Image sensor performance from a security camera perspective

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A typical image sensor – CMOS or CCD – is used in a wide range of different applications, sometimes facing situations not even anticipated by the sensor manufacturer. Consequently, this may lead to suboptimal performance in some camera products. It may also be the case that emphasis is put on a certain market and with less attention to other fields, resulting in designs where certain parameters are neglected even though neither market would be negatively affected by a design that is aiming at optimizing also those parameters. At present, the mobile imaging field is driving commercial image sensor development in one specific direction with much effort spent on counteracting the effects of increasingly smaller pixels but not necessarily so much attention paid to other issues. One important task for a security camera is to operate under very low lighting conditions, often in combination with large variations in intra-scene radiance and motion. Due to many simultaneous requirements, cameras will often suffer from photon starvation, that in turn leads to low signal-to-noise ratios. A straightforward way to increase the signal-to-noise ratio is to increase the amount of light available to the sensor by decreasing the f-number of the optics, often down to f/1.0. This should theoretically result in a higher light sensitivity of the camera. However, this changes the optical beam geometry which leads to a range of unwanted effects. Most notably, the pixel crosstalk may increase substantially, which will hamper the expected increase in signal-to-noise ratio. For a color camera this is worse than for a black-and-white camera, since a more aggressive color matrix would have to be employed in order to provide a consistent color reproduction. In this paper we will, by a few examples, visualize the unwanted effects of lower f-numbers by using a model based on measured data. We will also present a method that might be used to qualitatively assess pixel crosstalk from measured spectral sensitivity data.

INTRODUCTION

A security camera has to be able to cope with a range of complicated lighting situations and still give a high quality video. We have previously discussed this [1, 2] for scenes with extreme intra-scene illumination variation where we have emphasized the reproduction of low contrast objects. In this paper we focus on situations when there is a shortage of light and when methods to counteract this with longer exposure times and noise filtering have already been exhausted.

Adding light to the scene is in many cases not possible since it would reveal the camera or disturb the scene under surveillance, for example a traffic scene. Sometimes it is possible to use Near InfraRed (NIR) light, but if a color image is required this is not a possibility. What remains is to improve the throughput of the optics and thus increase the brightness of the image on the sensor surface. A straightforward improvement is to increase the aperture of the lens, and thus to lower the so called f-number.

Lowering the f-number means that more light will be received at the sensor surface since the light gathering area is larger, but it also means that the light beam will be expanded and thus will contain rays with larger angles from the normal. The added rays will thus enter the pixels with a larger angle than before and will require the sensor to be designed accordingly. Otherwise the added rays may avoid detection, so that some or all of the benefit is lost, or end up in adjacent pixels, leading to a blurry image. In sensors with color filter arrays the leakage into adjacent pixels also leads to crosstalk between the spectral bands.

Low f-number photography is not new. It has been used for a long time. A typical f-number for a consumer camera is $f/2.8$. For a security camera an f-number of $f/1$ is common. The $f/1$ lens has an 8 times larger light gathering area and thus should give an 8 times brighter image. Even lower f-numbers are possible. An f-number of $f/0.7$ (2 times the light gathering area of the $f/1$ lens) was realized already in the late sixties (Carl Zeiss Planar 50 mm $f/0.7$). So for low light security imaging it is very important that the sensor can cope with a wide beam geometry.

In this paper we investigate to what extent an image sensor can limit the benefit of a lower f-number. This is done by measuring and modeling the spectral sensitivity changes for a sensor in such a way that the benefits and drawbacks can be shown visually in simulated images. The method is described in some detail and the results are discussed from a security camera perspective.

METHODOLOGY

Spectral response measurements were performed using a monochromator attached to an integrating sphere. In order to obtain results at different f-numbers, the bare sensor to be tested was placed at a range of different distances from the exit port of the sphere. For each position the f-number was estimated as the ratio of the distance between sensor and exit port and the diameter of the

exit port. In this way it was possible to obtain data for f-numbers corresponding to $f/4$, $f/2.8$, $f/2.0$, $f/1.4$, $f/1.2$, $f/1.0$, and $f/0.7$. The spectral response curves obtained in this way were normalized by the f-number and integration time in order to find results that correctly represented the response of the sensor at the different f-numbers.

Assuming that the observed differences between the shapes of the spectral curves are due solely to pixel crosstalk and signal loss due to absorption, it is possible to construct a set of transformation matrices as previously described in the literature [3–5], one for each f-number. These matrices describe the connection between the pixel signal leakage and the modification of the spectral curves compared to some baseline, or original, spectral characteristics. In our case, the matrices were constructed using the $f/4$ curves as baseline. In order to derive the transformation matrices, a set of crosstalk kernels, describing the signal leakage from an illuminated central pixel (red, green-red, blue, or green-blue) to the immediately surrounding, non-illuminated, pixels, are constructed. In our case, the size of these kernels was limited to 3×3 pixels. From this information, it is now possible to determine how the spectral information is modified [5]. Conversely, if the spectral curves, as modified by the pixel crosstalk, are known, one may determine the leakage between pixels by simply varying the crosstalk kernels until the error between the baseline spectral data modified by the transformation matrix and the actual measured data is minimized.

Furthermore, if one assumes that the pixel crosstalk is wavelength independent, only one transformation matrix will be necessary for each f-number, instead of one for each wavelength sample and f-number. From our measurements, we find very good correspondence between the measured spectral curves and the transformed $f/4$ curves within the visible wavelength range using the wavelength-independent approach, which justifies this approximation in this case. It should however be observed that this assumption may not be found to hold in other cases [6]. Using only one transformation matrix that converts the baseline spectral data into the crosstalk modified spectra has the additional advantage that it is possible to calculate an exact relationship between the color correction matrices (CCMs) for the transformed and baseline sets of spectral curves, according to

$$\mathrm{CCM}_{\mathrm{modified}} = T \times \mathrm{CCM}_{\mathrm{baseline}}, \tag{1}$$

where $\mathrm{CCM}_{\mathrm{modified}}$ is the CCM modified by pixel crosstalk, T the transformation matrix, and $\mathrm{CCM}_{\mathrm{baseline}}$ the CCM calculated for the baseline spectra, in our case corresponding to $f/4$. Therefore, when comparing simulated images, the color reproduction will be exactly the same. However, since the individual color matrix coefficients will be different, the noise penalty imposed by the change in spectral characteristics will be reflected in the simulated data.

In this type of simulation, a noise free reference image is modified according to the needed processing in such a way that it will appear identical except for noise. It is thus assumed that any distortion of color will be perfectly counteracted by the applied color correction. The noise model contains both signal independent and signal dependent noise and takes into account light loss as well as spectral sensitivity changes.

RESULTS

In Fig. 1, the effect of changing the f-number on the spectral response of an image sensor is shown. The curves have been compensated for the differences in light intensity at the sensor surface due to changing f-number and thus reflect the change in relative sensitivity as a function of f-number. For this investigation, an image sensor with comparably small pixels, in the sub-2 μm range, was chosen in order to more clearly show the crosstalk effects as the f-number is decreased, which, as illustrated in Fig. 1, results in severe broadening and overlap between the curves.

As discussed above, crosstalk kernels, describing the leakage of signal from a center pixel to its immediate surroundings, were generated for all f-numbers, with $f/4$ as baseline. A few of these are shown in Fig. 2 for the green-red channel. Being chosen as baseline, the $f/4$ case shows no crosstalk while the $f/1.4$ and $f/0.7$ cases illustrate increasingly severe relative leakage, corresponding to the deteriorations of the spectral curves shown in Fig. 1.

In order to illustrate the effect on signal to noise ratio due to the increased pixel crosstalk, a set of images were simulated from the measured data. Fig. 3 shows the results of those simulations. For these images, the scene illumination was changed in order to compensate for the varying light levels due to changing f-numbers and therefore the exact same amount of light reaches the sensor in all cases. Thus, the differences between the images reflect the actual differences in sensitivity due to crosstalk for the different f-numbers. In the left column, images without a CCM applied are shown, while the right images are shown with the CCM applied. It should be noted that the colors in all images are identical, and only the noise is changing. This is due to the way the simulation is set up, where only the noise is modified by taking into account sensor parameters such as, e.g., sensitivity, read noise levels as well as the CCM, while the scene image itself is left unmodified. As the crosstalk increases, we can see that the noise level increases dramatically. In this case, the f-number is lowered from $f/4$ all the way down to $f/0.7$. The latter represents an extreme case that is not fully representative of security cameras on

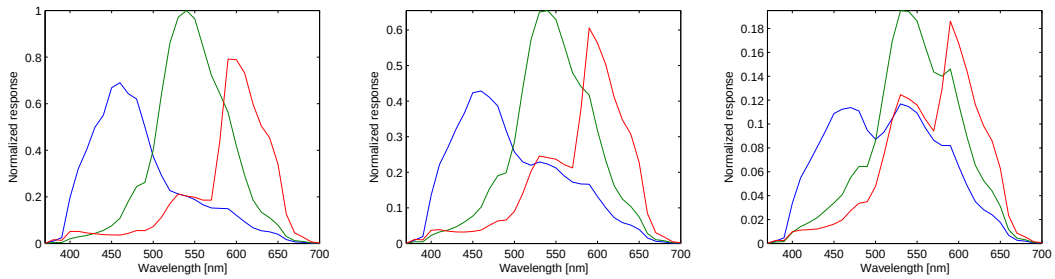

FIG. 1. Relative spectral response for different f-numbers. Left: $f/4$, middle: $f/1.4$, right: $f/0.7$.

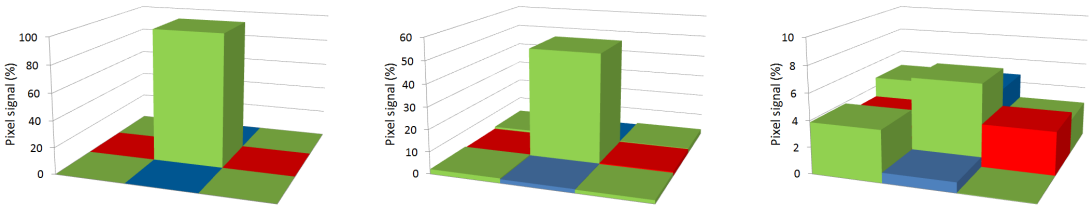

FIG. 2. Crosstalk kernels for the green-red channel derived from the spectral response curves in Fig. 1, see text for details. Left: $f/4$, middle: $f/1.4$, right: $f/0.7$.

the market today, and therefore the last images in the sequence shown are separated from the others by a horizontal line. The cases above this line, ranging from $f/1$ to $f/4$, do however represent typical f-numbers used in security cameras today. Even if we exclude the extreme $f/0.7$ case, it is quite obvious that lowering the f-number can have a dramatic effect on the relative sensitivity of a typical camera if the image sensor is not able to accommodate the wider angles of light implied by a lower f-number.

The images in Fig. 3 only show the impact on signal to noise ratios with different CCMs. Another effect of changing spectral characteristics with increasing pixel crosstalk is illustrated in Fig. 4. Here, the same CCM was applied to the spectral data for three different f-numbers, $f/4$, $f/1.4$, and $f/0.7$. If the f-number is not considered when applying a CCM to the image, the resulting image may be severely affected from a color reproduction point of view.

DISCUSSSION

The effect on image sensor performance as a result of increasing the angle of light reaching the pixels is well known [7–9]. However, mostly due to the dominance of mobile imaging, it seems that focus has been shifted towards the field-dependent effects of large chief ray angles rather than the purely geometric effects due to a wider cone of light. The reason for this is due to the fact that so far, the f-numbers are still comparably large so that the effects of the larger light cone have not yet started to be-

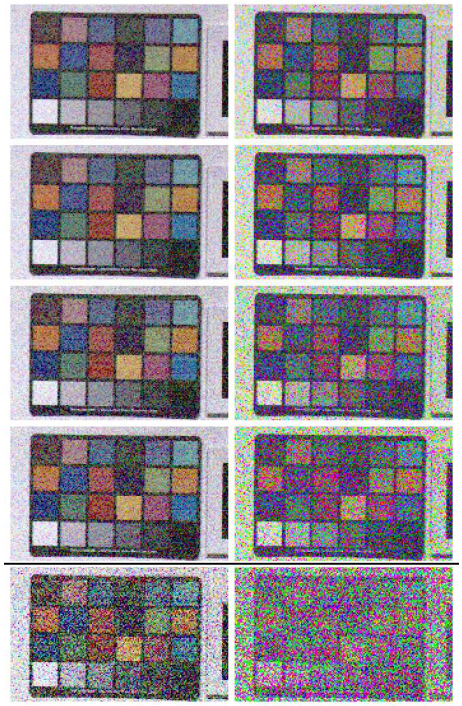

FIG. 3. Simulated images demonstrating the effect of lowering the f-number of the lens in front of a sensor with small pixels. F-numbers, from top to bottom, are: $f/4$, $f/2$, $f/1.4$, $f/1$, and $f/0.7$. For each row the light level is decreased in such a way that a sensor with an ideal response to f-number would be unchanged. Any change with f-number is thus a measure of the sensor capability. The left column shows the effect of sensitivity loss only and the right column shows the combination of sensitivity loss and spectral crosstalk. Color correction is assumed perfect and thus appears only as increased noise.

FIG. 4. Illustrating the deterioration in color reproduction with variations in f-number. Top: $f/4$, middle: $f/1.4$, bottom: $f/0.7$.

come noticeable. It is important to point out that while the chief ray angle can be modified by a better optical design where the exit pupil is moved towards infinity, the effects of an decreased f-number are purely geometric and are therefore an inherent property of the optical system as such, in principle independent of the optical design. Therefore, to remedy the unwanted effects of decreasing the f-number, the image sensor design has to be modified in such as way as to become more insensitive to these effects.

In practice, from a large amount of measured data, we have seen that the performance of image sensors with respect to this phenomenon shows a wide spread between different manufacturers and models. This tells us that it is possible to increase the performance considerably in lowlight situations if the f-number dependence is taken into consideration while designing the sensor. As we have shown in this paper, the performance loss can be considerable in some of the worst cases, making it more or less useless to decrease the f-number below some certain value.

In a security camera application, the lowlight performance is certainly very important, and therefore as much light as possible should be provided to the image sensor. As demonstrated in this paper, the relative sensitivity of an image sensor may be severely compromised with decreasing f-numbers, which on the other hand is needed in order to provide the sensor with sufficient light. The net result may still be an improvement in overall signal to noise ratio, even though not to the extent expected.

From a systems perspective, increased spectral crosstalk as the f-number is decreased will, apart from the signal to noise impact, also have an effect on the color reproduction as well as the overall sharpness of the image. The latter effect will in many cases be a combination of decreased sensor MTF as well as the increase of optical aberrations in the lens. Taken together, the overall complexity of the system will therefore increase due to the increased amount of image processing, adapting to a varying f-number, necessary to counteract these effects. As this is likely to lead to an increased overall cost of the camera system, it is important to apply improvements at the appropriate place in order to avoid overly expensive remedies at later stages of the imaging chain.

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