Multispectral Image Capturing System Based on a Micro Mirror Device with a Diffraction Grating

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Abstract

Although the color reproduction of RGB-based image capturing systems is sufficient for many tasks, there are some critical color matching applications like digitizing of high quality illustrated books, artwork imaging or catalogue selling. Due to the known theoretical limitations of RGB-techniques, multi-channel methods of image capture have been introduced in the recent years, typically based on a multitude of color filters.

In this paper a spectral imaging system is presented where the color information of an original image is separated by a diffraction grating. The grating is applied on a micro mirror, which is actuated by an electrostatic field causing a high frequency oscillation of the device. Due to the vibration different spectral intervals of the diffracted light can be detected by a CCD-line.

As a first step 35 different spectral intervals of each pixel are measured. The gamut of the resulting color space compared to standard RGB-based image capturing systems is shown. Finally, experimental results are discussed dealing with the limits of resolution of this micro mirror based multispectral device.

Introduction

A color accurate reproduction of an arbitrary original is a common problem in the printing process. The reason is that the color perception of a human depends on many parameters. Besides the spectral properties of the original these parameters are for example the light source, the environment, the characteristics of the paper substrate, and the specific observer. Additionally, different device dependent color spaces of the several in- and output devices are causing further problems.

Furthermore there are some critical color matching applications like digitizing of high quality illustrated books, artwork imaging or catalogue selling. Therefore the enlargement of the color spaces of the devices in the reproduction process became a very interesting field in color research. Hence using more than three color channels was very successful, different multispectral image capturing systems were introduced. Each of these systems is based on a certain number of different color filters, which are changed in a manual,[1] an electro mechanic[2] or an electronic way.[3]

Alternatively, a diffractive optical element can be used, like a prism or an optical grating for example. Especially the use of diffraction gratings has several advantages. The dispersion properties are well known [e.g. 4], and if phase gratings are used, the spectral signals are intense compared to other methods. Moreover, the distribution of the spectrum is linear and independent from material characteristics. These are the reasons why diffraction gratings became the standard tool in spectral photometers for color measurement.[5]

Therefore, it is obvious to use such a spectral photometric method also for an image capturing system. The advantage of such a solution is that the color values of the original can be determined independently from the used light source during the capturing process, if an alignment is done. Furthermore the number of usable spectral intervals is only limited by the wavelength resolution of the grating and the resulting amount of data which has to be handled and stored by a computer.

For a perfect image capture device (ICD) also a small system design is desired. Using a micro mirror with a diffraction grating will allow the integration into a micro electro mechanical system (MEMS) enabling a compact device. Another application for such a device can be the use as a micro spectrometer.

The single spectral ranges can be recorded from a monochrome CCD-line sequentially, if the spectrum is moving perpendicular to the sensor. An oscillating micro mirror driven by electrostatic forces can fulfill this task. Due to the small size of such a micro mirror high oscillation frequencies and therefore a high recording speed is achievable. The combination of such a micro mirror device (MMD) and a MEMS diffraction grating seems to be a promising approach for a small and integrated ICD.

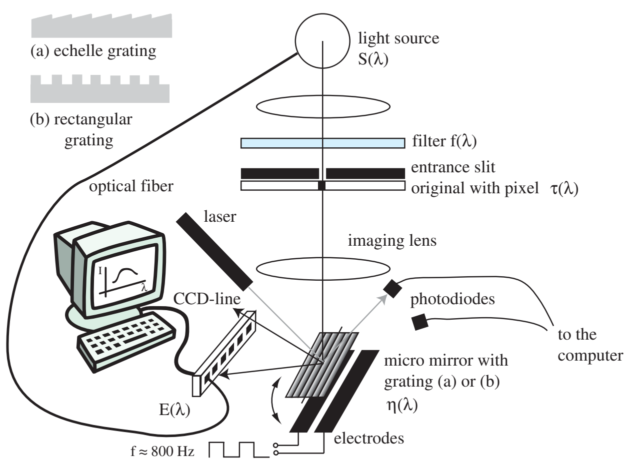

Figure 1. Principle illustration of a spectral image capture device based on a micro mirror with a diffraction grating. The laser beam and the photodiodes are determining the beginning and the end of the measurement. The optical fiber guides a reference signal of the light source onto the CCD.

System Design

A spectral image capture device has been realized as illustrated in figure 1. A transparent original modulates a polychromatic light beam. The light signal is guided onto the micro mirror with diffraction grating where it is separated into its spectral parts. Light of different wavelengths is diffracted into different angles, which can be approximated by the general grating equation

$$d\ (\sin\alpha\ -\sin\beta\ ) = m\lambda \qquad (1)$$

where d is the grating period, α is the angle of the incident light beam, β is the angle of the diffracted light beam, m is the diffraction order, and λ is the wavelength.

After the mirror, a monochrome CCD-line with a spectral sensitivity $E(\lambda)$, and orientated perpendicular to the spectrum is detecting one spectral range from the incoming light. By oscillating the mirror, the whole spectrum moves across the sensor and every interesting wavelength interval can be recorded. To increase the performance of the system it seems to be necessary to capture the color signal of several pixels in parallel. Therefore, an entrance slit in front of the original ensures that only one pixel line is illuminated and directed onto the micro mirror device. Since the wavelength interval under investigation has to be assigned to each measurement, a laser beam triggers the beginning and the end of the measurement. An optical fiber between the light source and the CCD monitors intensity fluctuations, which are taken into account during the analysis of the measurement.

For a spectral ICD based on diffraction grating several physical properties have to be considered. First of all a possibly high resolving power is useful which is given by [e.g. 6]

$$\frac{\lambda}{\Delta\lambda} = \frac{Nd(\sin\alpha - \sin\beta)}{\lambda} \qquad (2)$$

where $\Delta\lambda$ is the limit of resolution and N the number of illuminated grooves of the grating. Considering equation (1) and (2) a small grating period and a high number of grooves should be realized.

Using a small grating period results in a high angular dispersion of the spectrum. Therefore a high maximum angle of deflection for the micro mirror is necessary so that the whole spectrum can move across the CCD.

Furthermore the free spectral range of the grating has to be taken into account, because an overlapping of different diffraction orders has to be avoided. A wavelength of $\lambda/2$ in order $2m$ will be diffracted into the same direction as light of the wavelength λ in order m as equation (1) shows. Due to the size of the interesting spectral interval and due to the fact that an increasing diffraction order decreases the free spectral range, only the use of the first diffraction order is possible.

Rectangular and so called echelle gratings are utilized. Echelle gratings have higher diffraction efficiencies in a desired spectral interval and diffraction order depending on the used blaze angle. A disadvantage of these gratings is the more complicate manufacturing process compared to the rectangular ones. The gratings are realized by standard methods of micro technologies which are described in Ref. [7].

The general working principle of the described micro mirror is an elastically hinged mirror plate immediately actuated by an electrostatic field between plate and electrodes. The necessary high deflection angles are reached by driving the micro mirror in resonance.

With simultaneous consideration of all these points of interest and limitations in the manufacturing process we use gratings with a period of 1µm, and a size of 5.12 x 3.0 mm^2. The used echelle gratings have a blaze angle of 20°. The mirror is driven in resonance with a frequency of 800 Hz and a maximum angle of deflection of +/- 10 degrees. A photo of such a MMD is shown in figure 2.

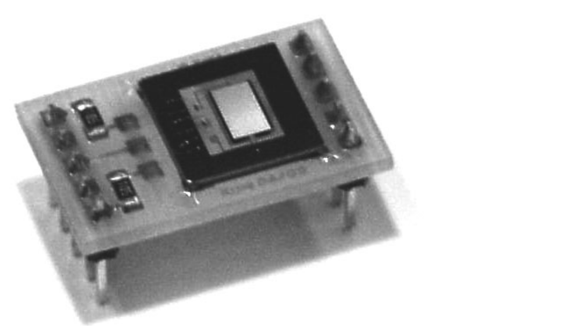

Figure 2. Photo of an actuator with a micro mirror and a diffraction grating.

Simulation of the Image Capturing Process

First of all some simulations were done showing the theoretical limitations of a spectral image capture device with 35 color channels. As mentioned above the MMD are working in resonance. Therefore a sinusoidal oscillation of the mirror can be adopted.

In the middle position of the micro mirror, the wavelength $\lambda_R = 550$ nm shall reach the CCD-line. Adopting a sinusoidal oscillation and using equation (1), the wavelength reaching the CCD-line can be described by the equation

$$\lambda = d\{\sin[a + A\cos(2\pi ft)] + \sin[\sin^{-1}(\lambda_R - \sin\alpha) + A\cos(2\pi ft)]\} \quad (3)$$

where A is the amplitude of the oscillation, f the resonance frequency, and α is the angle of the incident light beam in the middle position of the micro mirror.

In the measurement process of the spectra only a small part at the node of the oscillation shall be utilized so that a linear approximation can be done. To verify this, two simulations of the measuring process were done using a more accurate sinusoidal approximation based on equation (3) and a linear approximation.

The simulations are based on spectral data of different colors. Regarding the spectral properties of the experimental setup and simulating an alignment, the spectral distributions are calculated using the two approximations. Figure 3 shows an example for a cyan spectrum that was measured with a spectral photometer. Both simulated spectra are very similar and matching the cyan curve very well.

The next step is to evaluate the influence of the small deviations between the three spectral distributions concerning to the color values. Using the CIE formulas [e.g. 8] the color values are estimated regarding to the light sources A and D65 for each spectrum. To quantify the color accuracy, the color distances ΔE of the two simulated spectra are calculated with respect to the original spectrum. In this example, $\Delta E_{ab} = 0.98$ for the sinusoidal approximation and $\Delta E_{ab} = 0.99$ for the linear approximation. This simulation was repeated for several colors and the results are very similar to the example. Only if the spectral distributions have steep edges or discontinuities like optimal color stimuli, color distances up to a ΔE_{ab} of 3 can result.

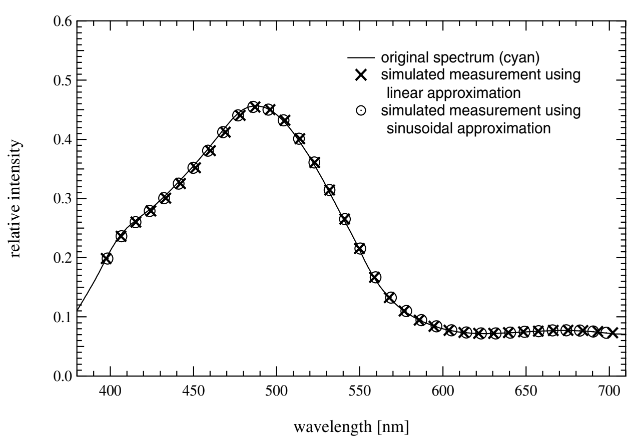

Figure 3. Simulation of the spectrum measurement process. The matching between the different spectra is very well.

Furthermore, the resulting color space is calculated using a spectral interval between 400 nm and 700 nm with a step width of 9 nm. Gaussian spectral distributions with a half width at full maximum of 30 nm are the smallest one which can be detected certainly with a resulting ΔE_{ab} smaller 1 if 35 color channels are used. The resulting chromaticity values of these spectral distributions terminate the possible color space. An illustration of this limitation is given in figure 4.

Modulation Transfer Function of the ICD

Beside high color accuracy, the reproduction of the image structure is also very important. In a first step, it shall be demonstrated that an original with an optical resolution of 300 dpi can be transferred by a MMD with a diffraction grating. Therefore, measuring the modulation transfer function (MTF) of our optical system seems to be a good method in evaluating the influence of the grating.

Therefore a black and white test chart with a spatial frequency of $\xi = 300$ lpi is used. The experimental setup is similar to figure 1. A halogen lamp illuminates the entrance slit directly in front of the test chart. Behind the test chart, an achromatic convex lens images the original over the static micro mirror onto the CCD-line, which is positioned in the first diffraction order. Finally, the modulation of the measured intensity signal is identified after a dark calibration. This measurement is repeated for several spectral ranges using additional narrowband interference filters. The results are illustrated in figure 5. Depending on the wavelength the measured MTF varies between 0.7 and 0.8.

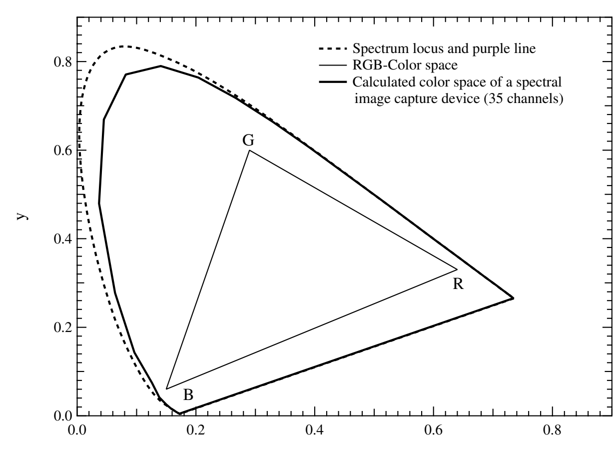

Figure 4. Simulated color space of a spectral image device with 35 color channels .The limitation is calculated with respect to the CIE light source D65. The RGB-values are based on the standard of the European Broadcasting Union for TV-phosphors.

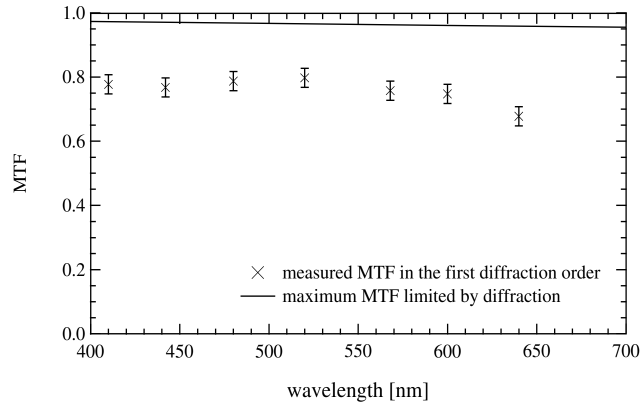

Figure 5. Illustrated is the maximum MTF (solid line) of the spectral ICD and the measured MTF depending from the wavelength. (static mirror)

The MTF of a perfect optical system is limited by diffraction only. For a system with a circular aperture, the maximum MTF is given by [e.g. 9]

$$MTF(\xi) = \frac{2}{\pi}\left[\arccos(\xi k\lambda) - \xi k\lambda\sqrt{1-(\xi k\lambda)^2}\right], \quad (4)$$

where k is the aperture number of the system. Influences caused by aberrations are not taken into account. A MTF of about 0.96 results, if the optical parameters of our spectral ICD are inserted into equation (4). The solid line in figure 5 illustrates the maximum MTF for our device depending on the wavelength.

Besides the MTF of the non-oscillating system, the dynamic behavior of the system is a central point of interest. The measured MTFs differ very strongly and vary between 0.4 and 0.7. Since nothing is changed between the different experiments except the mirror, this must be the crucial element in the dynamic setup. A suitable explanation can be either exterior influences like small deviations in the manufacturing process of the mirror hinges, dust or additional harmonics of the oscillation.

Spectral Separation Quality of the ICD

For an ICD based on a diffraction grating it is essential that the different spectral intervals can be sufficiently separated during the measuring process. To investigate the diffraction properties an experimental setup differing to figure 1 is used. A micro mirror is mounted onto a rotary stage changing the angle of the incoming light in small steps. Additionally various narrowband interference filters are placed successively in the optical path in front of the mirror.

The intensity signal depending on the position of the rotary stage and the used interference filter is measured by the CCD. Due to the known angular position of the rotation stage, the incident and diffraction angles can be calculated. Inserting these values in equation 1 allows determining the wavelength reaching the CCD. The result is shown in figure 6 where the measured relative intensity is plotted versus the wavelength. The solid line represents the known transmission properties of the used interference filters. The 66 measuring points, which are symbolized by the black squares, reproduce the transmission curves quite good.

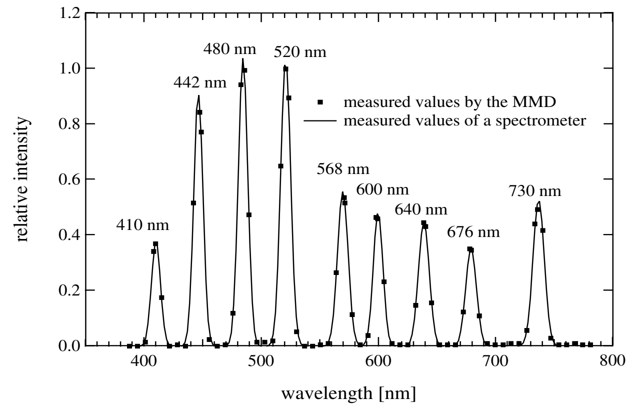

Figure 6. Relative intensity measured by the CCD-line versus the wavelength. The solid line represents the known spectral transmission properties of the interference filters and the specified wavelengths are the appropriate respective central wavelengths.

Conclusion

A spectral image capture device was presented, which is based on a MMD with a diffraction grating. Such a device has several advantages like a high possible integration or a high flexibility in respect of the number of color channels.

The measurement process was simulated and color accuracy in the image capturing process was verified in theory. For continuous spectra the color accuracy is very good. Only discontinuous spectral distributions are making small problems but these are not to note for practical use. Applying 35 color channels a big part of the entire color space can be detected by a spectral ICD. Increasing the gamut is possible if the number of channels is raised up. To do this without trouble, a high wavelength separation is necessary. This demand is fulfilled sufficiently as a look at figure 6 shows, where 66 instead of 35 color channels have been measured.

The MTF of the static system is sufficient regarding to the theoretical maximum but problems are observed in the more important dynamic case. The value of the MTF depends strongly from the used mirror. Further research will be done to explain this behavior.

Acknowledgements

This work was financially supported by the Deutsche Forschungsgemeinschaft within SFB 379.

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Biography

Martin Flaspöhler received his diploma degree in physics from the University of Osnabrück (Germany) in 2000 specializing in holographic data storage. Since 2001 he works at the Institute of Print- and Media Technology at the Chemnitz University of Technology. Here he is working in the field of micro systems for spectral image capturing. Further interests are color science, digital image capture and color management. He is a member of the Deutsche Physikalische Gesellschaft (German Physical Society).