Regionally adaptive enhancement of frame rate and resolution using a rolling shutter camera with a multi-aperture imaging system

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Abstract Combining rolling shutter of a CMOS image sensor with compound lenses, we can get high frame rate for moving object. Moreover, by super-resolution processing with multiple images, we can retrieve the resolution for static objects, which is decreased because of the compound lens structure. Region segmentation by detecting movement is performed to separate regions that contain moving objects from stable objects. High frame rate processing and super-resolution processing are applied the dynamic regions and static region, respectively to give frame rate and resolution for each region adaptively.

Keywords: compound-eye imaging, high frame rate, rolling shutter, CMOS image sensor, super-resolution

1. Introduction

Current image sensor technology have achieved high resolution enough for most imaging applications. Improvement of the frame rate is another important direction of development, however, there is, a trade-off between spatial resolution and temporal resolution because of the limitation of data transfer rate from the image sensor. Although image sensor equipped with image storage can achieve high-frame-rate image capturing without decreasing image resolution, consecutive photographing time is restricted by the storage capacity, and it is difficult to read the data of the captured motion picture immediately, and to use it for real-time application. In this study, we propose image-capturing method to provide appropriate spatial resolution and frame rate for the regions containing stationary objects and dynamic objects, separately. Our method uses a complementary metal oxide semiconductor (CMOS) compound-eye imaging device [1,2] to provide high-frame-rate capturing and super-resolution processing [3] to retrieve the image resolution. We show experimental results to confirm the validity of enhancement of temporal resolution and super-resolution using prototype system.

2. CMOS compound-eye imaging device for enhancing frame rate

A CMOS compound-eye imaging device consists of a lenses array, a CMOS image sensor, and a separator as shown in Fig. 1. The device has thin structure because of the use of a micro lens with a short focal length. An images obtained by the imaging device is a compound-eye image. We used a CMOS image sensor with rolling shutter, so that shutter timing is different depending on the vertical position in an image. Thus, we can obtain a plurality of images captured at different timings according to their vertical position within one frame period of the image sensor. The acquisition timing of each ommatidia image is controlled by the vertical position of the corresponding lens in the lens array, which has rhomboidal lattice arrangement.

The flow chart of processing for regionally adaptive enhancement of frame rate and resolution is shown in Fig. 3. After capturing a compound-eye image, ommatidia images are cropped out with detecting position using correlation with a reference image. Moving areas are detected by such as optical flow processing, and segmented. Super-resolution processing from the multiple ommatidia images is applied to the stationary area to retrieve spatial resolution. Dynamic areas also have possibility for spatial super-resolution, when the movement is not complicated much. Combining the processed stationary area and dynamic areas, we can obtain motion images, whose temporal resolution is enhanced for moving area with suppressing degradation of spatial resolution [4].

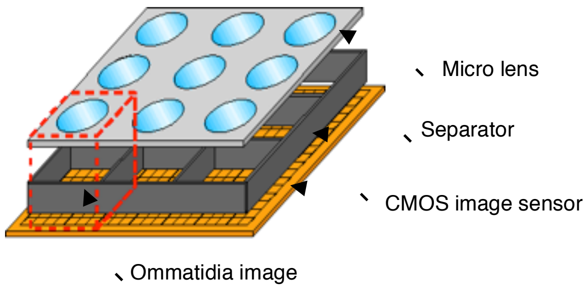
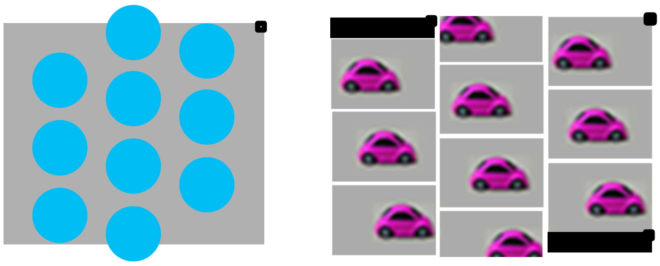


Fig. 1. Structure of compound-eye imaging device



(a) (b)

Fig. 2. (a) Rhomboidal lens arrangement, and (b) a compound-eye image composed of ommatidia images with different capturing timings according to the vertical positions.

3. Super-resolution processing

The resolution of each unit image is decreased because the unit image is captured by a portion of the image sensor. In order to retrieve the decreased image resolution, super-resolution processing [3] is performed from multiple images whose sampling positions are slightly shifted. The primary factors of image degradation are motion, blur, downsampling, and noise. The relationship between the high-resolution image, X, and its kth low-resolution observation,

Y_k is written in matrix-vector notation as,

$$Y_k = D_k B_k M_k X + N_k \\ = A_k X + N_k \qquad (1)$$

where D_k, B_k, and M_k represent the downsamping, blurring and motion operations of the kth observation, respectively. The matrix A_k is a combination of D_k, B_k, and M_k. N_k is additive zero-mean Gaussian noise.

Super-resolution image reconstruction is an inverse problem, because high-resolution image, X, is estimated using observed low-resolution images, Y_k. Super-resolution processing can be formulated by choosing an X to minimize the distance between the model of degradation expressed by equation (1) and measurement Y_k by solving a minimization problem. A basic iterative technique can solve the equation by the iteration for x,

$$\mathrm{X}^{(n+1)} = \mathrm{X}^{(n)} - \beta \sum_k [A_k^T sign(A_k X^{(n)} - Y_k) + \gamma \sum_{l=-P}^{P} \sum_{m=-P}^{P} \alpha^{|l|+|m|} (I - S_x^{-l} S_y^{-m}) sign(X^{(n)} - S_x^l S_y^m X^{(n)})] \qquad (2)$$

where β is a scalar defining the step size in the direction of the gradient, S is a shift matrix, and α is a scalar weight.

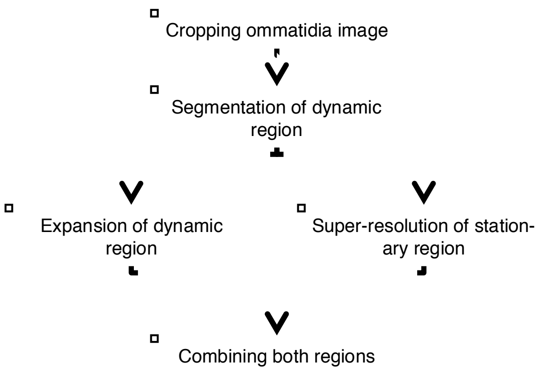


Fig. 3. Flow chart of processing for regionally adaptive enhancement of frame rate and resolution.

4. Experimental results of enhancement of temporal resolution and spatial super-resolution

We constructed a compound-eye imaging system using a color CMOS image sensor with Bayer color filter format, whose pixel size is 3.2 µm in each side, and pixel number is 2048 ×1536. 10 lenses, whose focal length is 2 mm, and diameter is 0.8 mm, are arranged in rhomboidal lattice structure at 1.64 mm interval.

We captured a moving object by the compound-eye imaging system at frame rate of 30 fps and generated multiple sequential images, which have frame rate of 10 fps, from the single compound-eye image. Figure 4 shows experimental results. We confirmed that the frame rate was increased by 10 times. Spatial resolution of the obtained sequential images was decreased instead of the enhancement of temporal resolution.

Experimental results of super-resolution from the degraded images are shown in Fig5. Each unit image was trimmed to 90×71 pixels to remove the area with large aberration in the captured image. We generated high-resolution image, which has 720 × 568 pixels, from 20 low-resolution images. We obtained two green image from each unit image, whose sampling position were slightly different from each other according to the color filter arrangement of the Bayer format. Figure 5 shows calculated high-resolution image, whose resolution was increased by 8 times.

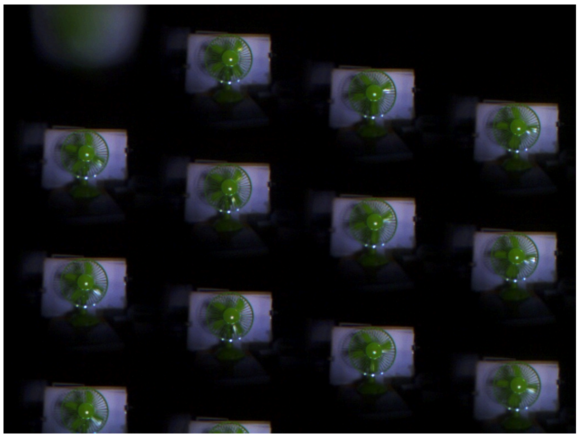
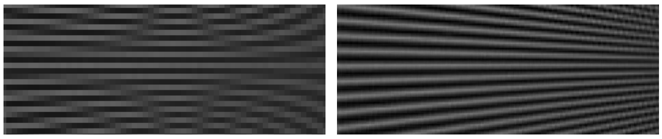


Fig4. An experimental result of a compound-eye image composed of ommatidia images with different capturing timings.



(a) (b)

Fig. 5. Experimental results of super-resolution. (a) A portion of an ommatidia image, and (b) a result of restoration of spatial resolution from 20 low-resolution images.

5. Conclusion

We proposed an image capturing method, which enable appropriate spatial resolution and temporal resolution for dynamic region and static region using simple CMOS compound-eye imaging system. We confirmed the proposed method by capturing image with the prototype system. We achieved temporal resolution enhancement by 10 times. In addition, we demonstrated to obtain high-resolution image of 8 times from 20 low-resolution images using super-resolution method for captured images.

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