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Estimation of any fields of lens PSFs for image simulation

Sangmin Kim, Daekwan Kim, Kilwoo Chung and JoonSeo Yim
Samsung Electronics, Hwasung-si, Gyeonggi-do, Republic of Korea, 18448

Abstract

In a mobile smartphone camera, image quality is more degraded towards the edges of an image sensor due to high CRA (Chief Ray Angle). It is critical to estimate the cause of this effect since image quality is degraded at image periphery from attenuating illuminance and broadening PSF (point spread function). In order to predict image quality from the center to the edge of the camera output, we propose a method to estimate lens PSFs at any particular image field. The method adopts Zernike polynomials to consider lens aberrations while having an arbitrary spatial sampling. Also, it employs estimating a pupil shape in accordance with an optical field. The proposed method has two steps: 1) estimation of a pupil shape and Zernike polynomial coefficients, and 2) generation of a PSF with estimated parameters. The method was experimented with a typical mobile lens to evaluate the performance of the PSF estimation at 0.0F and 0.8F. In addition, Siemens star images were generated with the estimated PSFs to compare resolutions at the center and the edge of an image. The results show that the image of the edge is worse than that of the center in terms of MTF (Modulation Transfer Function), showing the importance of assessing image quality at the edge for pre-evaluation of a mobile camera.

Introduction

Image simulation based on modeling a camera architecture is a critical part during development process of a camera system, which is accomplished by predicting the performance of the camera while considering multiple components of the system simultaneously [1]. Such simulation expedites the development process by characterizing the camera with various parameters [2].

With the rapid advancement in smartphone technology, it is essential to obtain good image quality in the outer field of an image. The main reason is that image quality is more degraded towards the edges of an image sensor due to high CRA (Chief Ray Angle) [3]. The high CRA deteriorates both SNR (Signal to Noise Ratio) and lens PSF (Point Spread Function) in the outer field. As CRA increases, illuminance decreases along the angular position according to the cosine fourth power law. Also, a lens suffers more optical vignetting along with the increase in CRA, resulting in a broadened PSF. Therefore, it is crucial to predict image quality in the outer field when evaluating the performance of a smartphone camera with image simulation.

Conventional simulation methods, however, do not support evaluation for the outer field. The reason lies in the use of simple PSF modeling using a circular aperture. Previous works in predicting lens performance assumed that lens is perfect and its PSF is spatially invariant [1-2]. This assumption gives a rise to inaccurate prediction of image quality given that lens performance degrades due to aberration and its PSF varies across the field. These problems are particularly prominent in mobile lens due to the high design constraint such as large optical format while keeping TTL (Total Track Length) low.

To apply realistic lens design for simulation, lens design tool such as Zemax or Code V was adopted in [4]. This method allowed lens PSF to be generated accurately across the field. However, it is difficult to use lens PSF directly in order to apply the effect of an image sensor due to the difference in spatial sampling between lens PSF and a pixel array. For example, typical mobile lens design used has spatial sampling of 0.202 um and 0.249 um for 0.0 field and 0.8 field for its PSF, respectively. This lens was designed for a CMOS image sensor with 0.7 um pixel size. The spatial sampling of such PSF is insufficient compare to the pixel size.

To overcome this problem, a method to estimate lens PSF using Zernike polynomials is proposed. Zernike polynomials are useful for describing wavefront aberration because they are defined over a unit circle with which a pupil shape is compatible [5]. This property permits consideration of lens aberration. Using Zernike polynomials, it is possible to have any arbitrary spatial sampling. Thus, lens PSF can be modeled more realistically for any pixel size. The proposed method also adopts estimation of a pupil shape to generate lens PSFs at any fields. The shape of a pupil changes along with an optical field while decreasing its area [6]. Optical vignetting, therefore, should be modeled for estimating lens PSF at an arbitrary field. The proposed method is presented in section 2, including the method to apply the effect of a pixel size. Experimental results from the method are described in section 3. Then, section 4 concludes the paper with remarks.

Method

The proposed method mainly consists of two parts as shown in Fig. 1: one for approximating lens PSF by estimating a pupil shape and Zernike polynomials, and the other for generating a PSF with estimated parameters.

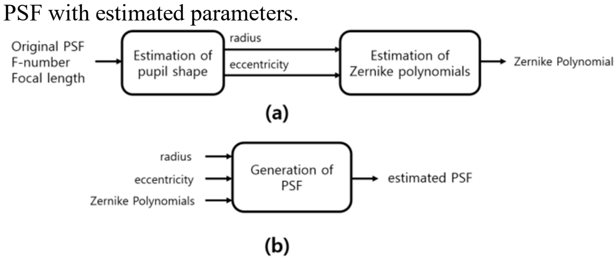

Figure 1. *The block diagram of the proposed method. (a): estimation of lens PSF, and (b) generation of lens PSF with estimated parameters*

Estimation of lens PSF

The process to estimate lens PSF is composed of two steps. In the first step, a pupil shape is determined with a radius and an eccentricity. Then, Zernike polynomial coefficients are estimated with these parameters, as described in Fig. 1(a). This step requires inputs such as an original PSF, and its corresponding F-number and focal length

Estimation of the pupil shape

A pupil shape is estimated with the assumption that a pupil can be described by a radius and an eccentricity. In this paper, the radius is defined as the straight line from the center to the circumference of an ellipse along the horizontal axis while the eccentricity affects the straight line in the vertical axis as defined in Eq. (1).

$$b = \frac{r}{\sqrt{1 - e^2}} \tag{1}$$

where, r and b are straight lines from the center to the circumference of an ellipse defined in the horizontal and the vertical axes, respectively, and e means the eccentricity.

Fig. 2 displays how the shape of a circle changes in accordance with the eccentricity according to Eq. (1) while keeping the radius, r.

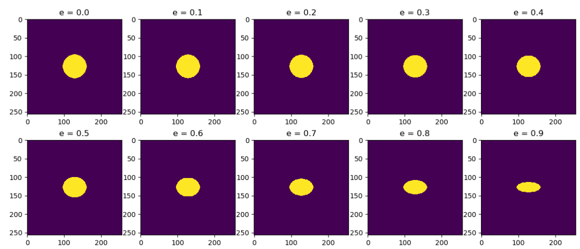

Figure 2. *The change in the shape of a circle in accordance with the eccentricity. In this figure, the vertical straight line, b, was computed by Eq. (1) with changing the eccentricity while keeping the radius, r.*

In order to determine the shape of a pupil, a radius is determined first with two steps. The first step is to decrease the original pupil radius and compute the PSF by using FFT (Fast Fourier Transform) for each decreased pupil, where the original pupil radius is derived from a F-number and a focal length given along with an original PSF. For each PSF, MSE (Mean Squared Error) is calculated with the original PSF. Next, the radius of a pupil that minimizes the MSE is selected and used for determining an eccentricity.

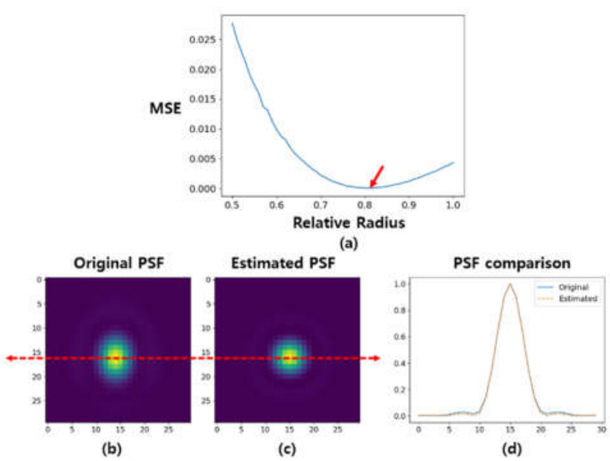

Figure 3. *An example of results from estimating a radius. (a): MSE in accordance with a pupil radius, (b): an original PSF, (c): a computed PSF with the radius that minimizes MSE, (d) PSF comparison between (b) and (c) extracted at the center along the horizontal direction.*

Fig. 3 shows an example of images to obtain a pupil radius from a lens design file in our database. Fig. 3(a) depicts MSE in accordance with a relative radius normalized to the original one. The red arrow indicates the minimum MSE where the relative radius is 0.81. With the selected radius of 0.81, a PSF is computed and compared as seen in Fig. 3(c) and Fig. 3(d), respectively. For comparison, original and computed PSFs are extracted at the center along the horizontal axis and displayed together, showing that they are very similar.

Estimation of the eccentricity

After obtaining a radius, an eccentricity is estimated to fully model a pupil shape. This process is very similar to approximating the radius of a pupil. First, a PSF is computed with the determined radius in accordance with an eccentricity, and MSE between each computed and original PSFs is calculated. Then, the eccentricity that minimizes the MSE is chosen.

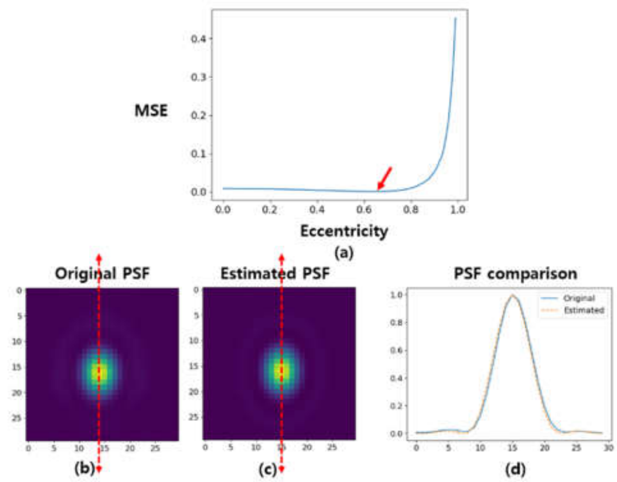

Figure 4. *An example of results from estimating an eccentricity. (a): MSE in accordance with an eccentricity, (b): an original PSF, (c): a computed PSF with the eccentricity that minimizes MSE, (d) PSF comparison between (b) and (c) extracted at the center along the vertical direction.*

An example of estimating an eccentricity is shown in Fig. 4. MSE in accordance with an eccentricity is depicted in Fig. 4(a). where the red arrow points to the eccentricity of 0.64 that has the minimum MSE. A PSF is computed with the estimated radius and eccentricity as displayed in Fig. 4(c), showing the similar shape to the original PSF. PSF profiles that are cut in the vertical axis are compared in Fig 4(d).

Estimation of Zernike polynomial coefficients

After estimating a radius and an eccentricity, Zernike polynomial coefficients are obtained by optimization with these parameters of a pupil radius to achieve lens aberrations and arbitrary spatial sampling. The optimization process is defined in Eq. (2).

$$\min_{Z} C(psf_{org}(x,\ y), psf_{est}(x,\ y|Z,\ r,\ e)) \tag{2}$$

where Z, r, and e are Zernike polynomial coefficients, radius, and eccentricity, respectively. C(•) means a cost function defined as MSE between original and estimated PSFs where the estimated one is computed with Z, r, and e.

The optimization works for minimizing MSE between original and estimated PSFs by updating Zernike polynomial coefficients. For Zernike polynomials, the radial order (n) of 7 and the angular frequency (m) of 7 are used because most low and high order aberrations can be covered with them [5]. These Zernike polynomials are applied as a phase term to the pupil computed with r and e. Then, the phase-included pupil is Fourier-transformed to generate a PSF.

After optimizing Zernike polynomial coefficients, lens PSF is generated with the obtained parameters to have an appropriate spatial sampling for considering the effect of a pixel array.

Image simulation considering the effects of a lens and a pixel array

An image simulation method to consider the effects of a lens and a pixel array is described in Fig. 5.

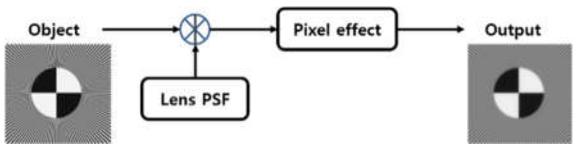

Figure 5. The block diagram of an image simulation method that considers the effects of a lens and a pixel array. The effect of a lens is applied by convolving an object with a lens PSF and that of a pixel array is by averaging locally.

An object, which is ideal with regard to resolution, is convolved with a lens PSF to include blur due to diffraction via lens. The convolution operation comes from the assumption that an optical system is linear and spatial invariant [7]. After that, the effect of a pixel array is applied to the convolved image, as shown in Fig. 6.

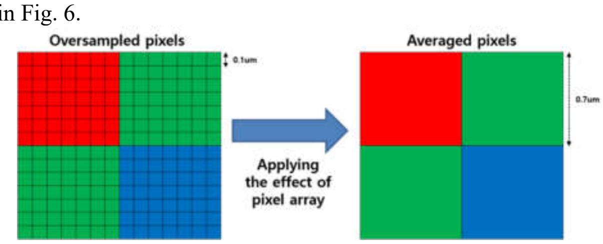

Figure 6. A method to model the effect of a pixel array based on local averaging.

In this method, the convolved image is locally averaged in accordance with a given pixel size. For example, if an object is sampled with 0.1 um spacing, 49 (7x7) image pixels need to be averaged locally when a pixel size is 0.7 um. This scheme of local averaging is the corresponding discretized operation to the continuous one described in the reference [8]. By using convolution and local averaging, a blurred output image, where the effects of a lens and a pixel array are included, is obtained.

Results

PSF estimation results for 0.0F and 0.8F

The performance of the proposed method was verified with a typical mobile lens PSF. The lens PSF was computed from a lens design file for a 108MP (mega pixel) CMOS image sensor with 0.7 um pixel size. For these experiments, lens PSFs for 0.0F (Field) and 0.8F were selected to represent optical characteristics at the center and the outfield of an image, respectively.

Fig. 7 shows PSF estimation results where 0.0F and 0.8F results are displayed in the first and the second row, respectively.

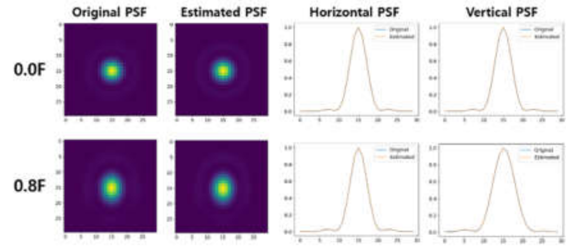

Figure 7. PSF estimation results. The first and the second rows show results for 0.0F and 0.8F, respectively. 2D PSF are compared in the first and the second column, and their horizontal and vertical profiles are compared in the third and the fourth columns, respectively.

Original and estimated 2D PSFs are compared in the first two columns, and their horizontal and vertical profiles are compared in the last two columns. It is seen that estimated PSFs do not show any difference with the original ones. This observation is supported by MSEs between them which are $4.600*10^{-9}$ and $2.915*10^{-9}$ for 0.0F and 0.8F, respectively.

MTF comparison between 0.0F and 0.8F

The approximated PSFs in Fig. 7 were used for image simulation to compare resolutions at 0.0F and 0.8F. For this purpose, a Siemens star chart was selected for an object because it is representative of measuring MTF (Modulation Transfer Function) of a camera system. The star chart was generated with reference to [9] such that each radius has 144 cycles along its circumference. Then it was convolved with the lens PSFs and went through local averaging to apply the effects of a lens and a pixel array as shown in Fig. 5 and Fig. 6. In this simulation, the pixel size was assumed to be 0.7 um.

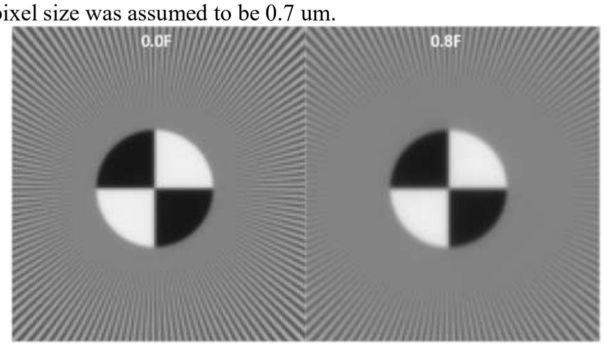

Figure 8. Image comparison between 0.0F and 0.8F. Left and right pictures show Simens star chart images for 0.0F and 0.8F, respectively. In each picture, the distortion patch with black and white colors at the center is used to locate a Simens star chart for MTF measurement.

Fig. 8 displays Siemens star chart images for 0.0F and 0.8F generated from the image simulation in Fig. 5. As shown in this figure, the Siemens star image of 0.8F looks more blurred around the distortion patch than that of 0.0F. This is caused by the inverse relationship between the width of a PSF and a resolution [10]. As seen in Fig. 7, the lens PSF of 0.8F is broader than that of 0.0F especially in the vertical direction, lowering the resolution of 0.8F. In order to compare resolution quantitatively, MTFs were measured from the Siemens star chart images in Fig. 8 by iQ-Analyzer (Image Engineering GmbH & Co. KG).

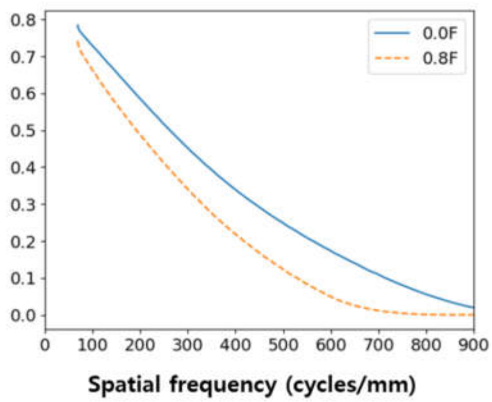

Figure 9. *MTF graphs for 0.0F and 0.8F. The blue solid line and the orange dashed line depict MTF graphs for 0.0F and 0.8F, respectively.*

Fig. 9 describes MTF values along the spatial frequency, showing 0.0F has higher MTF for all frequencies than 0.8F does. The representative MTF values between these fields are summarized in Table1.

	MTF50 [LP/mm]	MTF25 [LP/mm]	MTF10 [LP/mm]
0.0F	262.44	498.61	714.49
0.8F	192.17	371.87	529.15

Table 1. *Representative MTF values of 0.0F and 0.8F*

The simulation results from Fig. 8, Fig. 9, and Table1 demonstrate that the outer field suffers more degradation in resolution than the center, making it important to access the image quality at the outer field for the pre-evaluation of a smartphone camera system

Conclusion

The proposed method estimates a pupil shape to consider optical vignetting so that a PSF at any field can be approximated. Also, it estimates Zernike polynomials coefficients in order to cover not only lens aberrations but also arbitrary spatial sampling.

The method was verified with a lens PSF for a 108MP (mega pixel) CMOS image sensor with 0.7 um pixel size. In addition, along with the estimated lens PSFs, image resolutions of 0.0F and 0.8F were compared by using the image simulation method with local averaging, showing the necessity to evaluate image quality at the outer field.

Therefore, the proposed lens PSF estimation method can be applicable to pre-evaluation of image quality at any fields for a sensor with an arbitrary pixel size.

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Author Biography

Sangmin Kim received his B.S. and M.Sc. all in Electrical Engineering from Sogang University, Seoul, Korea, in 2007 and 2009, respectively. He was awarded the Ph.D. degree in Biomedical Engineering by Texas A&M University, College Station, USA in 2019. Since then, he has worked in Samsung Electronics, focusing on predicting performances of a camera system through simulation. His research interest includes signal and image processing for medical and mobile imaging, and an image simulation based on modeling a camera architecture.

Daekwan Kim received his B.S. in Astrophysics from the University of Calgary in 2008 and M.Sc. in Astrophysics from the University of Toronto in 2010. He is currently working in Samsung Electronics. His primary research interests include pixel level optics and computational imaging.

KilWoo Chung is a Principal Engineer of the Sensor Solution Team at Samsung Electronics. At the intersection of Image sensor, optics, and image signal processing, Dr. Chung's general research interests include a wide range of solutions in visual imaging and mobile camera systems. He was a Visiting Scholar in Electrical Engineering at Stanford University in 2019. He received the M.E. And Ph.D. degree from Stevens Institute of Technology, Hoboken, NJ, in 2007 and 2011, respectively, all in Electrical Engineering.

JoonSeo Yim received his B.S. and Ph.D. degree from Seoul National University (1991) and KAIST (1998) respectively, majored in Electrical and Electronics Engineering. He has worked in Samsung Electronics. His research interests include camera sensor innovation, evolutionary computation and design optimization methodologies