ECCTD'01 - European Conference on Circuit Theory and Design, August 28-31, 2001, Espoo, Finland

Color Filter Array and Color Correction for High Dynamic Range CMOS Image Sensors

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Abstract — **This contribution presents a novel approach to CMOS color image sensors featuring high dynamic range. First we introduce a novel Color-Filter-Array (CFA) that has been especially developed for CMOS imager featuring high dynamic range. Then color correction method is presented that is made with a fast algorithm realized using a Look-Up-Table (LUT). The LUT is created off-chip to improve a high quality and keep the on-chip logic small.**

1 Introduction

There are several ways to capture color images. For instance three image sensors each with their own color filter or a color filter wheel in front of one image sensor. Disadvantages of these approaches are high costs and complicated calibration.

A low-cost method for capturing color images is to use a single image sensor with a mosaic color filter array (CFA) deposited on the imager plane. These sensors are often used in single chip CCD video cameras.

Most single chip color image sensors use either a CFA containing red, green, and blue filters or the complementary system with cyan, yellow, and magenta filters. The advantages of using this type of filter arrays is that they yield a simple color correction and that their transmission factors exhibit comparable peak values. All three values yield thus approximately the same dynamic range. This is mandatory for CCD image sensors. Each pixel can use only a part of the spectrum of the incoming light, because all pixels are covered by color filters and this reduces the sensitivity. We developed a new color filter array containing 50% of filterless pixels. Now we are able to capture the entire visible spectrum of incoming light using these pixels and thus the sensitivity of the sensor can be increased. The basic requirement for this method is the use of an image sensor with extended dynamic range because the contrast difference between the color filtered pixels and the filterless pixels is very high.

In the first part of this paper a CFA is presented that has a high sensitivity for dimmly illuminated scenes and enables splitting images into luminance and chrominance channels. This CFA is only suitable for high dynamic image sensors. Especially the image sensor presented in [4] exhibits optical dynamic range of up to 120dB. This sensor is predestined to be used with the cyan, yellow, white CFA shown in Figure 1.

To get high quality images using this CFA normally a large-scale color correction is necessary. To avoid this effort in the second part of this paper a fast low-complexity color correction algorithm based on the *Tetrahedral Interpolation* [2] is presented.

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2 Color Filter Array

2.1 Pattern

In this section we introduce a new CFA suitable for high dynamic range CMOS image sensors. As mentioned above this CFA exhibits a high sensitivity. In opposite to the widely used red, green, blue filter set used for primary colors, we have fabricated sensors with the complementary color set. It consists of cyan, magenta, and yellow. To improve sensitivity and to obtain simple technology we have used only two filters, cyan and yellow, and completed them with a filterless “white” pixel. In advantage to the conventional color filter set, this set has a high luminance sensitivity, and is in this sense compatible to the rod/cone cell structure of the human eye. This means: In dark scenes this sensor captures a black and white image, while under daylight conditions, we obtain color images.

We use the modified Bayer pattern with an emphasis on luminance shown in Figure 1. Four pixels are assembled from one cyan, one yellow, and two “white” pixels. The difference between the Bayer and modified Bayer patterns is that the letter yields in less errors in detecting vertical and horizontal lines.

2.2 Spectral Sensitivity

The spectral sensitivity properties of the color filters is very important for the color correction process. In order to yield a high sensitivity the transmisson factors should exceed 80% in the area of permeability. Futhermore, the color filters used should

White	Cyan	White	Yellow
Yellow	White	Cyan	White
White	Yellow	White	Cyan
Cyan	White	Yellow	White

Figure 1: Modified Bayer pattern emphasizing luminance

enable to get correct red, green, and blue values for displaying images e.g. on a CRT display.

In Figure 2 the spectral transmission of the two applied color filters is presented. These filters have been deposited on a CMOS image sensor fabricated using a 1μm standard CMOS n-well p-substrate technology [4]. We used CYAN02 and YELLOW12 manufactured by Brewer Science, Inc.. With the well known linear procedure shown in Eq. 1, 2, and 3 it is possible to get the red, green, and blue spectral sensitivities, as shown in Figure 3:

$$R = 1.4(1.0W - 1.2C) \quad (1)$$

$$G = 1.4(0.8Y \cdot 0.85C) \quad (2)$$

$$B = 1.4(1.0W - 1.1Y) \quad (3)$$

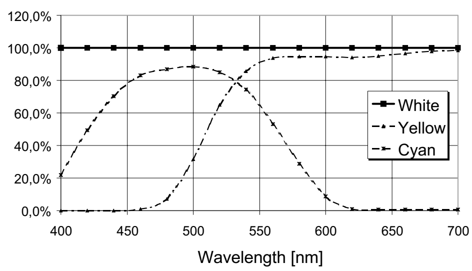

Figure 2: Spectral transmission of the color filters used

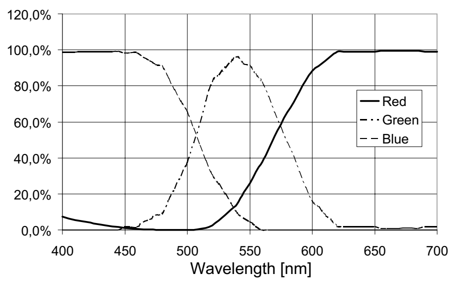

Figure 3: Computed spectral RGB sensitivity from the color filters used

3 Color Correction

Although the sensitivity of the color filters shown in Section 2.2 exhibits about the same peak value, in practice it will be affected by the spectral sensitivity of the CMOS imager itself. Futher, the spectral distribution of the illumination source will have influence on the output signals of the imager, too. It is necessary to adjust these values, and also account for different illumination conditions.

3.1 Data aquisition

To compute the desired values from the raw values captured from the image sensor it is necessary to have a reference test chart. Here the AGFA IT-8 Color-Test-Chart [1] is very suitable, because there are 288 different color fields with different luminance and chrominance values. This forms a good database for obtaining color values and correct color images. After aquisition of the captured color values we have two sets of color values, on the one hand the measured raw values and, on the other hand, the expected target values.

3.2 Look-Up-Table Generation

With these two data collection sets it is possible to create a *Look-Up-Table* (LUT). Missing raw or target values are interpolated using the bivariate-cubic-spline-interpolation [3]. It is sufficient to take a LUT exhibiting a size of $50 \times 50 \times 50$ from the original data collection of $2048 \times 2048 \times 2048$. The remaining values are interpolated at runtime.

This color correction algorithm can also correct some nonlinearity effects of the used sensor.

3.3 Interpolation

The online interpolation has been implemented using a fast algorithm. For this purpose the tetrahedral interpolation has been implemented.

The cubic space between the data samples of the LUT is divided into six tetrahedrals. For each tetrahedral four LUT-data samples are needed to compute the desired value. The computation is shown in Eq. 4. The coefficients c_n are depending on the used tetrahedral.

$$p(x, y, z) = p_{000} + \frac{c_1\ \Delta x}{x_1 - x_0} + \frac{c_2\ \Delta y}{y_1 - y_0} + \frac{c_3\ \Delta z}{z_1 - z_0} \quad (4)$$

The entire interpolation requires only a few operations listed in Table 1.

4 Experimental Results

Figure 4 shows the resulting color image of the IT-8 Color-Test-Chart. The color values of the image

quantity	operation
6×	Multiplication
9×	Addition
6×	Check condition
8×	Memory access

Table 1: Number and type of operation needed to correct color image

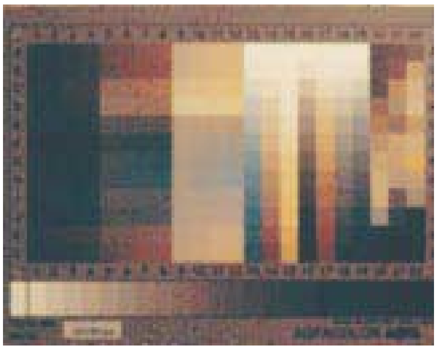

Figure 4: Resulting color image obtained with the presented method showing the IT-8 Chart

matches the color values of the Test-Chart provided by AGFA. We determined the difference between the real values and the expected values with the color-difference-formula CIE-1976-($L^*a^*b^*$). This is given by the Euclidean distance

$$\Delta E^*_{ab} = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \qquad (5)$$

between these values. In our case the color difference is in average 1.9. The illuminant of the measurement scene has a color temperature of 5000K (D50 illuminant). The resulting image was viewed and compared using a Sony Trinitron CRT.

5 Conclusions

Until now each pixel on an image sensor covered with the standard color filter arrays used for image sensor employ full area color filters. Color filters pass only a part of the spectrum. Therefore, such image sensors exhibit lower sensitivity than black and white image sensors. In this paper we have presented a new color filter array approach containing "white", i.e. "filterless", pixels. With a high dynamic range image sensors it is possible to use the presented color filter array with "white" pixels. This combination of a color and a black and white image sensor yields a novel high sensitivity color image sensor.

There are a lot of applications requiring high sensitivity and high dynamic range color image sensors. For instance there is a great need for such sensors in automotive applications (e.g. street-sign recognition) and monitoring of security areas (e.g. bank ATMs, access control).

References

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