

Spectral and Colorimetric Constancy and Accuracy of Multispectral Stereo Systems

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Abstract

Stereo multispectral systems enable at the same time the acquisition of accurate spectral and depth information. The left and right cameras of the system can either present the same spectral sensitivities (e.g., a monochrome sensor with 7 different band-pass color filters sequentially placed in front of it for both cameras) or complementary sensitivities. The latter alternative can be accomplished by the utilization of two different filters or sets of filters for each camera of the stereo system. Even if each camera alone does not provide complete spectral information about the acquired scene, the estimation of the spectra becomes possible when both cameras are considered together. But since the reflectance spectrum of objects is a function of the wavelength, of the illumination angle and of the observation angle, the information from the left and the right cameras is generally different. This problem is already known from the RGB stereo imaging, and becomes even more relevant when it comes to multispectral stereo imaging, whose purpose is in addition an accurate color recording.

In this paper, we analyze this problem experimentally by acquiring different series of stereo data and comparing them for determined regions of interest. We acquire two scenes under different lighting conditions with a standard color chart and objects whose reflectance spectra have a limited observation angle dependence. We utilize real multispectral data as well as spectra measured with a spectrophotometer to verify camera acquisition and compare them for different observation angles. We then estimate the acquired spectra using several of the possible spectral compositions, given by all the color channels available for the left and for the right camera. These estimated spectra are compared to the ground truth data and we show that the stereo system with 7 channels cameras using only 3 color channels from one camera and the 4 complementary color channels from the other camera has a good colorimetric accuracy.

Introduction

Multispectral cameras sample the visible wavelength range more finely than RGB cameras: they feature, e.g., bandpass color filters in front of a monochrome camera to obtain a better spectral accuracy than with the broadband red, green and blue channels of RGB cameras. Depending on the lighting conditions and the reflectance spectra analyzed, seven to sixteen different color filters are required for an accurate spectral estimation of the acquired scene [11, 1, 9, 6, 10]. Stereo systems, which allow the acquisition of 3D information from a scene, are commonly made of RGB cameras. In the last years, multispectral cameras have also been used in stereo systems, thus giving access to both accurate spectral and depth information from the acquired scene. These multispectral cameras are often RGB cameras with color filters placed in front of one or both cameras [14, 8, 20, 5, 17, 18], but can also be monochrome sensors with more than three different

optical filters.

In RGB stereo imaging, color differences between the two acquired images can not be avoided. They are caused by different lighting conditions, by reflectance spectra of the imaged objects which change with respect to the observation angle or by different spectral sensitivities of the two cameras for instance. These color differences are an important issue for stereo imaging since they make the stereo matching more difficult due to the different values in the red, green and blue color channels [7, 23]. Many algorithms have been developed in the past years to solve this problem, and the performance of some of them are evaluated by Xu et al. [24].

The correction of the color differences must be performed before any disparity estimation step in RGB imaging. In multispectral stereo imaging, the problem can also be comprehended in a different way. Indeed, mutual information is a widely-used similarity metric for multimodal imaging systems [16] and can be used to measure the transversal distortions between the color channels of multispectral cameras featuring a filter wheel for instance [3]. This metric can thus be utilized to match the right and the left image of the stereo system. The differences of color are therefore not a problem anymore for the disparity estimation, but remain an issue for the spectral estimation of the acquired scene. When using multispectral cameras instead of RGB cameras, one wants to achieve a good spectral accuracy, and the spectral estimation based on a multispectral stereo system should ensure this point. As far as the authors know, the spectral or colorimetric differences between the two multispectral images obtained with a stereo system has only been analyzed for patches of a color chart and the errors of the resulting multispectral stereo information were calculated only with respect to a spectrometer measurement at one given position so far [19]. In this paper, we also performed the analysis for other objects than color patches. Moreover, we took as reference spectral measurements for different positions, and not only for one unique position, to reflect the angle dependence of the measurement, and considered the different spectral reconstructions that are possible given the spectral channels available for the left and the right camera.

In the following, we will first explain how the cameras are simulated and which spectral data are used for the measurements and acquisitions. We will then give details about the experimental setup and the measurements. The results concerning the imaging with a real camera and the simulation are given before the conclusions.

Modeling and Acquisition with Color Cameras

We first consider a camera model giving the gray value from each of the color channels of the camera. Here, we assume that the camera transfer function is linear, i.e., that the relation between the irradiance reaching the sensor and the resulting gray

value given by the camera is linear, and we set the exposure time and the area of the sensor to unit values. The gray value g_i of color channel i is then given by the simplified equation

$$g_i = (r(\lambda_1) \dots r(\lambda_N)) \cdot \begin{pmatrix} s_i(\lambda_1) \\ \vdots \\ s_i(\lambda_N) \end{pmatrix} \quad (1)$$

where $s_i(\lambda)$ is the spectral sensitivity of color channel i and $r(\lambda)$ is the spectrum acquired with the camera, both given for discrete values of the wavelengths from λ_1 to λ_N . Camera noise is then added according to

$$g_i^n = g_i + n(g_i) \quad (2)$$

where the noise $n(g_i)$ is modeled as being normally distributed [2, 18]. This noisy gray value g_i^n has then to be quantized to 8 or 12 bits, depending on the camera type. The acquired spectrum can finally be estimated from this quantized gray value g_i^q using Wiener estimation to obtain the estimated spectrum $\hat{r}(\lambda)$, but other estimation methods can be utilized as well, for instance neural networks [12] or a wavelet basis [13].

Multispectral Cameras

The multispectral camera used here consists of a monochrome sensor and 7 bandpass color filters positioned in a filter wheel that is placed in front of the sensor. The filters are interference filters with their central wavelengths spread from 400 nm to 700 nm in steps of 50 nm and the bandwidth of the color channels is about 40 nm, as shown in Fig. 1(a). In the remainder of this paper, we will refer to this multispectral camera as *7 channels camera*.

We also seek to use another type of multispectral camera consisting of an RGB camera and color filters, thus enabling imaging with more than 3 color channels. The main drawbacks of such cameras compared to the 7 channels multispectral camera presented in the previous paragraph is the loss in spatial resolution due to the Bayer pattern of the red, green and blue filters on the sensor and the possible loss in spectral resolution, since less color channels are utilized. With such cameras, the acquisition can be performed by acquiring two images one after the other with two different color filters [21, 8], but the acquisition of images with 6 color channels in one *unique shot* becomes possible, when 2 cameras with two different color filters are utilized aligned using a beam splitter [14, 5] or in a stereo configuration [18]. The latter type of stereo multispectral camera using RGB cameras and color filters is analyzed in this paper.

The RGB camera will be referred to as *3 channels camera* and the multispectral camera constituted of the RGB camera and color filters placed in front of it as *6 channels camera*.

Color Filters for RGB Camera

In the literature, many different color filters have been selected to convert an RGB camera into a 6 channels camera. Some authors used dichroic filters splitting each of the R, G and B channels into two halves, but did not explain this choice in detail [14, 8, 20, 5]. In [22], the filters are chosen so as to obtain color channels as independent as possible, but the noise and quantization present in cameras are not taken into account. Berns et al. simulated the camera, including normally distributed noise (mean of zero and standard deviation of 2.5%) but no quantization, and compared the different available filter pairs using the spectral and colorimetric accuracy [2]. In [15], the basis vectors of the acquired spectra are used and then the mean square error

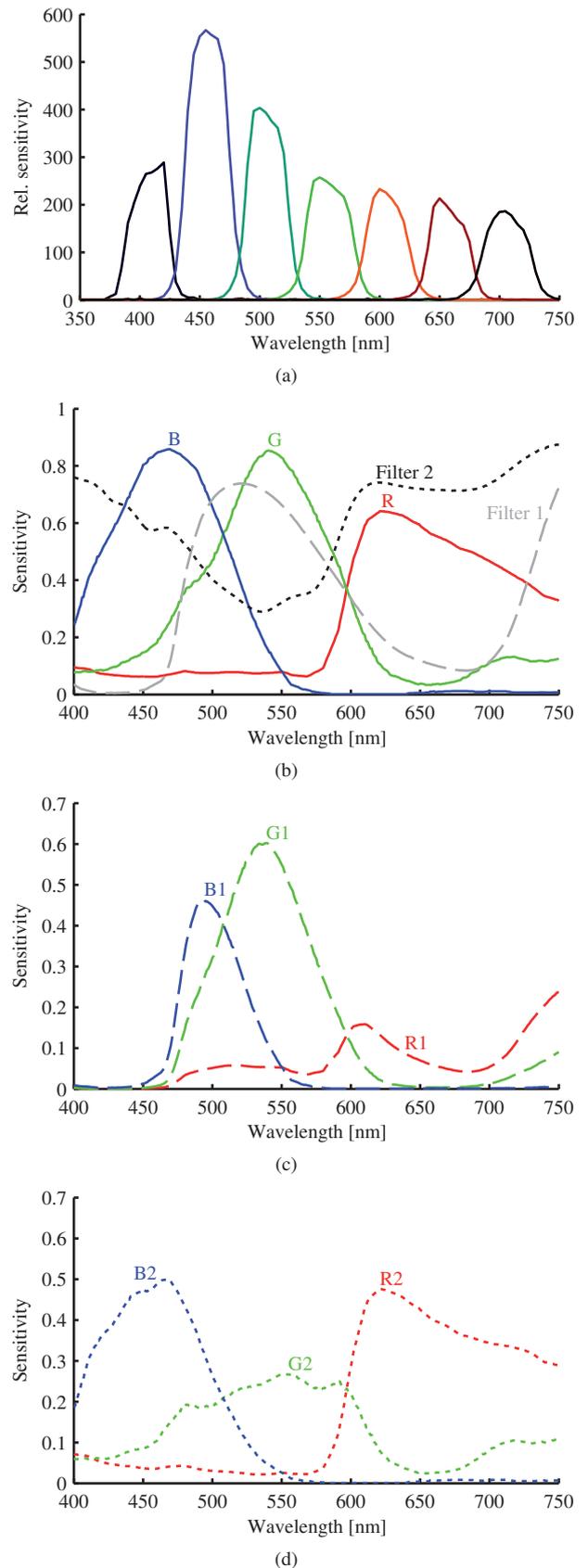


Figure 1. Spectral sensitivity of the seven color channels of the 7 channels camera (a); Spectral sensitivities of the R, G and B channels of the RGB camera (3 channels camera) and transmission curves of the two color filters utilized (b); Spectral sensitivity curves of the six spectral channels resulting when the RGB camera is used sequentially with filter 1 (c) and filter 2 (d) in front of it (6 channels camera).

of the spectral reconstruction is calculated; once more the quantization of the camera is not considered. A detailed comparison of filters from one given manufacturer has been performed by Shrestha et al. including normally distributed camera noise (standard deviation 2%) and quantization with 12 bits, utilizing different spectral reconstruction methods (polynomial method, neural network, linear regression, Imai and Berns' method) and different quality measures (root mean square error, CIELAB color difference, "goodness of fit coefficient" [17, 18]).

We used data sets containing spectral transmissions of standard filters and choose the best pair out of it. We performed the choice of the two color filters by simulating the camera composed of the RGB sensor and two filters out of standard filters from various manufacturers (GamColor, Lee, Edmund Optics, Schneider Kreuznach and Schott). We calculated the gray values obtained for the Vrhel data set using the manufacturer data in Eq. 1, added normally distributed noise with a standard deviation of 1% and quantized these data with 8 bits, as our RGB 3 channels camera works with this accuracy. We then performed the spectral estimation of the acquired spectra by a Wiener estimation and evaluated the quality of the filters with the color difference CIEDE2000 [4]. We also used some constraints on the color filters: the 2 filters for the 6 channels camera had to be from the same manufacturer, the maximum values of the filters transmission curves had to be at least 0.4, and the maximum values of each of the 6 sensitivity curves had to be at least 25% of the largest one. The spectral sensitivity of the RGB camera we utilized is shown in Fig. 1(b), together with the transmission curves of the 2 color filters we selected. The spectral sensitivity of the resulting 6 channels camera is shown in Figs. 1(c) and 1(d).

Acquisition and Simulation

We evaluated the spectral and colorimetric accuracy of the data coming from a stereo system for two different scenes with two different lighting conditions. The two cameras of the stereo system were the same, i.e., either 3 channels cameras, 6 channels cameras or 7 channels cameras. Both simulation and real acquisition data were utilized.

The evaluation was performed using two different scenes. In scene A, a ColorChecker SG (XRite) was placed on a soft-proofing monitor under a uniform D50 fluorescent lamp. Scene B was composed of various objects whose reflectance spectra are not extremely angle dependent, one of them being also a ColorChecker SG. This scene was illuminated by a halogen lamp placed at a angle of 45°. We used scene A for the real acquisition and compared the acquisitions from different angles for all the 140 color patches. Scene B was utilized for the real acquisition as well as for the simulation: we selected 22 regions of interest for which we compared the simulated and acquired spectra. These regions are tagged from 1 to 22 on Fig. 2.

For the *real acquisition*, we acquired an image of the scenes with the 7 channels camera and estimated the spectra from the different color patches or regions of interest, for different positions of the camera. The position of the camera varied between 5° and -15° for scene A, and between 10° and -10° for scene B. We could then compare the values for each patch or regions separately, evaluating thus the effect of the position of the camera and the angle of its optical axis relative to the scene. For the *simulation*, we measured the regions of interest from scene B with a spectrophotometer, the measurement device being at the two different positions 0° and 10°. We then simulated the gray values from the different cameras based on these spectra and on

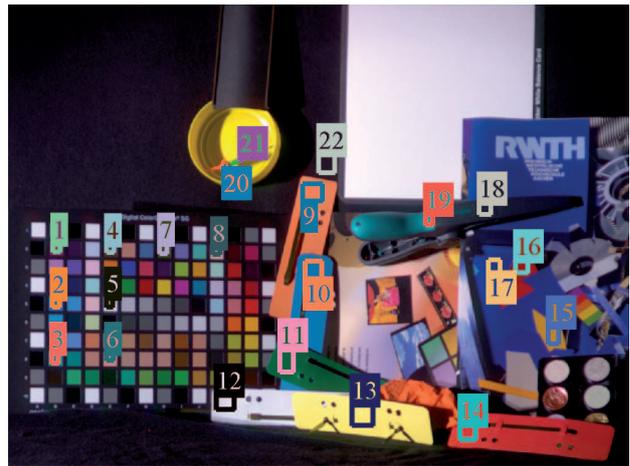


Figure 2. Scene B used for the real acquisition and the simulation. The measurements have been performed in the regions of interest 1 to 22 inside the colored frames.

the model provided in the second section. This allowed us to compare the values acquired for different acquisition angles, for the 3, the 6 and the 7 channels camera.

Influence of Spectral Channels Used

In the stereo system with a 6 channels camera, i.e., with two RGB cameras with different color filters, it is possible to switch the color filters utilized for the right and the left camera of the system. The spectra estimated for the regions of interest for both different configurations of the stereo system (filter 1 in front of the left camera and filter 2 in front of the right camera, and then vice versa) can thus be compared together and with the ground truth measured with the spectrophotometer.

The stereo system composed of two 7 channels cameras even enables more comparisons. One can take all the color channels from both cameras to reconstruct the spectrum for the regions of interest. It is also possible to take just partial spectral information from each camera to estimate the acquired spectrum and to use the fact that each region is captured by both cameras to perform the complete spectral estimation. One example would be to utilize the spectral information from the color channels 1, 3, 5 and 7 of the left camera and the complementary information from the color channels 2, 4 and 6 of the right camera to compute multispectral information.

Some of these possible comparisons are shown in the results.

Experimental Setup

The monochrome sensor of our multispectral camera featuring seven bandpass filters is a 1/2" CCD sensor with 1392 × 1040 pixels and a pixel size of 4.65 μm × 4.65 μm. The RGB camera we used for the simulation is a Basler Aviator 2300 with 2330 × 1750 pixels and a pixel size of 5.5 μm × 5.5 μm. The color filters calculated by our optimization for the 6 channels camera using this RGB camera are the GamColor filters 570 "Light Green Yellow" and 104 "Broadway Rose". The spectral measurement were performed with a spectroradiometer Konica-Minolta CS2000.

For the acquisition of scene A, the 7 channels camera was positioned at about 1 m in front of the color chart, and for scene B the camera as well as the spectrophotometer were at about 2 m from the objects.

Results of Real Acquisition

In this section, we will discuss the results from the acquisitions performed with the 7 channels camera. To get a first impression of the observation angle dependence of the reflectance spectra, we acquired scene A for a few different angles of the camera and compared the multispectral values. We then also compared the measurements from a stereo system with an angle of about 10° between both cameras.

Multispectral Acquisition for Different Angles

We imaged a color chart placed on a softproofing monitor under a uniform D50 light source (scene A) and translated the camera vertically, in order to cover an angle range between $+5^\circ$ and -15° relative to the color chart normal, in steps of approximately 5° . Note that the camera parameters like the exposure time of each color channel remained constant during all the acquisitions series.

The results in the CIELAB color space with respect to the illuminant D50 are displayed in Fig. 3: the values are projected onto the $L^*a^*b^*$ plane, the L^*b^* plane and the a^*b^* plane respectively. The values measured for the five angle positions are linked together for each color patch. For some of the color patches, the differences of the values between the minimum and the maximum acquisition angle are relatively high and can reach a color difference CIEDE2000 of 4.64. These differences mostly occur for the dark color patches: they might thus be caused by a change of the intensity imaged by the camera, since the distance between the scene and the camera could not be kept constant for all acquisitions. This issue is actually unavoidable in a stereo system.

Table 1. Values of the CIEDE2000 color difference between the acquisition for 0° and the other positions of the 7 channels camera (approximately $+5^\circ$, -5° , -10° and -15°). The mean, median and maximum values are calculated over the 140 color patches of the color chart of scene A.

Angles: 0° and	CIEDE2000 color difference		
	Mean	Median	Maximum
$+5^\circ$	0.35	0.29	1.23
-5°	0.36	0.32	0.85
-10°	0.48	0.37	2.00
-15°	0.72	0.45	4.03

The color differences between the acquisition perpendicularly to the color chart and the other angles are calculated in Tab. 1. From this comparison, we can see that the maximum differences between two images acquired with a relatively large angle for a stereo system are quite high (4.03) but the mean and median values stay below 1, which indicates that the color differences are barely noticeable.

Stereo Imaging with Multispectral Cameras

We then acquired the scene A and the scene B with a multispectral stereo system consisting of the 7 channels camera positioned perpendicularly to the scene and at an angle of $\pm 10^\circ$. From these two acquisitions, several spectral reconstructions are possible. The data from the left camera or from the right camera can be utilized alone, as it is the case for a usual "mono" multispectral camera. Since we have access to stereo data here, one straightforward idea to use this information is to mix the spectral channels of both cameras. We consider two cases in this paper: for the reconstruction "custom1", we use the color channels 1, 3, 5 and 7 from the right multispectral camera and the color

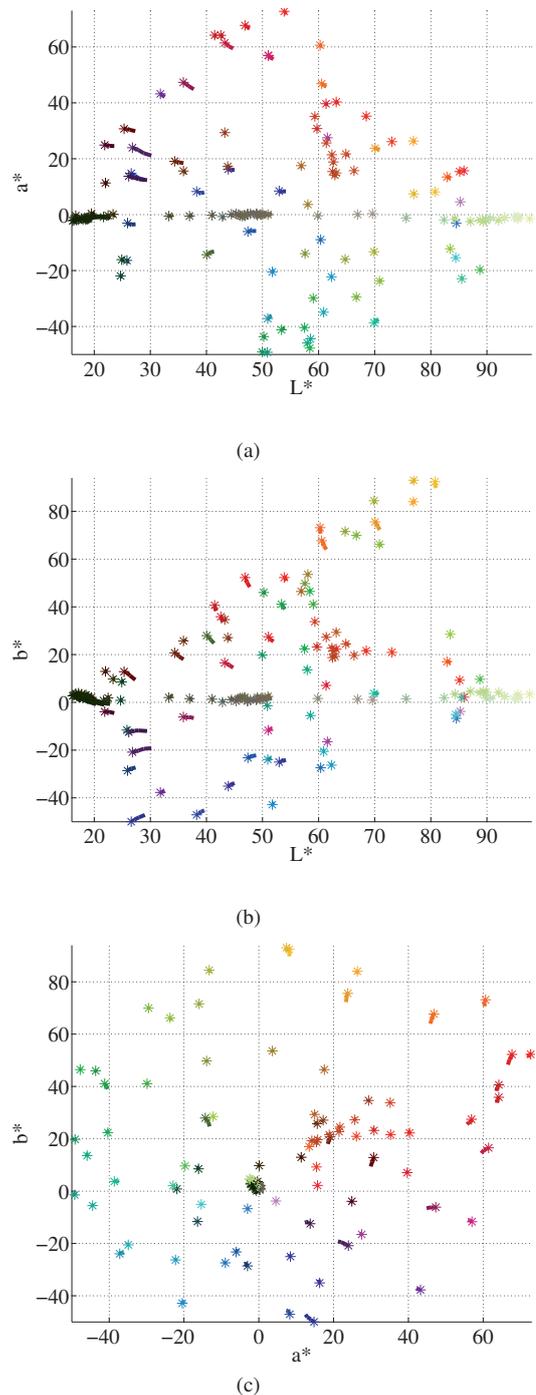


Figure 3. Displacements of the measured $L^*a^*b^*$ values of the color patches of an XRite ColorChecker SG photographed under a uniform D50 light source (scene A): the values acquired by a camera positioned at $+5^\circ$ to the color chart are symbolized by a star, and the following values for a camera displaced up to an angle of approximately -15° are shown with the continuous lines. The camera used here is the 7 channels camera and its parameters were not modified during the acquisition set. The acquired reflectance spectra of some of the 140 color patches clearly change as a function of the observer position.

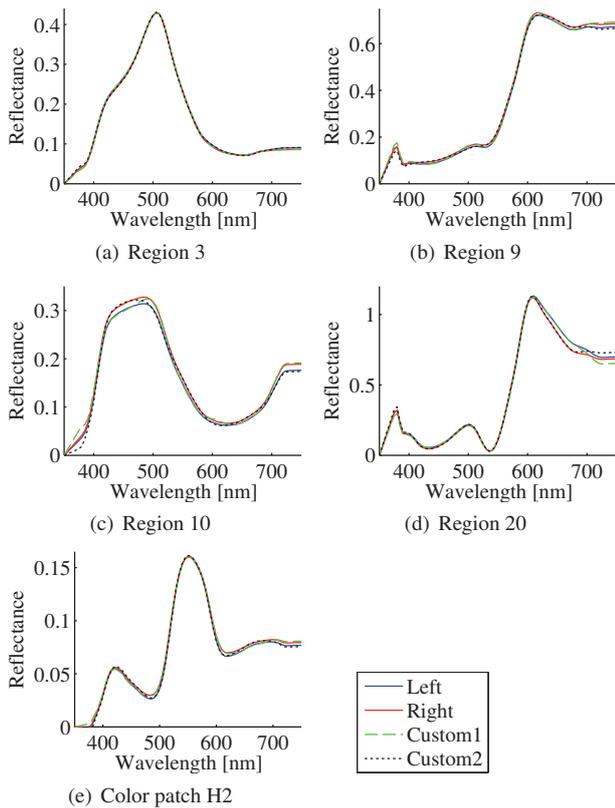


Figure 4. Reflectance spectra estimated from the real acquisition with the 7 channels camera for regions of scene B (a)-(d) and for a color patch of scene A (e). These spectra are reconstructed using either the data from the left camera (blue lines), from the right camera (red lines), from the reconstructions "custom 1" (green dashed lines) or "custom 2" (black dotted lines).

channels 2, 4 and 6 from the left camera; for the reconstruction "custom2", the color channels are interchanged and the utilized channels are the channels 2, 4 and 6 from the right camera and 1, 3, 5 and 7 from the left camera. Other reconstructions could be analyzed in further work.

The estimated spectra based on the multispectral acquisitions for some of the regions of interest of scene B (see also Fig. 2) and color patches of scene A are shown in Fig. 4. They stay quite close and some additional quantitative results calculated in the CIELAB color space with illuminant D50 are given in Tab. 2. The color differences presented in this table are the differences between each of the four reconstructions listed in the previous paragraph, which results in 6 differences calculated for each region of interest. The low values mean that the different reconstructions lead to comparable values in the CIELAB color space. Isolated high differences for the regions 10, 19, 20 and 21 might be caused by specular reflection in these regions.

Results of Simulation

The spectra measured with the spectrophotometer on the different regions of scene B and for two different positions of the measurement device (0° and $+10^\circ$) were utilized, together with spectral data from the cameras with 6 and with 7 channels, to simulate the data acquired with these cameras for each region. This enables a comparison of the different spectral reconstructions possible with 6 channels cameras, and also a comparison of the spectral accuracy obtained with 6 channels camera or with 7 channels camera. For the simulations, we first considered the

Table 2. Color differences CIEDE2000 for the 22 regions of interest of scene B acquired with the 7 channels camera, calculated between the different spectral reconstructions: the one using only the data from the left camera (L), the one using only the data from the right camera (R), the one using the reconstruction scheme "custom1" (C1) and the one using the scheme "custom2" (C2).

ROI	L/R	L/C1	L/C2	R/C1	R/C2	C1/C2
1	0.41	0.13	0.40	0.40	0.13	0.44
2	0.13	0.08	0.05	0.05	0.08	0.05
3	0.37	0.23	0.20	0.20	0.23	0.22
4	0.61	0.07	0.64	0.65	0.06	0.69
5	0.73	0.11	0.62	0.62	0.11	0.52
6	0.43	0.08	0.46	0.46	0.09	0.50
7	0.29	0.10	0.28	0.28	0.10	0.30
8	0.43	0.20	0.50	0.50	0.20	0.63
9	0.70	0.31	0.53	0.53	0.30	0.51
10	1.18	0.72	0.73	0.73	0.71	0.84
11	0.35	0.15	0.23	0.23	0.15	0.16
12	0.44	0.07	0.39	0.38	0.07	0.34
13	0.46	0.19	0.32	0.32	0.19	0.26
14	0.64	0.48	0.24	0.24	0.48	0.40
15	0.13	0.07	0.08	0.07	0.07	0.07
16	0.18	0.15	0.06	0.06	0.15	0.15
17	0.07	0.03	0.05	0.05	0.03	0.05
18	0.88	0.32	0.67	0.67	0.31	0.57
19	3.50	1.90	2.01	1.88	1.75	1.41
20	1.29	0.16	1.35	1.36	0.15	1.43
21	1.06	0.35	0.84	0.83	0.34	0.72
22	0.24	0.10	0.24	0.24	0.10	0.27

left and the right spectra that have been measured. We then performed the estimation of the acquisition from the simulated 6 channels camera or 7 channels camera.

With two 6 channels camera in a stereo system, it is possible to either utilize the whole spectral information from both cameras, or only the half of it. Here we focus on the reconstruction using 3 spectral channels from the left camera and the complementary 3 spectral channels from the right camera. This stereo acquisition can be performed with the filter 1 in front of the left camera and the filter 2 in front of the other, or with the filter 2 in front of the left camera and the filter 1 in front of the other, i.e., two configurations are possible and lead to two spectral reconstructions. The median value of the color differences between these two spectral reconstructions and the ground truth spectra measured on the left and on the right position lied between 4.16 and 4.18; the maximum value was 23.03. The colorimetric accuracy of such a stereo system is thus limited. Moreover, the color differences between the two different spectral reconstructions was 2.44 in median and 9.31 at the maximum: the choice of the spectral reconstruction, i.e., of the filter placed in front of each camera has an important impact on the reconstructed values.

To compare the acquisition with 6 channels cameras and 7 channels cameras, we chose one configuration for the 6 channels stereo system, and we utilized the configuration "custom2" for the 7 channels stereo system. We then compared these reconstructed data with the ground truth data. As can be seen in the Fig. 5, the reconstruction using the 7 channels camera is better than the one using the 6 channels camera, in the sense that its values are closer to the ground truth values. The CIEDE2000 color differences between the CIELAB values from the 6 channels ca-

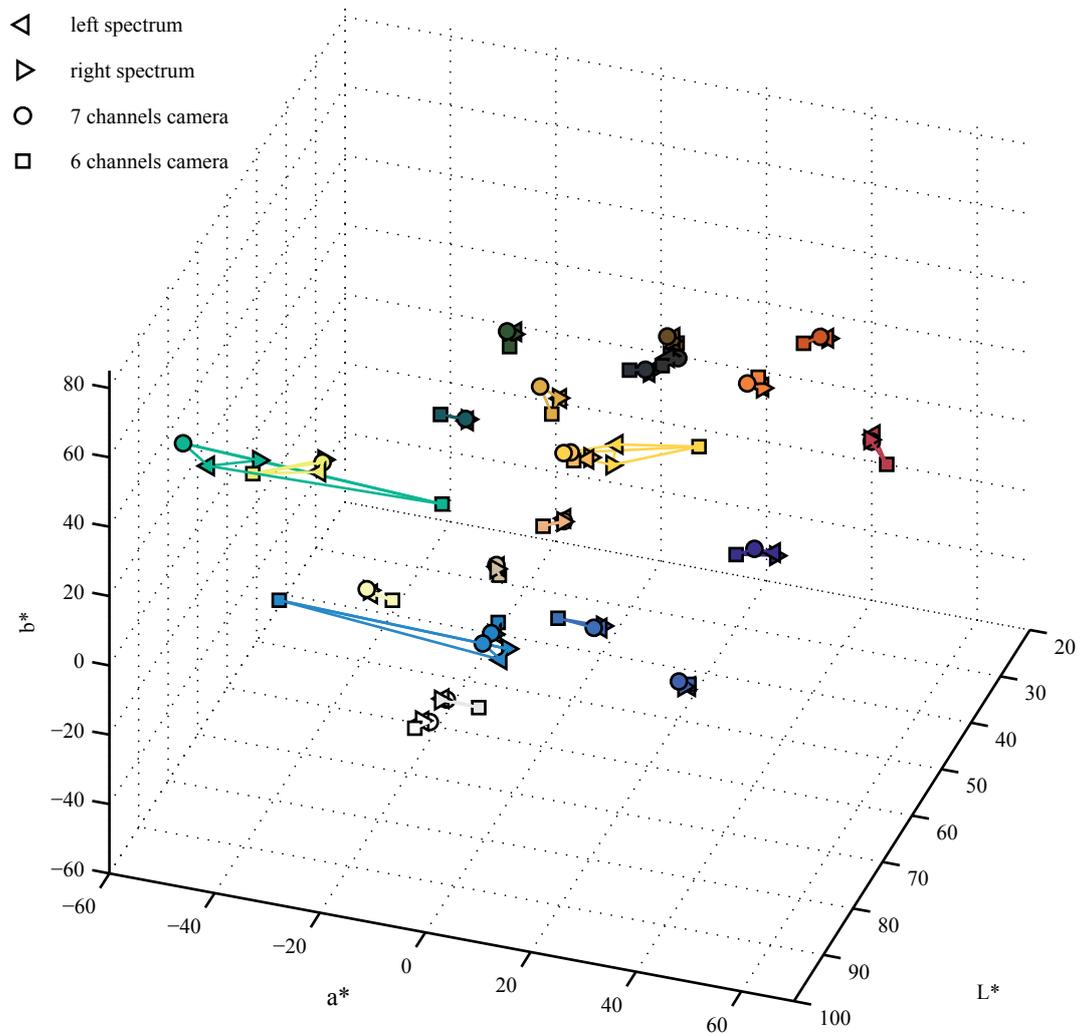


Figure 5. Results of the simulation in the CIELAB color space: the spectra measured with a spectrophotometer are shown with triangles, the values estimated with the 7 channels camera and the reconstruction "custom1" are represented by circles, and the values estimated by the 6 channels camera by squares. Each region of scene B is represented by a different color and the four values corresponding to it (two measurements and two estimations) are linked together.

mera and both the left and the right spectral measurements were larger than 3 for 11 of the 22 regions of interest and below 1 for only 2 regions. The color differences of the 7 channels camera were larger than 3 only for 3 of the 22 regions and below 1 for 10 regions. The median and maximum color differences of the measurements were 3.62 and 21.20 respectively for the 6 channels camera, and 1.31 and 6.47 for the 7 channels camera. The stereo multispectral imaging with the 7 channels camera thus allow a better spectral accuracy even when different color channels are considered for each camera.

Conclusion

In this work, we investigated the spectral data captured by stereo systems made of multispectral cameras. These multispectral cameras were monochrome sensors with 7 bandpass color filters as well as RGB cameras with broadband filters. We acquired two different scenes with the 7 channels multispectral camera and with a spectrophotometer, in order to have both real acquisition data and spectral ground truth enabling the simulation of the acquisition process with any other camera. With the real acquisitions using the 7 channels camera, we could observe the changes of the estimated spectra in the CIELAB color space as a function of the angle of observation. We compared 4 different reconstructions of the spectra using the data of each camera separately on the one hand and mixing the data from the color channels on the other hand. The estimated spectra were slightly different. Other kinds of reconstructions should also be compared in future work. The simulation showed that the stereo system with 7 channels outperforms the system with 6 channels in terms of color differences compared to the ground truth data acquired by each of the cameras separately.

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Author Biography

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