Computational Imaging

PSF engineering for improving a digital imaging

Hajime NAGAHARA †

†Faculty of Information Science and Electrical Engineering, Kyushu University
744, Motooka, Nishiku, Fukuoka, 819-0395, Japan
E-mail: †nagahara@ait.kyushu-u.ac.jp

Abstract A digital camera industry have been developed in a decade and has a lot of applications equipped with PC and mobile phone etc. However, optics and basic principle of image projection does not changed in latest digital camera. Computational imaging is a new research area for developing new imaging strategy for combining optics and processing of the digital imaging. Camera optics, such as lens, aperture, make an image on a sensor. The quality of the image is decided by the optical transfer function called point spread function (PSF). Computation imaging engineers the PSF for imaging and produces improved quality or function of the image after processing. I will introduce some examples of the PSF engineering methods; coded aperture, focus sweep and wavefront coding in computation imaging, and discuss about future of computational imaging combined with sensor technology in this talk.

Keywords: **computational imaging, coded aperture, wavefront coding, focus sweep.**

1. Introduction

A digital camera industry have been developed in a decade and has a lot of applications equipped with PC and mobile phone etc. However, optics and basic principle of image projection does not changed in latest digital camera. Computational imaging is a new research area for developing new imaging strategy for combining optics and processing of the digital imaging. Computation imaging engineers the PSF for imaging and produces improved quality or function of the image after processing. Regular camera optics is usually designed to focus a sharp image on a sensor surface. Point spread function (PSF) of the optics should be minimized and hopefully impulse function. However, we cannot always obtain such an image with ideal PSF in misfocusing situation or the blurred PSF is sometime better than impulse in extended depth from field and depth estimation application. I will introduces how to engineer such better PSFs and its applications.

Figure 1 shows an imaging model of a camera. Caputerd image j is a results of comvolution of latent sharp image i with point spread fuction k and addtion of a noise n. We can also consider this process in frequecy domain as shown in bottom figure of Fig. 1. If we know the frequency resopnse of PSF K, we can estimate the frequency of latent image $\hat{I}$ by deconbolution of J with blurred kernel K. We can obtain the latent image I after applying inverse FFT to $\hat{I}$. However, response of PSF K usually has small values (zero-crossing) as you can see in Fig. 1. The estimation image $\hat{I}$ is unstable or diverged, since the deconvolution is the division of J by K. Hence, we can easy to understand that it is important what kind of PSF the camera optics has. The property of PSF decides the result of the image processing. It is well know that pillbox or Gaussian PSF which is obtained by a regular camera is not good for image deblurring. Computational imaging hacks camera optics and controls the response of PSF for optimizing the image processing result. I will introduce three examples of the PSF engineering methods; coded aperture, wavefront coding, focus sweep for engineering the PSF.

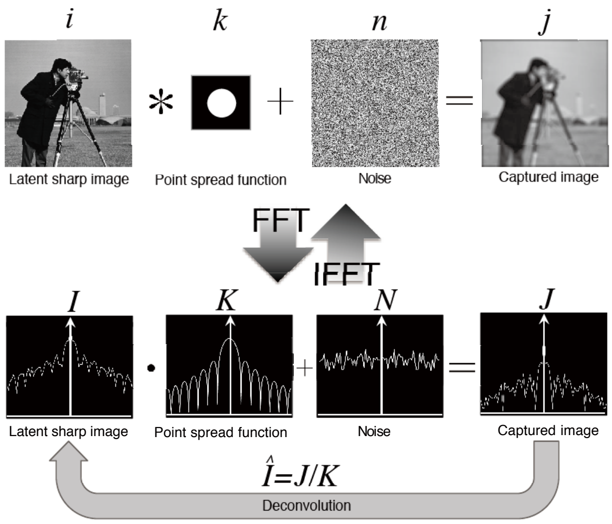

Fig. 1: Imaging model and deblurring by deconvolution

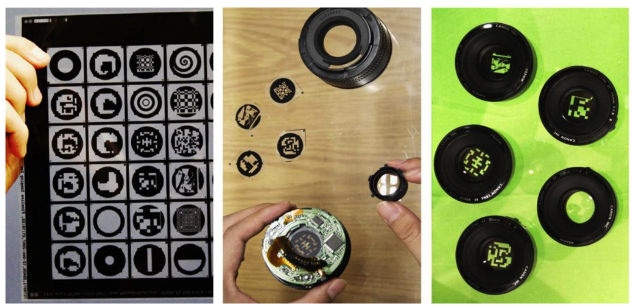

Fig. 2: Coded aperture

2. Coded Aperture

Coded aperture uses patterns of masks as an aperture, while revular cameras has circular shape of the apeture. The coded aperture is implemented by disassembling a lens and inserting a

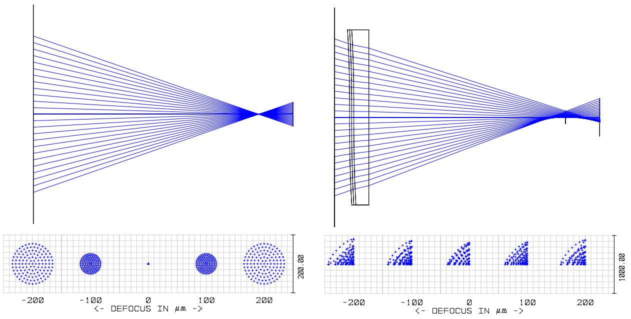

Fig. 3: Wavefront coding

photomask or cut board into apeture position as shown in Fig. 2. We can directly control the PSF by the pattern of the mask, since PSF shape is equal to the aperture shape under an ideal geometric optics. Veeraraghavan et al. [1] find the aperture patten for making the frequency response of PSF as broadband and realize a stable image deblurring. Levin et al. [2] proposed the aperture pattern for depth from defocus. Also Zhou et al. [3] analysed the properties of the patterns and optimize the patterns under the various nose levels. Nagahara et al. [4] developped programmable aperture camera. The camera can freely change the aperture patterns at real time by using liquid crystal display (LCoS) device. We can swich the patterns based on conditions of lighting and sensor noise, and applications; deblurring, depth from defocus, light field image acquisition.

3. Wavefront Coding

Regure camera optics is designed so that all of rays through an aperture are converged into an single point as shown in left figure of Fig. 3. This makes an inplus PSF on focus point and circular pillbox PSF on out focus positions. On the other hand, wave front coding [5, 6] places the special optical element called phase plate on the aperture position. As a result, the rays are not converged into an single point, and formed the traiangular shape PSF as shown in right figure of Fig. 3. The whole of the captured image is blurred by the PSFs, but more supprisingly, the PSF shape is almost similar shapes independent of the focus positions, while regular PSF has depth dependecy. This is a quite big advantage and good feature for deburring, since we can use a single PSF as a known kernel for the deconvolution of the blured image. We can extend depth from field, which is the depth range of the scene to be focused, by the combination of depth invariant PSF coding and deconvolution as post processing.

4. Focus sweep

Focus sweep [7] utilizes lens focusing for engineering PSF. Fig. 4 shows the focus sweep camera and illustrate how to engineer the PSF using focus changes. An image detector of the camera is mounted on a micro actuator. The position of the sensor is changing during an integration time of a single image to be captured. Sizes of the PSF are different on the different position of the sensor position as you can see the right figure of Fig. 3. As a result, we can obtain the integration of the PSFs by using the camera and focus sweeping operation. The integration PSF has depth invariance as similar to the wavefront coding. Focus sweep realizes extended depth from field by combination of focus sweeping and deconvolution as well. Matsui et al. [8] extended this focus sweep to depth from defocus method called half-sweep and realized more stable depth estimation of a scene.

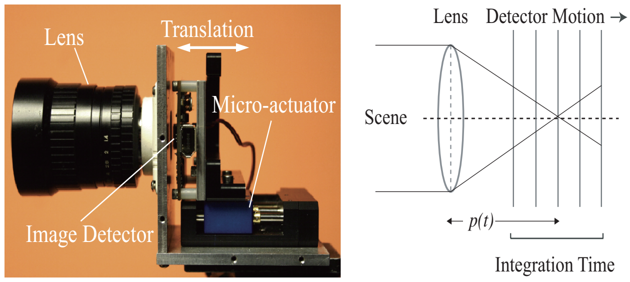

Fig. 4: Focus sweep

5. Conclusion

I introduced computational imaging which combines hacking camera optics and image processing for improving an image deblurring and extending depth from field. This is the new aspect of the imaging and new direction for improving the image processing. I also introduced three different implementations of PSF engineering methods; coded aperture, wavefront coding, and focus sweep.

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