INTRODUCING THE THIRD DIMENSION INTO SPECTROSCOPY

A new method for surface inspection and color measurement

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Abstract

A standard method in vision technology to acquire spectral information is the use of a CCD diode array spectrometer. Conventional spectrometers are able to record an optical spectrum integrated over a specified surface area. If one desires to determine the spectral information at several different spatial positions a mechanical component to move the optical head or multiple spectrometer channels become necessary.

Beside this conventional technology there are actually a large amount of two dimensional and even high quality CCD field chips available. Therefore the idea to use a CCD camera to measure multiple spectra simultaneously seems to be obvious.

We present a new optical component which can be positioned between a standard lens system and a standard digital CCD camera. Using this optic component a large set of spectra (> 1000) can be recorded simultaneously. The spectral information is obtained from the light of an illuminated or a self illuminating line. In one direction of the field chip the spectral information is saved and perpendicular to this direction the spatial information is stored simultaneously. By using this new optical component the information about multiple spectra along a line is available. The number of these spectra depends only on the spatial resolution of the matrix detector. The typical two dimensional information in spectroscopy consisting of wavelength and intensity is extended to a third dimension – the spatial information.

Using this component a huge number of new applications for industrial machine vision and on-line analysis are in reach. E. g. for controlling the color feed of a printing process or mixing bulk solids by color measurement can be improved significantly in comparison to RGB cameras. All applications concerning spectrally dependent information can now be established in combination with spatial information including the non visible spectrum (ultraviolet or near infrared) which opens up the wide field of material analysis.

In this paper we discuss the principle and the properties of this component concerning color measurement. One example application is presented. The technical advantages and limits of this new optical component are also discussed.

1 Introduction

For precise color measurement as defined in the DIN 5033 [4] spectral analysis is necessary. But conventional commercial spectrometers or spectrophotometers are usually able to measure only the optical spectrum from a specified surface area as one point. This is done either with one detector scanning the spectrum in narrow wavelength bands or with an diode array detector, in which case all the spectral components are electronically acquired at once.

If one desires to measure the spectrum at several spatial locations of the specified surface – like it is often required in industrial applications – the target under examination or the measuring instrument has to be mechanically scanned. An imaging spectrometer can be defined here as: an instrument capable of simultaneously recording spectral *and* spatial information from an illuminated or self illuminating objects surface. In this paper we introduce a new technology for spectral imaging based on an new imaging spectrograph. For all experiments discussed in this paper we used the *ImSpector* (see [11]).

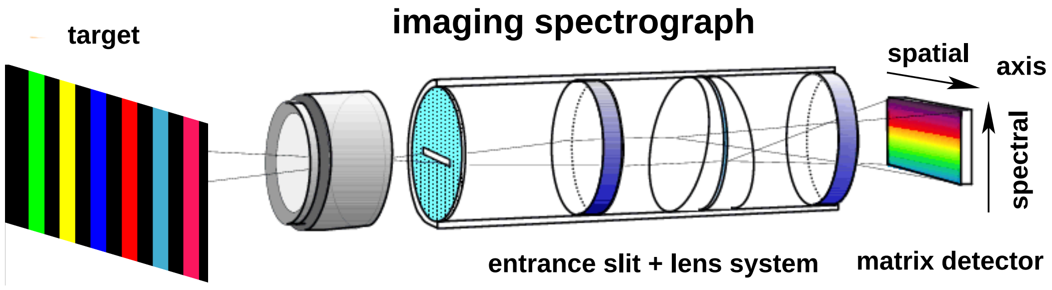


Figure 1: *Schematic of the imaging spectrograph ImSpector showing also the simultaneous mapping with a matrix detector.*

The results of a three dimensional information space can be measured with an area (matrix) detector which is connected to the dispersive, stationary spectrograph module. One dimension of the detector corresponds to a spatial line image and the other dimension corresponds to the spectrum. This is the operating principle of the ImSpector imaging spectrograph (see Fig. 1).

Emerging from the imaging spectrograph is a two dimensional image of the 'objects slice' where one axis represents the spatial width of the image in the direction of the slit and the other axis represents the wavelengths of the spectrum. When this image is typically collected by a monochrome CCD camera the first axis represents the average of the light coming from a small part of the 'object slice'. The second axis represents the light intensity at a particular wavelength. This data matrix consists of the spatial information in each row and the spectral information in each column. In the case of a non square detector matrix the spatial or the spectral axis can be adapted to the desired detector axis by rotating the imaging spectrograph in respect to the detector. In other words, the ImSpector converts an area monochrome detector (camera) to a spectral line imaging system.

There maybe still remains the task of scanning the surface in the other dimension perpendicular to this line as a function of time. By using an imaging spectrograph this is much easier to accomplish compared to methods using conventional spectrometer. In some applications the movement of the object (process stream, web,...) automatically forms the other spatial dimension. Otherwise a linear translation of either the objects or the detector system can easily be achieved.

This paper concentrates on color measurement applications corresponding to the visible range of the light spectrum. In the next section 2 the imaging spectrograph is introduced as a general sensor system for color determination. As an example application where standard color measurement systems may fail the determination of colors of bulk solids in discussed in section 3.

2 Color determination using spectral images

The imaging spectrograph offers a wide range of new applications. Despite the color measurement with the ImSpector is only a small fragment of this range it is one of the most interesting and vivid application.

In Fig. 2(a) an example target for color measurement is shown. To give a graphic description of the principle of spectral imaging the target does only vary in one spatial direction. The measurement area detected by the imaging spectrograph lies between the two white lines in Fig. 2(a). The geometric length and width of this area is determined by the distance of the entrance slit to the target (here 100 mm). Increasing the distance between the target and the imaging spectrograph the surface of this area increases proportionally. Corresponding to the properties of the optical lens used this area can vary from microscopic scale (below one mm) to macroscopic scale (more than several 10 m).

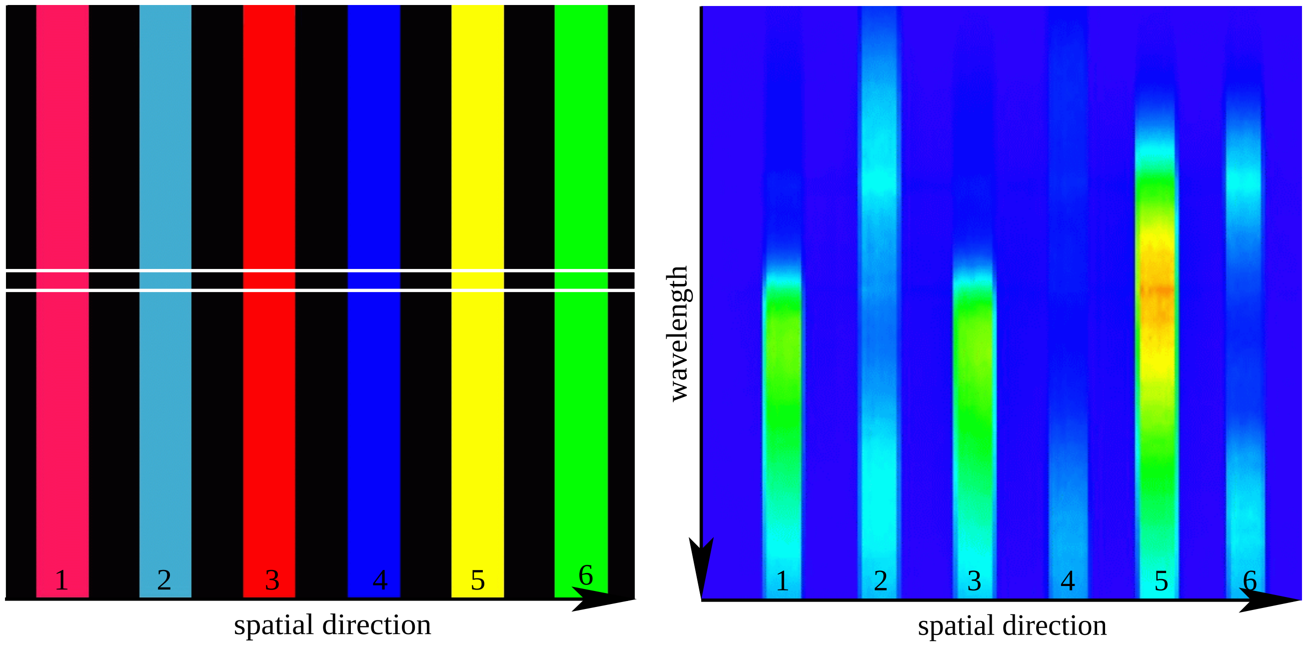
Fig. 2(b) shows a falsified color image of the spectral image data recorded with the imaging spectrograph corresponding to the displayed measurement area. It is very important to get used to this special arrangement of spectral data that can be explained as: The spatial direction (horizontal in Fig. 2(b)) corresponds to the horizontal spatial direction in Fig. 2(a). In the spectral direction the wavelengths varies from 320 nm to 800 nm. A color of blue means low intensity and a color of red means high intensity in that spectral range.

The matrix detector used for this measurement has a resolution of 640x512 pixels converted with a 12 bit analog digital converter (see [8]). This means the spectral image shown in Fig. 2(b) consist of 640 spectra each with 512 spectral bands. For spectral imaging in praxis the high dynamic range and resolution of the analog digital conversion is more important than the number of pixels of the CCD matrix detector. Because of the enormous flexibility of the analysis of the digital spectral imaging data for every application the focus on special wavelength bands of the spectra related to the region on the matrix detector can be individually adapted.

In Fig. 2(c) the spectral imaging data of Fig. 2(b) is shown as a three dimensional plot which reproduces an illustrated view of the dimensions of spectral imaging. Scanning over the target or recording a moving target leads even to a four dimensional space consisting of time (or one spatial direction), space, wavelength and intensity. Using a sequence of spectral images the image of the original target can be reconstructed (see also the spectral imaging analysis algorithms in [3]).

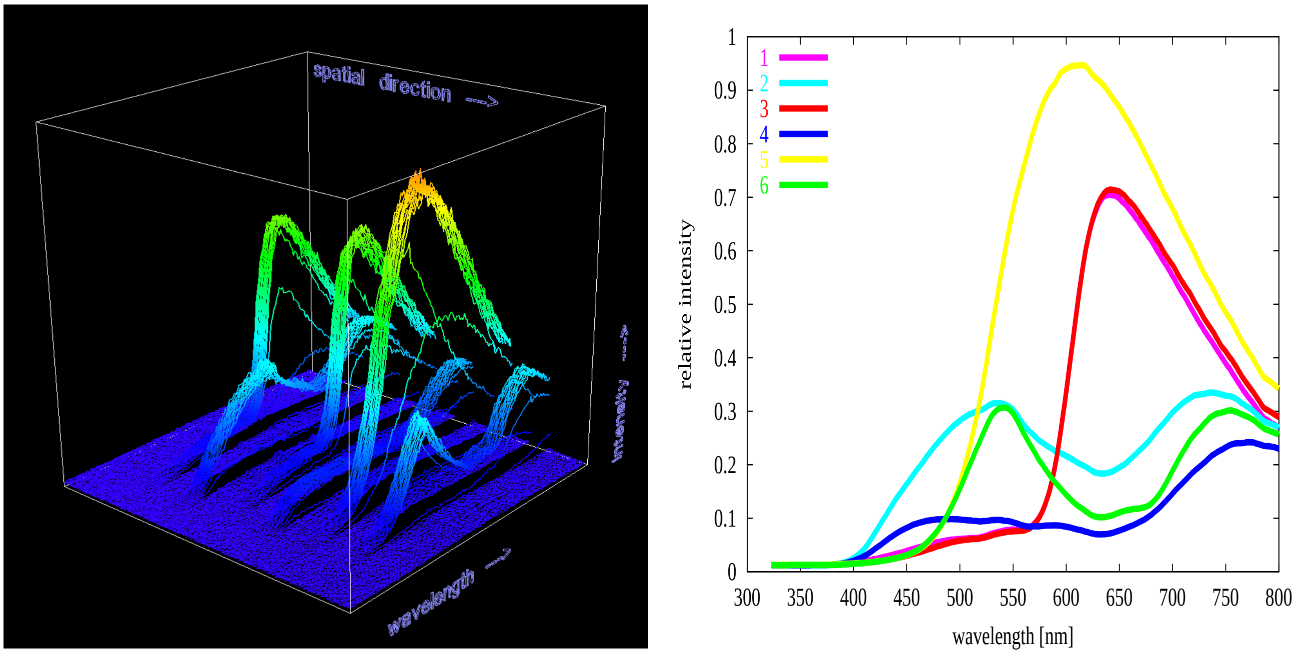
In Fig. 2(d) the spectra corresponding to the color strips of the target are shown in a conventional wavelength versus intensity plot. Each spectrum was calculated by averaging and smoothing all spectra of one color strip.

Of course every standard RGB detector system could distinguish between the different colored strips. But imagine a more complex spectral difference and spatial arrangement of the samples then spec-



(a) an RGB image of the color strips

(b) corresponding spectral image



(c) 3D view of spectral image

(d) extracted spectra (filtered mean of each strip)

Figure 2: *2(a) shows an image of the original color strips as they could be captured with an RGB camera. 2(b) displays one spectral image with falsified colors. It corresponds to one line of the original image in figure 2(a) (see the white frame around the measurement area). An impressive method of displaying the spectral image of 2(b) is shown in 2(c). 2(d) shows spectra extracted out of the spectral image. One spectrum corresponds to the filtered mean over one color strip.*

troscopic analysis is necessary.

In Fig. 2 the raw spectral data are displayed. To calculate the color space values from the raw data some conversion steps are required (see section 2.1). Some of these conversion steps are equal to the common color algorithms used in combination with a conventional spectrometer. In addition to that there are some supplementary conversion steps necessary when using the imaging spectrometer.

2.1 Converting spectral images for determining colors

Before starting any calculation of color space values or more generally starting classification e.g. via PCA[1], PLS[2] or MLR[3] the raw spectral imaging data has to be transformed. In Fig. 3 a schematic figure of this transformation is given.

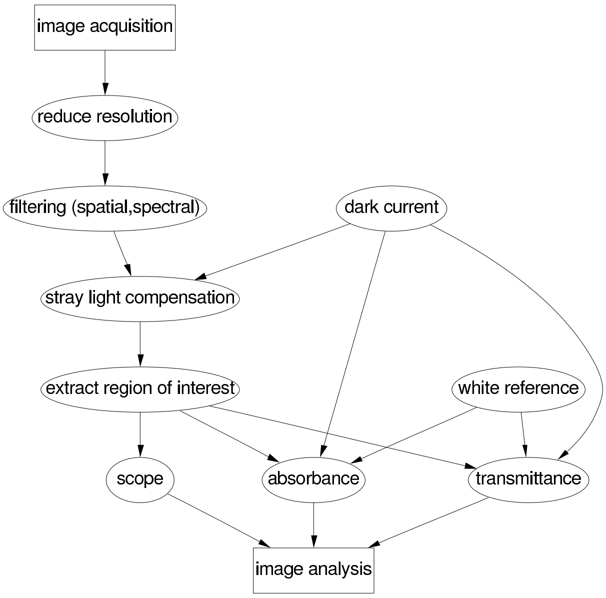


Figure 3: *Schematic figure of the transformation of spectral imaging data analysis procedure (PROC0). This procedure is necessary for further analysis e.g. color measurement or more general classification (e.g. via PCA, PLS or MLR.*

After the image acquisition with the CCD matrix detector for all practical applications the resolution of the original spectral image should be reduced. This reduction of the resolution can be realized either with hardware components or by numeric calculation and should be individually adapted for every application.

The filtering of spectral data either in spatial or spectral direction can help to reduce noise. There exist a vast number of filtering algorithms especially for the analysis of spectral data which are beyond the scope of this paper.

The straylight compensation – corresponding to the straylight in the lens system of the imaging spectrograph – is important for color measurement and can be realized by using the part of the lower

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[1] principal component analysis

[2] partial least squares

[3] multiple linear regression

wavelength of the spectra. The dark current is related to the pixel values of the CCD matrix detector in case of no light reaches the detector surface. This dark current lies usually in the order of $> 1\%$ of the total dynamic range. For precise measurements this dark current should always be calculated.

For calculating the reflexion/transmission or the absorbance out of the spectral data a white reference is needed as needed for color determination via conventional spectroscopy.

By extracting a region of interest the image analysis can be focused on the relevant data. E.g. special wavelength bands can be selected for a specific application.

2.2 Suitable lens systems and illumination

For a complete introduction into the concept of spectral imaging for color determination the lens system between the target and the spectrograph should also be discussed. In many application using the imaging spectrograph a standard optical lens should be sufficient.

But referring to the dependence on the angle between target, illumination and detector for exact color determination the lens system can be substituted by a special multi channel fiber optic (more than 50 channels are possible). The detector end of each fiber optic is directly positioned before the entrance slit of the spectrograph. Collecting the light via a collimating lens on the target end of each fiber optic color determination of non planar objects together with a defined target to detector and illumination angle can be realised.

The importance of illumination especially concerning color determination is well known. Both the spectral characteristics and the geometric arrangement of the illumination must be individually adapted for every specific application.

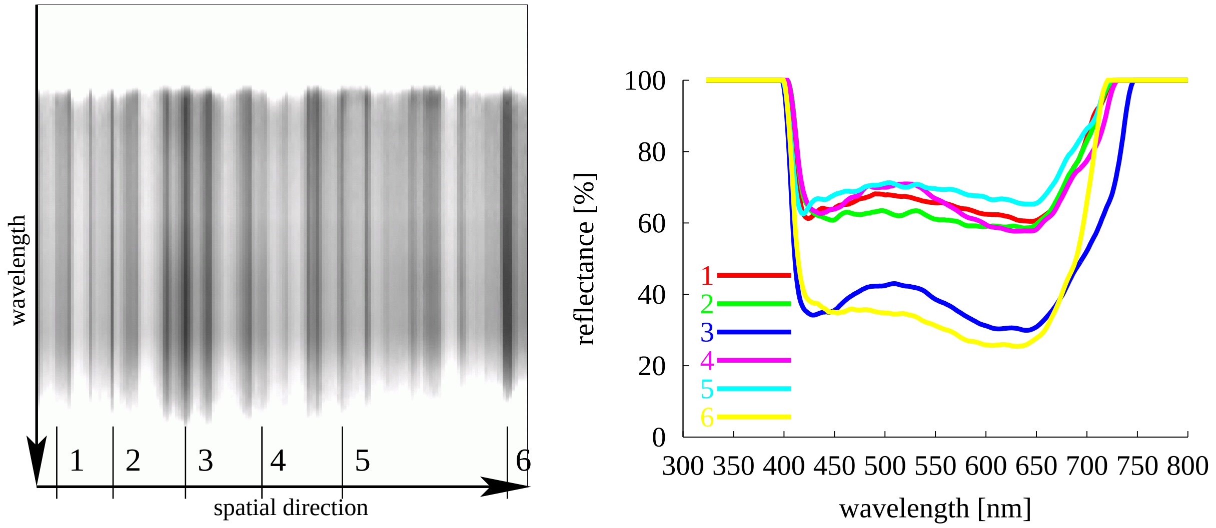
3 Color measurement on bulk solids

If the determination of color (or any other property which can be determined by evaluating spectral data) is important for the quality of a product then spectroscopic analysis is necessary. If in addition to that the spatial distribution of this property is needed (e.g. in the printing industry) spectral imaging can become a useful sensor system.

Analyzing bulk solids using conventional spectrometer often a significant dependence on the particle size can be observed. The reason is the nonuniform illumination and detector to target angle unavoidable with bulk solids. In that case the interesting color can only be evaluated at some special locations on the target.

In Fig. 4(a) a spectral image of bulk solids is displayed. The particle size is $\approx$0.5-2 mm and the geometric spatial width of the image is 40 mm. The strong dependence on the spatial position is obvious. But using the imaging spectrograph with high resolution in spatial and spectral direction the spectra with the significant information can be extracted out of the large number of available spectra. These spectra shown in Fig. 4(b) can now be used for color determination.

In addition to the preciseness of analysis via spectral imaging the availability of high speed and on-line data acquisition units leads to the main advantage of spectral imaging.



(a) spectral image of bulk solids with marked spatial positions

(b) the spectra marked in the upper figure

Figure 4: *A spectral image of bulk solids in reflectance mode is shown in 4(a). The strong dependence on the spatial position is obvious. Spectral imaging has the advantage to select suitable spectra for further analysis as shown in 4(b).*

4 Conclusions

Using spectral imaging for color determination extends the standard color determination via RGB detectors or a single spectrometer extremely. Compared to color measurement systems with the standard spectrometer which are more or less laboratory system spectral imaging is suitable for process control and machine vision. Compared to RGB matrix detector the spectral imaging technic increases the preciseness of the color determination.

The extreme fast development of matrix detector in the past years and most probably also in the near future will lead to a wide range of applications [5, 7, 10]. Nowadays technical limits in either speed, resolution or spectral range will be extended. Actually the applicability of spectral imaging in the industry is more limited due to the lack of suitable algorithms for analyzing the data than to the technical limits of the components.

The ImSpector is available in a wide range of wavelength from below 380 nm up to 2400 nm. In the spectral range above 800-1000 nm the standard CCD detector material shows not enough sensitivity for spectral analysis. Newer detector materials extend the possible applications to the near infrared [6] using InGaAs detectors or extend the speed of the data acquisition and the possibilities of data reduction (CMOS detectors).

References

[1] CIE. Colorimetry. CIE Publication No. 15.2. Central Bureau of the CIE. Vienna (1986)

[2] CIE. Industrial color difference evaluation. CIE Publication No. 116-1995. Central Bureau of the CIE. Vienna (1995)

[3] CubiCo. The spectral imaging software for analysing and calibrating spectral images. http://www.zeutec.de

[4] DIN Deutsches Institut fuer Normung e.V. Farbmittel. 1. Pigmente, Fuellstoffe, Farbstoffe, DIN 5033-1 bis DIN 55929 : Normen. Beuth Verlag (2000)

[5] Olle Hagman. Multivariate Prediction of Wood Surface Features Using an Image Spectrograph. 2nd International Workshop on Scanning Technology and Image Processing on Wood. Skelleftea. Sweden (1995)

[6] Kurt C. Lawrence et al. Hyperspectral imaging for poultry contamination detection. NIR news Vol. 12 No. 5 (2001)

[7] Jan Nystroem. Olle Hagman. Real-time spectral classification of compression wood in Picea abies. J Wood Sci 45:30-37 (1999)

[8] CCD matrix detector. The Pixelfly camera from PCO. http://www.pco.de

[9] G. Polder et al.. Hyperspectral image analysis for measuring ripeness of tomatoes. ASEA International Meeting. Wisconsin (2000)

[10] Charles Poynton. A Guided Tour of Color Space. http://www.inforamp.net/~poynton/PDFs/Guided_tour.pdf (1995)

[11] Spectral Imaging LTD. Real-time imaging spectrometry for surface inspection and online machine vision. http://www.zeutec.de/download/imspector_surface_inspection.pdf (1999)

[12] Spectral Imaging LTD. On Line multichannel spectrometry. http://www.zeutec.de/download/online_multichannel_spectroscopy.pdf (1999)

[13] Spectral Imaging LTD. ImSpector upgrades color to B/W machine vision platform. http://www.zeutec.de/download/imspector_bw_color.pdf (1999)

[14] Spectral Imaging LTD. Data processing in precise spectral imaging. http://www.zeutec.de/download/precise_spectral_imaging.pdf (1999)

[15] Spectral Imaging LTD. Online spectral/color control in textile dyeing. http://www.specim.fi/pdf/ImS_Application2.pdf

[16] Spectral Imaging LTD. Online spectral/color measuring for printing control. http://www.specim.fi/pdf/ImS_Application3.pdf

[17] G. Wyszecki and W. S. Stiles. Color Science: Concepts and Methods, Quantitative Data and Formulae. John Wiley & Sons. Inc.. New York (1982)