J. Vis. Commun. Image R. 35 (2016) 257–264

Contents lists available at ScienceDirect

J. Vis. Commun. Image R.

journal homepage: www.elsevier.com/locate/jvci

Spatially variant defocus blur map estimation and deblurring from a single image ☆

Xinxin Zhang, Ronggang Wang *, Xiubao Jiang, Wenmin Wang, Wen Gao

Peking University Shenzhen Graduate School, China

ARTICLE INFO

Article history:
Received 7 September 2015
Accepted 5 January 2016
Available online 11 January 2016

Keywords:
Spatially variant blur
Edge information
Defocus image deblurring
Image deblurring
Blur map estimation
Ringing artifacts removal
Image restoration
Non-blind deconvolution

ABSTRACT

In this paper, we propose a single image deblurring algorithm to remove spatially variant defocus blur based on the estimated blur map. Firstly, we estimate the blur map from a single image by utilizing the edge information and *K* nearest neighbors (KNN) matting interpolation. Secondly, the local kernels are derived by segmenting the blur map according to the blur amount of local regions and image contours. Thirdly, we adopt a BM3D-based non-blind deconvolution algorithm to restore the latent image. Finally, ringing artifacts and noise are detected and removed, to obtain a high quality in-focus image. Experimental results on real defocus blurred images demonstrate that our proposed algorithm outperforms some state-of-the-art approaches.

1. Introduction

Conventional camera with low *f*-number is sensitive to defocus and has shallow depth of focus, which often results in defocus blur. For a scene with multiple depth layers, sometimes only one of them can be in-focus during the process of image capturing. This may be done deliberately by cameramen for artistic effect. However, in an out-of-focus image, texture details are blurred or even become invisible. And it also affects the performance of object detection, recognition, tracking and compression [30,31]. Therefore, in many scenarios, out-of-focus should be avoided.

In most cases, multiple depth layers lead to spatially-variant blur effects. The defocus process is analyzed with the thin lens imaging system. As illustrated in Fig. 1, a light ray emitting from a point on the focal plane focuses on a point in the camera sensor. But a light ray emitting from a point behind or in front of the focal plane forms a circle region on the sensor which is called the circle of confusion (CoC) on the sensor. We can see that the larger the distance between the object and the focal plane is, the larger the diameter of CoC becomes. The diameter of CoC characterizes the amount of blur and can be calculated by the similar triangle principle.

The spatially variant defocus deblurring from a single image is a great challenging problem. Firstly, the blur amount is closely related to the depth of field. However, we cannot get the exact depth values from a single image, so we cannot use the thin lens model to solve the deblurring problem. Secondly, the blur amount may change abruptly at object boundaries or change continuously in an image, which are shown in Fig. 2(a) and (b) respectively. On one hand, when blur amount changes abruptly, the image can be split into several regions and the spatially variant deblurring problem can be transformed to local uniform deblurring problem. Whereas, blurred image segmentation and image ringing artifacts along edges are the primary problems to be solved. On the other hand, when the blur amount changes continuously, the depth layers is hard to be separated. Thirdly, as shown in Fig. 2(c), out-of-focus for some regions is made deliberately for artistic effect, and plenty of high-frequency information is lost.

Spatially variant defocus deblurring has attracted much attention in recent years. In order to get more available information for kernel estimation, a group of methods used special camera equipment to capture photographs. Vu et al. [14] estimated depth from a pair of stereoscopic images and exploited the depth-of-field to calculate the diameter of CoC for each depth layer. Levin et al. [9] restored a single refocus blurred image captured from a modified camera. They inserted a patterned occluder within the aperture of the camera lens to create a coded aperture and combined it with a sparse prior so as to improve the accuracy of blur scale estimation. Zhou et al. [17] used a pair of optimized coded apertures to capture

☆ This paper has been recommended for acceptance by M.T. Sun.

* Corresponding author.
E-mail address: rgwang@pkusz.edu.cn (R. Wang).

http://dx.doi.org/10.1016/j.jvcir.2016.01.002
1047-3203/

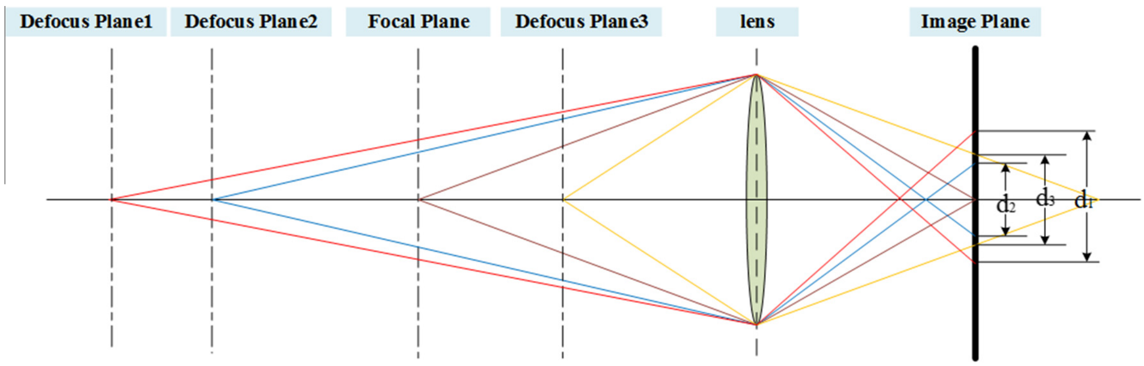

Fig. 1. Thin lens model.

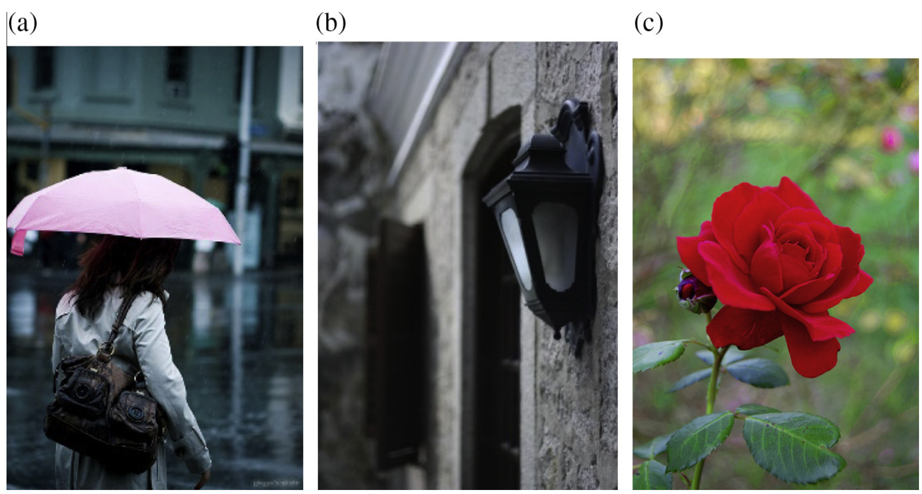

Fig. 2. (a) A defocus image in which blur amount changes abruptly at object boundaries. (b) A defocus image in which blur amount changes continuously. A lot of high frequent information is lost in (c).

photographs and obtained a high quality in-focus image from the two images. Nevertheless, in most cases, for any given photograph, we cannot obtain camera information and the accurate scene depth from a single image without additional information.

In recent years, a variety of methods [1,12,13,18–21,28] have been proposed to recover the defocus map from a single image. They assumed the defocus blur kernel to be a disk model or a Gaussian kernel. Oliveira et al. [11] supposed the defocus blur kernel to be a normalized disk and used the Random-c transform to infer the radius of the disk model. Cheong et al. [4] assumed the blur kernel to be a Gaussian kernel and obtained blur amount from the ratio of local variances of the first- and second-order derivatives. Dorsey et al. [6] proposed a local blur estimation method to handle abrupt blur changes and speed up the existing deconvolution algorithm. However the estimated blur amount is various for nearly every location. Xue and Blu [26] proposed a SURE-based criterion to estimate the blur kernel without relying on the edge information. Shi et al. [22] estimated the just noticeable blur (JNB) by the dictionary method. Similarly, Chan and Nguyen [2] assumed that either the foreground or the background was in focus while the other part suffered uniform defocus blur and applied a matting method to separate them. It got good results for two-layer defocus photographs, but it could not handle multi-depth-layer images. There are a few approaches handling the defocus map effectively, but the reconstructed images still suffer visual artifacts.

Another group of methods estimated blur kernels with a variety of sparse priors. Xu et al. [16] and Li et al. [29] used the Gaussian prior and the l_1 regulation term respectively to constrain blur kernels. Hu et al. [23] extracted depth layers and removed blur by an expectation–maximization (EM) scheme. Though different depth layers could be separated precisely, it depended on user intervention and could not process the blurred image with continuous depth changes well.

In this paper, we propose a multiple-depth-layer based spatially variant defocus deblurring method for a single image. We firstly estimate the blur amount using edge information and apply the KNN matting interpolation method [3] to produce a full blur map. Secondly, the full blur map is segmented with an assumption that the blur is locally uniform. Then we adopt the BM3D-based deconvolution method [5] to restore the input image with local blur kernels to obtain a latent image. However, the restored image may contain ringing artifacts and noise. Finally, these visual artifacts are detected and removed by our proposed method. Experimental results demonstrate the effectiveness of our proposed method over other state-of-the-art approaches.

The paper structure is organized as follows. Section 2 introduces the framework of the proposed work. Section 3 discusses the details of our proposed blur map estimation method. In Section 4, the BM3D-based deconvolution is utilized to restore the latent image and we propose a method to detect and further