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# Optical characterization with filter-on-chip CMOS sensor-systems

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**Abstract** Mosaic filter-on-chip CMOS sensors enable the parallel acquisition of spatial and spectral information. These mosaic sensors are characterized by spectral filters which are applied directly on the sensor pixel in a matrix which is multiplied in the x- and y-direction over the entire sensor surface. Current mosaic sensors for the visible wavelength range using 9 or 16 different spectral filters in 3×3 or 4×4 matrices. Methods for the reconstruction of spectral reflectance from multispectral resolving sensors have been developed. It is known that the spectral reflectance of most natural objects can be approximated with a limited number of spectral base functions. In these cases continuous spectral distributions can be reconstructed from multispectral data of a limited number of channels. This paper shows how continuous spectral distributions can be reconstructed using spectral reconstruction methods like Moore-Penrose pseudoinverse, Wiener estimation, Polynomial reconstruction and Reverse principal component analysis. These methods will be evaluated with monolithic mosaic sensors. The Goodness of Fit Coefficient and the CIE color difference are used to evaluate the reconstruction results.

**Keywords:** Multispectral, filter-on-chip, spectral reconstruction.

## 1 Introduction

To meet the growing expectations concerning the quality in industry, biology and medicine miniaturized photonic micro sensors are now available for simultaneous optical characterization of shapes, colors and spectra.

The latest developments in photonic micro sensor systems enable simultaneous recording of those information with specialized multispectral resolving mosaic filter-on-chip CMOS sensors.

## 2 Sensor technology

The mosaic filter-on-chip CMOS sensors are characterized by spectral filters which are applied directly on the sensor pixel in a matrix which is multiplied in the x- and y-direction over the entire active sensor surface. Current mosaic sensors for the visible wavelength range using 9 or 16 different spectral filters in 3×3 or 4×4 matrices.

For the realization of these sensors two technologies are used. First is a monolithic approach where the filters are directly applied on the CMOS sensor surface. Second is a hybrid approach where the filters are applied on a separate substrate and the substrate is afterwards arranged on the CMOS sensor surface [1].

## 3 Methods and algorithms

The following section provides a general guideline for the application of multispectral resolving mosaic filter-on-chip CMOS-sensor-systems in the visible wavelength range. This includes the performed metrological characterization of the system, the derived correction of the sensor data, the derived sensor value extension and the provision of ready to use sensor data for final application (Figure 11.1).

With the metrological characterization of the spectral, optical and electrical properties of the sensor-system a value correction and extension model can be derived [2], [3]. Using pre-characterized properties, a correction matrix for the pixel reflectance can be calculated to minimize spectral crosstalk [4], [5]. With the acquisition of dark and white

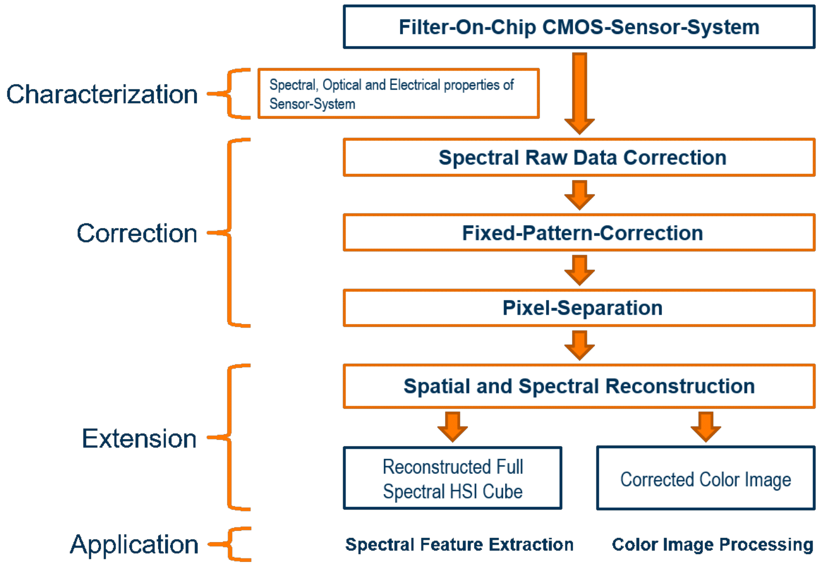


**Figure 11.1:** Characterization, correction and extension model for mosaic filter-on-chip CMOS-sensor-systems.

reference images during the pre-characterization a fixed pattern correction for the correction of intensity differences per spectral band can be implemented for the purpose of pixel value harmonization [6].

Afterwards a pixel separation for the alignment of the separated multispectral sub-images among themselves can be applied. Furthermore, shifts in the measured spectra can be minimized by a finite aperture correction [7]. For the sensor value extension typical reconstruction methods can be categorized into linear and nonlinear techniques.

Examples for linear techniques are Moore-Penrose pseudo-inverse (*MPPI*) [8], Wiener estimation (*Wiener*) [9] and Reverse principal component analysis (*PCA*) [10]. Nonlinear estimation methods like Polynomial reconstruction (*Poly*) [11] have more variations, but some of them can be considered as combinations of multiple linear estimations. Some of the reconstruction methods require an iterative process, such as the ones based on compressive sensing theory [12]. It is known that the spectral reflectance of most natural objects can be approximated with a limited number of spectral base functions. In these cases the continuous spectral distributions can be reconstructed from multispectral data of a limited number of channels [12].

The paper will show how continuous spectral distributions can be reconstructed using these reconstruction methods for monolithic mosaic filter-on-chip CMOS-sensor-systems. The Goodness of Fit Coefficient (*GFC*) [13] and the CIE color difference (*DeltaE*) [14] are used to evaluate the reconstruction results of experimental measurements with a 16-channel monolithic mosaic filter-on-chip CMOS camera.

For the accuracy of colorimetry, the *GFC* must be at least 0.995 [15]. $GFC > 0.999$ is to be regarded as a good fit and $GFC > 0.9999$ as a perfect fit of the spectra [14]. CIEDE2000 is a CIE recommended color difference formula that contains new terms for improving the predicted color difference in the blue range and for neutral colors for pairs of samples with small color differences [15].

## 4 Results and summary

In the following section the spectral reconstruction methods will be evaluated under realistic conditions. For every evaluation the following data is necessary: Spectral characteristics of the multispectral resolving sensor (Figure 11.2, left), target sets for calibration and reconstruction which consist of the reflectance spectra of different "Colorcheckers" (Figure 11.2, middle) and a radiation spectrum of an illuminant (Figure 11.2, right).

By pointwise multiplication of the spectral characteristics of the multispectral resolving sensor with the reflection spectra of the reconstruction set, the sensor-system responses are determined. Then the reconstruction matrices of Moore-Penrose pseudo-inverse, Wiener estimation, Reverse PCA and Polynomial reconstruction are calculated. In the investigation, the coupling factor $p$ will be 0.99 for Wiener estimation and the number of principal components for PCA $l$ will be 8. After the sensor-system responses are determined the reflection spectra are reconstructed using the reconstruction matrices. The standard light *D50* is assumed to be the recording light source when converting from spectrum to L*a*b* color space. Under the standard observer assumptions with 2° field of view, the color difference between the measured and reproduced colors were determined. At the end, the reconstructed spectra are evaluated according to *GFC*.

Furthermore the color differences in the visible wavelength range from 380 to 780 nm where analyzed. In the evaluation, the mean value, the minimum value and the median value of all reconstructed reflection spectra by *GFC* are named $GFC_{Mean}$, $GFC_{Min}$ and $GFC_{Median}$ respectively. The mean, minimum, and median of all color differences are named as $DeltaE_{Mean}$, $DeltaE_{Min}$, and $DeltaE_{Median}$.

For the practical evaluation the Colorchecker Passport is used as calibration set. The Spyderchecker is used as the reconstruction set. The multispectral images are acquired with a digital resolution of 10 bits. To minimize random noise, 25 images of the calibration and reconstruction set were chosen and the mean value of the images was calculated for further processing. The reflectance spectra of the reconstruction set which are measured with a spectrometer are shown as Ground Truth to evaluate the performance of the reconstruction methods (Figure 11.3).

The reconstruction results of *MPPI*, *Wiener*, *Poly* and *PCA* were evaluated with $GFC_{Mean}$, $GFC_{Min}$ and $GFC_{Median}$ (Table 11.1).

The Poly reconstruction method shows the best approximation of the reconstructed spectra to the Ground Truth. Furthermore, the $DeltaE_{Mean}$ values of the reconstruction set were determined (Figure 11.4).

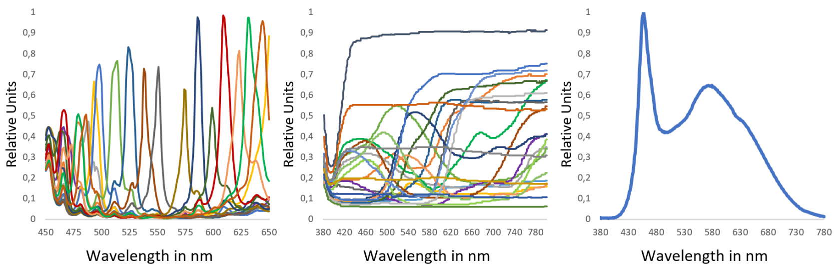


**Figure 11.2:** Example data for the evaluation of spectral reconstruction methods.

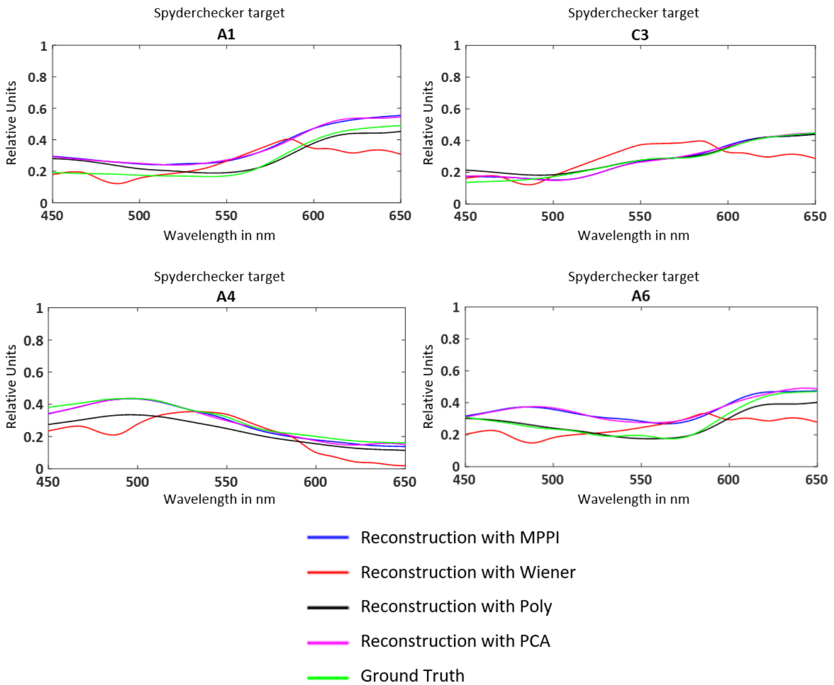


**Figure 11.3:** Evaluation of different reconstruction methods for 16-channel mosaic filter-on-chip CMOS camera (reconstructed spectra).

In the graph, the $DeltaE_{Mean}$ values according to spectral reconstruction methods are displayed for every color number of the Spyderchecker reconstruction set. Furthermore, the average of the $DeltaE_{Mean}$ values is displayed for the spectral reconstruction methods.

To illustrate the color deviation in the reconstructed color images the color differences determined for the targets of the reconstruction set are plotted on the respective target (Figure 11.5).

The color difference of the reproduced colors in *MPPI* and *PCA* can be easily perceived by human eyes. This is where the limited wavelength range of the camera becomes noticeable.

**Table 11.1:** Evaluation of different reconstruction methods for a monolithic mosaic sensor ($GFC_{Mean}$, $GFC_{Min}$ and $GFC_{Median}$).

| | $GFC_{Mean}$ | $GFC_{Min}$ | $GFC_{Median}$ |
|---|---|---|---|
| MPPI | 0.9949 | 0.9727 | 0.9981 |
| Wiener | 0.9594 | 0.9414 | 0.9594 |
| **Poly** | **0.9986** | **0.9944** | **0.9990** |
| PCA | 0.9947 | 0.9712 | 0.9976 |

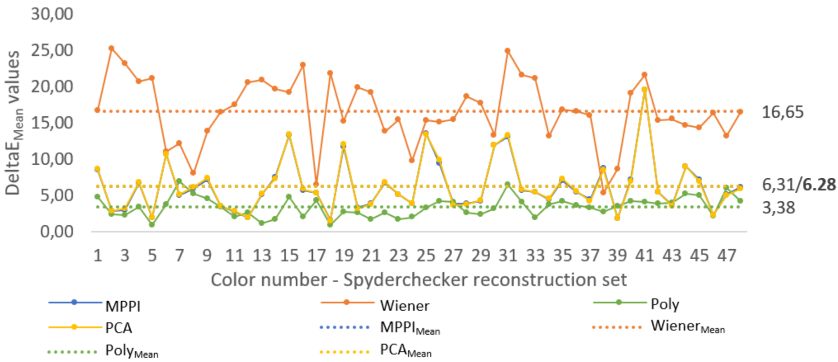


**Figure 11.4:** Evaluation of different reconstruction methods for a monolithic mosaic sensor ($DeltaE_{Mean}$, $DeltaE_{Min}$ and $DeltaE_{Median}$).

The paper gives an overview about the characterization and correction of mosaic filter-on-chip CMOS-sensor-systems. Furthermore, the paper shows how continuous spectral distributions can be reconstructed using a 16-channel monolithic mosaic filter-on-chip CMOS-sensor-system with spectral reconstruction methods. Methods for the evaluation of spectral reconstruction and color calculation have been shown. For the evaluation of spectral reconstruction methods with multispectral resolving filter-on-chip CMOS-sensor-systems a combination of target sets for calibration and reconstruction have been investigated. It could be shown that in the performed evaluation Polynominal reconstruction method provides the most robust and accurate approaches for the spectral reconstruction with multispectral resolving mosaic filter-on-chip CMOS-sensor-systems.

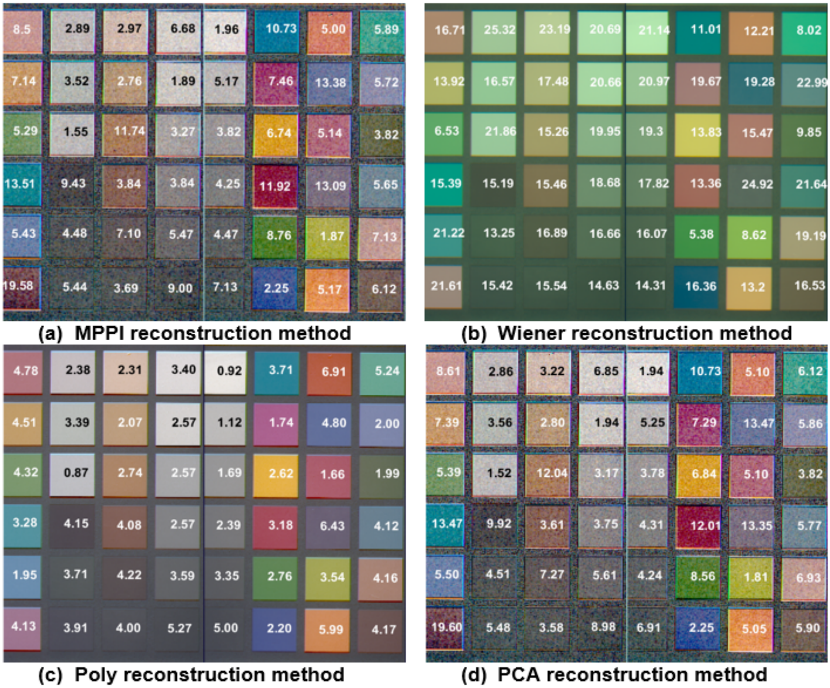


**Figure 11.5:** Evaluation of different reconstruction methods for 16-channel mosaic filter-on-chip CMOS camera (reconstructed color images and $DeltaE_{Mean}$ values).

It should be noted that the results have been evaluated in a lab environment. Current monolithic mosaic filter-on-chip CMOS cameras cannot cover the entire visible wavelength range for correct color calculation because of limitations in the filter technology and the usage of additional bandpass filters.

Multispectral resolving mosaic filter-on-chip CMOS cameras provide a new approach for Multi-/Hyperspectral Imaging. It has been shown that an extended sensor model can be developed and used to get corrected and extended sensor data for improving the capabilities of these cameras in optical characterization tasks.

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