Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp146-147

Resolution Measurement of the CMOS Image Sensor Loading Micro-lens Array for Three-Dimensional Information Acquisition

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1. Introduction

The active system measuring Time-Of-Flight (TOF) [1] and the passive system utilizing multiple cameras [2] or multiple lenses [3] have been proposed to get both two-dimensional image and depth information. We have developed one-eye passive camera system loading micro-lens array for small mobile device applications. Because of loading micro lens array, the new camera can get two-dimensional image, refocus image, and depth information, simultaneously [4, 5]. In addition, this makes the system possible to be small size, low cost, and low power consumption.

This paper reports our prototype CMOS image sensor loading the micro-lens array. The reconstruction of two-dimensional image from the raw image is characterized to determine the factors for the resolution of reconstructed image.

2. Optical Design and Reconstruction

Utilizing a micro-lens array, we created a virtual image optical system as shown in Fig. 1. The virtual image optical system has advantage of shortening the distance between the main lens and the CMOS sensor compared with the real image optical system. This can be advantage in miniaturization required in mobile devices. Light rays from the object surface are collected by the main lens. These collected rays are distributed to each micro-lens. On each micro-lens, the light rays are collected again. As a result, the compound-eye image with lots of micro-lens images is formed on the CMOS image sensor.

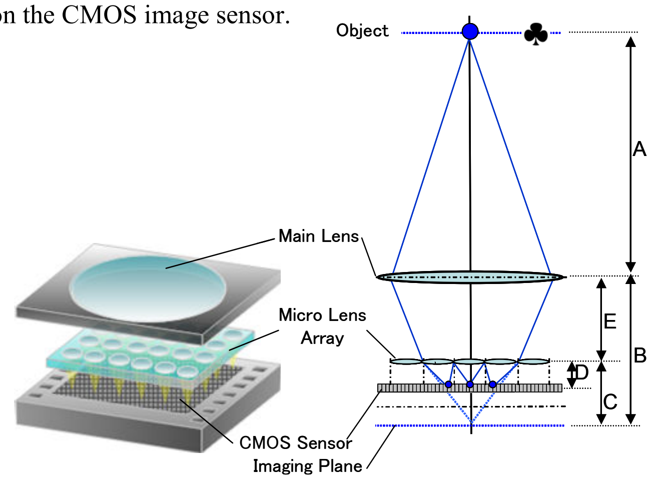

Fig.1. Schematic of optical system using main lens and a micro lens array

If the distance between main lens and object, the distance between main lens and imaging plane, and the focal length of the main lens are A, B, and f, respectively, the distances are related by :

$$\frac{1}{A}+\frac{1}{B}=\frac{1}{f} \quad (1).$$

The equation (1) can be modified as:

$$B=(1+M)f \quad (2)$$

where M(=B/A) is image magnification ratio of main lens. At a certain position of the micro-lens array the equations (1) and (2) can be described with the suffix '0' as:

$$\frac{1}{f}-\frac{1}{A}=\frac{1}{B}=\frac{1}{E-C}=\frac{1}{(1+M_0)f+\frac{D_0}{N_0}-\frac{1}{N}D} \quad (3)$$

where C, D, and E are distances between imaging plane and micro lens, the micro lens and the sensor, and the main and micro lens, respectively, and while N(=D/C) is image magnification ratios of micro lens. We can obtain N from the equation (3) as:

$$N=\frac{D}{-M_0 f+\frac{f^2}{A-f}+\frac{D_0}{N_0}} \quad (4).$$

The equation (4) shows that the image shrink ratio of the micro lens is determined by the distance between the main lens and object.

Fig. 2 shows the reconstructed image from the compound-eye image. Splitting the light rays makes each micro-lens image have the same image areas to those of the neighboring micro-lens images. In case each image from micro lens is shrunk N times, the original image can be obtained by the image processing of 1/N time multiplication and replacement of the images. Because this system multiplies the shrunk images to reconstruct, the converted two-dimensional image loses the high spatial frequency, which means that the converted image has depleted resolution consequently.

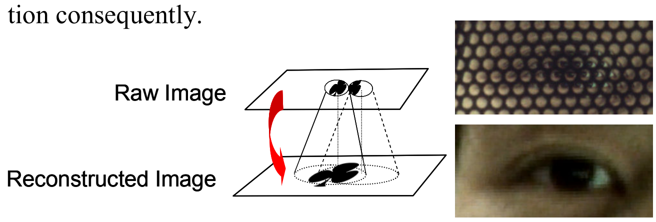

Fig. 2 The image conversion from compound-eye image to two-dimensional image

The depletion ratio is dependent on the amount of shrinkage. The smaller ratio of shrinkage shows more depletion of the resolution. Because the amount of shrinkage is dependent on the distance between the object and the main lens, the depletion of resolution of the converted two-dimensional image is considered to have dependency on the distance, consequently.

3. Experiment and Results

We evaluated the resolution of the converted image from the optical system in Fig. 1 to check the relation between shrink ratio and depletion of resolution. SFR (Spatial Frequency Response) was utilized to identify the resolution. SFR is an index representing the spatial frequency in contrast. Because SFR is determine as the variation ratio of modulation amplitude and average of brightness at a certain spatial frequency, it is utilized to define up to how high frequency can be reconstructed. Because of the lens aberration, contrast in image is lost before it becomes resolution limit. The threshold of SFR was defined as the limit spatial frequency where the contrast is lost as low as approximately 0.1. For characterization, the object was taken utilizing main lens with focal length of 12.5mm, which was positioned to be the focal distance of 300cm.

From the equation (4), shrink ratio N is considered to have the proportional relation to the distance between the main lens and object while each optical component is fixed. Figure 3 shows the relation between the limit spatial frequency and magnification ratio of reconstruction, 1/N. In the experimental results, 1/N drops as the distance of objects becomes larger. This result represents that A is proportional to N as equation (4) describes. From the comparison between SFR of reconstructed image and N, it is shown that SFR rises as N becomes larger. The limit spatial frequency is obtained by the image magnified 1/N times, so SFR of the micro-lens image is obtained from limit spatial frequency multiplied by 1/N. Fig. 3 shows SFR multiplied by 1/N, which represents that SFR becomes Nyquist frequency as the distance of objects becomes larger. Reasons for getting decrease of SFR as the micro-lens is closer range is considered as reduction of image magnification decreases rapidly at close range by the pixel size quantization error.

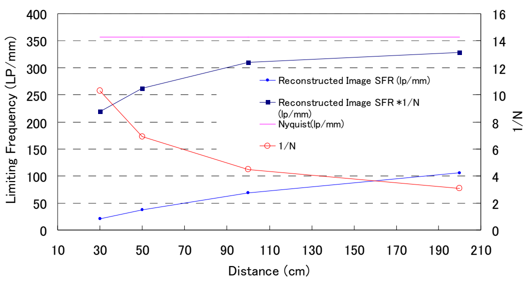

Fig.3. SFR measured at the different distance

Fig. 4 shows plots 1 / N reconstruction ratio, SFR at the reconstructed image, the estimated frequency from binning at the same time. It shows that SFR was declined while 1/N reconstruction ratio is greater. Decrease in SFR showed the same trend, with a estimated frequency calculated from the magnification in particular. This result means that deterioration of high SFR by shrink of image made the image resolution decrease. Because the image was shrunk twice by main and micro lenses, optical resolution was decreased in the compound eye optics system as a result. The aberrations of micro lenses make the image distortion, which was considered to make differences between SFRs of the reconstructed image and those of the estimation utilizing the simple binning.

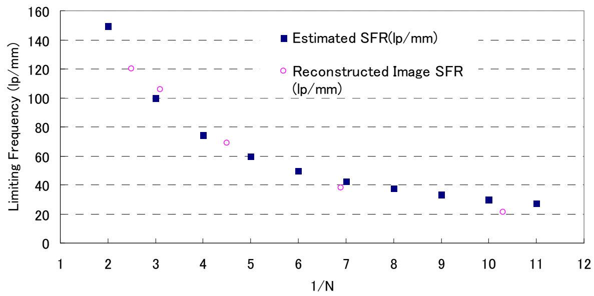

Fig.4. The relation between SFR and 1/N

4. Conclusions

Optical resolution of a prototype compound eye camera loading micro lens array was evaluated by characterization of SFR. Decrease in optical resolution of the image from shrinking twice by main and micro lenses was found out through the experiments. SFR of the reconstructed image was found to be decreased consistently with resolution due to binning. The distortion from aberrations of micro lenses was considered to make differences between SFRs of the reconstructed image and the estimation.

Meanwhile, quantization error effects in compound eye optical system and aberrations of micro lenses affecting SFR decreasing are being considered as further studies.

Acknowledgements

The authors would like to thank T. Ida, N. Matsumoto, Y. Taguchi, G. Kawata, H. Kamijo, H. Kobayashi, T. Katagiri and T. Ogasahara of the Toshiba Corporation for their support.

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