Multispectral Image Capture Across the Web

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Abstract

Multispectral image acquisition typically results in a huge amount of data and often involves a complicated mechanical setup in which a given number of interference filters is mounted on a filter wheel in front of a monochrome digital camera. Such constraints present serious problems for multispectral image capture over a wide area network. We solved these problems by using an electronically tunable spectral filter and a modular client-server software architecture. The client parts of the software are implemented in Java and allow for interactive operation of the multispectral camera across the Web.

Introduction

In recent years, there is a growing interest in the development and application of multispectral image acquisition and analysis.[1–7]

Multispectral cameras not only achieve much better colorimetric accuracy than conventional three-channel cameras, but also allow to obtain spectral data such as surface reflectances and spectral power distributions of illuminants.

Many previously described multispectral cameras have, however, a number of disadvantages which limit the application of multispectral image capture and analysis to a single working position in the laboratory where the camera is located. In a typical setup, a given number of interference filters is mounted on a filter wheel in front of a monochrome digital camera.[6] This limits the number of readily available spectral channels and requires mechanical filter switching. Another problem of multispectral image acquisition is the huge amount of data being typically collected from each color target.

Here we report a system for multispectral image acquisition and analysis which offers solutions for these problems.

Liquid Crystal Tunable Filter

The key element of our system is a liquid crystal tunable filter (LCTF) which allows for continuous tuning of its peak transmission wavelength over the full range of the visible spectrum. The spectral transmission profile is similar to a gaussian function and the LCTF is operated completely electronically, without any moving parts.

The optical principle of this type of spectral filter was introduced by Bernard Lyot in 1933, when he suggested to use a series of birefringent plates between polarizers in order to set up a monochromatic filter.[8] Birefringent materials have slightly different refractive indices n_o and n_e for two orthogonal planes of polarization, respectively known as the planes of the ordinary and the extraordinary rays. The difference $\Delta n = n_e - n_o$ leads to a phase lag between the ordinary and extraordinary rays. For a birefringent plate of thickness *d*, the phase lag δ between the two rays is

$$\delta = 2\pi d \Delta n / \lambda \tag{1}$$

where λ is the wavelength in vacuum. A single stage of a Lyot filter consists of such a retarder plate between parallel linear polarizers; the plane of polarization forms an angle of 45° with the n_o and n_e directions of the birefringent plate. This results in a circularly polarized wave propagating through the plate, and the angle of polarization at the end of the plate is given by δ. For a wave of amplitude A, the second polarizer lets pass only the parallel component $A_{\|}$:

$$A_{\|} = A\cos(\delta). \tag{2}$$

Since filter transmittance is defined as a ratio of light *intensities* I rather than amplitudes A, and

$$I \propto A^2, \tag{3}$$

we conclude from equations (1) to (3) that the transmittance $\tau_1(\lambda)$ of a single Lyot stage can be expressed as

$$\tau_1(\lambda) = \cos^2(2\pi d \Delta n / \lambda). \tag{4}$$

The transmittance function (4) of a single stage shows a series of minima and maxima and more selective filters consist of a series of such stages where the thicknesses of the birefringent plates decreases.

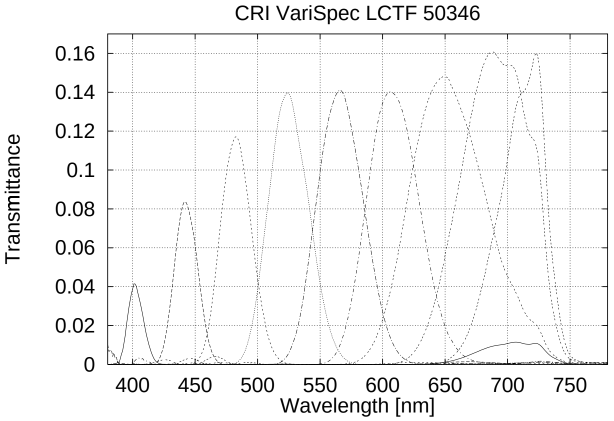

Figure 1. Spectral transmittance curves of the liquid crystal tunable filter VariSpec Model VIS2 (SN 50 346) for initially unpolarized light; measured with a Minolta spectroradiometer CS-1000.

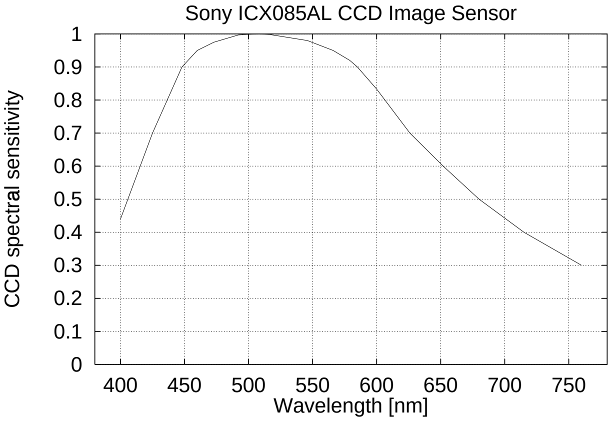

Figure 2. Relative spectral sensitivity of the PCO SensiCam Model 370 KL camera according to the datasheet available at http://www.pco.de/html/icx085al.pdf.

In a *tunable* spectral filter of the Lyot type, there is a liquid crystal cell added to each retarder plate in order to allow for an additional phase shift under control of an electric signal.[9] The spectral width of the passband of such a filter is primarily determined by the thickest retarder plate whereas the other stages attenuate all but one of the multiple transmittance maxima of the thickest plate.

We used a liquid crystal tunable filter (LCTF) VariSpec Model VIS2 (Cambridge Research & Instrumentation, Inc., Boston, MA) with a nominal bandwidth of 30 nm and a nominal accuracy of the selected peak wavelength of 4 nm. This allows to select about 80 significantly different tuning positions in the range from 400 nm to 720 nm.

Figure 1 shows the measured transmittance curves of our LCTF for nine peak wavelength positions. At a first glance, these curves correspond well to the specifications of this filter model. There are, however, in addition to the desired gaussian like areas of high sensitivity, minor sidelobes: The biggest sidelobe near 700 nm belongs to the filter profile which peaks near 400 nm. The four smaller sidelobes in the range from 400 nm to 480 nm successively belong to the filter profiles peaking near 605, 650, 685, and 720 nm. These artifacts have to be carefully compensated for in applications requiring spectral or colorimetric measurements of high accuracy.

Digital Camera

Behind the tunable filter, a monochrome digital camera served for image capture. We used a PCO SensiCam Model 370 KL camera with 1280 x 1024 pixels on a progressive scan CCD image sensor (PCO Computer Optics, 93309 Kelheim, Germany). The spectral sensitivity of the image sensor (Sony ICX085AL) has its maximum near 510 nm and shows only 10 percent variation in the wavelength range from 450 nm to 580 nm (see Figure 2).

The CCD sensor is Peltier cooled to a temperature of -12 centigrade for low noise image acquisition and the output signal is 12 bit AD converted. The CCD camera features an electronic shutter and the exposure time can be varied in 1 msec steps over the range from 1 msec to 1000 sec. The linearly 12 bit encoded pixel data are transferred by a high speed serial link to a specialized PCI interface (PCO Interface Board 520KP).

Computing Environment

In our system, the tunable filter and the CCD camera are both controlled by a Intel Pentium II based computer linked to the campus-wide Local Area Network (LAN) and the Internet. In order to allow for interactive use of this multispectral image acquisition system, we developed a modular client/server solution in which only a minimal server program is running on the ”SpectraCam” computer.

The server program is listening for requests made by suitable client programs via the network. Each request simply specifies the desired peak wavelength for the tunable filter, the exposure time for the electronic shutter of the CCD camera, and the region of interest. The ”SpectraCam” server executes the request by sending the corresponding control signals to the tunable filter and to the camera, and replies to the client by transmitting the gathered pixel data. The time required to process such a request depends primarily on the exposure time. For typical color image targets and lighting conditions, the whole process takes less than 1 second, and then the server is ready to process the next request.

As a simple example of a sequence of client requests, consider the acquisition of 3 channel signals suitable for a given set of CRT RGB primaries. If the client is interested in the top-left image region 128 pixels wide and 64 pixels high, the corresponding requests could be, with T for exposure time:

1. λ = 445 nm, T = 200 ms, x = 1 to 128, y = 1 to 64
2. λ = 540 nm, T = 100 ms, x = 1 to 128, y = 1 to 64
3. λ = 610 nm, T = 100 ms, x = 1 to 128, y = 1 to 64

In reply to each of the 3 requests, the ”SpectraCam” server will send the linearly encoded 12-bit data of the 8192 pixels to the client program.

At the same time, another user from elsewhere on the Internet could want to examine the spectral power distribution of light reflected from a small patch located center-left on the color image target. As he also might want to precompensate approximately for the spectral power distribution of the tungsten lamp illumination, his client program would make the following series of requests:

1. λ = 400 nm, T = 350 ms, x = 1 to 16, y = 505 to 520
2. λ = 440 nm, T = 80 ms, x = 1 to 16, y = 505 to 520
3. λ = 480 nm, T = 50 ms, x = 1 to 16, y = 505 to 520
4. λ = 520 nm, T = 40 ms, x = 1 to 16, y = 505 to 520
5. λ = 560 nm, T = 30 ms, x = 1 to 16, y = 505 to 520
6. λ = 600 nm, T = 30 ms, x = 1 to 16, y = 505 to 520
7. λ = 640 nm, T = 20 ms, x = 1 to 16, y = 505 to 520
8. λ = 680 nm, T = 20 ms, x = 1 to 16, y = 505 to 520
9. λ = 720 nm, T = 20 ms, x = 1 to 16, y = 505 to 520

He then could display the data as a line-plot graph or compute linear combinations of the 9 channel pixel data.

We have implemented the ”SpectraCam” server program and a variety of clients in the Java programming language. The specific library functions required for the operation of the digital camera were called through the Java Native Interface (JNI)[10], and the liquid crystal tunable filter was controlled by means of the Java Communications API which contains support for RS232 serial ports.

Conclusion

This paper has addressed the specific problems of multispectral imaging in a networked environment. The proposed solution consists of an electronically tunable spectral image filter in front of a monochrome CCD camera, and modular software components based on a client-server architecture. Since the client programs can be written as Java applets, our system not only is a valuable laboratory tool for color research but also offers the possibility of interactive multispectral image acquisition and analysis across the Web.

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