

Determination of Stripe Edge Blurring for Depth Sensing

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Abstract—Estimation of the blurring effect is very important for many imaging systems. This letter reports an idea to efficiently and robustly compute the blurring parameter on certain stripe edges. Two formulas are found to determine the degree of imaging blur only by calculating the area sizes under the corresponding profile curves, without the need for deconvolution or transformation over the image. The method can be applied to many applications such as vision sensing of scene depth. A 3-D vision system is taken as an implementation instance.

Index Terms—Computer vision, image processing, point spread function, stripe edge blurring, 3-D reconstruction.

I. INTRODUCTION

VISION is one of the most important senses of living beings and about 80% of human information is obtained by vision. In machine, vision is similarly effective for depth sensing or 3-D reconstruction of the environment or target since we are in a 3-D space [1]. This letter reports an idea of how to formulate an efficient and reliable method for determination of stripe edge blurring from images for vision sensing of scene depth. The method is initially based upon analysis of point spread function (PSF) which describes the response of an imaging system to a source point, which often causes blurring of object edges [2]–[4]. The function defines how a point source would appear if imaged with the device. For a camera or projector, the effects are reflected on the image plane of certain distances [5], [6].

In the literature, the existing contributions have mainly attempted the following methods for image deblurring: 1) image sharpness, 2) peak signal to noise ratio, and 3) blind deconvolution. The first two methods are based upon a global operation and often need a reference image. In most cases, we are usually not able to apply a nonblind deconvolution technology [7], [8]. It is always desired to reliably identify the blurring based upon PSF estimation.

This letter promises to formulate a function for analysis of stripe edge blurring based upon fast PSF computation. It can be used for many purposes in different sensing applications, e.g., 1) to estimate the degree of image blur, for image evaluation and restoration, 2) to find the edge position in subpixel precision, for applications of accurate measurement and super-resolution, and

Manuscript received April 30, 2010; revised July 20, 2010; accepted August 13, 2010. Date of publication September 27, 2010; date of current version November 17, 2010. This work was supported by Alexander von Humboldt Foundation, NSFC (60870002), Zhejiang DST (2010R10006, 2009C21008, Y1090592), NCET, RGC-HK (CityU 117507). The associate editor coordinating the review of this manuscript and approving it for publication was Prof. Kiseon Kim.

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Digital Object Identifier 10.1109/JSEN.2010.2070062

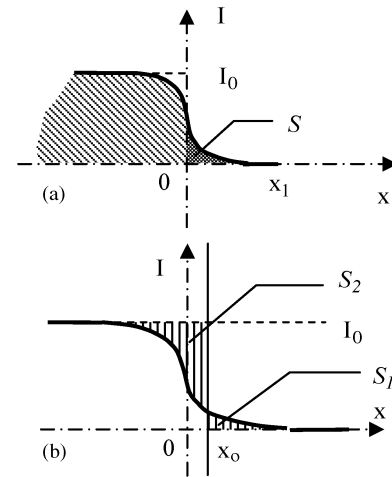


Fig. 1. Irradiant flux of blurred area and its computation model. (a) Profile curve caused by out-of-focus blur on a stripe edge; (b) determination of the blur radius.

3) to determine the out-of-focus displacement, as a cue of scene depth. Although it is a general method, this letter takes the 3-D sensing system as an implementation instance.

II. STRIPE EDGE BLURRING AND DEPTH SENSING

A. Stripe Edge Blurring

In this letter, we concern the blurring in a vision sensing system mostly caused by out-of-focus. If with traditional methods, the blur radius σ in a specific image point has to be computed by numerical integration and Fourier transform of the image intensity curve along the orthogonal direction of the stripe edge. For example, the function $I(x)$ on a stripe edge is illustrated in Fig. 1(a). I_0 is the theoretical or maximum intensity on the stripe edge. It is, of course, very complicated and inefficient.

This letter proposes a formula to determine the blur radius with low computational cost and high precision. With a step light projected on the object surface, the blur radius is proportional to the time rate flow of irradiant light energy in the blurred area, i.e., $\sigma = \sqrt{2\pi}S/I_0$, where S is the area size as illustrated in Fig. 1(a). This can be proved in the following way.

In the 1-D case, consider the illumination whose intensity profile is a step function [Fig. 1(a)]. The brightness on the illuminated scene is the convolution of the PSF and source intensity curve, i.e.,

$$\begin{aligned} I(x) &= \int_{-\infty}^{+\infty} I_0(u)g(x-u)du \\ &= I_0 \int_{-\infty}^0 \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-u)^2}{2\sigma^2}} du \end{aligned}$$

$$\begin{aligned}
&= I_0 \int_{-\infty}^0 \frac{1}{\sqrt{\pi}} e^{-\left(\frac{x-u}{\sqrt{2}\sigma}\right)^2} d\left(\frac{x-u}{\sqrt{2}\sigma}\right) \\
&= \frac{I_0}{\sqrt{\pi}} \int_{\frac{x}{\sqrt{2}\sigma}}^{+\infty} e^{-v^2} dv. \tag{1}
\end{aligned}$$

The blurred illumination function has a shape illustrated in Fig. 1(a). The area size under this blurring curve is the integration of $I(x)$ from 0 to $+\infty$, i.e.,

$$\begin{aligned}
S &= \int_0^{+\infty} I(x) dx = \frac{I_0}{\sqrt{\pi}} \int_0^{+\infty} \int_{\frac{x}{\sqrt{2}\sigma}}^{+\infty} e^{-v^2} dv dx \\
&= \frac{I_0}{\sqrt{\pi}} \int_0^{+\infty} \int_0^{\sqrt{2}\sigma v} e^{-x^2} dx dv \\
&= \frac{I_0}{\sqrt{\pi}} \int_0^{+\infty} \sqrt{2}\sigma v e^{-v^2} dv \\
&= \frac{-I_0\sigma}{\sqrt{2\pi}} \int_0^{+\infty} e^{-v^2} d(-v^2) \\
&= \frac{I_0\sigma}{\sqrt{2\pi}}. \tag{2}
\end{aligned}$$

From (2), we know that the blur radius σ is proportional to the area size under the blurring curve: $\sigma = 2.5066S/I_0$.

With this formula, we only need to compute the area size S for every stripe to determine the blur radius. In a simple way, the edge position (where $x = 0$) is detected firstly by a gradient method, and then S is determined by summing the intensity function from 0 to x_1 . However, even using a subpixel method for the edge detection, errors are still considerable since $I(x)$ changes rapidly around the edge point.

This letter further finds a more accurate method in the sense of energy minimization. As illustrated in Fig. 1(b), we have

$$\begin{aligned}
F_s(x_o) &= S_1(x_o) + S_2(x_o) \\
&= \frac{I_0}{\sqrt{\pi}} \int_{\frac{x_o}{\sqrt{2}\sigma}}^{+\infty} e^{-v^2} dv + I_0 - \frac{I_0}{\sqrt{\pi}} \int_{-\infty}^{\frac{x_o}{\sqrt{2}\sigma}} e^{-v^2} dv. \tag{3}
\end{aligned}$$

It can be prove that the derivative of (3), $F'_s \geq 0$, if $x_o \geq 0$, where “=” holds if and only if $x_o = 0$. The same situation occurs when $x_o \leq 0$. Therefore, at $x_o = 0$, we have $S = \min(F_s)/2$. This means that the same quantity of light energy flows from S_2 to S_1 . Using this method to compute S is stable and it yields high accuracy. Fig. 2 shows an example of the proposed method carried in our experiments. In the system, a pattern of color light stripes is generated by the computer and sent to a digital projector. When the camera captures such an image of illuminated scene, the blur distribution is analyzed according to the formulas proposed in this letter. As the blur radius is proportional to the scene distance, by analysis of every

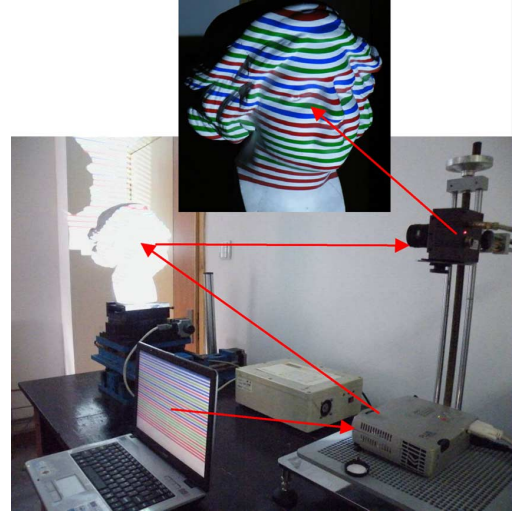


Fig. 2. Instance of applications for depth sensing.

edge points we can calculate the 3-D surface by visual sensing of scene depth.

III. CONCLUSION

This letter proposed a novel method to accurately and efficiently estimate the PSF and blur radius for vision sensing systems. The method mainly includes two formulas, i.e., one for fast determination of stripe edge blurring and the other for finding the accurate solution by an energy minimization function. It does not involve any blind deconvolution or Fourier transform over the whole image. Besides the method can be used to determine the blur degree for image evaluation and restoration, the method is also useful for finding the edge position in subpixel precision and it is, thus, an accurate measurement method in many applications. For instance, since the blur radius can be converted into scene distance, it can be cooperated in a 3-D sensing system as shown in this letter.

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