Improvement of Multispectral Image Capture by Compensating for Stray Light

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Abstract

This paper focusses on the improvement of multispectral image capture by compensating for stray light, which is generated in the optical path of a multispectral camera. The generation of stray light is an unwanted optical effect. It typically harms the quality of the captured image by raising the captured signals. In order to quantify the significance of this effect, a series of measurements with a multispectral camera has been carried out. The results will be given. Based on the measurements, a model for describing the effect has been developed. Stray light can quite exactly be approximated by a superposition of brightness which varies over the image as a function of the position and the image data itself. A test procedure consisting of a set of multispectral measurements has been defined. The measurements are used to derive the model parameters. Based on the model, a corrective algorithm has been developed, which eliminates the effects of stray light in a multispectral capturing device. The algorithm has been verified and results are pointed out. The improvement of multispectral image capture with the algorithm being applied is shown by figures of ΔE_{00} and spectral distributions of colors captured from the Color Checker.

Introduction

Stray light, which is generated in the optical path of a multispectral camera, is an unwanted optical effect that harms the quality of the captured image. It typically results in an increase of the channel signals. Hence, the contrast ratio suffers. Moreover, if, for example, a color patch is captured once within a black frame and again within a white frame, the measured channel signals for the color will be different. So, the spectral estimation algorithm processing these signals will not yield the same results, though, of course, the captured object does not change at all. The more a camera system is susceptible to the generation of stray light, the worse the color constancy of the captured images will become.

In [1] Jansson and Breault proposed a model for stray light and a compensating method. Their model is based on a convolution of the image data with a point spread function describing the effect of stray light for each pixel. The compensation is done by an iterative algorithm which under certain circumstances converges so quickly that it can be terminated after the first iteration. Their method works well for sharp, locally limited point spread functions.

In this paper, another approach for modeling the effects of stray light in multispectral cameras is presented [2]. Like in [1], stray light is modeled as a superposition of brightness which is a function of the image data. Yet, the measurements showed that stray light is not always a locally limited problem - often opposite parts of the captured image effect each other. A way of describing long range as well as short range spatial dependencies of stray light is introduced into the model by a set of parameters. The way they can be derived by a particular set of measurements is described. The model is not restricted to a certain number of channels or wavelength ranges; it can be applied to any camera system, including conventional digital (monochromatic or standard RGB) cameras. The model parameters are adjusted by carrying out a set of characterizing measurements. Based on this model, an algorithm is derived that compensates for the effects of stray light in multispectral images. Once the stray light characteristics of a given multispectral camera are known, the algorithm can be applied to any image taken by this camera in order to eliminate the stray light present and increase the image quality.

A number of test images with varying, intentionally generated stray light were captured and corrected by the algorithm presented. The results are compared to the original images. This comparison shows a significant increase of the image quality and, with it, an improvement of the multispectral measurement.

Sources and Effects of Stray Light

The term stray light denotes any light inside the optical path of a multispectral camera that reaches the image sensor but does not originate directly from the captured object. For example, stray light can result from multiple reflections inside the objective lens or from reflexions between the sensor and the objective lens. Optical filters, used in multispectral cameras for the spectral separation, are another source of stray light. If the captured object is located inside a chamber, there can be stray light emerging from surrounding walls which are unintentionally illuminated by the lamp or reflections from the object itself.

The presence of stray light negatively effects the multispectral capturing. The characteristic effect is that a remarkable offset is added onto the channel values. As a consequence, the images tend to become pale and to lose contrast. Of course, the reconstructed spectra, which are calculated from the channel values, possess errors, as well.

Measurements showed that the amount of stray light in a multispectral camera has a distinct spatial dependency within the image. Some regions of the image are simply more affected by stray light than others due to the above mentioned reasons (optical filters, geometry of the camera). Another reason for the spatial dependency is the captured object itself. Bright objects, which reflect more light than dark ones, increase the amount of stray light in the optical system. Hence, the multispectral capture of a given sample is subject to the brightness of the other parts of the image. These errors will be propagated to the spectral reconstruction algorithm, resulting in incorrectly reconstructed spectra. In fig. 1 the influence of stray light on a multispectral measurement is illustrated by a comparison of two measurements of the same color patch. The first was done with a black frame, the second was done with a white frame. The second measurement severely differs from the first one due to stray light which is generated by the white frame.

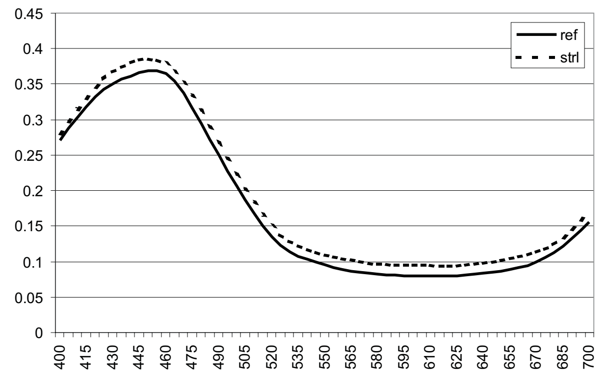

Figure 1. Influence of stray light on a multispectral measurement. The same patch of the Color Checker was measured twice, firstly with a black frame (ref) and secondly with a white frame (strl) in order to artificially generate stray light. The measurement with stray light is considerably brighter than the reference measurement.

The next paragraph deals with the derivation of a model that describes this effect with respect to its spatial dependency. Later, this model will be inverted in order to gain a method that eliminates the effect from multispectral images.

Model

In this paper, the influence of stray light on the channel signals is modeled as a superposition of brightness, which has a spatial dependency and is a linear function of the image contents itself. Moreover, the measurements showed, that the stray light characteristics can differ between the channels of a multispectral camera. However, in order to maintain the readability of the equations, in the following, the considerations are made for one channel only. They are scalable and can be applied to multiple channels correspondingly.

The measured signal $\widetilde{Y}_{x,y}$ of pixel (x,y), which is influenced by stray light, can be expressed as

$$\begin{aligned} \widetilde{Y}_{x,y} &= \int \left(S_{x,y}(\lambda)\, r_{x,y}(\lambda) + \widehat{S}_{x,y}(\lambda) \right) \tau(\lambda)\, d\lambda \\ &= Y_{x,y} + \widehat{Y}_{x,y} \end{aligned} \tag{1}$$

where $S_{x,y}(\lambda)$ is the power spectrum of the light source, $r_{x,y}(\lambda)$ is the spectral reflectance function of the captured object, $\widehat{S}_{x,y}(\lambda)$ is the spectral distribution of the stray light, $\tau(\lambda)$ is the spectral sensitivity of the considered camera channel, $Y_{x,y}$ is the original channel signal without the influence of stray light, and $\widehat{Y}_{x,y}$ is the channel signal offset resulting from stray light. Terms with spatial dependency carry indices (x,y) indicating the position of a pixel.

The reconstruction of the spectral distribution of the stray light $\widehat{S}_{x,y}(\lambda)$ is not necessary. In fact, the aim of the compensating algorithm is to extract the undistorted channel signal $Y_{x,y}$ from the measured signal $\widetilde{Y}_{x,y}$, which is influenced by stray light.

The approach in this paper is to model the signal offset $\widehat{Y}_{x,y}$ in pixel (x,y) as an accumulation of a number of stray light offsets resulting from all pixels (x_0,y_0) in the image

$$\widehat{Y}_{x,y} = \sum_{x_0} \sum_{y_0} k_{x,y,x_0,y_0} Y_{x_0,y_0}, \tag{2}$$

where k_{x,y,x_0,y_0} are couple coefficients correlating each pixel with each other one. They specify the ratio of the pixel value Y_{x_0,y_0} that appears as stray light at the regarded pixel $\widehat{Y}_{x,y}$. The cumulative stray light offset is calculated by summing up the contributions of all pixels (x_0,y_0). Replacing Y_{x_0,y_0} in eq. 2 by eq. 1 leads to

$$\widehat{Y}_{x,y} = \sum_{x_0} \sum_{y_0} k_{x,y,x_0,y_0} \left(\widetilde{Y}_{x_0,y_0} - \widehat{Y}_{x_0,y_0} \right). \tag{3}$$

A characteristic feature of equation 3 is, that the signal offset $\widehat{Y}_{x,y}$ in pixel (x,y) is a function of the *measured value* $\widetilde{Y}_{x_0,y_0}$ in pixel (x_0,y_0) and its *unmeasurable part, the stray light influence* $\widehat{Y}_{x_0,y_0}$. One way of gaining $\widehat{Y}_{x_0,y_0}$ is to correspondingly apply eq. 2 to the pixel (x_0,y_0). In the end, this procedure leads to a recursive model. However, the measurements presented later in this paper yield, that typical values of k are located in the range of 0.1% only. This and the intention to keep the model non-recursive and thus simpler to invert, motivates to consider that

$$\widehat{Y}_{x_0,y_0} \ll \widetilde{Y}_{x_0,y_0} \tag{4}$$

so that eq. 3 results in the approximation

$$\widehat{Y}_{x,y} \approx \sum_{x_0} \sum_{y_0} k_{x,y,x_0,y_0} \widetilde{Y}_{x_0,y_0}. \tag{5}$$

The physical interpretation of this approximation is that stray light of second and higher order $(k^2, k^3, \ldots)$ is not considered. In other words, stray light coupled into other parts of the image is not expected to generate considerable amounts of additional stray light. The results shown later will point out that this assumption is justified very well.

The model parameters k_{x,y,x_0,y_0} are initially unknown. In the next section, it will be shown that they can be derived from a number of particular measurements. But first, the spatial resolution that is required for adequate modeling is considered.

Let's make an examplary calculation: If the resolution of the captured image is 1024 x 768 pixels, the stray light effects from each pixel to each other one are modeled by coefficients k_{x,y,x_0,y_0} of 2 Bytes, the required memory space will accumulate to $(1024*768)^2 * 2Bytes = 1.125 \frac{TBytes}{channel}$. This is, of course, an unreasonable amount of memory. Also, calculating and compensating for the stray light effects from each pixel to each other pixel means a gigantic numerical effort. Fortunately, the measurements indicate that such a high spatial resolution is not required for an adequate description of stray light. As a consequence, the demand of disk space and the numerical effort can be reduced significantly. It turned out that the measurement of the coefficients based on a subsampled image $\widehat{Y}'_{x,y}$ are sufficient. The subsampled image is defined by dividing the original image into a checker-type set of sub-regions (5 rows, 6 columns). For each region the average signal value is calculated, thus, forming the pixel values in $\widehat{Y}'_{x,y}$. An "image" with only 30 pixels results. As a consequence, the number of the couple coefficients k'_{x,y,x_0,y_0} dramatically decreases to $(5*6)^2 = 900$. The corresponding equation for the small image corresponding to eq. 5 is:

$$\widehat{Y}'_{x,y} = \sum_{x_0} \sum_{y_0} k'_{x,y,x_0,y_0} \widetilde{Y}'_{x_0,y_0} \tag{6}$$

Once the subsampled couple coefficients are known, any image can be compensated for by calculating and subtracting the cumulated offset values using this equation and an appropriate twodimensional interpolation algorithm. The following paragraph describes how the coefficients can be derived from a set of multispectral measurements.

Table 1: **Typical values of the couple coefficients k_{x,y,x_0,y_0} (multiplied by 1000 in order to increase readability). The case $(x_0,y_0) = (2,2)$ is shown. It can be recognized that, for instance, $0.638\ {}^0\!/_{00}$ of the value in $(2,2)$ are added as stray light to the value of pixel $(0,0)$. Note that the value of $k_{2,2,2,2}$ results from an interpolation of the four coefficients neighbouring directly.**

	y					
x	0	1	2	3	4	5
0	0.638	0.813	0.959	0.589	0.507	0.452
1	0.708	1.389	3.025	2.185	0.569	0.494
2	0.757	2.208	3.875	7.981	0.646	0.493
3	0.667	1.288	2.288	0.943	0.468	0.430
4	0.550	0.698	0.851	0.456	0.386	0.370

Fitting the Model Parameters

The model parameters, i.e. the couple coefficients k'_{x,y,x_0,y_0}, are obtained by carrying out a number of measurements. First, the image of a black reference $\widetilde{B}_{x,y}$ is captured. Then, a subsampled version $\widetilde{B}'_{x,y}$ of this black image is calculated. In order to generate stray light originating from a well defined position in the image, a small, white, rectangular patch is used. Its size exactly matches the size of one subfield. This is placed on the black reference at the position of the first subfield $(x_0,y_0) = (0,0)$. After an image has been taken the white patch is moved to the next subfield and so on resulting in 30 images. From these captured images $\widetilde{Y}_{x,y}$, the subsampled images $\widetilde{Y}'_{x,y}$ are calculated following the same procedure as described in the paragraph above. Following this method, a set of 31 subsampled images is generated: one black reference image and 30 images with just a single white macro-“pixel” resulting from the white reference. The other nearly black “pixels” of these 30 images contain mainly stray light resulting from the respective position of the white reference plus a black offset which can easily be subtracted using the black reference image. From these images, the couple coefficients can be calculated by evaluating a quotient of the channel signals with the black offset being corrected according to

$$k'_{x,y,x_0,y_0} = \frac{\widetilde{Y}'_{x,y} - \widetilde{B}'_{x,y}}{\widetilde{Y}'_{x_0,y_0} - \widetilde{B}'_{x,y}} \tag{7}$$

where $\widetilde{B}'_{x,y}$ is the subsampled image of the black surface (black reference image), $\widetilde{Y}'_{x,y}$ is the value of the subsampled image in pixel (x,y), $\widetilde{Y}'_{x_0,y_0}$ is the value of the subsampled image in pixel (x_0,y_0), i.e. the value of the pixel, where the white sample is located. The case $(x_0,y_0) = (x,y)$ describes the amount of stray light in pixel (x,y) originating from its own position. This cannot be determined from the procedure described so far, so the method generally cannot be used to calculate the couple coefficients k'_{x_0,y_0,x_0,y_0}, because this would require the white sample and the black reference to be positioned at the same spot at the same time. A solution to this problem is that the couple coefficient is set to the average value of the neighbouring coefficients. See tab. 1 for a typical couple matrix resulting from this procedure.

Compensating Algorithm

The stray light is modeled as a linear cumulative offset that is a function of the image content and added to the actual channel signals (eq. 1). The task of the compensating algorithm (see fig. 2 for the principal structure) is to calculate and subtract this offset

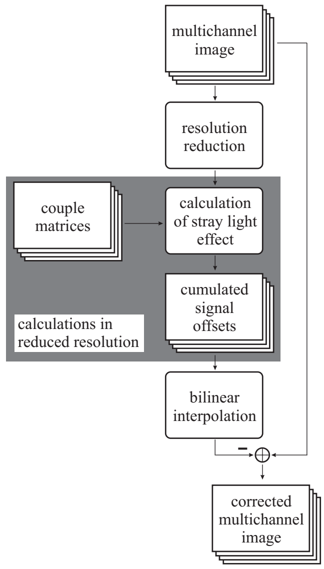

Figure 2. Principal structure of the compensating algorithm. The evaluation of the channel offset is done in the reduced resolution in order to save disk space and reduce the numerical effort. The offset values are then interpolated to the original resolution and subtracted from the original image.

from each pixel value in order to gain the original, undistorted value $Y_{x,y}$ in eq. 5 following

$$Y_{x,y} = \widetilde{Y}_{x,y} - \widehat{Y}_{x,y}. \tag{8}$$

For this purpose, a subsampled image $\widetilde{Y}'_{x,y}$ has to be calculated from the image $\widetilde{Y}_{x,y}$ that is to be compensated for. The reduction of the resolution of the original image is performed using the known method described earlier in this paper. The result is the subsampled, 5*x*6 “pixel” image $\widetilde{Y}'_{x,y}$. The couple coefficients k'_{x,y,x_0,y_0}, which are known from the preceding calculations for the specific camera, are used to calculate the cumulated signal offset for each pixel in the subsampled image following eq. 6. In order to gain the offset values for each pixel $\widetilde{Y}_{x,y}$ at the original resolution, a bilinear interpolation is applied to the offset values calculated for the reduced resolution. Finally, the interpolated values are subtracted from the originally measured image. As a result the image $Y_{x,y}$ is approximately free of stray light. The results show that the first order approximation delivers quite exact results in view of practical application.

Results

A variety of multispectral measurements were carried out in order to check the appropriateness of the proposed model and the compensating algorithm. The tests verified, that the algorithm was able to correct the influence of stray light in such a manner, that the spectral reflectance distribution of a sample object could be captured independently from the brightness of the rest of the image. The following measurement procedure was applied to test the algorithm: the color patches of the GretagMacbeth Color Checker were used as color samples. First, a reference measurement with as little stray light as possible was made by covering all other parts of the color checker with a black frame. In order to synthetically generate different amounts of stray light, the black frame was gradually substituted by a white frame. The ratio of the white surface was increased successively from 0% to 100% in steps of 25%. As expected, the varying amounts of stray light present in the optical path led to different spectral measurements.

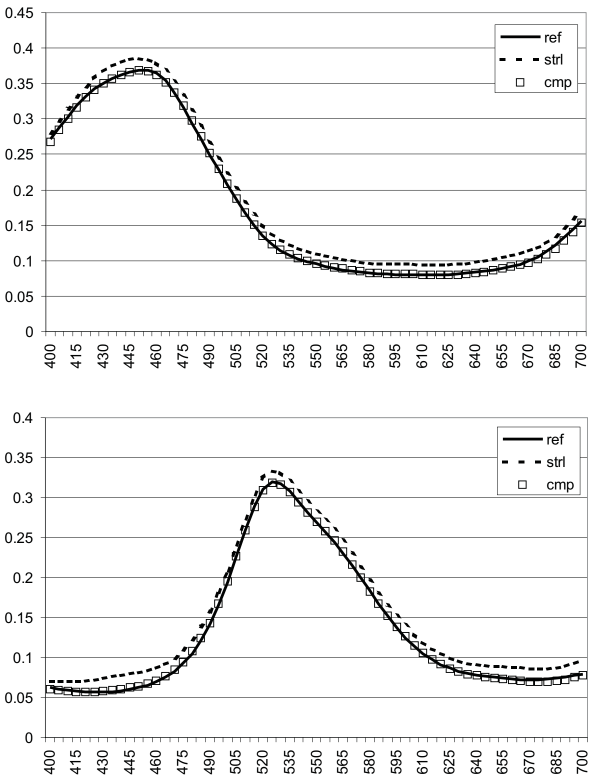

Figure 3. Reference spectra (ref), measurements with stray light (strl), and compensated spectra (cmp, small squares) resulting from the method. The compensated spectra quite exactly fit the original reference measurements.

Fig. 3 illustrates this effect by means of exemplary spectra resulting from the measurement of two color patches (blue and green) of the Color Checker. The figure shows the reference measurement with the black frame, the measurement of the same patch with a 100% white frame and the same measurement after being corrected by the proposed algorithm. There is a considerable difference between the reference measurement and the uncorrected measurement with the white frame. After correction by the proposed method, the difference is practically equal to zero. Table 2 shows the root mean square (RMS) errors between the reference measurement, the original measurement, and the corrected measurement resulting from the proposed method as a function of the amount of stray light present in the optical system.

In order to quantify the corresponding visual differences, the spectra were transformed to CIEXYZ and CIELAB values (illuminant D65, CIE 1931 standard observer). Table 3 shows the color differences in ΔE_{00} between the reference measurement, the uncorrected measurement and the corrected measurement.

See fig. 4 for a sample image and the corresponding stray light generated by the captured object. The stray light was magnified by the factor of 20.

Discussion

A model describing the effects of stray light in a multispectral camera is proposed. It is parametrized by carrying out a specific set of measurements. Based on this model, a method aiming at the extraction of stray light from the captured images has been developed. The results achieved by the method are documented by means of RMS errors in the spectral domain and ΔE_{00} in CIELAB. These results are highly satisfactory and help to increase the accuracy of multispectral measurements.

Table 2: Root mean square (RMS) errors between the reference measurement with a black frame and measurements including different amounts of straylight (quoted in the column "ratio") originating from a surrounding with reflectance between 0 and 1. The columns indicated by "raw" show the original data calculated from the measurements. The columns indicated by "corr." show the results, after the image has been corrected by the proposed algorithm. In each case, the algorithm is able to improve the measurement quality and stability dramatically. All numbers have been multiplied by 1000 in order to increase readability.

	blue		green	
ratio	raw	corr.	raw	corr.
0.25	0.371	0.200	0.435	0.230
0.50	1.687	0.129	1.707	0.097
0.75	3.721	0.163	7.463	0.152
1.00	13.948	0.221	13.614	0.143

	red		rose	
ratio	raw	corr.	raw	corr.
0.25	1.551	0.148	1.800	0.069
0.50	9.177	0.333	7.033	0.160
0.75	16.909	0.607	9.800	0.192
1.00	22.852	0.547	20.209	0.378

Table 3: Color differences in ΔE_{00} between the reference measurement with a black frame and measurements including different amounts of straylight with and without correction (illuminant D65, CIE 1931 standard observer).

	blue		green	
ratio	raw	corr.	raw	corr.
0.25	0.33	0.19	0.31	0.15
0.50	0.75	0.14	0.69	0.07
0.75	1.15	0.07	1.44	0.22
1.00	2.25	0.20	1.93	0.16

	red		rose	
ratio	raw	corr.	raw	corr.
0.25	0.92	0.13	0.66	0.11
0.50	2.19	0.49	1.35	0.25
0.75	3.05	0.73	1.64	0.26
1.00	3.57	0.68	2.34	0.38

A drawback of this method obviously is the fact that only such stray light can be accounted for that results from the captured image region, because the correction is based on the image data only. Stray light that is cast from other directions than the captured object itself will not be considered. In order to achieve good results with the method, external stray light should be excluded as well as possible, e.g. by using light traps in the camera set-up.

Some of the CCD sensors examined in this study suffer from an unwanted drift of the operating point as a function of brightness. It was found that if a sensor line is exposed partly, the operating point goes down so that the response of the rest of the line will decrease, though its illumination is unchanged. The described method reveals such behaviour, as well, by bearing negative couple coefficients k_{x,y,x_0,y_0}, because the image can in part become darker than the black reference. But the model is not limited to positive couple coefficients, so this sensor characteristic is compensated for, as well.

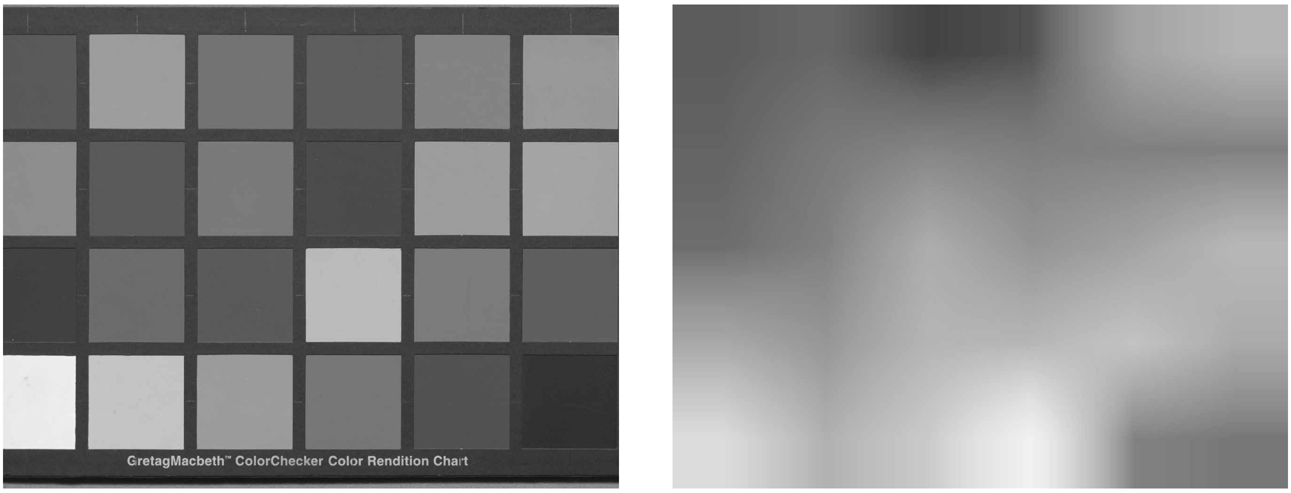

Figure 4. Multispectral test image (left) and the corresponding stray light image (right). The indicated stray light image is generated from the left image and, in this case, magnified by a factor of 20. Usually, it is subtracted from the left image in order to gain the corrected image. Note that the white patch at the bottom left is in some sense mirrored to the top right, which is due to the optical characteristics of the camera. Stray light is not always a locally limited effect.

An essential advantage of the proposed method is its low time consumption. A 16-channel, 1 Megapixel image is corrected within less than a second, making it possible to apply stray light correction being practically unnoticed by the user.

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Biography

Stephan Helling received his diploma degree in Electrical Engineering from the Aachen University of Technology in 2001. He is now engaged in research on multispectral imaging systems with focus on multispectral cameras at the same university. He is member of IS&T and the German Society for Color Science and Application DfwG.

