

Depth Recovery Using Defocus Blur at Infinity

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Abstract

This paper presents a depth recovery technique based on the maximum defocus blur associated with a camera focus setting. The depth-blur relation is formulated by a mathematical model and verified by defocus calibration. Image intensity histogram analysis is used to identify the blur extent. Different from the existing depth from defocus approaches, our method is capable of depth recovery using a single image, possibly up to scale. Experiments on real scene images have demonstrated the feasibility of the proposed method for depth recovery.

1. Introduction

Depth recovery is one of the essential problems in computer vision research. The objective is to obtain the distance of an object in a scene using the intensity images captured by the cameras. Depending on the number of camera viewpoints required for 3D reconstruction, the most commonly used techniques can be classified as shape from stereo/motion and depth from focus/defocus [2]. The former requires the images captured from multiple viewpoints, while the latter usually involves changing the internal parameter settings of the camera system [8, 6]. Nevertheless, both methods require multiple image captures for depth recovery.

Although stereo or motion based approaches are capable of generating dense depth map of the scene, they suffer from the corresponding problem associated with different viewing positions. The computational cost is also relatively high due to the correspondence searching. In the methods of conventional depth from focus or defocus, multiple images are captured from the same viewpoint with different focus settings of the camera [1]. Some focus measures are applied to derive the best focused image or the amount of defocus, which are then used to compute the distance of the object [9, 4]. Recently, depth recovery from a single image

captured using a coded aperture is also proposed in Computational Photography community [7, 3]. However, it usually requires a good design of the coded pattern and modification of the camera system.

In this paper, we present a theory of depth recovery using the defocus blur obtained from an object placed at an infinite distance from the camera. The relationship between depth and defocus blur of the object is derived as a function of the camera focus range and the observed blur extent at infinity. Through a calibration stage for determining the blur at infinity of a given camera focus range, the depth of an object located at any position can be calculated using the derived depth-blur relation function. Thus, our approach is capable of depth recovery from a single defocus image captured by a calibrated camera, which is not currently available in any algorithms.

Different from the existing techniques for blur identification (e.g. [10, 5]), a novel method based on image intensity histogram analysis is proposed for defocus calibration. In case of the illumination condition change and the blur extent varies, the scale factor is identified by a groundtruth depth-blur relation. It is then used to derive the blur at infinity for other depth computations in the environment. The experimental results have demonstrated the robustness of our blur identification method as well as the feasibility of the proposed depth recovery technique.

2. Image Formation for Defocus Blur

For a thin lens model with focal length f , the relationship between the position of a point P in the scene and the corresponding focused position P' in the image is given by the well known lens formula

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} \quad (1)$$

where p is the distance of the object from the lens on one side, and q is the distance of the image plane from the lens on the other side.

If we consider an object point Q with a distance z from the lens, then Eq. (1) can be rewritten as

$$\frac{1}{z} + \frac{1}{z'} = \frac{1}{f} \quad (2)$$

where z' is the distance of the *virtual* focus position from the lens. Furthermore, the corresponding image point of Q is modeled as a *blur circle* centered at C according to geometric optics. From Eq. (2) and the relation

$$\frac{d}{D} = \frac{q - z'}{z'} \quad (3)$$

the diameter d of the blur circle is given by

$$d = Dq \left(\frac{1}{f} - \frac{1}{z} - \frac{1}{q} \right) \quad (4)$$

where D is the diameter of the lens and q is the distance from the lens to the image plane. Since the distance q is generally unknown, substituting Eq. (4) with Eq. (1) gives

$$d = \frac{Dpf}{p - f} \left(\frac{1}{p} - \frac{1}{z} \right) \quad (5)$$

That is, the size of the blur circle for any scene point located at a distance z from the lens can be calculated by Eq. (5).

It is clear that the blur circle diameter d depends only on the depth z if fixed camera settings of D , f and p are given. In this work, we make several further observations on the imaging model. First, Eq. (5) can be rewritten as

$$d = c - \frac{cp}{z} \quad (6)$$

where

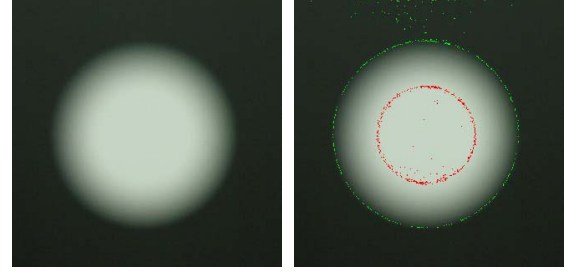
$$c = \frac{Df}{p - f} \quad (7)$$

From Eq. (6), the size of the blur circle is linearly related to inverse distance of the object. Moreover, the blur circle diameter $d \rightarrow 0$ as the distance $z \rightarrow p$, and conversely $d \rightarrow c$ as $z \rightarrow \infty$. In the latter case the constant c given by Eq. (7) represents the maximum diameter of the blur circle when the object approaches infinity.

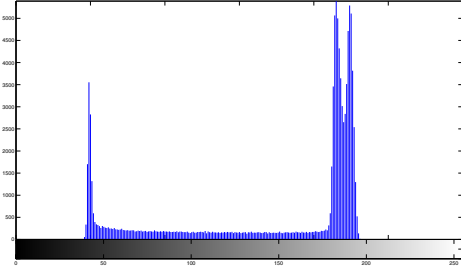
If we rewrite Eq. (6) as a function of d , then the depth z of the object is given by

$$z = \frac{cp}{c - d} \quad (8)$$

In the above equation, the focusing range p corresponding to a fixed lens position at q from the image plane can be obtained from camera focus calibration. Since it is not possible to obtain the accurate camera parameters such as aperture diameter and focal length without an elaborate calibration process. Thus, the constant c will be given by the blur extent estimated from the scene at infinity, instead of the



(a) Original blur image. (b) Blur transition detection.



(c) Graylevel histogram used for blur identification. The valley with almost constant pixel counts corresponds to the blur region between the green and red dots illustrated in Figure 1(b).

Figure 1. Real scene image and graylevel histogram for blur identification. The focus range is set as 300 mm and the object is placed at 5400 mm from the camera.

direct computation using Eq. (7). It is shown in the experiments that the relationship between the object distance and the corresponding blur extent basically follows the curve described by Eq. (6), except for a scale factor given by different values of the constant c .

3. Blur Identification and Modeling

For any focus range setting given by a camera system, the amount of out-of-focus blur in the image is a function of scene distance according to Eq. (1). To establish the relationship between the distance and the defocus blur, a black solid circle pattern is used to identify the blur extent for various object positions. Different from the previous approaches which estimate the blur parameter based on a Gaussian point-spread function [9], the blur extent is measured directly from the defocused black and white image in this work. An image graylevel transition identification technique based on histogram analysis is used to identify the blur extent robustly.

Figure 1 shows the real image captured with certain degree of defocus blur (Figure 1(a)) and the corresponding graylevel histogram (Figure 1(c)). It is clear that two clus-

ters on both sides of the histogram represent the black and white regions in the image. Furthermore, the blur pixels in the images correspond to the histogram areas with intensity values between the two clusters, since the optical defocus process introduces a gradual intensity transition for the black and white image. Let T_1 and T_2 be the upper and lower bounds of the left and right clusters in the histogram, respectively. Then the number of pixels with intensity values below T_1 and T_2 represent the non-white and black regions in the image, respectively. Ideally, these two regions should be bounded by an inner and an outer circle with radii, say R_1 and R_2 , respectively. Thus, the blur extent defined by the intensity values between T_1 and T_2 can be derived from

$$b = \Delta R = R_2 - R_1 = \frac{1}{\sqrt{\pi}}(\sqrt{A_2} - \sqrt{A_1}) \quad (9)$$

where A_1 and A_2 are the number of pixels below thresholds T_1 and T_2 , respectively.

In the above algorithm for blur extent estimation, T_1 and T_2 in the histogram are the only parameters to be identified. These two parameters can be obtained by finding the abrupt pixel count changes for two consecutive graylevels with a given threshold. Since T_1 and T_2 correspond to the upper and lower bounds of the blur regions, they are identified by searching from the middle of the histogram to the left and right, respectively. In practice, due to the acquisition noise and digitization, the image pixels with the intensities T_1 and T_2 might not be perfect circles, as illustrated in Figure 1(b). Thus, a circle fitting algorithm based on Hough transform is used to derive the radii R_1 and R_2 for blur extent computation. It should be noted that the proposed method does not need to identify the centers of the circles explicitly, which is usually not possible for defocused images.

Figure 2 shows the blur extent (in pixel) versus object distance obtained from real images. It shows that the blur extent approaches to an upper limit as the object moves beyond a certain range. The blur extent at infinity and the distance with minimum defocus blur represent the camera constant c and the focus range p as suggested by Eq. (2), respectively. These two parameters can be derived from a least-squares fitting using the equation and the calibrated blur-distance pairs. The red and green marks illustrated in Figure 2 represent the identified blur extents using the above algorithm and the curve fitting results, respectively.

It should be noted that the blur extent also depends on the intensities of the captured image pattern. Thus, there might exist a scale factor λ for the blur extent obtained from a different scene or a different illumination condition. Since the scaling is constant in terms of the scene distance, it can be easily identified by the ratio of the blur extents at infinity for different scenes. The resulting blur-depth relation curve can then be established and used to recover the distance of any blur extent.

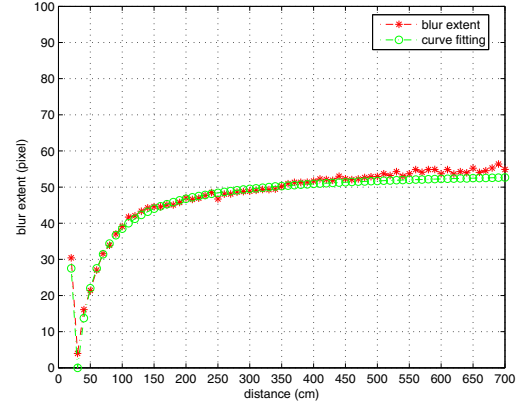


Figure 2. Blur extent vs. object distance. The circles represent the curve fitting result.

Except for the defocus calibration process, it might not always be able to obtain the blur at infinity. In this case, a known groundtruth depth z and the observed blur extent d can be used to derive the constant c by

$$c = \frac{zd}{z - p} \quad (10)$$

where p is the focus range of the camera. This constant can then be plugged into Eq. (8) for depth computation. One should notice, however, even the groundtruth distance or the blur at infinity are not available, it is still possible to recover the relative depth between two object locations based on the initial depth-blur calibration curve.

4. Experimental Results

A planar object pattern placed in front of the camera is used to demonstrate the feasibility of the proposed depth recovery technique. Figure 3 shows the images of the object captured at 700, 800, 900, 1000, 1100, 1200 mm with the camera's focus range set as 300 mm. The blur extents of the images are identified by the variations of intensity profiles on the pattern boundaries. The calibrated blur-distance relation given in Figure 2 is used to estimate the depth of the planar object based on the observed blur extent.

Due to the possible illumination change between the calibration stage and depth recovery experiments, the blur at infinity might differ by a scale factor between these two cases, as described in Section 2. Thus, the observed blur-distance relation at 1200 mm is selected as a groundtruth to derive the blur at infinity c using Eq. (8). The resulting constant c is then used in the same equation to calculate the depths corresponding to all other images based on the observed blur extents.

Table 1 shows the depth recovery results of the images in Figure 3. DI, BL, DE and ER represent the actual distance of the object (in mm), identified blur extent in the image (in pixel), computed depth (in mm), and the error between the actual and estimated distance, respectively. It is seen that all of the errors are less than 3% in the experiment.

5. Conclusion and Future Work

Depth from optical defocus is a method of finding the object distance from a single viewpoint. The existing approaches require two or more images captured by different camera focus settings to calculate the object distance. In this work, we have proposed a depth recovery technique based on the maximum blur extent associated with the optical system. The blur extent for defocus calibration is identified by image histogram analysis. Our method is capable of depth recovery using a single defocused image, possibly up to scale. Experiments have showed that the error is less than 3% provided that a reference groundtruth distance is available.

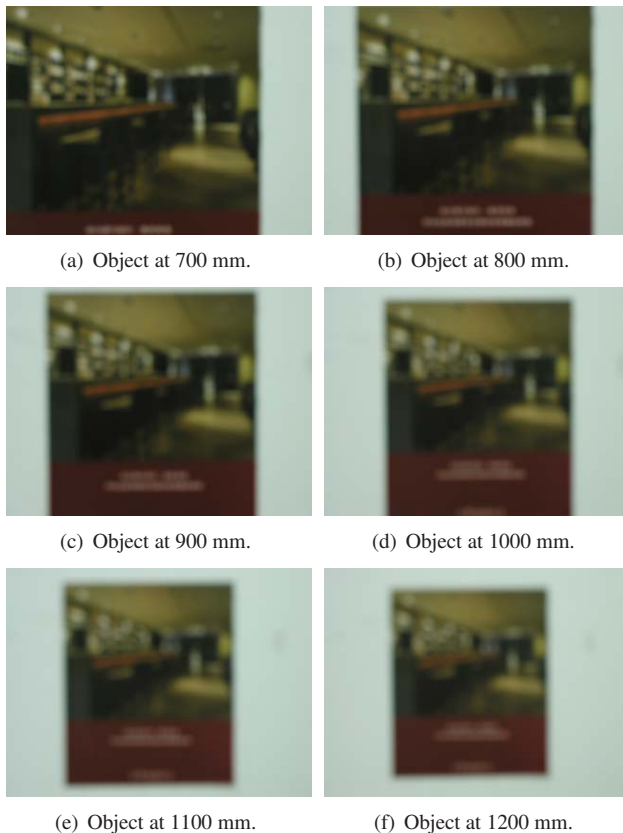


Figure 3. Real scene images used for blur identification and depth recovery.

Table 1. Depth recovery by selecting 1200 mm as groundtruth distance.

DI	700	800	900	1000	1100	1200
BI	40.8	44.2	47.1	50.4	52.2	53.5
DE	700	787	881	1020	1114	1200
ER	0.0%	1.6%	2.0%	2.0%	1.3%	0.0%

In the future, defocus calibration of different camera focus ranges will be considered. By establishing the relationship between the maximum blur extent and the camera focus range, it is possible to recover the object distance associated with any defocused image. The applications of the presented technique to machine inspection and microscopy will be further studied.

Acknowledgments

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