Spectral Image Acquisition with Rewritable Color Filters

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Abstract

We present techniques for spectral image acquisition. The spectral domain of the images is represented by a low-dimensional component image set, which is used to obtain an efficient compression of the high-dimensional spectral data. First, computational techniques to design color filters with a constraint of positive spectral values is described. Then, we present two prototypes of our spectral imaging systems that can be used to acquire the low-dimensional component image set optically through rewritable color filters. The first prototype is based on a spectral synthesizer that illuminates the sample with the light corresponding to a wanted color filter. The second prototype is based on a linear variable filter (LVF) and a liquid crystal spatial light modulator (LCSLM) that implements the rewritable color filter in front of a CCD-camera. We also show how liquid crystal tunable filter (LCTF) based system can be used to implement arbitrary color filters. The optically acquired component image set can be used for computational spectral image reconstruction or it can be directly used for pattern recognition tasks.

1. Introduction

Spectral color representation is evolving from traditional remote sensing into newer fields such as telemedicine, e-commerce, and electronic museums. The spectral color representation avoids the problem of metamerism and it can be also extended outside the visible range of color. Many industrial processes need accurate color representation, which can be obtained by spectral measurements. Due to these needs, the spectral imaging devices are currently under a focus of growing interest.

To measure spectral images, devices such as a CCD-camera with narrow band interference filters, an acousto-optical tunable filter (AOTF), Fourier transform based interferometric imaging system, a liquid crystal tunable filter (LCTF) with narrow band filters or a prism-grating-prism (PGP) based line scanning camera can be used. There are two basic approaches to measure spectral images. One approach is based on the acquisition of a two-dimensional image at different wavelengths at different times. Another approach is based on the acquisition of line images with a simultaneous measurement of spectra at different wavelengths by scanning a camera or an object along the spatial axis. All these systems produce a large amount of data to be stored or transmitted.

In this study, our interest is in low-dimensional spectral imaging systems. With low-dimensional we mean that a few color filters can be used in acquisition and then, if needed, the spectral image can be reconstructed computationally. Ref. [1] and the references there contains more information on low-dimensional spectral imaging systems. We are interested in adaptive spectral imaging systems, which means that the color filters can adapt according to an application. To implement this kind of spectral imaging system, computational techniques for color filter design and a rewritable filter based spectral imaging system are needed. In this paper, we review our rewritable filter based spectral imaging systems. These systems and techniques are published in Asian Conference on Color Vision (ACCV'98) [2], Journal of the Optical Society of America A [3], Optical Review [4], and in AIC Color 01-conference [5].

2. Spectral image acquisition

2.1. Color filter design

An efficient computational compression technique for spectral images is the principal component analysis (PCA). The eigenvectors of the PCA are orthogonal and for the color spectra, they usually contain negative coefficients, which cannot be directly used in optical implementations. For optical purposes, it is possible to implement the positive and negative parts of the eigenvectors separately, however, this leads to more complicated optical systems.

We have proposed techniques based on clustering methods to design a low-dimensional color filter set containing only positive coefficients for the color spectra. The color filters are designed for spectral databases, *i.e.* they can be designed according to an application. The clustering methods used include a self-organizing map (SOM), pairwise nearest neighbor (PNN), and c-means. In our earlier study, it was shown that these methods produce almost similar sets compared to each other [6].

Our color filters can be directly used in optical implementations and they are adaptive to various applications. Fig. 1 shows the filter set of 4 filters designed by SOM for the color spectra database of 1269 samples measured from the Munsell book of color.

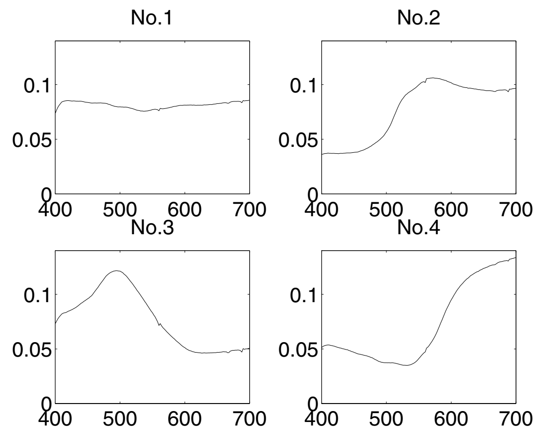


Figure 1: *Designed filters for the Munsell spectral database.*

The designed color filters can be implemented optically using a liquid crystal spatial light modulator (LC-SLM) or LCTF. Next we describe three optical setups for implementing arbitrary color filters.

2.2. Spectral synthesizer based system

We have proposed a method for implementing arbitrary color filters as illuminations [3]. The optical setup is called as a spectral synthesizer, which can be used to implement light, that corresponds to a shape of the wanted color filter.

To synthesize the light corresponding to the color filter, we constructed the optical setup shown in Fig. 2. There the grating dispers the white light to a spectrum. In the dispersion plane the spectrum is filtered using an LCSLM, which is controlled by the computer. The schematic drawing of controlling the LC-panel is shown in Fig. 3 and the LC-panel characteristics is shown in Fig. 4. This characteristics information is used to program the filters to LC-panel [3]. The filtered light is finally collected using another grating and reflected to an object by the mirror.

The experimental setup for the spectral image acquisition system is shown in Fig. 5. In this system, we illuminate the sample by synthesized lights corresponding to designed color filters and the reflected intensity images of an object are detected by the CCD-camera. This spectral acquisition system is fast and it can be used in dark room measurements.

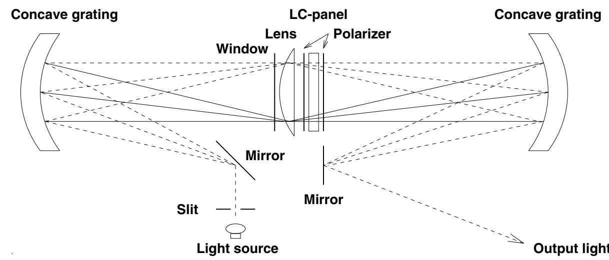


Figure 2: *Optical setup for the spectral synthesizer.*

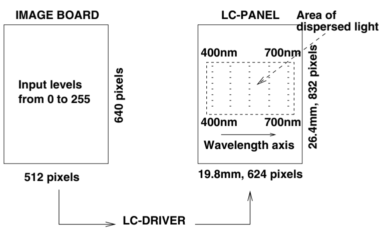


Figure 3: *Schematic drawing of control of the LC-panel.*

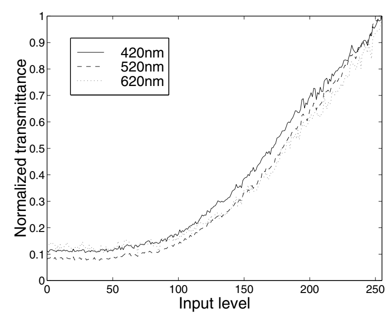


Figure 4: *Spectral characteristics of the LC-panel.*

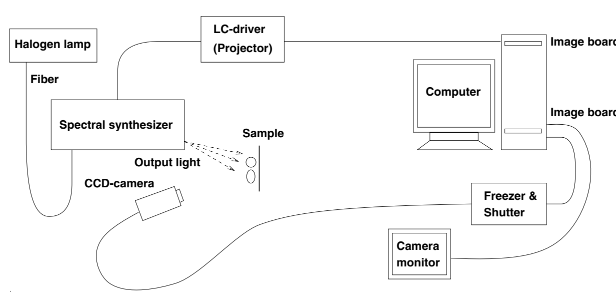


Figure 5: *Spectral image acquisition system.*

2.3. LVF-LCSLM based system

We have also developed a rewritable filter based system that can be used in outdoor measurements [4]. The designed color filters are implemented in front of the CCD-camera. An experimental setup is shown in Fig. 6. The filter part consists of a LCSLM and a linear variable filter (LVF). The LVF is a kind of interference filter whose wavelength range is from 400nm to 700nm. Fig. 7 shows the relationship between the transmitting center wavelength of the LVF and its position. The transmitting wavelength of the LVF is linearly varied depending on the position parallel to the moving direction of the stage. The designed color filters are written on the LCSLM as in the case of a spectral synthesizer based system. The LVF and LCSLM are attached to each other and mounted on a linear stage. The intensity image of a sample is taken by a CCD-camera through the joint device (LVF and LCSLM). The shutter of the CCD-camera is opened for a period while the joint device is moving just in front of the lens aperture of the CCD-camera. By this system, we can implement arbitrary color filters by changing the input pattern on the LCSLM.

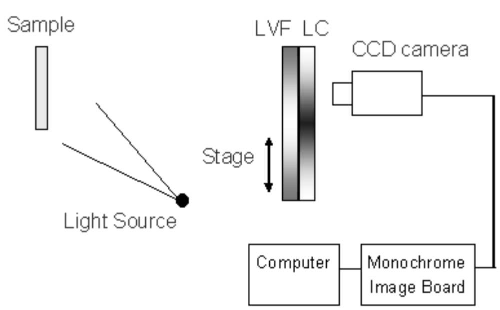


Figure 6: *Experimental setup for LVF-LCSLM based system.*

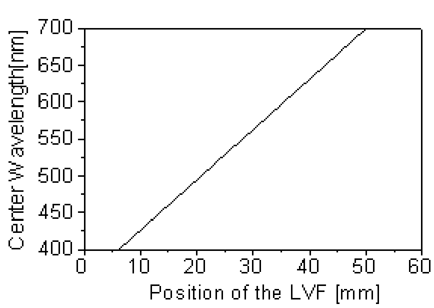


Figure 7: *Characteristics of LVF.*

2.4. LCTF based system

In Ref. [5] we used a LCTF based system to implement color filters with arbitrary transmittance. An experimental setup is shown in Fig. 8. An intensity image of an object illuminated by a light source is taken with a monochrome CCD camera through the LCTF. The transmittances of the LCTF measured for every 10-nm interval are shown in Fig. 9.

In order to implement designed color filters with arbitrary spectral transmittance, we control the holding-time for each narrow-band shown in Fig. 9 corresponding to a computationally designed filter function, and a time-integrated intensity image is taken with the CCD camera. The experimental results of filter implementation can be found in Ref. [5].

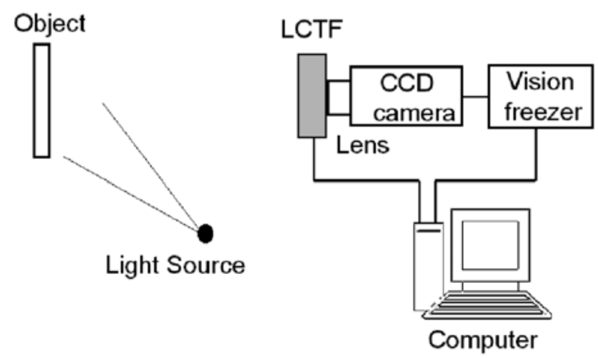


Figure 8: *Experimental setup for LCTF based system.*

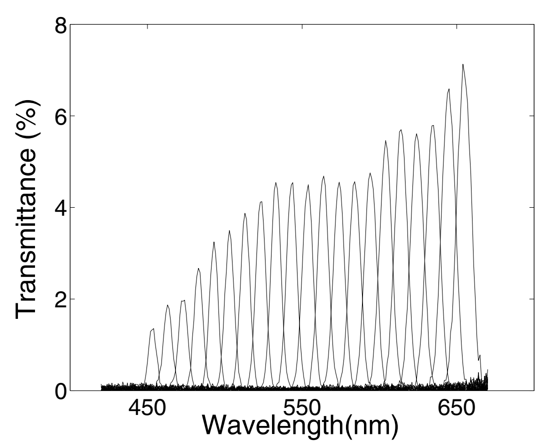


Figure 9: *The transmittances of the LCTF measured for every 10-nm interval.*

3. Experimental results

In this paper, we show an example of the filter implementation using the spectral synthesizer. We show also two spectral image acquisition examples using the spectral synthesizer and the LVF-LCSLM based system. The more detailed experimental results with our rewritable color filter based systems can be found in Refs. [3, 4, 5].

Fig. 10 shows the optically implemented color filters using the spectral synthesizer. The color filters correspond to the designed color filters shown in Fig. 1. Note that we can implement filters inside the light source spectrum, which was in every case the halogen lamp. Therefore, the filters in Fig. 1 are multiplied by the light source spectrum.

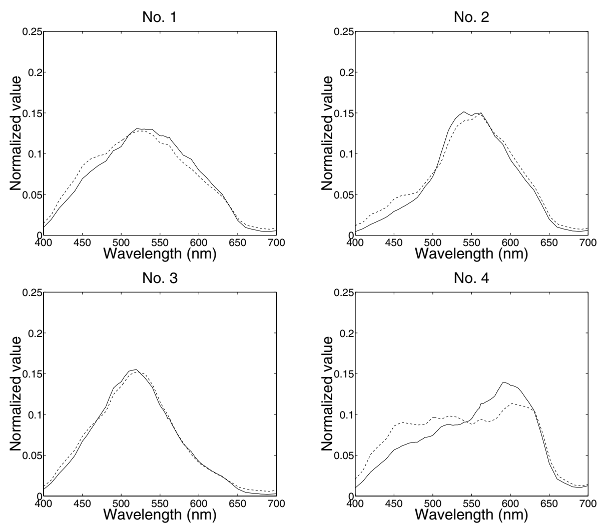


Figure 10: *Optically measured results of the filtered illuminator. Solid lines are designed color filters multiplied by the light source spectrum and dotted lines are measured results.*

Next, two examples of the spectral image acquisition using designed color filters are shown. First, we show the results of the spectral synthesizer based system. The real world object was a setup of a strawberry and an orange with colored papers as a background. The spectral synthesizer was used to illuminate the sample by four lights, that correspond to color filters shown in Fig. 1. The detected intensity images by the CCD-camera under each illumination are shown in Fig. 11. The spectral image was reconstructed computationally using a pseudo-inverse matrix based method. Fig. 12 shows two examples of the spectra. The reconstructed spectra are compared to spectra measured by 31 narrow band interference filters.

Next, we show an example of spectral image acquisition using the LVF-LCSLM based system. The image was acquired outdoors during sunny weather. The object was a collection of real flowers. Fig. 13 shows the acquired inner product images by the LVF-LCSLM based system. The spectral image was reconstructed computationally using a pseudo-inverse matrix based method. Fig. 14 shows two examples of the spectra. The reconstructed spectra are compared to spectra measured by 31 narrow band interference filters.

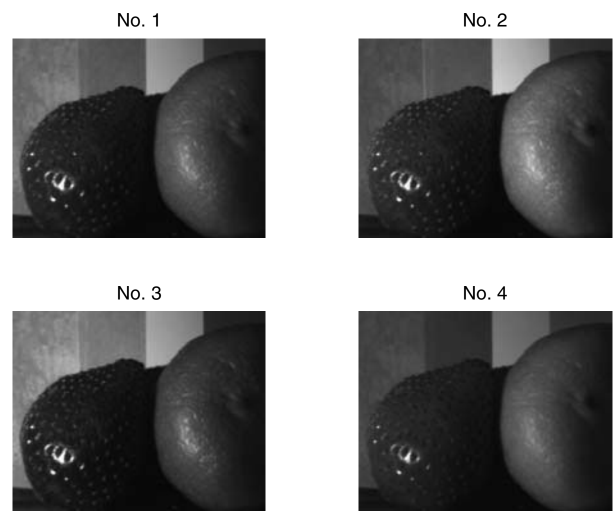
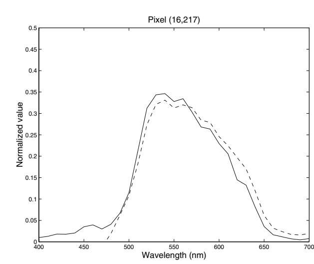
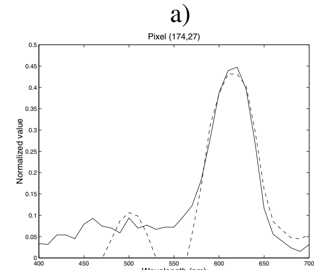


Figure 11: *Detected intensity images of the sample, when the sample was illuminated by the synthesized lights, which correspond to 4 color filters.*



a)



b)

Figure 12: *Spectra at two different locations of the spectral image. Solid lines: 31 interference filters, dashed lines: reconstructed from the spectral synthesizer based system data.*

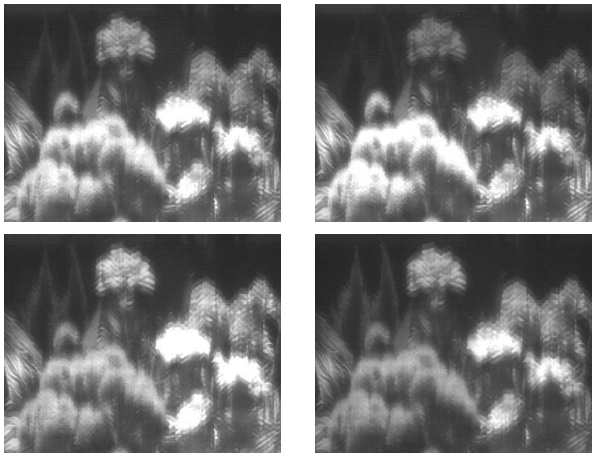
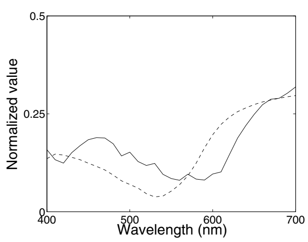
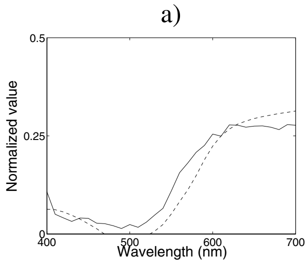


Figure 13: *Detected intensity images of the sample using 4 color filters in LVF-LCSLM based system.*



a)



b)

Figure 14: *Spectra at two different locations of the spectral image. Solid lines: 31 interference filters, dashed lines: reconstructed from the LVF-LCSLM based system data.*

4. Discussion

We reviewed our rewritable color filter based spectral image acquisition systems. The computationally designed color filters were implemented using LCSLM and LCTF. The acquisition speed of the systems are as follows. The spectral synthesizer based system is the fastest, because the filters can be changed according to an updating time of the LC-panel. For example, the 4 filter data can be acquired in seconds. The LVF-LCSLM system needs mechanical scanning and therefore, the acquisition time depends on the scanning speed, which is usually about ten seconds. The LCTF based system holds the exposure time of each selected wavelength, and it is the slowest, it takes several minutes to acquire the images.

The advantages of these systems are that they can adapt, *i.e.* the color filters can be designed and implemented optically according to an application. The acquired data is convenient for storing and transmitting a spectral image, and it can be directly used in pattern recognition tasks. The high-dimensional spectral image can be reconstructed computationally, if needed. We reconstructed the spectral images using a pseudo-inverse matrix based method. However, there are more efficient methods, for example, Wiener estimation [7], which could improve the reconstruction results.

Acknowledgments

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