Digital camera filter design for colorimetric and spectral accuracy

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Abstract

A filter optimization was investigated to design a set of filters for a five channel multi-spectral camera, three of which result in high colorimetric performance when used alone, and the full set having high quality spectral performance. Each candidate filter was selected from a set of 33 glass filters with three different thicknesses where filters may be combined in optical series. The effectiveness of the filter selection is demonstrated by computer simulation taking into account the spectral sensitivity of the imaging system, and a comprehensive database of natural and man-made object spectral reflectances.

1 Introduction

Theoretically, the spectral sensitivities of a color imaging apparatus should satisfy the Luther condition in which the spectral sensitivities are a linear transformation of color matching functions. However in most cases it is not possible to satisfy the Luther condition due to the physical limitations of the manufacturing process. Optimization of spectral sensitivities has been the subject of much research in color photography[1,2] as well as digital devices.[3-9] In prior studies, optimizations of the spectral sensitivities were carried out in density units,[1,2] color difference[3,4] and a metric based on color difference.[5-7] Filter optimization using colorimetric-based cost functions are highly desirable for reproducing colors under controlled illumination. Three spectrally distinct channels are typically used although a fourth layer in photography showed advantages in color reproduction.[2] On the other hand, for a purpose of spectral matching, three channels are not sufficient and five or more spectrally distinct channels are required.[4] The traditional filter designs for trichromatic capture are not appropriate for multi-channel image acquisition when spectral reflectance estimation is the goal because spectral band selectivity is poor and there is a lack of sensitivity for the near infra-red region of the electromagnetic spectrum. For example, without sufficient data in the near infra-red region we were unable to obtain good spectral matches using a multi-channel image acquisition for colors such as cobalt blue due to a near infra-red tail.[10]

In our approach, we combine both colorimetric and spectral filter designs performing a two-step filter selection from a database of available color glass filters for multi-channel digital image acquisition. In the first step, a set of filters is selected colorimetrically for a digital camera system under pre-determined illumination using various cost functions. Based on the selected colorimetric filter set, additional filters are chosen in order to improve the spectral estimation accuracy of the multi-channel imaging system. In order to evaluate this spectral estimation, a camera signal simulator was built using the spectral sensitivities of the optical path in the imager and a database of spectral reflectances as well as spectral information of the illuminants. The simulated camera signals are used in conjunction with the eigenvectors of the target reflectances to estimate the spectral reflectance for each set of filters. A filter set that consistently gives accurate results for various cost functions, for various reflectance databases and under various illuminants can be selected as the desired filter set for multi-channel image acquisition.

2 High quality colorimetric and spectral performance filter design

The optimization merit functions chosen for the colorimetric performance filter design are μ-factor[7] and Universal Measure of Goodness (UMG).[5] The former is a data-independent metric, approximating the orthonormal CIE color matching functions with the linear transformations of the spectral sensitivity functions by minimization. The latter is a data-dependent metric, minimizing the average the CIE L*a*b* color difference between the measurement and estimation from the channel signals. It is also dependent on the recording and viewing illuminant pairs. If the noise model of the imager is available, it might be able to additionally process noise information. UMG requires much more computation than μ-factor since UMG needs to calculate the various statistical information of all the object samples. The better choice of filters should be a comprehensive comparison of the results from the two metrics mentioned above (μ-factor and UMG).

The chosen three channels that give high quality colorimetric performance are selected as the first three of five channels for a spectral estimation system. Considering the fact that it is desirable to sample in the near infra-red region of the spectrum (to capture colors such as cobalt blue) the fourth filter is chosen to be a near infra-red band-pass filter. The fifth filter is selected by an optimization process. A plethora of spectral reflectance samples from targets and spectral databases are used to generate eigenvectors. The digital signals corresponding to the spectral reflectance samples are simulated using a model of the imaging system that includes the spectral transmittance of the candidate filters, the spectral sensitivity of the imaging device, the spectral reflectance of the individual patches of the targets and the spectral power distribution of the illuminants. The simulated digital counts are then related to the coefficient of eigenvectors produced by a reference target and a transformation is generated from digital signals to spectral reflectance. The generated transformation is used to estimate the spectral reflectance of each test target. The color difference equation, metamerism index and root-mean-square error factor between the measured and predicted spectral reflectance are calculated and they are used as cost functions to select the best combination of filters.

3 Experimental

The imaging system we used was a Roper Scientific Photometrics Quantix 6303E monochrome CCD camera using a cooled grade 3 Kodak CCD type KAF-6303E. The camera provides 3,072 by 2,048 pixels image, 12 bit linear data with the availability of three different gains and 2 different readout speeds (1MHz and 5MHz). A motorized filter wheel manufactured by Integrated Scientific Imaging Systems with six 1.5 inch filter positions is attached in front of the camera. The purpose of this experiment is the design of the filters for the filter wheel resulting in both high quality colorimetric reproduction using three channels and high quality spectral image reproduction using all five bands. A Nikon 50 mm lens was mounted in front of the filter wheel and a Unaxis Balzers broadband near-infrared radiation reduction filter was used in front of the lens with the help of a filter holder. The imaging system is depicted in the Fig. 1. The spectral sensitivity of the imaging system was measured for the following configuration: the CCD sensor with gain 2 and 5 MHz readout speed, the Nikon lens adjusted to fstop 16, and the broadband near-infrared radiation reduction filter in front of the lens. A monochromatic light was produced using a double monochromator manufactured by Optronic Laboratories Inc. (Model 740A-D) with 5 mm round slit and a stabilized Optronic Laboratories Inc. light source module (Model 740-20). The monochromatic light varied from 380nm to 780 nm in intervals of 5 nm were imaged by the Quantix camera through a diffuser and the resulting digital counts in the central region were averaged. Next, the camera was replaced by a calibrated detector with known responsitivity (Optronics Laboratories, Inc. OL730-5C Silicon Photo detector SIN:1152 Hex Key) and the source spectral irradiance was measured over the same range used above by the Optronics Laboratories Inc. radiometer 730 A. The relative spectral sensitivity was calculated using the averaged digital counts, the measured irradiance and the responsivity of the calibrated detector. The normalized spectral sensitivity is shown in Fig. 2.

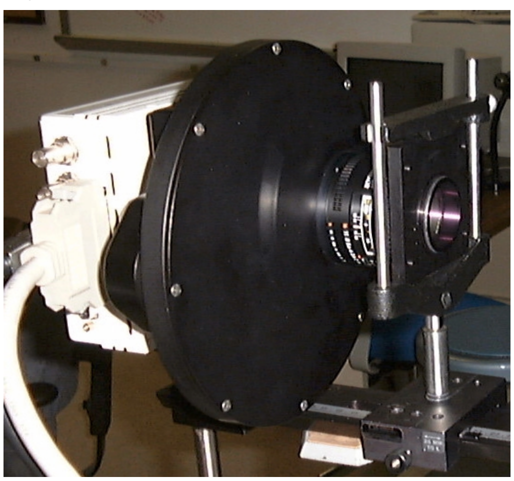

Figure 1. Quantix camera with filter wheel, Nikon lens and near infra-red cutoff filter.

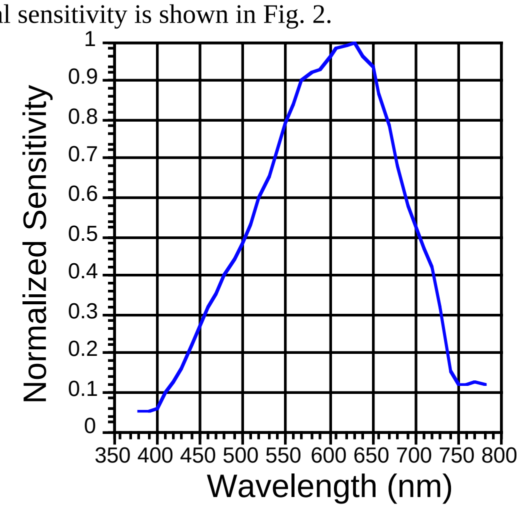

Figure 2. Normalized spectral sensitivity of the imaging system.

A set of 33 glass filters manufactured by Schott were considered in the filter design for high quality of colorimetric performance. The transmittance of all these filters were defined with a thickness of 3mm, easily varied to 2mm and 1mm, via equations 1 and 2:

$$T_{2mm} = T_{3mm}^{2/3} \tag{1}$$

and

$$T_{1nm} = T_{3mm}^{1/3} \tag{2}$$

where T_{1mm} , T_{2mm} and T_{3mm} are respectively the filter transmittance for 1mm, 2mm and 3 mm of thickness.

If a composed filter of one channel is layered with several filter elements with different thickness, its total transmittance T_{total} can be written as:

$$T_{total} = \prod_{i=1}^{k} T_i^{x_i/3} \tag{3}$$

where x_i is the thickness of the corresponding filter element and k is the total number of filters. So the total spectral sensitivity function including the imaging system spectral sensitivity is

$$SS = D \cdot T_{total} \quad (4)$$

where $\boldsymbol{D}$ is the spectral sensitivity function of the imaging system.

The glass filters consist of 17 long-pass cut-off filters, 14 green and red band-pass filters and 2 infra-red cut-off filters. Instead of trying the brute force method of combining all possible combination of filters with three types of thickness we opted to consider some constraints to reduce computational load. It can be seen that even for searching 3 optimal filters from the set, the computation will take too much time. Some analysis on the filter information has to be done in order to finish the search in a reasonable time. From a previous result,[5] single-peaked filters are preferred, and the peak position of blue channel is located between 400nm and 500nm (strictly 420 —470nm), that of green channel between 500nm and 600nm (strictly 520 —550nm), that of red channel between 550nm and 650nm (strictly 565 —630nm). Using the strict range of the three channels, the corresponding computation load is much less since the range is even smaller.

After determination of the trichromatic filter set, four targets were selected in order to determine the remaining two filters: the GretagMacbeth ColorChecker DC digital camera color reference chart, a target made using 226 chips from the New Munsell Student Color Set, a set of four panels painted by a painting conservator from the National Gallery of Art, Washington, D.C. that consist of 219 patches with pigments used in restoration, and an oil painting target consisting of 68 pigments representing blues, greens, yellows, reds, earth colors, brown and radiant colors that are among the most frequently used by artists.[11] The spectral reflectances of the ColorChecker DC and the Munsell Target were measured using the Gretag Spectrolino 45/0 spectrophotometer and the spectral reflectances of the painting targets were measured using the GretagMacbeth SpectroEye 45/0 spectrophotometer. Besides the targets mentioned above, we also used spectral reflectance of 219 natural colors found at a spectral reflectance database at the University of Joensuu[12] and 170 object spectral reflectances measurements available at the University of North Carolina.[13]

The imaging system signals were simulated constrained the fourth filter as a near infra-red band-pass filter for each target and for D50 illumination for each possible glass filter as the fifth filter of the system. Color difference in CIE94, spectral reflectance rms error and metamerism index using Fairman parameric method[14] between standard illuminants D50 and A using ΔE^*_{94}were calculated for each combination.

4 Results

This research is still being performed and refined. A preliminary three-filter selection for high quality colorimetric performance results in an average μ-factor of 0.97 and UMG of 0.76 of the cost function values obtained under D65 and A illuminants as shown in the Table I. The first illuminant in the parenthesis is the recording illuminant and the second illuminant in the parenthesis is the viewing illuminant for the UMG quality factor.

Table 1. Performance of the selected filter for high quality colorimetric performance

Quality factor	**μ-Factor**	**UMG (D65, D65)**	**UMG (D65, A)**	**UMG (A, D65)**	**UMG (A, A)**	**UMG (Average)**
Selected filter	0.97	0.86	0.60	0.85	0.65	0.76

Table 2. Performance of the selected filter for high quality spectral performance

Target	**Mean ΔE^*_{94} (D50, 2°)**	**Maximum ΔE^*_{94} (D50, 2°)**	**Mean spectral reflectance rms error factor**	**Maximum spectral reflectance rms error factor**	**Mean Metameric Index (ΔE^*_{94}, D50, A)**	**Max Metameric Index (ΔE^*_{94}, D50, A)**
ColorChecker DC	0.7	3.6	0.020	0.053	0.6	5.8
Munsell Target	0.6	3.2	0.018	0.060	0.5	2.6
Conservation Target	0.9	3.3	0.037	0.102	0.6	3.1
Oil Paint Target	0.7	1.9	0.030	0.066	0.6	2.2
Nature spectra	1.3	5.0	0.037	0.087	0.5	2.2
Object spectra	0.6	16.2	0.020	0.023	0.6	21.8
Overall	**0.8**	**5.3**	**0.027**	**0.065**	**0.6**	**6.3**

As the result of the high spectral performance filter design a fifth filter was selected as a filter with band-pass near-UV region giving an overall ΔE^*_{94} color difference (D50, 2 degree observer) of 0.8 in average and 5.3 as the maximum value and an average spectral rms error factor of 0.03. It is possible to see from Table 2 that the only set with high color difference was the object spectra set. In this set the only color with ΔE^*_{94} above 2.1 was the Swiss knife red as shown in

Figure 3. This reflectance presents a very steep inclination that is often difficult to estimate using eigenvector analysis. In the other hand, the best estimation for this set was the brown suede color with ΔE^*_{94} of 0.02 whose match is shown in the Figure 4.

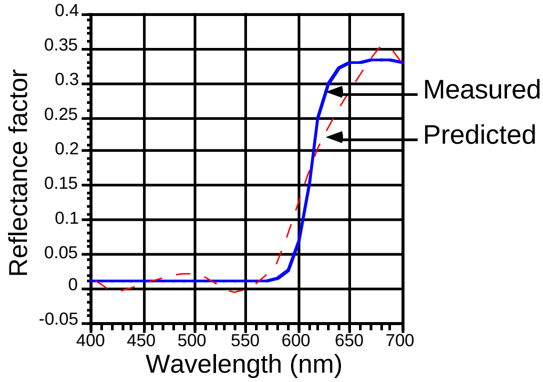

Figure 3. Spectral estimation of the Swiss knife red color.

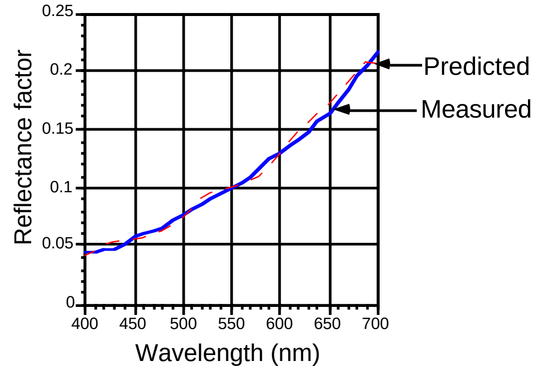

Figure 4. Spectral match for the brown suede color.

5 Conclusion

We can conclude that it is possible to find a set of filters for multi-channel imaging and spectral estimation where a subset of filters can be optimized for colorimetric performance as well. This approach adds the advantage of flexibility to our image acquisition system so that in one configuration it will produce highly accurate colorimetric rendition from three channels and in its alternative setup using an additional two channels it will deliver high quality spectral estimation. Currently we are performing noise characterization of our imaging system to include noise considerations in our filter design.[4] In this case Wiener estimation would be used instead of eigenvector analysis for spectral estimation. Noise propagation through various components and stages of our imaging system should also be addressed.[15] This is a work in progress and the designed filters is in process of evaluation using an actual imaging system.

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