Robust laser stripe extraction for three-dimensional reconstruction based on a cross-structured light sensor

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Cross-structured light sensor architecture for 3D reconstruction was established. An improved center of mass method was proposed for laser stripe extraction. For each initial laser stripe center point, the center of mass method was performed along the normal direction that was calculated using the Hessian matrix. The normal directions can be used to divide the laser stripe center points into two categories. Laser stripe extraction experiments showed that the proposed method is fast and robust. 3D reconstruction of a cylinder was used to analyze reconstruction accuracy, with relative accuracy of less than 0.15 mm. 3D reconstruction of a shoe last showed that cross-structured light sensors can obtain more abundant information than single-structured light sensors. © 2017 Optical Society of America
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1. INTRODUCTION

3D scanning using a structured light sensor is widely applied to the measurement of geometric parameters and 3D reconstruction of object surfaces in many fields, including automatic welding [1], robot navigation [2,3], industrial inspection [4], biomedical treatments [5], and food detection [6,7]. This method has several advantages, which include noncontact measurement, large measurement ranges, high-speed performance, and high accuracy.

Structured light can be divided into two categories: cored-pattern and fixed-pattern light. In this paper, only fixed-pattern light was taken into consideration. All the applications mentioned above used a fixed-pattern structured light sensor with a single linear laser stripe, which is called a single-structured light (SSL) sensor. Additionally, structured light with other types of laser stripe has been used to perform specialized tasks. Usamentiaga et al. [8,9] used dual and multiple laser stripes to estimate and remove the vibrations from final 3D reconstruction results. Zhu et al. [10] used circularly structured light to detect an inner surface. Zhang et al. [11–13] designed a cross-structured light (CSL) sensor to detect weld lines for visual tracking of a wall-climbing robot. Pham et al. [14] proposed a method that combined an accelerometer with a CSL system to estimate the slope of a green on a golf course. CSL sensors are a popular subject of study with researchers.

The accuracy of 3D reconstruction using structured light sensors is largely determined by the extraction of the laser stripe. The robustness, accuracy, and efficiency of the laser stripe extraction process should thus be taken into consideration for 3D reconstruction based on structured light. The most commonly used methods for laser stripe extraction in images are Gaussian approximation, center of mass methods, linear approximation, Blais and Rioux detectors, and parabolic estimators. These five methods displayed similar performance levels within the same range and can achieve high accuracy if the laser’s brightness distribution is normal and the image has low noise [15]. In other works, Haug and Pritschow [16] indicated that the center of mass method may produce relatively good results with high efficiency. However, if the laser line is not directed toward either the vertical or horizontal direction, the intensity distribution along the scanning direction (i.e., horizontal or vertical) is far from the Gaussian distribution and the center of mass method may thus result in inaccurate laser stripe extraction. Therefore, calculation of the normal direction of each point in a laser stripe in an image is essential. Wu et al. [17] used a directional template to calculate the normal direction for laser stripe extraction by the center of mass method. The shortcoming of the method is that only four directions, including the vertical, horizontal, 45° right, and 45° left directions, can be calculated. Sun et al. [18] used a Sobel operator to detect the edge points of the laser stripe and calculated their normal directions. Finally, a closed solution for extraction of a light stripe center was proposed based on spatial...
moment theory. However, the normal direction that was calculated using the Sobel operator is not robust and is easily affected by image noise. Steger [19] proposed a method for laser stripe extraction using a Hessian matrix with a Gaussian kernel that had good directionality, subpixel, accuracy and high robustness. However, this method also had the obvious disadvantage of high computational complexity because of the multiple convolutions required over the whole image. Additionally, Molleda et al. [20] proposed a fast, accurate, and robust method that used an improved split-and-merge approach with various approximation functions, including linear, quadratic, and Akima splines, to extract the laser stripe. If the surface is rough, however, any approximation functions will fail and may result in poor performance. Forest et al. [21] used a finite impulse response filter approach to detect the peak position of the laser stripe that can be applied to various surface types with different optical properties and different noise levels.

While CSL sensors have been used in some applications, there have been few reports of their use in 3D reconstruction. In industrial applications, the light condition is generally complex, and some on-line applications require real-time processing, so the laser stripe extraction process must be both fast and robust. In this paper, an improved center of mass method for laser stripe extraction is proposed for 3D reconstruction using a CSL sensor. The Hessian matrix is used to calculate the normal direction of the laser stripe robustly, and the center of mass method is performed along the normal directions of all calculated points in the laser stripe. The remainder of this paper is organized as follows. In Section 2, the 3D reconstruction system with the CSL sensor is introduced. In Section 3, an improved method for laser stripe extraction is proposed. In Section 4, three experiments on laser stripe extraction and 3D reconstruction are performed, and the results are discussed. Brief conclusions about the work in this paper are given in Section 5.

2. 3D RECONSTRUCTION SYSTEM WITH A CSL SENSOR

A. CSL Sensor Architecture

The architecture of the CSL sensor is shown in Fig. 1 and consists of a color camera, a cross laser projector, and a mobile platform. The camera and the laser projector are fixed together, and the object to be scanned is placed on the mobile platform. The screw is used to change the rotational movement produced by the motor into translation movement, which makes the platform movable along the specified direction.

When the scanning process begins, the object moves continuously, and the object is illuminated using the laser beam from front to back. During scanning, images with the laser stripe projected on the object surface are captured at fixed time intervals. Then, the laser stripes in each image are extracted via the proposed method. Finally, 3D cloud points that represent the object surface can be obtained after the entire surface of the object has been scanned.

B. Advantages of the CSL Sensor

The difference between the CSL sensor and the SSL sensor is that the laser projector can emit double rather than single laser beams. The laser projector for the CSL sensor can emit two mutually perpendicular laser beams, and its projection on the continuous surface is in the form of two crossed lines or curves. 3D reconstruction using SSL sensors is generally performed in horizontal or vertical scanning at a fixed interval. If the scanned object contour is located tangentially or nearly tangentially to the laser line, then part of the contour may be lost. However, that type of contour loss will not occur when the CSL sensor is used.

Figure 2 shows a comparison of the CSL sensor with the SSL sensor during object surface scanning for 3D reconstruction. In the scanning process, the structured light sensor is fixed, while the object can move relative to the sensor. As shown in Fig. 2(a), there are two intersection points, \( P_1 \) and \( P_2 \), between the object contour and the laser line at time \( t_i \), but no intersection occurs at time \( t_{i+1} \). Therefore, contour section \( C_{12} \) will not be scanned, and it may then be lost after 3D reconstruction. Similarly, if the SSL sensor scans the object in the horizontal direction, as shown in Fig. 2(b), another contour section, \( C_{34} \), will also be lost. Therefore, regardless of the scanning direction of the SSL sensor,
there is always a contour section that will be unavoidably lost. Figure 2(c) shows the 3D reconstruction process based on the CSL sensor. As shown in Fig. 2(c), the contour section \( C_{1,2} \) may be lost during scanning with laser line 1, but the loss will be repaired later by laser line 2. Additionally, scanning with the CSL sensor may generate double data that are obtained from the SSL sensor.

C. Calibration of the CSL Sensor

To realize 3D reconstruction based on the CSL sensor, the process parameters, including the camera parameters, the two crossed laser planes, and the direction of motion all need to be calibrated. For simplicity, the global coordinate system is aligned with the camera coordinate system. Therefore, the equations of the two crossed laser planes and the direction of motion are all expressed with respect to the camera coordinate system.

1. Calibration of Camera Parameters

In this paper, the pinhole camera model is expressed as follows:

\[
z_C = K[R|t]P^W = \begin{bmatrix} f_x & 0 & u_0 \\ f_y & 0 & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} P^W,
\]

where \( P^W = [x_W \ y_W \ z_W \ 1]^T \), \( P^C = [x_C \ y_C \ z_C \ 1]^T \), and \( p = [u \ v \ 1]^T \) describe a point \( P \) using homogeneous coordinates with respect to the target coordinate system, the camera coordinate system, and the image coordinate system, respectively; \( K \) is a camera matrix, wherein \((f_x, f_y)\) represents the focal lengths of the camera in the \( u \) and \( v \) directions; \([u_0, v_0]^T\) is the point of the optical axis projected in the image plane, i.e., the principal point of the image; and \( R \) and \( t \) are the rotation matrix and the translation vector, respectively. For simplicity, all vectors and transformation matrices that are not labeled with respect to the reference coordinate system are hereinafter represented with respect to the camera coordinate system.

The lenses do not actually completely obey the ideal pinhole model given by Eq. (1) because of lens distortion. In general, radial distortions and tangential distortions are often used to improve the camera model. The relationship between the ideal point \( p_i = [u_i \ v_i]^T \) and the distorted point \( p_d = [u_d \ v_d]^T \) in the image plane is shown as follows:

\[
\begin{align*}
u_u &= k_1 u_d r_d^2 + k_2 u_d^2 r_d^2 + p_1 (2u_d^2 + r_d^2) + 2p_2 u_d v_d, \\
u_v &= k_1 v_d r_d^2 + k_2 v_d^2 r_d^2 + p_1 (2v_d^2 + r_d^2) + 2p_2 v_d u_d,
\end{align*}
\]

where \( r_d = \sqrt{u_d^2 + v_d^2} \), and \((k_1, k_2)\) and \((p_1, p_2)\) are the radial distortion parameters and tangential distortion parameters, respectively.

All camera parameters can be calibrated using the method proposed by Zhang [22]. First, a minimum of four images of a chessboard target are captured from different viewpoints. Then, all corners of the chessboard are extracted from each image, and their coordinate values can then be calculated based on the size of the chessboard squares. Finally, the camera parameters are calculated using a nonlinear refinement based on the maximum likelihood criterion.

2. Calibration of the Laser Plane

The two laser planes that are emitted by the cross laser projector are derived from the same light source and are split using a special spectroscope. However, the angle between the two laser planes is not exactly 90° because the spectroscope’s processing technology contains errors. Therefore, the two laser planes can be regarded as two stand-alone laser planes when the calibration is performed. A modified calibration method for the laser plane based on the laser intersection line was proposed.

When capturing an image for camera calibration, additional images with crossed laser stripes and without any ambient light were also captured in the same view. In other words, two images with and without the laser stripes are captured.

Figure 3 shows the projection of the laser plane in the image plane. Laser line \( \Pi_L \) is the intersection line of laser plane \( \Pi_L \) and target plane \( \Pi_C \) and is also the intersection line of target plane \( \Pi_C \) and light beam plane \( \Pi_B \). The light beam plane \( \Pi_B \) can be derived from the image line \( I \), which is the projection of \( \Pi_C \) in the image plane.

Because the camera has been calibrated, the transformation \([R|t]\) is known for each of the target planes. The \( z \) axis, which is the same as the normal vector of the target plane, and the origin of the target coordinate system can be expressed as \( n_C = r_3 = \left[ r_{13} \ r_{23} \ r_{33} \right]^T \) and \( P_{TORG} = t = \left[ t_1 \ t_2 \ t_3 \right]^T \), respectively. Here, \( r_3 \) is the third column vector in the matrix \( R \). Therefore, the equation for target plane \( \Pi_C \) can be written as

\[
r_{13}(x - t_1) + r_{23}(y - t_2) + r_{33}(z - t_3) = 0. \tag{3}
\]

Suppose that two laser stripes have been extracted from each image; two line segments that represent the laser lines in the image can be obtained by fitting the line twice. The two end points of the single laser line in the image, \( p_1 = [u_1 \ v_1]^T \) and \( p_2 = [u_2 \ v_2]^T \), are thus known, and the expressions for the two light beams \( O_C P_1 \) and \( O_C P_2 \) can then be expressed as

\[
\begin{align*}
f_x x &= f_y y, \\
u_i - u_0 &= v_i - v_0 = z, & i = 1, 2.
\end{align*}
\]

By combining Eqs. (3) and (4), the two end points \( P_1 \) and \( P_2 \) can then be written as follows:

---

Fig. 3. Projection of the laser plane.
The linear equation for the spatial laser stripe $L_C$ can then be derived from the two end points, $P_1$ and $P_2$:

$$L_C = P_1 + s \cdot D_L,$$

where $s$ is the distance from a point in the line $L_C$ to the first end point $P_1$, and $D_L = [m \ n \ l]^T$ is the normalized direction from $P_1$ to $P_2$. Thus, the parameter $s$ can be expressed as $s_1 = 0$ and $s_2 = L_C$ for the two end points, where $L_C$ is the distance between end points $P_1$ and $P_2$.

Figure 4 shows a demonstration of the laser plane calibration process. All laser lines $L_{C_i}$ from various views are located in the same laser plane, $\Pi_x$, in theory. The equation for laser plane $\Pi_x$ can be expressed as

$$ax + by + cz + d = 0,$$

where $a^2 + b^2 + c^2 = 1$. Therefore, the normal vector $n_L = [a \ b \ c]^T$ of the laser plane is vertical to each of the laser lines. The following equations can then be obtained:

$$D_{Li}^T \cdot n_L = 0, \quad i = 1, 2, \ldots, n,$$

where $n$ is number of laser lines. Equation (8) also can be rewritten as

$$Dn_L = \begin{bmatrix} D_{L1}^T \\ D_{L2}^T \\ \vdots \\ D_{Ln}^T \end{bmatrix} \begin{bmatrix} m_1 & n_1 & l_1 \\ m_2 & n_2 & l_2 \\ \vdots & \vdots & \vdots \\ m_n & n_n & l_n \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = 0. \quad (9)$$

Equation (9) is a set of overdetermined homogeneous linear equations, for which the nonzero solution is the right null space of matrix $D$. Matrix $D$ can be decomposed by singular value decomposition as follows:

$$D = U \Sigma V^T,$$

where matrices $U_{nxn}$ and $V_{3x3}$ are both unit matrices, and matrix $\Sigma$ is a diagonal matrix. The third column vector $v_3$ in matrix $V$ is the solution to Eq. (9), i.e., $n_L = v_3$.

The remaining parameter $d$ in Eq. (7) can be derived by minimizing the square sum distances of all points in each laser line to the laser plane. For a single laser line $L_{C_i}$, the square sum distances of all points from $P_{1i}$ to $P_{2i}$ to the laser plane can be expressed as follows:

$$SSD_i = \int_{t_1}^{t_2} (ax + by + cz + d)^2 \, ds,$$

where

$$\begin{cases} x = m_i \cdot s + x_{1i} \\ y = n_i \cdot s + y_{1i} \\ z = l_i \cdot s + z_{1i} \end{cases}$$

and $P_{1i} = [x_{1i}, y_{1i}, z_{1i}]^T$ is the first end point of the $i$th laser line. Therefore, the parameter $d$ can be derived from the following equation:

$$d = \arg \min \left( \sum_{i=1}^{n} SSD_i \right) \Rightarrow \frac{\partial \sum_{i=1}^{n} SSD_i}{\partial d} = 0. \quad (12)$$

Because Eq. (11) is a quadratic equation about $d$, Eq. (12) is a linear equation about $d$. Thus, by solving this equation, $d$ can then be written as

$$d = \frac{\sum_{i=0}^{n} (am_i + bn_i + c\ell_i)^{2} + (ax_{1i} + by_{1i} + cz_{1i})s_{2i}}{\sum_{i=0}^{n} s_{2i}}. \quad (13)$$

3. Calibration of the Motion Direction

The chessboard target is also used to calibrate the direction of motion of the mobile platform. The target plane is fixed on the moving platform, and images of the chessboard target are captured at regular intervals. Because the intrinsic parameter matrix $K$ is known, the transform matrix $[R_i | t_i]$ of the target plane at the $i$th instant can be estimated. Since the movement of the chessboard target is purely translational, the rotation matrix $R_i$ is in theory constant, while the translation vector $t_i$ represents the origin of the target coordinate system. Therefore, change in the translation vector $t$ describes the movement of the chessboard target. The least squares method is used to perform linear fitting processes for all $t_i$, and the resulting direction of the fitted line is the direction of motion $v_m$ of the mobile platform.

3. EXTRACTION OF TWO CROSSED LASER STRIPES

Because of the diffuse reflection of the laser beam, the projection of the laser beam in the image is not a single pixel width, and it is necessary to extract the center of the laser stripe. The center of mass method for laser stripe extraction is effective, simple, and accurate, but it lacks directionality. The Hessian matrix method offers good directionality and high accuracy but suffers from low efficiency and implementation difficulty in online measurements. Based on these two methods, an improved algorithm that combines the center of mass method and the Hessian matrix for laser stripe extraction is proposed. The Hessian matrix is used to calculate the direction of the point in the image. The following four steps are used to extract the laser stripe in this method:

A. Extraction of the initial center points of the laser stripes;
B. Calculation of the normal vector for each initial center point;

![Fig. 4. Demonstration of the laser plane calibration process.](image-url)
C. Refinement of the laser stripe in subpixels based on the center of mass method along the normal direction;

D. Classification of all the center points into two laser stripes based on their normal directions.

A. Extraction of the Initial Laser Stripe Center

To avoid a global search for the laser stripe center within the entire image and to increase the extraction efficiency, the initial center points of the laser stripe must be extracted in advance. Since the brightness of an image with laser stripe is mostly low, except in laser projection region, the bright foreground containing a whole laser stripe can be effectively segmented using an adaptive thresholding algorithm proposed by Otsu [23]. The resultant image can be treated as a mask image $M$. Initial center points of the laser stripe can be detected by thinning algorithms [24]. Thinning is a morphological operation that is used to remove selected foreground pixels and generates a skeleton. The obtained skeleton is very close to the real laser stripe and can be regard as the initial laser stripe.

B. Calculation of the Normal Direction of the Center Point

In theory, the center point is the brightest point along the cross section of the laser stripe, and thus its second derivative should reach a maximum. The Hessian matrix can be used to calculate the normal direction of the laser stripe center. The Hessian matrix is obtained through a second-order Gaussian convolution, as shown in the following expression:

$$H = \left[ \begin{array}{c}
\frac{\partial^2 g(u,v)}{\partial u^2} & \frac{\partial^2 g(u,v)}{\partial u \partial v} \\
\frac{\partial^2 g(u,v)}{\partial u \partial v} & \frac{\partial^2 g(u,v)}{\partial v^2}
\end{array} \right] \otimes I(u,v) = \begin{bmatrix} I_{uu} & I_{uv} \\
I_{uv} & I_{vv} \end{bmatrix},$$

(14)

where $g(u,v)$ is a two-dimensional Gaussian equation, with a size that is dependent on the image noise, $I(u,v)$ is the brightness at point $p = [u \ v]^T$ in the image, and the symbol $\otimes$ denotes a convolution operation. The normal direction of point $p$ can then be obtained by calculating the eigenvalues and eigenvectors of its Hessian matrix $H$. If $\lambda_1$ and $\lambda_2$, which satisfy the relation $|\lambda_1| > |\lambda_2|$, are two eigenvalues with matrix $H$ and $e_1$ and $e_2$ are two corresponding eigenvectors, then the eigenvector $e_1$ is the normal direction of the point.

C. Refinement of the Subpixel Laser Stripe Center

After the initial center point $p_{i}^*$, and its normal direction $e_i$, have been obtained, the point set $p_i^k = [u_i^k \ v_i^k]^T$ in the cross section of the laser stripe along the normal direction can be obtained as follows:

$$p_i^k = p_{i}^* + k \cdot e_i, \quad k = -k_1, \ldots, -1, 0, 1, \ldots, k_2,$$

(15)

where $k_1$ and $k_2$ are the widths of the laser stripe in two opposite directions along the normal direction. Here, $k_1$ and $k_2$ can be derived using the restriction that all points $p_i^k$ ($k = -k_1, \ldots, k_2$) must also be located in the mask image $M$, i.e., $p_i^k \in M$. Because the point $p_i^*$ is a subpixel, its brightness values $I(p_i^*)$ must be calculated via bilinear interpolation. Therefore, the refined center point $p_i = [u_i \ v_i]^T$ of the laser stripe can be calculated using the center of mass method in the form of the following equations:

$$p_i = \begin{bmatrix} u_i \\
v_i \end{bmatrix} = \left[ \begin{array}{c}
\sum_{k=-k_1}^{k_2} f(p_i^k)u_i^k / \sum_{k=-k_1}^{k_2} f(p_i^k) \\
\sum_{k=-k_1}^{k_2} f(p_i^k)v_i^k / \sum_{k=-k_1}^{k_2} f(p_i^k)
\end{array} \right].$$

(16)

D. Classification of the Laser Stripe

There are two laser stripes in each image, and thus all center points obtained must be divided into two categories, designated stripe-1 and stripe-2. The two laser planes that were emitted by the cross laser projector are orthogonal, which means that the normal directions of the two laser stripes in the image are also approximately orthogonal. Therefore, all center points can be distinguished based on their normal directions. In general, the initial center point $p_{i}^*$ is very close to the refined center point $p_i$, and thus the normal direction of $p_i$ can be represented by the estimated normal direction $e_i$.

The normal direction $e_i$ and its inverse $-e_i$ cannot be distinguished. In this paper, the $y$ value of the normal direction is set to be positive, i.e., the normal direction is $e_i = [e_{ci} \ e_{si}]^T$ if $e_{ci} \geq 0$; otherwise, $-e_i$ is replaced. The normal angle is thus located in the range $[0, 180]$. The frequency counts are calculated for all normal angles, and a histogram of the angle distribution can then be obtained. Because all center points are derived from the two laser stripes, their angles can also be divided into two classes. The angle threshold for the segmentation value can be obtained easily by simply maximizing the interclass variance [23]. For a single class, the mean and standard deviation of the angle are calculated, and any angles that are far from the mean value will be removed.

E. 3D Point Calculation

Using a combination of Eqs. (1) and (7), a point $p = [u \ v]^T$ in the image can be recovered to a corresponding 3D point $P = [x \ y \ z]^T$ by solving the following equations:

$$\begin{bmatrix}
x \\
y \\
z \end{bmatrix} = \begin{bmatrix} f_x & 0 & u_0 \\
0 & f_y & v_0 \\
1 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\
y \\
z \end{bmatrix},$$

(17)

During continuous scanning of a surface using structured light, the actual recovered 3D points should be added to the current movement vector relative to the starting position. The actual coordinates of the recovered points can then be expressed as follows:

$$P_t = P + s_i \mathbf{v}_{in},$$

(18)

where $P$ is calculated from Eq. (17), $\mathbf{v}_{in}$ is the unit vector of the direction of motion, and $s_i$ is the distance between the starting position and the current position of the mobile platform.

4. EXPERIMENTS AND DISCUSSION

A. Calibration of the CSL System

The prototype CSL sensor for 3D reconstruction is shown in Fig. 5. The color camera Grasshopper GRAS-03k2c, which was manufactured by the PointGrey Corporation, Richmond, British Columbia, Canada, with 640 x 480 pixel resolution and 5 mm lens focal length, was used. The laser projector power was 5 mW, and the wavelength of the laser light as 650 nm (red light). The computer used for data processing contained a 2.8 GHz CPU and 4 GB of RAM. The programming
language C++ was utilized to perform the proposed method, wherein, some data structures and common image process algorithms from OpenCV were also used.

Nine target images with or without laser stripes were captured. All calibrated CSL sensor parameters are listed in Table 1. The mean errors $e_p$ that were generated from fitting of the laser planes were calculated using the following equation:

$$e_p = \frac{1}{9} \sum_{i=1}^{9} \sqrt{SSD_i / f_{s2}}. \quad (19)$$

The error results were 0.039 mm and 0.050 mm for the two different laser planes. From Table 1, the angle between the two laser planes can be calculated; the result is 90.067°, which indicates that the two laser planes are not exactly perpendicular.

### B. Laser Stripe Extraction

Because the laser light is red, a red channel image is used here. Figure 6 shows the procedure for extraction of the laser stripe. An image of the original laser stripe is shown in Fig. 6(a), and the initial center points of the laser stripe are shown in Fig. 6(b). Figure 6(c) shows the refined laser stripe center points that were extracted using the proposed method.

A simplified Hessian matrix method that computes the Hessian matrix for the initial laser stripe center point only, and not for the entire image, is used for comparison with the proposed method. The simplified Hessian matrix method is used for comparison here because the original Hessian matrix method [19] is too time-consuming to run in real time. Figures 7(a) and 7(b) show the laser stripes that were extracted by the proposed method and by the simplified Hessian matrix method, respectively. From the results in Fig. 7, it can be concluded that the method proposed in this paper obviously produces better results than the simplified Hessian matrix. Some of the laser stripe center points that were obtained by the simplified Hessian matrix, as shown in the circular area marked in the image, obviously deviated from the real positions. Because the brightness along the normal section of the laser stripe is disturbed by the image noise and thus loses its continuity, the solution to the zero position problem of the first-order derivative may be to overcome this inaccuracy. Additionally, the position of the initial center and its normal direction also affect the extraction of the center of the laser stripe when using the simplified Hessian matrix. The proposed method considers all highlighted pixels in the cross section along the normal direction, and thus it reduces the effects of noise disturbances and the influence of the initial centers to a great extent.

Figure 8 shows the results of calculations of the normal direction. In each image, normal directions represented by the arrows from the edges of the laser stripe were calculated using a Sobel operator, while those from the center of the laser stripe were calculated using the Hessian matrix. In Fig. 8(a), the

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**Table 1. Parameters for the CSL Sensor After Calibration**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Physical Meaning</th>
<th>Values</th>
</tr>
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<tr>
<td>$f_x, f_y$</td>
<td>focal length</td>
<td>(685.47, 682.74)</td>
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<tr>
<td>$u_0, v_0$</td>
<td>principal point</td>
<td>(314.72, 187.79)</td>
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<td>$k_1, k_2, p_1, p_2$</td>
<td>distortion parameters</td>
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<td>$a_1, b_1, c_1, d_1$</td>
<td>laser plane $\Pi_1$</td>
<td>(0.662, 0.596, -0.454, 137.881)</td>
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<tr>
<td>$a_2, b_2, c_2, d_2$</td>
<td>laser plane $\Pi_2$</td>
<td>(0.742, -0.602, 0.295, -114.268)</td>
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<tr>
<td>$v_m$</td>
<td>motion direction</td>
<td>(-0.0476, 0.949, -0.313)</td>
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</table>
image contains no noise, while the image shown in Fig. 8(b) contains added normal noise with a zero mean and 10 standard deviations. Comparison of Fig. 8(a) with Fig. 8(b) shows that the normal directions that were calculated using the Hessian matrix are stable under noisy conditions, but those that were calculated using the Sobel operator are easily influenced by the noise disturbances, particularly in regions where the quality of the laser stripe is poor. Statistics on the angular deviations from the normal directions between the noise-free image and the noise-added image are shown in Table 2. It can be concluded that the normal directions that were calculated using the Hessian matrix are more accurate than those calculated using the Sobel operator in a noisy environment. Therefore, the proposed method is more robust than the method based on use of the Sobel operator.

Table 2. Angle Deviations from Normal Directions

<table>
<thead>
<tr>
<th>Method</th>
<th>Number of Points</th>
<th>Mean/Degree</th>
<th>Maximum/Degree</th>
<th>Std./Degree</th>
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<tbody>
<tr>
<td>Hessian</td>
<td>680</td>
<td>0.74</td>
<td>12.899</td>
<td>1.025</td>
</tr>
<tr>
<td>Sobel</td>
<td>1564</td>
<td>6.620</td>
<td>79.911</td>
<td>6.847</td>
</tr>
</tbody>
</table>

Figure 9 shows the frequency counts of the angles of the normal directions. The figure shows that the normal directions from the two laser stripes can easily be divided into two categories. In this sample, the angle threshold is equal to 89°.

C. Reconstruction of the Cylinder

A known cylinder with a diameter of 80 mm was reconstructed by the proposed method and the reconstruction accuracy was estimated. During the process of 3D scanning with the CSL sensor, the speed of the moving platform is 8.0 mm/s, and the frame rate of image capture is 15 fps. Two sets of points, \(S_1\) and \(S_2\), around the cylindrical surface were recovered, as shown in Fig. 10. \(S_1\) and \(S_2\) were generated from the two laser stripes. The union of these two point sets is called \(S_{All}\). Three cylinders, denoted by \(C_1\), \(C_2\), and \(C_{All}\), were then fitted from the three point sets \(S_1\), \(S_2\), and \(S_{All}\), respectively. In general, a cylinder requires seven parameters to be described fully, where three parameters denote the direction of its axis, three parameters provide a point in axis, and the remaining parameter denotes the diameter. All parameters for the three fitted cylinders are shown in Table 3.

As shown in Table 3, the three reconstructed cylinders are not identical; the measured diameters are smaller than the real values, and not all axes coincide. The angle and the distance between the two axes of cylinders \(C_1\) and \(C_2\) are 0.0296° and 0.0253 mm, respectively. There are two main reasons why these three cylinders are not identical:

1. Approximately 1/3 of the cylinder surface was recovered, so the fitted cylinder is not highly accurate, particularly in terms of its diameter, because of the incomplete data used.
2. The two sets of recovered points \(S_1\) and \(S_2\) do not coincide completely because of errors generated in sensor calibration and the laser extraction process.

Fifty images containing laser stripes were used to test the efficiency of the proposed method. The mean time consumption for extraction of the laser stripe was 34.164 ms, with a maximum value of 46.346 ms, which indicates that the proposed method can be used in real-time measurement applications.

Table 3. Parameters of Fitted Cylinders

<table>
<thead>
<tr>
<th>No.</th>
<th>Axial Direction</th>
<th>Point in Axis</th>
<th>D/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_1)</td>
<td>(-0.0023, -0.9453, 0.3262)</td>
<td>(15.78, 130.20, 254.94)</td>
<td>78.94</td>
</tr>
<tr>
<td>(C_2)</td>
<td>(-0.0027, -0.9453, 0.3261)</td>
<td>(15.95, 104.60, 263.86)</td>
<td>79.06</td>
</tr>
<tr>
<td>(C_{All})</td>
<td>(-0.0024, -0.9453, 0.3262)</td>
<td>(15.83, 101.25, 265.12)</td>
<td>79.27</td>
</tr>
</tbody>
</table>
To test whether or not the two sets of recovered points coincide well, the errors, which are defined as the distances from the recovered points to the reconstructed cylinder surface, must be calculated. Figure 11 shows two distribution maps for the errors in the two cylindrical surfaces $C_1$ and $C_2$. In the figure, the horizontal axis is the angle of circumference, while the vertical axis is the cylinder height. As shown in Fig. 11, most of the major absolute errors are located at the two sides and in the center region. There are three main reasons for this behavior, which are described as follows:

1. In the center region where the two laser stripes overlap, the extracted center points of the laser stripes are not all correct.
2. In common laser projectors, the energy along the laser stripe is not uniform, in that the energy is higher closer to the center, meaning that the laser intensity projected on the edge is not high, and this leads to inaccurate extraction of the laser stripe center.
3. The curvature of the projective laser curve from the laser plane in the cylindrical surface is not consistent, and the values at the two sides are larger than that at the center. Higher curvature and lower resolution means that the resolution and accuracy of the laser stripes at the two sides are lower than the corresponding values at the center. Therefore, the errors in the two side regions are relatively high.

Mathematical statistics are used to determine the magnitudes of these errors. The histograms for the errors from fitting of the cylinder with point sets $S_1$, $S_2$, and $S_{All}$ are shown in Fig. 12, where the continuous plot denotes the fitted Gaussian distribution. The results indicate that all errors follow an approximate Gaussian distribution with zero mean and low standard deviation, which means that the error of each recovered point is affected by the white noise that is generated in the laser stripe extraction process. All statistical parameters, including the mean and the standard deviation of each of the three sets of errors that were generated from the three sets of points are shown in Table 4.

As Table 4 shows, the means of the three sets of errors are all nearly zero, and the two standard deviations of the errors generated by fitting cylinders $C_1$ and $C_2$ are both less than 0.15 mm. Additionally, the errors follow the Gaussian distribution well with a zero mean. However, after all recovered points are combined, the standard deviation of the errors increases somewhat. The main reason for this is that the two recovered point sets, $S_1$ and $S_2$, are not completely coincident. Fortunately, the offset between $S_1$ and $S_2$ is small, and the errors from the fitting points set $S_{All}$ still follow a Gaussian distribution. This indicates that the accuracy of the point sets that were obtained by the CSL sensor using the proposed method remains still relatively high and thus can meet the requirements of general applications.

D. Reconstruction of a Shoe Last

The bottom surface of a shoe last, as shown in Fig. 13, is reconstructed to verify the practicality of the proposed method. The cloud of all 3D points of the bottom surface of the shoe last
E. Discussion

As shown in Fig. 7, the center points of the laser stripe in the crossed region are incorrect. This is because the brightness of the cross overlap is composed of the overlay of the two laser stripes, and the brightness distribution in the normal section is thus not a single peak. Consequently, application of the proposed method will result in the laser stripe centers deviating from their real positions in the cross region. Therefore, all incorrect center points should be removed because of the lack of continuity in the normal direction.

It is difficult to measure the absolute accuracy of the 3D reconstruction process using the CSL sensor with the proposed method because it is difficult to measure the real position of each recovered point with respect to the camera coordinate system. The statistical results for the errors shown in Table 4 can be regarded as the relative 3D reconstruction accuracy results. The root mean square (RMS) values of these errors are approximately equal to their standard deviations because the mean value is close to zero. While the RMS of the errors is less than 0.15 mm, more than 10% of the errors exceed 0.2 mm. In other words, the relative accuracy is not very high. The following four factors influence the process accuracy:

1. The distance between the laser projector and the camera, where greater separation leads to higher accuracy.
2. The angle between the laser beam and the X direction, where a larger angle leads to higher accuracy.
3. The distance from the image sensor (bigger Z), where greater distance leads to lower accuracy.
4. The accuracy of laser stripe extraction.

The first three factors are fixed for a given CSL sensor and object. However, the fourth factor is dependent on the laser projector and the method used for laser stripe extraction. In our experiments, the laser projector is cheap and is not of an industrial grade. The light along the laser line is not uniform, and the light becomes dimmer with increasing distance from the center. Therefore, the accuracy of laser stripe extraction has the greatest influence on the accuracy overall. A high-performance laser projector should thus be used for high-precision applications.

The CSL sensor constructed in this work can be used to scan an object surface to obtain its 3D point cloud, which is used as the basis for inverse engineering. Additionally, the CSL sensor can also be mounted on top of an assembly line to obtain target surface information and can extract robotic trajectories for operations such as welding, spraying, and painting.

5. CONCLUSIONS

A robust laser stripe extraction method for 3D reconstruction based on the use of a CSL sensor was proposed in this work. The method was based on the use of the center of mass method, which was performed along the normal direction rather than along a row or column. The normal direction at the initial center point of the laser stripe was calculated using a Hessian matrix, which is more robust than the Sobel operator. The proposed laser stripe extraction method can run in real time and provides a better performance than the simplified Hessian matrix method. An experimental 3D reconstruction of a cylinder was performed using the CSL sensor. The results show that the RMS of the reconstruction error is less than 0.15 mm, which illustrates that the accuracy of the proposed CSL sensor method is relatively high. Another experiment was performed to obtain the 3D point cloud of the bottom surface of a shoe last, and the results indicated that scanning based on the CSL sensor can recover the required information more completely than that based on the SSL sensor.

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