Proc. VIIth Digital Image Computing: Techniques and Applications, Sun C., Talbot H., Ourselin S. and Adriaansen T. (Eds.), 10-12 Dec. 2003, Sydney

Concept of Color Correction on Multi-Channel CMOS Sensors

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Abstract. Color image acquisition and image processing have become a key in modern data application. In order to provide high quality images, the field of accurate acquisition is most important in respect to all further processing steps. But a whole variety of current image sensors possess incorrect color rendition due to insufficient accuracy of optical sensor parameters. This is detrimental especially for color sensors, because in these cases specific color information will be incorrectly acquired. Further, traditional color correction methods do not use information on the specific sensor spectral sensitivity, thus losing the only capable information for substantial color correction. The problem is investigated by introducing an algorithmic correction method which is capable of correcting dysfunctional sensor properties. It can be easily integrated into traditional sensor designs and is also extendable to various designs/technologies. Further we will show concepts of multi-channel sensors capable of high quality color rendition and finally, this approach is demonstrated on several new CMOS sensor designs with examples and simulation results.

1 Introduction

1.1 Color Acquisition Scheme

In human visual system the vision of color is the perceptual result of light in the visible region of the electromagnetic spectrum, having wavelengths from about 400 nm to 700 nm, incident upon the retina. The human retina contains three types of color photo receptor called cones, which respond to incident radiation with different spectral response functions. A fourth type of photo receptor cell, the rod, is also present in the retina, but rods are effective only at extremely low light levels and (although important for vision) do not play a significant role in human color vision.

Because there are three different types of color photo receptors in human retina, three numerical components are necessary for comprehensive description of color and these three numerical components are also sufficient providing that appropriate spectral weighting functions are used for detection. These functions have been the concern of the science of colorimetry which analysed and quantified the properties of human perception. In 1931, the Commission Internationale de L'Éclairage (CIE) adopted the first standard functions for a hypothetical Standard Observer, specifying the transformation of a spectral power distribution into a set of three numbers for characterisation of a color [1]. This triple of numerical components defines mathematical coordinates of the color space and there are a variety of different representation for color space specification, including CIE systems, device dependent RGB, HSV, YIQ and so on. Despite the differences between this color spaces specifications, each color space description can be transformed into any other, so all these color spaces are just different notations for the same aspect of human color vision. The task of a color sensor is to assign a specific input spectrum to color space coordinates in the same way the human visual system would do. Unfortunately current color sensor implementation are not very accurate at this. Almost all image sensors and photographic devices are directly based on the tristimulus theory, stating that three elements with different spectral sensitivity are sufficient to model the human vision, and thus, exclusively using a set of three photo active elements. These photo elements i can be described by their specific spectral sensitivity $s_i(\lambda)$, resulting from the combined characteristics of photo active material and color filter (if existent). The output of the elements is described by:

$$S_i = \int I(\lambda) \cdot s_i(\lambda) d\lambda \qquad (1)$$

where $I(\lambda)$ is the spectral power distribution of irradiated light and S_i is the resulting color component. Theoretically, the characteristic of $s_i(\lambda)$ should be bound to the CIE Standard Observer because the sensor has to mimic the human eye in order to reproduce an image as the human visual system does. An ideal sensor could implement directly the spectral sensitivity given by the CIE XYZ color space specification. These sensitivities are defined always positive and thus would be suited for absorption filters. But under technical constraints a comprehensive representation is not entirely possible, because it is not feasible to create materials with these optical properties. Furthermore, current color sensor implementation often try to directly represent a RGB color space instead of CIE XYZ, using three elements which are sensitive to red, green and blue portions of the visual spectrum that are assumed to correspond to the prime colors of the targeted color space. But because of substantial differences between implementable spectral sensitivities and RGB specification derived from CIE standard functions, such sensor implementations show significant errors in color rendition (Figure 1).

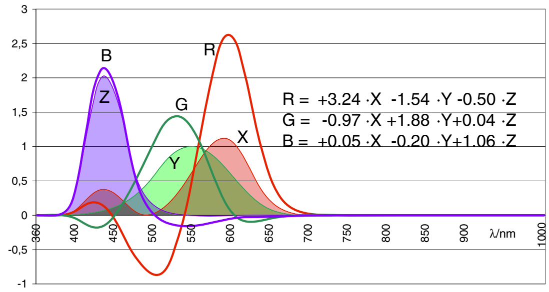

Figure 1 Theoretical sRGB spectral sensitivity with CIE XYZ

In order to reduce the resulting errors in color, an adequate color correction scheme is essential for color image acquisition and a wide range of color correction schemes was developed. But usually the assumption is made that a precise correction is possible exclusively based on of the defective tristimulus sensor data. According to this premise a specific sensor output is assumed to be always correlated with a specific color. In many cases the color rendition is analysed and optimized for a few examples under idealized condition, i.e. using color chart images, and the remaining color space is just interpolated. Many methods are described for practical realization, i.e. look-up tables or more or less nonlinear mathematical approaches [3]. Nevertheless, all these methods show substantial inadequacy and the reason is the neglect of the defective spectral sensitivity of technical sensor designs.

1.2 CMOS Sensor Specifics

CCD (Charge Coupled Device) is the currently dominating image sensor technology. It is specially designed for image acquisition and thus has very good properties in these terms, but it requires special manufacturing lines and is not capable of logic integration for i.e. data preprocessing on Chip. Hence, SOC (System on Chip) sensor design is not possible with CCD. Compared with CCD, CMOS technology has a lot of advantages. It is cheap, manufacturing has no special requirements and it is possible to integrate the sensor together with data processing circuitry on the same chip. Sensors with integrated controller, A/D-converter and additional processing units denote extremely reduced costs for manufacturing and also reduced power dissipation which is most important especially for mobile applications [4]. On the other hand, the major disadvantage of CMOS sensors is the spatial distributed noise of the active sensor elements, called „Fixed Pattern Noise“, which has enormous impact on the image quality. But possible correction methods are known, i.e. correlated double sampling (CDS), current-mode signal processing, special A/D converter techniques and algorithmic correction schemes [5] etc., which can be integrated on the sensor itself. Further image preprocessing including color correction, filtering etc. can be integrated as well.

Additionally, CMOS sensors are affected by infrared light. The influence of infrared light is destructive especially to color sensors, where specific color information is disturbed. In [2] a method for an algorithmic infrared correction based on the spectral correction method is shown, which will be extended in this approach for color correction on multi channel sensors.

2 Spectral Color Correction Method

Assuming a technical sensor S, the defective sensor outputs S_j, as defined by (1), can be transformed to a standard color space using the spectral correction method. The target color space is given by the description of an ideal sensor A with direct output of color space coordinates, i.e. the CIE Standard Observer (CIE XYZ). The ideal sensor is defined by:

$$A_i = \int_{\lambda} I(\lambda) \cdot a_i(\lambda) d\lambda \tag{2}$$

To achieve the best reconstruction A'_i of a color space coordinate A_i from N technical sensor outputs S_j a linear combination is used:

$$A'_i = \sum_{j=1}^{N} c_{ji} \cdot S_j \tag{3}$$

This is obviously possible because of (1), when

$$A'_i = \sum_{j=1}^{N} c_{ji} \cdot \int_{\lambda} I(\lambda) \cdot s_j(\lambda) \cdot d\lambda = \int_{\lambda} I(\lambda) \cdot \sum_{j=1}^{N} c_{ji} \cdot s_j(\lambda) \cdot d\lambda \tag{4}$$

where s_j are the spectral response functions of the defective sensor implementation. By comparing (4) with (2), it follows that

$$a'_i(\lambda) = \sum_{j=1}^{N} c_{ji} \cdot s_j(\lambda) \tag{5}$$

where $a'_i(\lambda)$ is the best reconstruction of an ideal color space spectral response function $a_i(\lambda)$. Hence, the best reconstruction A'_i of the ideal color space coordinate A_i can be calculated using (3) independent from incoming radiation $I(\lambda)$ just by static coefficients. To determine the coefficients c_{ji} the method of least square error is used for reconstruction of $a'_i(\lambda)$ according (5), so the approximation error is minimized. The solution is given by:

$$\int_{\lambda} a_i(\lambda) \cdot s_k(\lambda) d\lambda = \sum_{j=1}^{N} c_{ji} \cdot \int_{\lambda} s_j(\lambda) \cdot s_k(\lambda) \cdot d\lambda \quad \text{for } k = 1 \ldots N \tag{6}$$

Thus, for each ideal color space coordinate i with spectral response function $a_i(\lambda)$ a set of *N* coefficients c_{ji} can be found to derive the best approximation $a'_i(\lambda)$ with minimized L2-norm from *N* technical sensor outputs. The combination of all sets of coefficients can be noted as transformation matrix $[T]$, so the reconstruction of the color coordinates can be realized as simple matrix operation.

It is also possible to use additional spectral response functions as estimation target i.e. an infrared response function to reconstruct an infrared image, which leads to a complete new field of applications (visual enhancement, night vision camera etc.).

Usage of nonlinear correction schemes to adjust defective sensor outputs S_j is not promising, because with nonlinear functions higher order terms of the sensor function will be included into the correction equation, making the optimization dependent on the incoming radiation $I(\lambda)$, thus resulting in an optimized solutions only for a specific illumination condition. This can be proven by assuming a nonlinear approach f, which can be described by a polynomial approximation:

$$\begin{aligned} A'_1 = f(S_1, \ldots, S_n) = c_0 + c_{11} \cdot S_1 + c_{12} \cdot S_2 + \ldots + c_{1n} \cdot S_n + \\ c_{211} \cdot S_1 \cdot S_1 + c_{222} \cdot S_2 \cdot S_2 + \ldots + c_{2nn} \cdot S_n \cdot S_n + \\ c_{212} \cdot S_1 \cdot S_2 + \ldots + c_{21n} \cdot S_1 \cdot S_n + \ldots \end{aligned} \tag{7}$$

Insertion of (1) will expand the equation, resulting in a linear part which already has been described, but also introduce higher order terms as products of integrals over the incoming radiation $I(\lambda)$, thus leaving the search for optimized coefficients c_{xyz} dependent on this incoming radiation:

$$\begin{aligned} A'_1 = \int a_1(\lambda) \cdot I(\lambda) \cdot \delta\lambda = c_0 \\ + c_{11} \cdot \int s_1(\lambda) \cdot I(\lambda) \cdot \delta\lambda + c_{12} \cdot \int s_2(\lambda) \cdot I(\lambda) \cdot \delta\lambda + c_{13} \cdot \int s_3(\lambda) \cdot I(\lambda) \cdot \delta\lambda \\ + c_{211} \cdot \int s_1(\lambda) \cdot I(\lambda) \cdot \delta\lambda \cdot \int s_1(\lambda) \cdot I(\lambda) \cdot \delta\lambda \\ + c_{222} \cdot \int s_2(\lambda) \cdot I(\lambda) \cdot \delta\lambda \cdot \int s_2(\lambda) \cdot I(\lambda) \cdot \delta\lambda \\ + \ldots \end{aligned} \tag{8}$$

As a color correction scheme is aiming at an adequate modelling of the human visual system under general lighting conditions, this special case optimization cannot be used. Thus the linear combination as described in the spectral correction method is preferred.

The reconstruction error of the spectral correction method is dependent on either the quality of the basic functions or on their number. A high number of imperfectly fitting base functions can yield as similar negligible error as a small number of good fitting functions. Adopting this principle to sensor design, the sensor concept is not bound to tristimulus theory. A sensor with sufficient number of color channels can be as accurate as an ideal sensor, even if each color channel itself is imperfect.

3 Application Concept

3.1 Simulation

For visual verification a sensor simulation tool kit was developed, which models a optical path with light source, a sensor of given characteristic and a color correction module including CIE standard system for comparison. The application concept of the spectral correction method using multi channel sensors was verified on various data, i.e. from measurements of a single-chip CMOS color video sensor, basically consisting of a sensor array with common CMOS photo diodes in a 0.6µ technology and circuitry for gamma correction, video signal generation etc. [6] and of other photo diode implementations from different CMOS technologies.

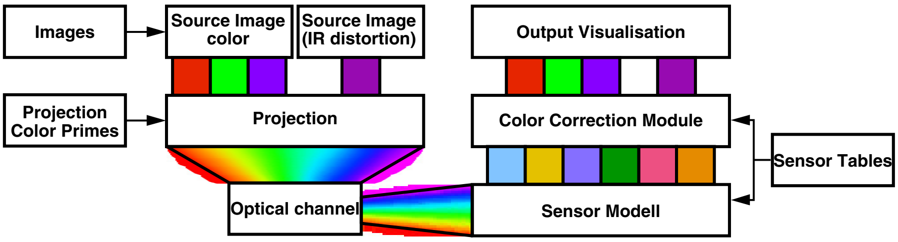

Figure 2 Simulation Tool Kit (schematic)

3.2 4-Channel Sensor using a Modified Bayer Mosaic

The approach of spectral color correction is first demonstrated on a CMOS sensor using a Bayer color filter array (CFA) [6]. Bayer CFA is widely used on current color image sensors and consists of a four pixel square with color filters for red/green and green/blue as illustrated in Figure 3a.

The quality of color rendition using a correction for general lighting condition is not very good and even the possibilities of color correction schemes are quite limited, because the three channels of the used Bayer mosaic are insufficient for a better color correction (Figure 9). But to enable the spectral correction method the number of channels can be increased with insignificant effort: The color sensor elements are basically characterized by their color filters and an additional color channel can be easily realized by i.e. an element with no color filter. Our suggestion is to use one of the two green sensitive sensor fields of the Bayer mosaic by leaving out the color filter in the most simple case. Alternatively it is also possible to use a color filter different from the others (Figure 3b).

Figure 3 Original (a) and modified Bayer mosaic (b)

The sensor as described in [6] was utilized as representation for common 3-channel color receptors, because it is using a standard CFA which is also employed on sensors based on CCD. Hence the obtained results from this sensor can be adopted to other CCD sensor implementations as well.

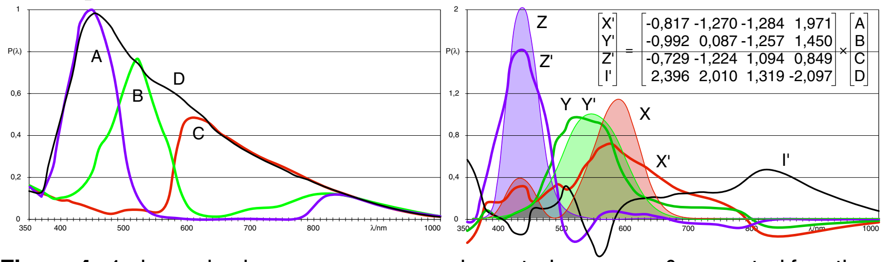

Figure 4 4-channel color sensor: measured spectral response & corrected functions

To use this sensor with the spectral correction method, the spectral sensitivity functions were measured and corrected using the CIE XYZ color space as reference.

The results are shown in Figure 4 and indicate a reasonable approximation for Y and Z coordinates except for minor divergences. But the X coordinate still is affected by disturbances especially in infrared range. This is caused by insufficient separation in the spectral range from 600 to 800 nm. Regardless the approximation errors are still obvious visual picture quality is remarkably improved in comparison to the standard 3-channel image using the original Bayer mosaic. Comparison images from simulation are shown in Figure 9. For a better color approximation the spectral sensitivity functions should be improved, i.e. by enhanced CFA characteristics. Another method offering better color rendition even with uncritical CFA parameters can be obtained by an increased number of color channels.

3.3 4-Channel/8-Channel Sensor using a Dual Photo Diode

A possibility to increase the number of color channels is to enlarge the color filter array, but this will reduce the spatial resolution of the sensor. Additionally, spectral sensitivity can be influenced by properties of the basic silicon material itself. On Silicon, high energy photons cannot penetrate the material, they are absorbed within a few hundred nanometer beneath the material surface while low energy photons such as infrared are passing through the entire substrate and can generate electron-hole-pairs also deep within silicon. Therefore an additional parameter of spectral sensitivity is the depth of the pn-junction used by the photoelectric effect. This parameter can be exploited to design photo devices with different spectral sensitivities but using the same spatial position on the sensor, resulting in additional advantages such as decreased moiré effect and increased optical resolution with comparable additional effort.

The most simple design based on depth-depending junctions is a dual photo diode as shown in Figure 5a. This photo device can provide two outputs with different spectral sensitivity. To enable adequate color rendition an additional CFA with a two color pattern is needed to acquire sufficient signals for the spectral correction method. In this case, the spatial resolution of the sensor is doubled compared to sensor designs with Bayer CFA. Results prove a reasonable color rendition of this 4-channel sensor but it still needs to be improved for high quality requirements. Using the dual photo diode with a conventional or modified Bayer Mosaic filter will reduce the advantages of better moiré reduction but will significantly increase color rendition by applying up to 8-channels for color correction as shown in Figure 7.

3.4 6-Channel Sensor using a Triple (Quad) Photo Diode

If a Triple-Well/BiCMOS process is available, it is possible to implement additional photo devices such as a triple (quad) photo diode as seen in Figure 5b. The basic device [8] consists of three vertically stacked photo diodes (p-substrate/n-well, n-well/p-well, pwell/n+), but due to design rules it is often feasible to implement a nwell/p+ diode as well, which has a similar spectral sensitivity as the pwell/n+ diode because of similar design parameters. In addition the design of an active pixel cell is simplified by using four photo diodes because symmetries can be used much easier than on a layout with only three photo diodes.

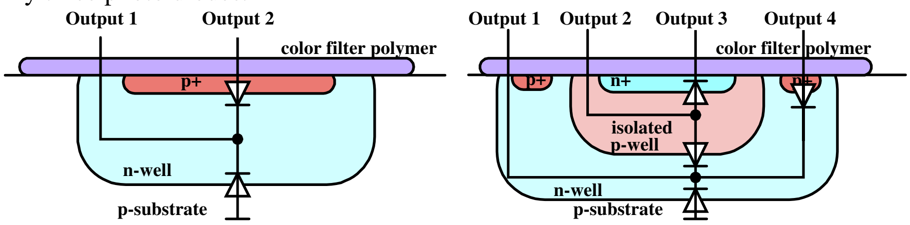

Figure 5 a) Dual Junction Photo Diode and b) Triple/Quad Junction Photo Diode

For a basic color sensor with tristimulus output no additional color filter would be needed but the resulting color rendition of this device is very low. An additional two-color-pattern can improve color rendition by using 6 channels for spectral correction while obtaining a moiré reduction comparable to the 4-channel dual photo diode device. As expected the quality of color rendition of the 6-channel sensor ranges between the 4- and 8-channel sensor discussed in section 3.3 (Figure 9).

4 Future developments

The presented photo devices are currently under construction to confirm the stated concepts in practical use. Comparison of simulated results and measurements will further provide necessary data for other related developments, i.e parameters for read-out circuits; regarding i.e. accuracy, speed and noise; additional data processing units i.e. matrix multiplication circuitry based on mixed signal concepts etc. (Figure 10).

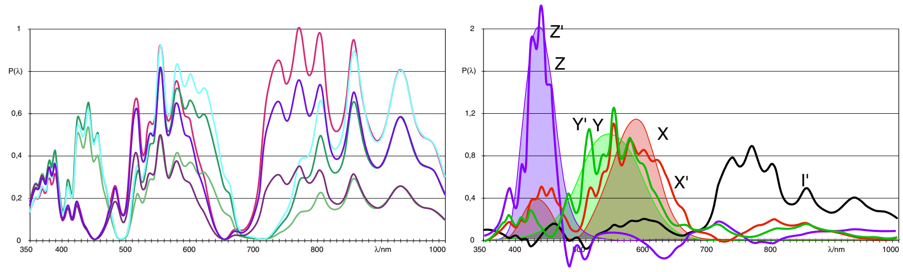

Figure 6 6-channel triple diode color sens■r: measured spectral response and corrected functions with CIE XYZ for comparison

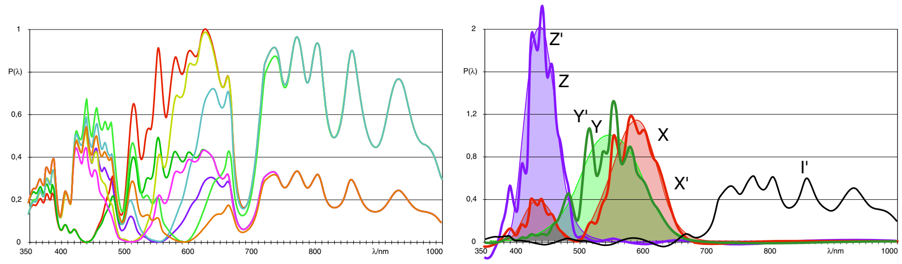

Figure 7 8-channel dual diode color sensor: measured spectral response and corrected functions with CIE XYZ for comparison

An additional vulnerability of an array of color sensor cells exists in their sensitivity to color moiré caused by the spatial arrangement. This effect is part of the underlying principle and cannot be eliminated completely. The elements which are forming a planar color pixel have slightly different positions in the sensor array resulting in color disturbances especially for high spatial frequencies which are recurrent in natural images. An usual compensation method is the use of optical diffusion filters but a negative side effect is the reduction of optical resolution. Another possible approach to decrease this effect is the usage of optimized color filter layouts with reference to the spectral sensitivities of the pattern and their position on the sensor matrix. This is especially promising for multi color sensors where a resulting color triple is calculated from a larger number of components. Specially adopted filter algorithms can additionally reduce color moiré to a minimum without affecting the spatial resolution of the sensor. But these approaches still need further investigation.

5 Conclusion

Because of extensive differences between spectral sensitivities of common color detectors and the human eye, color acquisition is generally affected by errors which have to be corrected in an additional data processing step. The basic presumption of sufficiency of tristimulus color image sensors is superseded under this circumstances. As stated, tristimulus based color correction methods are not able to eliminate systematic errors of defective color acquisition. Algorithmic correction methods (i.e. according (6)) based on spectral sensitivity can find optimized solutions on existing devices for general lighting parameters but cannot fit high quality needs by using standard sensor designs.

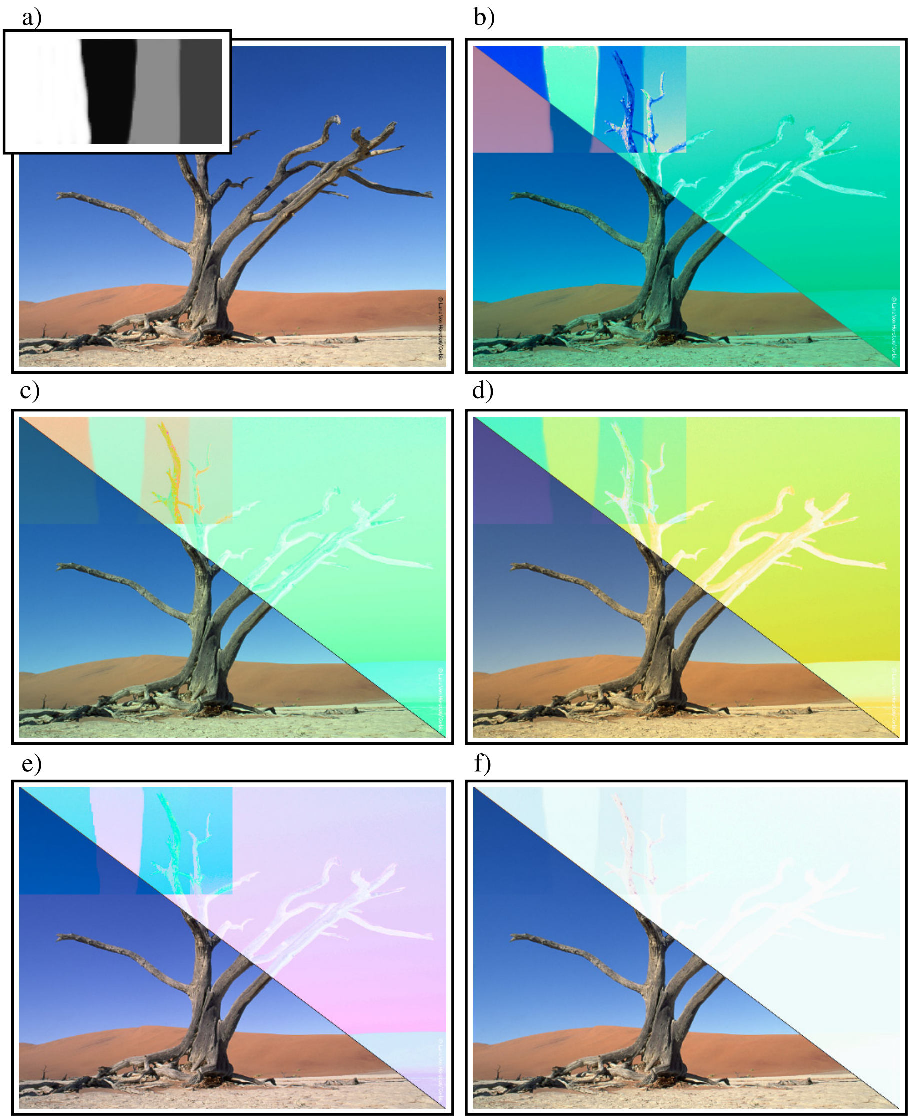

Figure 9 Simulation Results: a) Reference image with an additional infrared distortion; b) 3-channel bayer mosaic sensor; c) 4-channel color correction (Figure 4); d) 4-channel dual diode; e) 6-channel triple-diode (Figure 6); and f) 8-channel dual diode sensor (Figure 7). *Images show the color correction result in the lower left and the difference to the original in the upper right (darker color correspond to higher error).*

Applying the method of spectral correction to sensors with more than three color channels per pixel can significantly improve color rendition to achieve human like vision under current technical feasibility. Other researches on multi spectral image sensors confirm by far better results compared with conventional tristimulus image sensors [7]. Multi color sensing is already used in practical application: i.e. in the field of photogra-

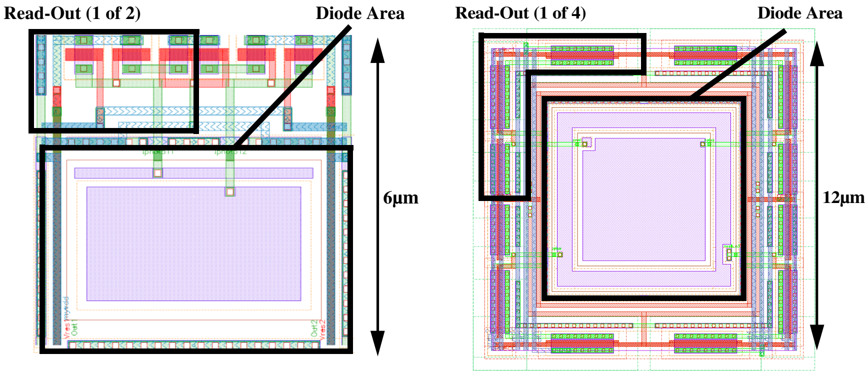

Figure 10 a) Dual Junction Photo Diode and b) Triple/Quad Junction Photo Diode; layout sample with circuitry for read-out

phy the New-Reala technology by Fuji uses four light-sensitive emulsion layers for better color reproduction and Sony is using a four color filter CCD, stating that color reproduction errors have been minimized by half, and the reproduction of blue-green and red colors has been particularly enhanced.

A method for color correction based on spectral sensitivities was presented. Simulation results of practical examples allow to compare achievable quality with current consumer CCD systems. Applications and simulation results were shown for a class of new CMOS color sensor designs.

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