1. Introduction

To capture a movie in a low-light condition is a very important task in broadcasting, digital cinemas, surveillance, and so on. Recent progress of CMOS image sensors (CISs) has contributed such applications\(^1\)-\(^6\). However, small defects, which can be neglected in moderate applications, are emphasized because the number of incident photons on pixel is very few in extremely low-light conditions. Random telegraph signal (RTS) noise and shot noise by large dark current are major factors of abnormally large noise\(^7\)-\(^9\). Moreover, in movies, exposure time is limited by the frame rate. Although the F-number of imaging lens should be reduced for obtaining more photons, it increases the aberration of the lens or the size and weight.

We have proposed a low-light camera\(^1\)\(^0\) based on multi-aperture optics and selective averaging, which is suitable for capturing movies and is more compact than single-lens cameras with the same F-number. We assume a multi-aperture camera composed of multiple sets of a lens and an image sensor. Because multiple images are acquired at the same time, it is possible to increase the signal to noise ratio by averaging them by the factor of the root of M when the camera consists of M apertures. However, large random noise cannot be eliminated by the simple averaging. To remove these kinds of noise, selective averaging has been proposed. The dark sensor noise is measured pixel by pixel before capturing, and the set of apertures that gives the smallest effective noise is determined for every pixel. This method is based on a one-pass algorithm and does not need any iteration. Therefore, it is possible to apply this method to real-time movie acquisition. The effectiveness of this method was verified by simulation and experiments in our previous works. In Ref. 10, a prototype monochrome multi-aperture camera was used. Although the effectiveness of the selective averaging for color imaging has been verified qualitatively by simulation\(^1\)^{11}, no quantitative evaluation was performed.

In this paper, the color reproduction error after selective averaging is quantitatively evaluated in the CIE-xy color space. The rest of this paper is organized as follows. In section 2 the principle of selective averaging method and the processing flow of color image

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Bo Zhang\(^†\) (member), Keiichiro Kagawa\(^†\) (member), Taishi Takasawa\(^†\), Min Woong Seo\(^†\) (member), Keita Yasutomi\(^†\) (member), Shoji Kawahito\(^†\) (member)

Abstract We have demonstrated effectiveness of the selective averaging with a multi-aperture camera for reducing image sensor noise such as random telegraph signal (RTS) noise and large dark current shot noise. In this paper, noise reduction capability in color reproduction with the proposed method is studied by simulation, where we assume an ultra-high-sensitivity 2 x 2-aperture color camera. In the prototype camera, which is being developed, low-noise Bayer color-filter 0.18um CMOS image sensors based on the folding-integration and cyclic column ADCs with 1280 x 1024 effective pixels are utilized. The synthetic F-number is 0.6. Simulation shows that the effective noise in terms of the peak of noise in histogram is reduced from 1.44 electrons to 0.74 electrons, and RTS noise and large dark current shot noise are successfully removed. Color reproduction errors are quantitatively evaluated. The root-mean-square errors of blue, green, red, and white in the CIE-xy color space becomes approximately a half after the selective averaging.

Keywords: multi-aperture, low-noise, high-sensitivity, noise reduction, random telegraph signal (RTS) noise, selective averaging
reproduction in a multi-aperture camera are described. Section 3 shows the simulation results of noise histograms and color reproduction errors. Section 4 gives conclusions.

2. Multi-aperture camera

Fig. 1 shows a schematic drawing of the multi-aperture camera used in this study. A camera system is composed of an array of a lens and an image sensor which is called an aperture. Sensor noise reduction based on this multi-aperture camera and the selective averaging described in Sec. 2.1 has been demonstrated with monochrome CISs.

To apply the selective averaging to color image sensors, a 2 x 2-aperture color camera is being developed (Fig. 2). The system is composed of 2 x 2 sets of a low-noise and high-dynamic-range CIS and a bright video lens with an F-number of 1.2 and a focal length of 8mm. The synthetic F-number becomes 0.6. This CIS is composed of 1280 x 1024 effective pixels whose pitch is 7.1 µm x 7.1 µm and equipped with Bayer color-filters. The pitch of the apertures is 110mm x 110mm. Because the size of the print circuit board (PCB) is 220mm x 220mm, the scale of the aperture array is extensible by tiling the PCBs with keeping the aperture pitch all the same. This PCB has two channels of Camera Link, and transfers the captured images at the maximum frame rate of 30 frame per second (fps).

2.1 Noise reduction by selective averaging

In the multi-aperture camera, multiple images of the same subject are captured simultaneously. Such redundancy is able to contribute to noise reduction. For example, averaging can be a simple noise reduction method. Although the noise level can be reduced by simple averaging because the signal power is increased by summing up multiple signals, the blinking points caused by the RTS noise and large dark current shot noise in low-light conditions cannot be removed. Median filter is effective to eliminate these kind of large noise. However, this filter does not increase the signal power.

We proposed selective averaging to reduce the RTS and dark current shot noise as well as to increase signal to noise ratio. This method is based on pixel-wise selection of apertures considered in averaging with the measured dark random noise before image capturing. Fig. 3 shows a fundamental procedure of the selective averaging. Before this operation, the variance of pixel value in the dark condition is measured. If the number of the apertures is M, an averaged value is figured out from M pixel values. However, if there are pixels with very large noise, they should be excluded in averaging to obtain less total noise.

In this method, for reproducing one pixel, the measured variances are sorted from the minimum to the maximum. Then, a combination variance is calculated by

\[
S_m^2 = \frac{1}{m^2} \sum_{i=1}^{m} \sigma_i^2,
\]

where, \(m\) is the number of the selected apertures, \(\sigma_i^2\) is a sorted variance, and \(S_m^2\) is the combination variance. The minimum combination variance is found out to determine the selected apertures for each pixel by scanning \(m\) from 1 to M. This operation is performed for every pixel. In Fig. 3, Pixel B has large noise, so that \(S_3^2\) becomes the smallest. Thus, pixel B is not selected.

In image capturing, only the selected apertures are averaged to reproduce a single image from M images obtained by the multi-aperture camera. RTS noise and...
large dark current shot noise become more visible in very low-light conditions because digital and analog gains have to be boosted to depict a small number of incident photons. However, such noisy pixels are automatically excluded by the operation above.

2.2 Image reproduction

Fig. 4 shows the flow chart of color image reproduction for Bayer color-filter image sensors. Although the operation is basically the same as that for monochrome image sensors, interpolation to deal with sparse spatial sampling by the color filters is added. The operation flow includes three steps: preparation, aperture selection, and capturing. In preparation, the variances of dark pixel values are calculated from n frames of measured dark images.

Image acquisition is composed of two steps: aperture selection and capturing. Because the multi-aperture camera has parallax, it is necessary to eliminate it based on the intrinsic camera parameters such as focal length and distortion coefficients, extrinsic camera parameters such as translation and rotation, and the distance of subject. Here, this operation is called disparity correction, which is performed only when the subject distance or a camera parameter such as the focal length for zooming changes. The details of this procedure is described in Ref. 11. The same disparity correction is performed on the dark variance images for apertures selection as well as the captured images. Because Bayer color-filters are assumed in this paper, both of the variance and the captured images for R, G, and B channels are sparse. After the disparity correction, dense images are generated by interpolation. In the aperture selection, the selective averaging is applied to determine the selected aperture for R, G, and B channels separately, so that an index table showing the selected apertures is obtained. In Fig. 4, 1 means "selected", and 0 means "not selected".

In capturing, M images captured at the same time are selectively averaged after the disparity correction to reproduce a single noise reduction image based on the index table of the selected apertures.

3. Simulation results

Fig. 5 shows the noise distribution in dark. In this simulation, real measured noise of the CIS shown in Ref. 3 is used. “Raw” shows the measured sensor noise itself. The histograms of simple averaging and selective averaging are also shown in the figure. The noise of the simple averaging is reduced to approximately a half of raw in the peak of noise histogram. However, the large noise components in the tail of the histogram remain. On the other hand, they are removed with the selective averaging.

Reproducibility of color is verified with the noise model shown in Fig. 6. A hand-made color-checker image imitating the Macbeth color checker is used in
simulation. The pixel count is 200 x 300. Firstly, a Bayer color-filter image, which is basically a single-layer monochromatic image, is generated from the RGB-color color-checker image. To simulate a low-light condition, the maximum pixel value of the captured image is set to as small as 10 electrons. Measured sensor noise and simulated photon shot noise are added to obtain a noisy image. No disparity is considered in this simulation.

Figs. 7(a)-(c) show the reproduced images of selective averaging, simple averaging, and raw, respectively. Fig. 7(d) shows the original image. For the raw image, granular structure caused by interpolation is observed. Because the photon shot noise is large, RTS noise and dark current shot noise are not visible in the bright regions. For the simple averaging, bright noise spots are observed because the pixels with large noise are included in averaging. Each of Figs. 7(a)-(c) is accompanied by enlarged images for G, B, and grey regions from the top to the bottom, respectively. As shown in the enlarged image of Fig. 7(b), there are several bright dots with different colors from the original color, which look like primary colors, namely, R, G, or B. It is because the probability that more than one pixel has large noise is very small; only one component among R, G, and B channels has large noise. For the selective averaging, granularity seen in Fig. 7(c) becomes smaller by virtue of averaging, which is also seen in Fig. 7(a). In addition, large noise pixels are removed. Thus, the quality of the reproduced image is improved significantly with the selective averaging.

Fig. 8 shows the effectiveness of the noise reduction methods in the CIE-xy color space, where the selective averaging, the simple averaging and the raw are compared. In Fig. 8(a), the distributions of the reproduced color coordinates for the R, G, B, and W areas are shown. The ground truth indicates a true color coordinate in the original color-checker image, which is shown as a point. Fig. 8(a) shows that the distributions for the selective averaging and the simple averaging are smaller than that the raw image. In Fig. 8(b), the distribution only for the G area is indicated to clearly show the effectiveness of the selective averaging. The distributions of the selective averaging and the simple averaging are smaller than that of the raw, which means the noise is reduced. The data points of the simple averaging in the circles that are located in the areas of B and R correspond to large noise shown in Fig. 7(b). Thus, the distribution of the selective averaging is the smallest.

Table 1 shows the calculated errors in terms of standard deviation $\sigma$ and distance between the gravity center of the distribution and the point of the ground truth. The standard deviation and distance of the selective averaging is smaller than that of the simple averaging, which are approximately a half as much as that of the raw. This result is reasonable because at most four pixel values are averaged.

4. Conclusion

In this paper, a color image reproduction method based on a multi-aperture camera and selective
averaging for low-noise movie capturing is proposed. This method eliminates extremely large noise such as RTS noise and dark current shot noise, and increases the signal to noise ratio. For a 2 x 2-aperture camera using Bayer color-filter low-noise CMOS image sensors, simulation results show that the peak noise level in the dark and the color reproduction errors for the Macbeth color-checker are reduced approximately to a half by the selective averaging.

References

Bo Zhang received the B.E. degrees from Xi'an Polytechnic University, Xi'an, China, in 2008, and the M.E. degrees from Shizuoka University in 2013. He is currently a Ph.D. student at Shizuoka University. His research interests are CMOS image sensors and multi-aperture imaging system.

Keiichiro Kagawa received the Ph.D. degree in engineering from Osaka University, Osaka, in 2001. In 2001, he joined Graduate School of Materials Science, Nara Institute of Science and Technology as an Assistant Professor. In 2007, he joined Graduate School of Information Science, Osaka University as an Associate Professor. Since 2011, he has been an Associate Professor with Shizuoka University, Hamamatsu, Japan. His research interests cover high-performance CMOS image sensors, imaging systems, and biomedical applications.

Taishi Takasawa received the B.S. degree from Tokai University, Kanagawa, Japan, in 2003. In 2009, he joined Shizuoka University, Hamamatsu, Japan, where he is engaged in the design of the digital circuit and the verilog language.

Min-Woong Seo received the Ph.D. degree from Shizuoka University, Hamamatsu, Japan. From 2012 to 2014, he was a JSPS Postdoctoral Research Fellow at the same research group. Since 2014, he has been a Specially Appointed Assistant Professor with Shizuoka University. His research interests are in CMOS imaging devices, bioimaging, and mixed analog/digital circuit designs.

Keita Yasutomi received the Ph.D. degree from Shizuoka University, Hamamatsu, Japan, in 2011. He is currently an Assistant Professor with the Research Institute of Electronics, Shizuoka University. He is a member of the ITE, IEICE, and IEEE. His research interests include time-resolved CMOS image sensors and low-noise imagers.

Shoji Kawahito received the Ph.D. degree from Tohoku University, Sendai, Japan, in 1988. He is presently a Professor with the Research Institute of Electronics, Shizuoka University and the CTO of Brookman Technology Inc. He is a Fellow of the IEEE and ITE. His research interests are in analog circuits and pixel architecture designs for CMOS imagers.