A Closed Form Self Calibration of One-Dimensional Light Stripe Feature Width Function for Indoor Navigation

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Abstract—Light stripe projection (LSP) is one of useful methods to recognize 3D information in various vision applications. In general, light stripe feature (LSF) is detected by LOG (Laplacian Of Gaussian) operator. Because LOG variance parameter is corresponding to LSF width, improper parameter value causes severe performance degradation. Our previous work proposed a method predicting LSF width by modeling LSF irradiance as 2D Gaussian function [1]. Although the method could enhance the performance of LSF detection, calibration method included time consuming genetic algorithm-based optimization procedure. This paper proposes a closed form calibration method assuming LSF irradiance can be approximated as 1D Gaussian function if field of view (FOV) of light plane projector (LPP) is much wider than that of camera or the LPP generates uniform LSF. Experimental results show that derived function can correctly predict LSF width, and related parameters can be calibrated in a closed form.

I. INTRODUCTION

LIGHT stripe projection (LSP) is a method of acquiring 3D information with light plane projector (LPP) and camera. Light plane generated by LPP makes light stripe feature (LSF) onto object surface. By finding the common solution of the light plane equation and the line equation of a pixel on LSF acquired by camera, the 3D coordinates of a point on object surface corresponding to the pixel on LSF can be measured [2]. If LSP is applied to a situation where the variation of depth to objects is large, like environment and object recognition for intelligent vehicle [3-4] and mobile robot [5-7] in indoor navigation, two problems arise. The first is defocusing problem. LSF detection system should be able to capture focused LSF image on object surfaces located in a wide depth range. The second problem is LSF width variation. An example of LSF width variation when the depths to objects are various is shown in Fig.1.

Jianfeng Li et al. [8] accorded focused plane with the light plane of LSP by inclining image plane based on Scheimpflug condition. The Scheimpflug condition, well known and used in photography for a long time, provides considerable improvement in the depth-of-view without the loss of intensity (the lens aperture can be kept at maximum). S. Chang et al. [9] focused the middle of camera scene depth and applied 2D wavelet transform. Subsequently, by increasing LSF-related components and decreasing other components in frequency domain, they could enhance defocused LSF. While detecting LSF with Canny operator, they applied 2-channel wavelet transform to 1D profile perpendicular to LSF direction. Subsequently, by using the average of low frequency components as high threshold value (HTV) and the average of high frequency components as low threshold value (LTV) of Canny operator, they could enhance LSF detection performance.

The most general LSF detection method is using Laplacian of Gaussian (LOG) assuming that LSF has Gaussian function shape [10-12]. LOG is the same as removing noise by Gaussian filtering and finding a position having the maximum second derivative value. The most important parameter of spatial filtering is window size. Too small a window will amplify high frequency noise and too large a window will ignore the detail of features [13]. Therefore, considering LSF width, it is important to set the size parameter of LOG operator to proper value.

Our previous work, or [1], proposes a method to improve LOG-based LSF detection when depth variation is large as in indoor navigation. It handles the situation when intelligent vehicle or mobile robot uses LSP for navigation in indoor environment, such as underground parking lot. Generally, indoor navigation system uses wide angle lens so that they do not suffer defocusing problem. Furthermore, it is reasonable to assume that indoor wall is homogeneous Lambertian surface. However, the variation of depth to object is very large and the system cannot use background subtraction,
because it should detect LSF while moving. Exceptionally, it is assumed that background subtraction can be used during calibration procedure. The proposed method consisted of five steps: 1) Reconstructing irradiance map of LSF using high dynamic range imaging (HDRi) [14] and then modeling LSF irradiance map as 2D Gaussian function. 2) Approximating parameters of 2D Gaussian function as functions of distance and then deriving LSF width function of distance. 3) Based on the one-to-one relation between y coordinates and distance of LSP, deriving LSF width function of pixel coordinates. 4) Deriving novel LSF detection method by using half of LSF width for specific pixel coordinates as the base length of LOG filtering. In other words, LOG-based LSF detection sets its window size to predicted LSF width. 5) Self calibration procedure for the proposed LOG-based LSF detection method using background subtraction. When the result of the proposed method was compared with the result of normal LOG-based LSF detection that used constant base length, it was observed that the proposed method proved superior to the normal method. Especially, it was confirmed that the optimal base length of normal method for a specific scene depended on the distribution of scene depth, brightness, and object shape. Consequently, it was verified if the proposed method can provide additional and more accurate LSF information to LSP-based indoor navigation system.

The self-calibration procedure was executed using several image pairs captured at underground parking lot. Although some parameters were calculated in closed form, parameter calibration required time consuming genetic algorithm-based optimization. This paper proposes a closed form calibration method when LSF irradiance can be approximated with 1D Gaussian function, i.e. when field of view (FOV) of LPP is much wider than that of camera or the LPP generates uniform LSF.

II. HDRi IRRADIANCE MAP RECONSTRUCTION

The sectional irradiance of LSF was reconstructed from sectional intensity difference captured with different exposure times. 42 image pairs of fine sand-paper target located at distance $d$ were captured changing the exposure time $t$ from 1.6ms to 65.5ms by 1.5ms. A pair of image consisted of two images: on-image captured with LPP on and off-image captured with LPP off. The sectional intensity difference was calculated by subtracting these two images. The exposure $X$ is defined as the product of irradiance $E$ at imager and exposure time $t$. Intensity value $Z$ can be represented by a nonlinear function of exposure $X$ as shown in (1). The nonlinear function $f$ is the composition of the characteristic curve of the imager as well as the nonlinearities introduced by the later processing steps. We can make a reasonable assumption that the function $f$ is monotonically increasing, so its inverse $f^{-1}$ is well defined. Equation (2) can be converted into (3). $i$ is a spatial index over pixels and $j$ indexes over exposure times. The problem is finding $E_i$ and $g$ simultaneously in a least-squared error sense. Because intensity $Z$ is a set of finite number of values, $g$ also can be represented by the same number of values. Therefore, the problem is solved by finding $E_i$ and $g$ minimizing the quadratic objective function (4) [14]. $N$ is the number of pixel locations and $P$ is the number of photographs. $Z_{\text{min}}$ and $Z_{\text{max}}$ represents the least and the greatest pixel values respectively.

\[
X = f^{-1}(Z) \quad (1)
\]
\[
\log f^{-1}(Z_{ij}) = \log E_i + \log t_j \quad (2)
\]
\[
g(Z_{ij}) = \log E_i + \log t_j \quad (3)
\]
\[
\mathcal{O} = \sum_{i=1}^{N} \sum_{j=1}^{P} [g(Z_{ij}) - \log E_i - \log t_j]^2 + \lambda \sum_{i=1}^{N} g'(z)^2 \quad (4)
\]

Fig 2 (a) ~ (c) shows the example of on-image, off-image, and their difference image respectively. In this case, the distance between camera and target is 100cm and the exposure time is 65.5ms. The vertical line in Fig.2(c)
designates the location where intensity difference profiles are sampled. For one difference image, neighboring 10 sectional profiles are sampled. Fig. 2 (d) shows sampled sectional profiles with 42 different exposure times. Every sectional profile remembers the exposure time when captured as a property value. Fig. 2 (e) shows the sectional irradiance profile estimated by HDRi irradiance map reconstruction and Gaussian function corresponding to the estimated parameters. It is noteworthy that the estimated Gaussian parameters are sufficient to describe the sectional irradiance profile. Fig. 2 (f) shows the function \( g \) from intensity \( Z \) to irradiance \( E \) acquired by HDRi irradiance map reconstruction.

III. AMPLITUDE AND STANDARD DEVIATION FUNCTION WITH RESPECT TO DISTANCE

Assuming that sectional irradiance profile \( E \) of light stripe is represented by Gaussian function and its amplitude \( A \) and standard deviation \( \sigma \) is a function of distance \( d \), the sectional irradiance profile \( E \) is a function of \( y \) coordinates and distance \( d \) like (5).

\[
E(y,d) = \frac{A(d)}{\sigma(d) \sqrt{2\pi}} \exp \left( \frac{(y - \mu)^2}{2 \sigma(d)^2} \right)
\]  

(5)

By performing HDRi irradiance map reconstruction while increasing the distance between camera and sand-paper target from 30cm to 5.5m by 10cm, the parameters of Gaussian function corresponding to sectional irradiance profile were estimated. As a result, it was found that amplitude function with respect to distance \( d \), \( A(d) \), was inversely proportional to distance square. While light travels from LPP to sand-paper target, the light is spread in one dimension that the energy is inversely proportional to the distance. A light stripe on Lambertian surface such as fine sand-paper acts like a line light source that while light travels from sand-paper to camera the energy is inversely proportional to distance again. Consequently, \( A(d) \) can be denoted by (6). \( K_{amp} \) is a calibration parameter and can be estimated from measured amplitudes with respect to distance in the sense of least square error. Fig. 3 shows measured amplitude and estimated amplitude function. In the mean time, it was found that standard deviation function with respect to distance \( d \), \( \sigma(d) \), was inversely proportional to distance and had a constant offset. It is supposed to be caused by the minimum sensible irradiance of imaging element, quantization noise, and brightness nonlinear function. Consequently, \( \sigma(d) \) can be denoted by (7). \( a_{std} \) and \( b_{std} \) are calibration parameters and can be estimated from measured standard deviations with respect to distance in the sense of least square error. Fig. 4 shows measured standard deviation and estimated standard deviation function.

\[
A(d) = \frac{K_{amp}}{d^2}
\]  

(6)

\[
\sigma(d) = \frac{a_{std}}{d} + b_{std}
\]  

(7)

IV. LSF WIDTH FUNCTION WITH RESPECT TO DISTANCE

LSF width function with respect to distance \( d \), \( w(d) \), was derived. LSF width is defined as the length of region above intensity threshold \( \theta \) that distinguishes definitely LSF from background. With the value of exposure time \( t \), irradiance threshold \( \theta \) can be calculated from \( \theta \) by (3). The characteristic of imaging element \( g \) was measured during calibration procedure. Because \( w(d) \) is the difference of two \( y \) coordinates where \( E(y,d) \) is equal to \( \theta \), it is defined like (8).

\[
E(y,d) = \frac{A(d)}{\sigma(d) \sqrt{2\pi}} \exp \left( \frac{(y - \mu)^2}{2 \sigma(d)^2} \right) = \theta
\]

\[
|y - d| = \sqrt{2\sigma(d)^2 \left( \ln A(d) - \ln \sigma(d) - \ln \sqrt{2\pi} - \ln \theta \right)}
\]

\[
w(d) = 2 \left[ \frac{a_{wld} + b_{wld}}{d} \right] \left[ \log \frac{K_{amp}}{d^2} - \log \left( \frac{a_{std}}{d} + b_{std} \right) - \log \sqrt{2\pi} - \log \theta \right]
\]  

(8)

It is noticeable that \( w(d) \) is a function depending only on \( d \) and \( \theta \).
In case of LSP, one-to-one relation between $y$ coordinates and distance $d$ is established like (9) [2]. Where, $f$ denotes focal length and $\alpha$ denotes the angle between light plane and camera $y$-axis. $b$ denotes the baseline, the distance between camera and LPP. Therefore, we can derive LSF width function with respect to $y$ coordinates $w(y)$ by substituting the distance function of $y$ coordinates $d(y)$ into $w(d)$ of (8).

$$d(y) = \frac{f \cdot b \cdot \tan \alpha}{f - y \cdot \tan \alpha}$$

(9)

V. SELF CALIBRATION

Self calibration was developed in order to instantly adapt the system to new environment. Self calibration estimates three parameters, i.e. $K_{amp}$, $a_{std}$ and $b_{std}$ of (6) and (7), using four measured LSF widths. LSF widths are measured at two positions with definitely different distance $d$. At each position, two LSF widths are measured with two different irradiance thresholds.

At the first position corresponding to distance $d_1$, $w_{11}$ denotes $w(d_1)$ with irradiance threshold $\theta_1$ and $w_{12}$ denotes $w(d_1)$ with irradiance threshold $\theta_2$. With (8), these can be represented in (10) and (11).

$$w_{11} = 2 \cdot 2 \sigma_1^2 \left\{ \log A_1 - \log \sigma_1 - \log \sqrt{2\pi} - \log \theta_1 \right\}$$

(10)

$$w_{12} = 2 \cdot 2 \sigma_1^2 \left\{ \log A_1 - \log \sigma_1 - \log \sqrt{2\pi} - \log \theta_1 \right\}$$

(11)

By subtracting squared (11) from squared (10) as below, standard deviation at the first position $\sigma_1$ can be estimated like (12).

$$w_{11}^2 - w_{12}^2 = 8 \sigma_1^2 \ln \left( \frac{\theta_1}{\theta_2} \right)$$

$$\sigma_1 = \sqrt{\frac{w_{11}^2 - w_{12}^2}{8 \cdot \log \left( \frac{\theta_1}{\theta_2} \right)}}$$

(12)

At the second position corresponding to distance $d_2$, $w_{21}$ denotes $w(d_2)$ at $d_2$ with $\theta_2$ and $w_{22}$ denotes $w(d_2)$ at $d_2$ with $\theta_3$. By the same manner, standard deviation at the second position $\sigma_2$ can be estimated like (13).

$$\sigma_2 = \sqrt{\frac{w_{22}^2 - w_{21}^2}{8 \cdot \log \left( \frac{\theta_4}{\theta_3} \right)}}$$

(13)

VI. EXPERIMENTAL RESULT

With the configuration of $f=2141$, $b=17\text{cm}$ and $\alpha=82^\circ$, while moving calibrated sand-paper target from 70cm to 5m at intervals of 5cm, we measured the LSF width. The exposure time $t=65.5\text{ms}$ and the intensity threshold $\theta_Z=40$. Fig. 5 shows the examples of detected LSF at various distances and Fig. 6 shows measured LSF width. By (3) with $g$ calibrated to used camera, $\theta_Z$ is converted to $\theta_E=5.0548$. Fig. 6 also shows the calculated LSF width with respect to distance $d$ by (8).

Fig. 7 shows measured LSF width with respect to $y$ coordinates, which is the center of two LSF edge points. By (8) and (9), LSF width function with respect to $y$ coordinates, $w(y)$, can be calculated. Fig. 7 also shows the calculated light stripe width. It is found that the calculated $w(y)$ is very similar...
to measured w(y). Therefore, we can conclude that if we have four parameters, that is \( g, K_{amp}, a_{std} \) and \( b_{std} \), we can predict LSF width with certain intensity threshold at any \( y \) coordinates on image.

By measuring light stripe width at 2m and 3m, self calibration was tested. Two irradiance thresholds for each distance were set to irradiance values corresponding to 20% and 80% of maximum intensity value respectively. Fig. 8(a) is the intensity profile at 2m and Fig. 8(b) is the intensity profile at 3m. In each figure, two dotted lines show two threshold values. Parameter values from self calibration were very similar to parameter values measured with full set of difference images. Table 1 is the comparison of parameter values between two methods. Fig. 9 shows two LSF width graphs with respect to \( y \) coordinates; one uses measured parameter values and the other uses estimated parameter values. It can be observable that self calibrating successfully estimated surface characteristic parameters.

**VII. CONCLUSION**

Our previous work proposed LSF width function-based LSF detection [1]. It was observed that the proposed method successfully predicted LSF width at a certain coordinates \((x,y)\) and LOG-based LSF detector could be improved by using the predicted LSF width as the base of Mexican hat wavelet function [16]. However, the method used genetic algorithm-based self calibration procedure, which could be time consuming and need much computational resources.

This paper deals with a special case of the previous method, that is, when FOV of LPP is much wider than that of camera or LPP generating uniform LSF is used. In such a case, it is shown that irradiance map of LSF could be modeled as 1D Gaussian function and parameters of the Gaussian function can be approximated as functions of distance. Therefore, similar to the previous work, we find out that LSF width function of \( y \) coordinate provides reliable estimate to LSF detector, and enhance the performance. Most of all, in such a case, self calibration can be implemented in a closed form. It means that any system using this method can frequently calibrate tuning parameters without excessive workload, and maintain its performance to a good level.

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