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Half-sweep imaging for depth from defocus

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ABSTRACT

Depth from defocus (DFD) is a technique that restores scene depth based on the amount of defocus blur in the images. DFD usually captures two differently focused images, one near-focused and the other far-focused, and calculates the size of the defocus blur in these images. However, DFD using a regular circular aperture is not sensitive to depth, since the point spread function (PSF) is symmetric and only the radius changes with the depth. In recent years, the coded aperture technique, which uses a special pattern for the aperture to engineer the PSF, has been used to improve the accuracy of DFD estimation. The technique is often used to restore an all-in-focus image and estimate depth in DFD applications. Use of a coded aperture has a disadvantage in terms of image deblurring, since deblurring requires a higher signal-to-noise ratio (SNR) of the captured images. The aperture attenuates incoming light in controlling the PSF and, as a result, decreases the input image SNR. In this paper, we propose a new computational imaging approach for DFD estimation using focus changes during image integration to engineer the PSF. We capture input images with a higher SNR since we can control the PSF with a wide aperture setting unlike with a coded aperture. We confirm the effectiveness of the method through experimental comparisons with conventional DFD and the coded aperture approach.

1. Introduction

There are many methods, referred to as depth from defocus (DFD) techniques [1,2], for estimating scene depth using a single camera. The methods use defocus blur (i.e., blurring that depends on the scene depth) present in the captured images. DFD usually employs a pair of images, one near-focused and the other far-focused, to determine differences in the size of defocus blur resulting from depth differences in the scene. However, the circular shape of the aperture of a regular camera is not beneficial for DFD estimation, since the blurred pattern is not unique for different depths. For more robust DFD estimation, many researchers have investigated coded aperture techniques [3–6], which use special patterns for the camera aperture to control the shape of the point spread function (PSF). Additionally, it is well known that the shape of the PSF directly affects the frequency response of an imaging system, which is described by the optical transfer function in the field of optics. We can select aperture patterns that drastically change the PSF shape in the image domain or its frequency response in the Fourier domain according to scale changes in the PSF due to object depth differences, thereby achieving more accurate DFD estimation in discriminating scene depths. However, the use of a coded aperture attenuates the intensity of captured images, since incident light from the scene is blocked in engineering the PSFs. The attenuation decreases the signal-to-noise ratio (SNR) of the images and limits improvement in DFD estimation.

On the other hand, wavefront coding [7] and a lattice focus lens [8] have been proposed so that incident light is not attenuated. In these cases, special optical elements, called phase plates or lattice lenses, are inserted at the position of the camera aperture to alter the PSFs. Although these methods have an advantage in terms of the image SNR over using a coded aperture, they require specially crafted and expensive optical elements. They are not adaptive to captured scene depths or contexts, since the property of the PSF is fixed and must be predefined before using the camera. It is also difficult to achieve compatibility with regular imaging using a normal circular aperture.

In this paper, we propose a new imaging operation, called half-sweep imaging, for DFD estimation. DFD sometimes ignores the quality of the restored image. We focus on achieving high quality all-in-focus image restoration as well as robust DFD estimation in order to consider visualization of computational photography. The technique, inspired by focus sweeping [9,10], is extended to DFD applications. Half-sweep imaging obtains two images by sweeping the focus during the image exposure time. It has the advantage of a higher SNR for captured images, since we can engineer the image PSFs even if the camera aperture is open. The operation requires continuous changing of the lens focus or sweeping of an image sensor, which is easy to implement since we can utilize the auto-focusing mechanism or an actuator for image stabilization, which current commercial cameras already possess. Moreover, the method is completely compatible with regular imaging and adaptive to scene depth when we stop the sweeping motion or freely adjust the sweeping length and position. Employing the proposed method, we integrate multiple PSFs with different focus settings obtained by focal sweeping to control the frequency responses of imaging PSFs. We split a sweep into half regions to capture images. Thus, two images are obtained for the same scene, but with different PSFs (i.e., transfer functions of imaging). As a result, one of the PSFs and captured images has zero-crossings in its frequency response, which help with depth estimation,

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while the sum of the PSFs has a broadband spectrum, which allows restoration of a better all-in-focus image. This paper is an extended version of the paper [11], which appeared in PSIVT2011.

2. Related work

Many researchers have proposed PSF engineering methods to improve DFD estimation. Surya et al. [12] proposed and implemented a DFD system using two images taken with different circular aperture diameters. Rajagopalan et al. [13] investigated the optimal value of the diameter of a circular aperture for effective DFD. However, the performance of DFD using a circular aperture is unstable owing to its simple symmetric pattern; a special coded pattern must be used for the aperture to improve estimation.

As an early work on coded apertures, Hiura and Matsuyama [3] used three or four pin holes as the apertures of a multiple-focus camera. Three differently focused images captured by the camera were then used to realize robust depth estimation. However, this aperture coding was far from optimal.

Levin et al. [4] proposed using an aperture with a pattern more distinguishable than that of a conventional circular aperture. They defined K–L divergence as a metric for the PSF scale difference due to depth difference and found an optimal pattern for DFD estimation by maximizing the metric. The Fourier spectrum of the pattern contains many zero-crossings, and their positions are displaced when the blur size changes as a result of the depth difference. If we use a different size of PSF for deconvolution, the restored image has severe artifacts due to disagreement with the true PSF spectrum. The artifacts increase the penalty for misrecognizing the depth and improve the stability of DFD estimation. As a result, they allow DFD estimation from a single image, while most commonly used DFD methods require at least two differently focused images to solve ambiguity in the blurred image due to texture. However, the aperture is not suited to restoring an all-in-focus image through deconvolution, since the frequency response of a zero-crossing point is such that we have zero information at that frequency.

Zhou et al. [5,6] proposed a coded aperture pair to restore a high-quality focused image and estimate depth. It is well known that a broadband PSF in the Fourier domain is favorable for blurred-image restoration through deconvolution, since it provides image information for the entire frequency range even though the captured image is blurred [14,15]. However, as mentioned by Levin et al. [4], zero-crossings are favorable for depth estimation. These properties are not compatible with each other when using only a single aperture pattern. A dilemma arises in practical DFD applications in that it is necessary to restore the true texture for accurate depth estimation; however, restoring the texture requires knowledge of the correct depth information. Therefore, Zhou et al. [5,6] proposed the use of a pair of coded apertures that optimize image restoration and depth estimation simultaneously. In the case of their proposed aperture pair, the frequency response of a single PSF has zero-crossings, but the sum of PSFs has a broad band since the PSFs have complementary responses. Nevertheless, the need to replace two lenses with a coded aperture pair remains a difficult problem in image capture. Levin [16] theoretically analyzed the pair of coded aperture patterns for DFD and concluded that Zhou's pair is optimum for DFD and deblurring as well.

A programmable-aperture camera that can quickly switch aperture patterns has been developed [17]. Green et al. [18] proposed a multi-aperture camera that uses special made mirrors. There are examples of implementations that have realized easy capture and increased flexibility for multiple coded apertures. However, PSF engineering using a coded aperture has an intuitive problem: the SNR of the image is lower than that of conventional DFD measurement, since the aperture blocks incident light in controlling the PSF shape. Therefore, there is the limitation that noise in the image destabilizes depth estimation and contaminates the restored image.

Wavefront coding engineers the PSF without blocking incident light unlike in a coded aperture. To apply this method, a special optical element called a phase plate is placed at the position of the camera aperture. The phase plate controls the wavefront of rays according to the positions in the aperture. Dowski et al. [7] proposed a phase plate for DFD estimation whose PSF spectrum has many zero-crossings as in Levin's coded aperture [4]. Levin et al. [8] theoretically analyzed the upper bound of the PSF response for image deblurring and designed an optic, called a lattice focus lens, to realize the PSF. The lens can be used to estimate scene depth and achieve optimal defocus deblurring, since the PSF of the lattice focus lens is depth-variant. Wavefront coding engineers the PSF with an open aperture and realizes image acquisition with a higher SNR. However, the cost of the phase plate is expensive and its property is not adaptive to a scene.

Nagahara et al. [9,10] proposed focus sweep imaging, which moves the focus points during image integration to capture a single image. This method integrates different scales of PSFs to realize PSFs with a broadband frequency response and invariant shapes across the entire scene depth. The authors proposed applying this imaging operation to an extended depth of field by deblurring without any depth estimation or knowledge. The advantages of focal sweep are a higher SNR, compatibility, and flexibility. We can obtain a captured image with a higher SNR since focus sweeping engineers the PSF with an open aperture. Focus sweeping is realized by changing the imager position or using an auto-focus mechanism. We can adaptively change a sweeping region according to the target depth range of the scene. If we terminate the sweeping, a regular image is obtained. However, the PSFs are almost depth invariant and are not applicable to depth estimation. Hasinoff et al. [19] discussed the optimal number of focal stack images across a scene depth for various imaging systems. They applied focal sweep imaging to acquire focal stack (multiple) images, thereby obtaining the best all-in-focus image. Although this has been verified through simulation, the authors did not compare DFD accuracy in their paper.

In this paper, we confirm the effectiveness of our focal sweep approach compared with the conventional method, which uses two images captured with different focal planes, and the coded aperture pairs method [5,6] in terms of the restored all-in-focus image and the accuracy of depth estimation. In all our experiments and analyses, we assumed the target scene to be a static scene, because it is necessary to capture two images of the same target in our method. The static scene assumption is often held in most of the above-mentioned DFD works that use multiple, at least, two input images. The comparative methods used in our analyses, namely, the conventional and coded aperture pair methods, also require two images as input and make the same static scene assumption. Our main contribution in this paper is to reveal how to control and engineer better PSFs to realize robust depth estimation and all-in-focus image restoration.

3. Half-sweep imaging

Focus sweep imaging [9,10] sweeps the focal plane across a scene during the image exposure time. It is achieved by moving the lens or image sensor position along the optical axis. We can manipulate the PSF by controlling the range or speed of the sweep. In this paper, we propose an extension of focal sweep imaging called half-sweep imaging for DFD application. Full-sweep imaging [9,10] sweeps the focal plane across the entire depth of the target scene during the exposure time to realize an extended depth of field. Our half-sweep imaging splits the sweep range into two regions and captures two images corresponding to the front and back halves of the sweeping regions. Consequently, we capture two images with depth-variant blur (PSFs) for DFD estimation, while the original full sweep obtains depth-invariant blur for restoration. In this section, we present the properties and advantages of PSFs in half-sweep imaging.

Fig. 1 shows the projective geometry where the image sensor is at a distance p from a lens with focal length f, and the aperture diameter is a.