colorimeter I1 is distinctly visible even by the naked eye. We also want to highlight that the 3×3 matrix type of our calibration offers practical advantages like accessibility for end-user and the opportunity to apply it for all measurements in Argyll software directly.

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Věrohodné zobrazení barev je zásadní v mnoha oblastech, od umění a módy až po obnovu kulturního dědictví. Z tohoto důvodu jsou kolorimetrické sondy běžně používány profesionály v oblastech zabývajících se problematikou barev. Kolorimetry je však nutné v pravidelných intervalech rekalibrovat, aby byla zachována jejich přesnost. Vyvinuli jsme metodu kalibrace pro komerčně dostupné kolorimetry, která umožňuje zlepšit jejich funkci a v některých případech opravit již nepoužitelná zařízení. Naše metoda používá vědecký spektrometr jako etalon a numerickou metodu, která poskytuje kalibrační soubor. Ten poté lze aplikovat přímo na cílové zařízení. Kalibrace kolorimetru výrazně zvyšuje jeho životnost a přesnost, a tím snižuje zbytečné plýtvání zdrojů na nová zařízení.
Klíčová slova: kolorimetr, kalibrace, spektrometr, zobrazení barev