Multispectral stereo acquisition using two RGB cameras and color filters: color and disparity accuracy

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in: 18. Workshop Farbbildverarbeitung. See also \textsc{BibTeX} entry below.

\textsc{BibTeX}: 
\begin{verbatim}
@inproceedings{Klein2012b, 
  author = {Julie Klein and Bernhard Hill}, 
  title = {Multispectral stereo acquisition using two {RGB} cameras and color filters: color and disparity accuracy}, 
  booktitle = {18. Workshop Farbbildverarbeitung}, 
  year = {2012}, 
  publisher = {TU Darmstadt: Institut f"ur Druckmaschinen und Druckverfahren, Graphisch-Interaktive Systeme und Fraunhofer-Institut f"ur Graphische Datenverarbeitung}, 
  pages = {89--96}, 
  address = {Darmstadt, Germany}, 
  month = {September 27--38} 
}
\end{verbatim}

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Multispectral stereo acquisition using two RGB cameras and color filters: color and disparity accuracy

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Abstract A multispectral stereo system featuring two RGB cameras and color filters enables the simultaneous acquisition of accurate color information and depth information from a scene, in only one shot. The filters must be carefully chosen given the RGB cameras and the light source utilized for the acquisitions. We use a set of broadband filters obtained by optimization out of filters from various manufacturers and compare them to dichroic filters. The spectral accuracy of both multispectral cameras is evaluated, in a mono as well as in a stereo configuration. The disparity estimation must be performed using images with different spectral information: we explain our algorithm that uses mutual information as similarity metric for the stereo matching. We also compare the performance of our algorithm on multispectral images with the results obtained with standard algorithms on RGB images.

1 Introduction

Multispectral imaging can be performed with a monochrome sensor and different bandpass color filters placed in front of it for instance \([1, 2]\). It is also possible to use RGB cameras with additional optical filters: this enables the acquisition of three color channels at once, instead of capturing only one color channel at a time when using a monochrome camera. With two RGB cameras positioned in a stereo system and a different optical filter for each camera, a multispectral image can even be acquired in one shot \([3, 4]\). Such a multispectral stereo system thus gives access to accurate color and depth information at the same time, as shown in Fig. (1).

Acquisition of stereo multispectral images using two RGB cameras and color filters has been gaining interest in several research groups \([3, 4, 5, 6]\). Many challenges come with multispectral stereo acquisition compared to RGB stereo imaging. Since the spectral
Figure 1: Acquisition of a 3D scene using two RGB cameras with a different color filter in front of each one. The spectral sensitivity functions of the two acquisition systems for the example of Infitec filters are shown on the left.

information acquired by the two cameras is different, disparity estimation as it is well known from common stereo RGB cameras must be adapted and extended in this case. Doi et al. developed an accurate stereo matching algorithm for multispectral cameras, but could utilize a similarity measure derived from the sum of squared differences since the same color channels were available from both cameras [7]. Such a metric cannot be used for multimodal imaging, where contrast inversion between color channels might occur. A more complex metric is envisaged that can handle not only the difference of spectral information but also the differences resulting from the illumination as seen from the viewpoints of the two cameras. For the case of RGB stereo systems, this difference must be corrected before the disparity estimation [8]. In order to achieve best results, the components of the multispectral system have to be optimized: for each combination of RGB cameras and light source, selected color filters provide the optimal sensitivity for multispectral color reproduction. The selection of suitable filters is therefore an important point of this study.

The reflectance functions of the objects analyzed in this paper have a limited angular dependence: the spectra acquired from the two camera positions of the stereo system do not differ strongly, as stated in [4, 6]. This allows the accurate reconstruction of the spectra reflected by the objects using the information from the two camera positions. More complex materials where the bidirectional reflectance distribution function varies more strongly will be examined in future work.

In the following, we first present the optimization step for the choice of the color filters and the experimental setup. Then we explain our disparity estimation algorithm and compare its results with those of a standard algorithm on RGB images. The spectral accuracy of the stereo-multispectral systems is then evaluated in section 4 before we conclude the paper.

2 Choice of filters and experimental setup

In the literature, the choice of the color filters for such a multispectral camera featuring RGB cameras and filters is often not explained. In some applications, dichroic filters splitting each channel R, G and B into two halves are utilized [4, 5]. Shrestha et al.
performed a detailed comparison of filters from a given manufacturer by modeling the whole acquisition [3]. We chose our filters with the optimization explained in the following. We considered filters from different manufacturers and calculated the camera values for the Vrhel dataset, which is an ensemble of reflectance spectra from various objects representing a good overview of common colors (120 spectra from DuPont color chips, 64 spectra from Munsell color chips and 170 spectra from natural objects). Optimized filters could also be chosen for a given scene with a specific distribution of spectra, rather than using the Vrhel dataset which represents all kinds of spectra. Yet, this was not considered in this study since we wanted to use one filter set being applicable to a large range of scenes. For the selection of optimized filter sets, the color difference CIEDE2000 [9] between the spectral reconstructions from the camera values and the exact spectral data of the Vrhel dataset was calculated. The camera was modeled using the spectral responses of its three channels R, G and B and of the filters, including normally distributed noise and quantization on 8 bits. The acquired spectra were reconstructed from the camera values by a Wiener estimation. We picked out the filter pair providing the lowest color difference and offering a maximum transmission of at least 0.4 along the visible wavelengths range (1 being full transmission) and maximum sensitivities for all the channels that reached at least 25% of the overall maximum sensitivity [6]. In this way, a minimum channel sensitivity was ensured. These values were a practical compromise to avoid high levels of noise during the acquisition.

![Sensitivity curves](image)

Figure 2: Sensitivities of the multispectral system made of two RGB cameras and two optical filters: using GamColor filters (a) and using Infitec filters (b).

The 3D scenes were illuminated by a halogen light source and acquired by two Basler Aviator cameras avA2300-25gc (Basler AG, Ahrensburg, Germany). Given the spectral data of light source and cameras, the color filters resulting from the optimization step were the GamColor filters 104 "Broadway rose" and 570 "Light green yellow" (Gamproducts, Inc., Los Angeles, USA): the sensitivity curves of the 6 channels obtained with them are shown in Fig. (2a). We also considered Infitec dichroic filters (Infitec GmbH, Ulm, Germany) which are often utilized for 3D projection; they lead to the sensitivity curves shown in Fig. (2b). Given the transmission functions of the Infitec filters, no signal can be acquired below 425 nm: the spectra that are reconstructed with such a multispectral camera should thus be taken with care at these low wavelengths. Moreover, a blind spot at ca. 575 nm can lead to reconstructed spectra containing errors. For future work, it would be desirable to use color filters covering the whole wavelength range without any blind spot or to use the complete RGB information from one of both positions.
3 Disparity accuracy

In multimodal imaging, mutual information is often utilized as similarity measure [10, 11, 12] because of the possible contrast inversions between the color channels. The mutual information of two images (or two image windows) can be defined as the sum of the Shannon entropies of each image from which the joint entropy of the images is subtracted. The registration of both images is assumed to be reached when the mutual information is maximized; in this case their joint entropy is minimal and "the amount of information they contain about each other is maximal" [10]. Another measure could be the phase of correlation, as suggested by Tsuchida [4]. We utilized mutual information, calculated by using simultaneously the three color channels of each camera.

We performed the stereo matching with a multiscale approach, beginning with the smallest version of the original images scaled by factor $1/8$. The mutual information is calculated only for integer pixel positions and the position of its maximum value is taken with a pixel accuracy for the first iterations. Then, in the last iteration, we sought subpixel accuracy at the position of the maximum: when the left and right images are merged together, the disparity correction must be performed with a subpixel accuracy in order to obtain color information as accurate as possible. The subpixel position of the maximum of mutual information is approximated using a second order polynomial on the $3 \times 3$ neighborhood of the pixel position where mutual information reaches its maximum value. For a more robust disparity map, the disparity is calculated in both directions, i.e., from the left to the right image and from the right to the left one and the disparity corresponding to the largest value out of the two disparity maps is kept [13].

The disparity estimated on a 3D scene is shown in Fig. (3a). The results were satisfactory: the small objects in the foreground have been detected, a disparity could be estimated for the white reference and the disparities of planar surfaces are homogeneous. Using these disparity values, the spectral reconstruction of the scene was performed (Fig. (3b)). No major color errors are visible, except some small errors on the mini colorchecker or in the shadow of the lemon tea on the white reference for instance.

![Figure 3: Disparity estimated from the multispectral stereo system (a) and spectral reconstruction of the 3D scene (b). The disparity values range from 0 pixel (black) to 105 pixels (white) and the background of the scene has been set to black.](image)

Our stereo multispectral system can easily be modified into a standard RGB stereo system by removing the color filters in front of the cameras. This allows a comparison of the disparity map obtained with the multispectral system using our algorithm and the
disparity map obtained with the RGB system using a state-of-the-art algorithm. These results are shown in Fig. (4a) and the difference between our disparity estimation using multispectral information and the one using RGB cameras can be seen in Fig. (4b). High values were reached on the homogeneous surface of the white colorchecker for which the RGB algorithm could not estimate any disparity. The displayed differences were clipped to 5 pixels. The median difference between both estimations is 0.35 pixel for the 3D scene, which means that the estimation based on multispectral images is as good as the one based on RGB images.

![Figure 4: Disparity estimated with the RGB images (a) and absolute difference of RGB and multispectral disparity estimation (b). The disparity values range from 0 pixel (black) to 105 pixels (white). The difference values are clipped to 5 pixels (white).](image)

### 4 Spectral accuracy

Besides the accuracy of the stereo image disparity map, we also evaluated the color accuracy of the multispectral acquisitions, including the light source. Once the disparity is estimated for all the image positions, the left and right images are merged to obtain a stereo image with 6 color channels. For each pixel position, the acquired spectra were reconstructed using a Wiener estimation and the 6 channel values of the two cameras with the Wiener matrix derived from the spectral sensitivities of the channels. The spectral sensitivities of the imaging system can be determined e.g. as explained in [14]. Afterwards, these spectra were compared to a reference measurement performed with a spectroradiometer.

In the beginning, we calculated the accuracy of a "mono" multispectral camera, i.e., placing both cameras at the exact same position. In practice, this means that we utilized one RGB camera and placed the two color filters of each set consecutively. This shows how accurately the system "6-channel camera" constituted of an RGB camera and color filters can acquire and reconstruct spectral information. The object we imaged was a color checker and we calculated the color difference CIEDE2000 [9] between the reference measurement and the acquisition by the 6-channel cameras applying each of the two filter sets. This was done for the 140 color patches of the color checker. The minimum, the mean, the median and the maximum values are summarized in the left part of Tab. 1. The 6-channel multispectral cameras are quite accurate, with median color differences of
3.29 and 4.07, respectively, depending on the color filters utilized. The results with Infitec filters are slightly better. The maximum differences occur for dark patches of the color checker.

Figure 5: Color accuracy measured on the color patches of an XRite color checker, acquired by the 6-channel stereo system featuring Infitec filters. For each color patch, the reconstructed color (upper triangle) is compared with the reference measurement (lower triangle) and the color difference CIEDE2000 is calculated.

Then, we calculated the accuracy of the stereo multispectral system, i.e., with cameras at two different positions. In the right part of Tab. 1, we see that the color differences with respect to the reference measurement remain low with median values of 4.62 and 4.80. The differences can reach high values like 13.9 and 24.9: some outliers occurred due to locally false estimation of disparity, which led to false spectral reconstruction on some color fields of the colorchecker. The results obtained with the Infitec filters are shown in Fig. (5): here, no reconstruction error due to false disparity estimation can be seen and the maximum color difference is reached for a black patch in the first column. Regarding the color difference obtained with the Infitec filters as well as with the GamColor filters, this multispectral system is adapted to accurate color acquisition.

5 Conclusions

We presented the acquisition of a 3D scene with a stereo multispectral system composed of RGB cameras and color filters where the capture of spectral information is split over the two cameras. First results concerning disparity estimation and spectral reconstruction for a real system were outlined. We first chose the optical filters by modeling the camera responses for the acquisition of the Vrhel dataset. The result was a filter pair with broadband characteristics, and we also utilized a pair of dichroic filters. Then, we performed the disparity estimation using the images from both sides of the stereo system.
Table 1: Color difference CIEDE2000 calculated on the XRite color checker SG with two acquisitions from the same position (mono system) and with two acquisitions from different positions (stereo system). The reference spectra have been measured with a spectrofotometer. The color differences obtained with the two sets of filters (GamColor and Infitec) are compared and the minimum (Mini.), mean (Mean), median (Medi.) and maximum (Maxi.) values of the color difference are given.

<table>
<thead>
<tr>
<th>Filter set</th>
<th>Color difference for mono system</th>
<th>Color difference for stereo system</th>
</tr>
</thead>
<tbody>
<tr>
<td>GamColor</td>
<td>0.53</td>
<td>4.84</td>
</tr>
<tr>
<td>Infitec</td>
<td>0.56</td>
<td>4.12</td>
</tr>
</tbody>
</table>

that do not contain the same spectral information. We compared our results to disparity estimation derived from stereo RGB images and they were still satisfactory, but we aim at improving the algorithm in future work. We also measured the spectral accuracy of the scene reconstructed from the stereo system equipped with the two filter sets. These studies resulted in low color differences on the average with respect to a reference measurement. This means that both stereo multispectral systems are suitable for accurate color imaging. In future work, we will also consider objects whose bidirectional reflectance distribution functions are less constant over the acquisition angle.

**Acknowledgments**

The authors would like to thank the anonymous reviewers for many interesting comments and acknowledge gratefully funding by the German Research Foundation (DFG, grant AA5/2–1).

**References**


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