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Sub-pixel extraction of laser stripe and its application in laser plane calibration

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Abstract: For calibrating the laser plane to implement 3D shape measurement, an algorithm for extracting the laser stripe with sub-pixel accuracy is proposed. The proposed algorithm mainly consists of two stages: two-side edge detection and center line extraction. First, the two-side edge of laser stripe is detected using the principal component angle-based progressive probabilistic Hough transform and its width is calculated through the distance between these two edges. Secondly, the center line of laser strip is extracted with 2D Taylor expansion at a sub-pixel level and the laser plane is calibrated with the 3D reconstructed coordinates from the extracted 2D sub-pixel ones. Experimental results demonstrate that the proposed method can not only extract the laser stripe at a high speed, nearly average 78 ms/frame, but also calibrate the coplanar laser stripes at a low error, limited to 0. 3 mm. The proposed algorithm can satisfy the system requirement of two-side edge detection and center line extraction, and rapid speed, high precision, as well as strong anti-jamming.

Key words: sub-pixel extraction; center line extraction; laser plane calibration; progressive probabilistic Hough transform (PPHT); principal component (PC) angle; 2D Taylor expansion

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Linear feature, distinguished from edge and line, is formed with two-side edges and is more complex than the line of varying width. The extraction of linear feature in digital images has applications in the fields of remote sensing and medical analysis, which can be used for extracting rivers or roads from satellite images[1-3] and blood vessels or nerves from medical images[4-5]. Meanwhile, it is also adopted to extract the laser stripe for 3D shape measurement[6-7], where an object can be scanned by a 3D measurement system comprised of laser and camera.

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The major goal of extracting a linear feature is to develop a low-level algorithm to extract its width and center line from 2D images[8]. In general, the resolution of images is often quite low compared to the precision requirements of 3D measurement, so it is necessary to obtain the extracted linear feature with sub-pixel resolution. For this purpose, the sub-pixel extraction technique should be used to acquire high accuracy position information in terms of its neighborhood pixels.

A linear feature detection algorithm that uses multiple-orientation Gabor filtering was proposed by Chen et al. [9], and they assumed that the linear feature has a Gaussian profile and extracted it by convolving the image with oriented filters in 1° steps. Because of the very large number of filters, this approach extracts a precise pixel line with slow speed. Furthermore, the laser stripe in the region between bright and dark dissatisfies the Gaussian profile. Another linear feature detection algorithm that removes the bias from the extraction results was proposed in Ref. [10], in which the precise sub-pixel width and center line were obtained. However, it is difficult to apply this algorithm to directly extract these two features of the laser stripe due to their varying brightness and width.

In this paper, sub-pixel extraction of laser stripe falling onto the pattern is proposed for calibrating the laser plane to reconstruct the 3D object. On the one hand, the two-side edges of the laser stripe are detected using the principal component (PC) angle-based progressive probabilistic Hough transform (PPHT) and its width is obtained through the distance between these two edges. On the other hand, the center line of laser strip is extracted with 2D Taylor expansion at a sub-pixel level and the laser plane is calibrated with the 3D reconstructed coordinates from the extracted 2D sub-pixel points.

1 Two-Side Edge Detection

Detecting the integrated two-side edges of the laser stripe is difficult under the calibration pattern due to the varying absorption on its surface. However, a laser stripe is mainly composed of red and green components, and its projection on the pattern shows a straight line. Thus, the solution to be considered here is one to detect these two edges using a modified Hough transform (HT) in the color Canny edge image.

1.1 Robust PCA

Principal component analysis (PCA) is frequently applied in data analysis and it aims to express the covariance structure of data by means of the small numbers of the principle components. This paper employs robust PCA[11-12] for calculating the PC angle in its neighboring regions, which reflects the direction of the laser stripe to vote the accumulator in the Hough space.

For the Canny edge image in the two-dimensional space, suppose that each observation $\boldsymbol{x}$ denotes edge pixel and its neighbors. The projected observation $\boldsymbol{y}$ of the observation $\boldsymbol{x}$ considered in respect to the center $\boldsymbol{\mu}$, with the metric established by a 2×2 projection matrix $\boldsymbol{P}$, is defined as

$$\boldsymbol{y}=\boldsymbol{P}(\boldsymbol{x}-\boldsymbol{\mu}) \tag{1}$$

where the projection matrix $\boldsymbol{P}$ is yielded with the eigenvectors. Moreover, the two principal components generate the 2×2 scatter matrix $\boldsymbol{S}$ given by

$$\boldsymbol{S}=\boldsymbol{P}^{\mathrm{T}}\boldsymbol{L}\boldsymbol{P}=\begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \tag{2}$$

where $\boldsymbol{L}$ is the diagonal matrix with the eigenvalues $\lambda_{1,2}$.

$$\lambda_{1,2}=\frac{1}{2}[s_{11}+s_{22}\pm\sqrt{(s_{11}-s_{22})^2+4s_{12}^2}] \tag{3}$$

To distinguish regular observations from outlier ones, the robust score distance of each observation is employed to detect the anomalies by

$$sd^2=\sum_{i=1}^{2}\frac{y_i^2}{\lambda_i} \tag{4}$$

Since the principal components are assumed to be independent, the distribution follows a chi-square distribution with 2 degrees-of-freedom. Given a significance level α, the outlier detection criterion is

$$\mathrm{Out}(\alpha,\boldsymbol{\lambda})=\{\boldsymbol{y}\mid sd^2>\chi_2^2(\alpha)\} \tag{5}$$

After eliminating the outlier observations, the center $\boldsymbol{\mu}$, scatter matrix $\boldsymbol{S}$ and the eigenvalues $\lambda_{1,2}$ can be re-estimated with the regular observations, as shown in Fig. 1. If the proportion of the eigenvectors is known, the PC angle θ and response value R are defined with the re-estimated parameters as

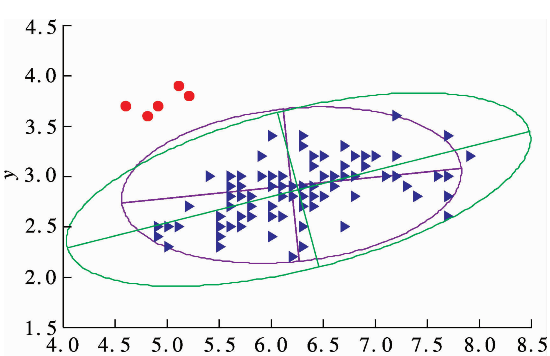


Fig. 1 Example of robust PCA used for eliminating the outlier observations

$$\theta=\tan^{-1}\left(\frac{\lambda_1-s_{11}}{s_{12}}\right),\quad R=\sqrt{\frac{\lambda_2}{\lambda}} \tag{6}$$

Here, the PC angle θ indicates the angle of the major principal axis of regular observations and the response value R reflects the roundness of the PC ellipse, $R\in[0,1]$.

1.2 PC angle-based PPHT

The Hough transform is one of the most widely used techniques for straight line pixel level detection due to its robustness to noise and missing data. This paper focuses on a variant of the Hough transform called the progressive probabilistic hough transform (PPHT)[13], which exploits the difference in the fraction of votes with supporting points to minimize the amount of computation to detect lines.

To eliminate the outlier pixels and reduce the vote scope, the PC angle calculated from the robust PCA in neighboring regions is combined with PPHT to detect the two-side edge of the laser stripe. Furthermore, the accuracy of the PC angle-based PPHT is higher than the traditional algorithm using the same information. The main steps of this algorithm are listed as follows:

1) Check the Canny edge image I. If it is empty then finish.

2) Randomly select a foreground pixel p in I and transform it into polar form.

3) Detect the selected pixel in terms of robust PCA. If it is an outlier then go to 1), otherwise calculate PC angle θ and response value R.

4) Vote the accumulator C with the lines supported by p in $[\theta-R\Delta\theta, \theta+R\Delta\theta]$.

5) Remove the selected pixel from the Canny edge image I.

6) Check if the highest peak in the accumulator C that is updated by the new pixel is higher than threshold maxNum then continue, otherwise go to 1).

7) Search along a corridor from $[\theta-R\Delta\theta, \theta+R\Delta\theta]$ specified by the peak in the accumulator, and find the longest segment that exhibits a gap not exceeding threshold maxGap.

8) Remove the pixels in the segment from the Canny edge image I.

9) Unvote the accumulator C from all the pixels concerning the segment that previously voted.

10) If the segment is longer than the minimum length, add it to the output list, then go to 1).

The two key differences between the gradient-based PPHT[14] and PC angle-based PPHT are listed as follows: The first is to detect the selected edge pixel using robust PCA to distinguish the regular pixels from the outlier ones, which decreases the computation requirement to process the outlier pixels and increases the signal to noise ratio. The second is to establish the elastic range of PC angle θ by means of the roundness response value R, which reduces the unnecessary accumulated value in the Hough space and decreases the search scope of the line segment.

2 Center Line Extraction

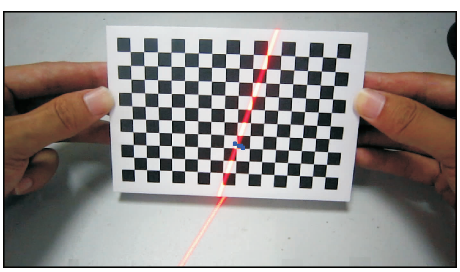
Due to the varying brightness and width of the laser stripe, it is difficult to directly extract its center line on the pattern. However, the laser stripe is mainly composed of red and green components, and its blue component is similar to the gray value of the pattern background. For this reason, the corrected intensity value is calculated using the difference between the gray value and the blue value of the laser stripe, with which the center line is extracted by using the 2D Taylor expansion.

2.1 Detection of line profiles in 1D

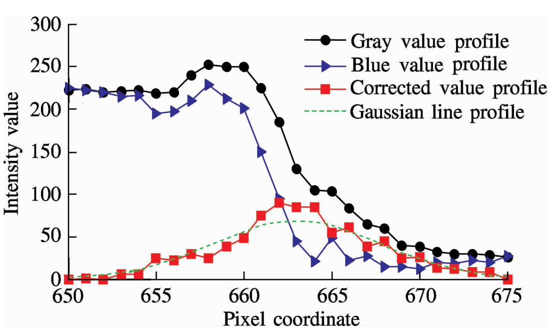
The common linear features detection algorithm uses a symmetric Gaussian line profile of width w and intensity h, as shown in Fig. 2, and it is defined as

$$f_g(x) = h\mathrm{e}^{-(x-\mu)^2/(2w^2)} \tag{7}$$

where h denotes the boundary intensity; μ denotes the central point; and w denotes the line width as measured from the center line. In general, h indicates the maximum or minimum intensity around the symmetric Gaussian line.



(a)



(b)

Fig. 2 Example of corrected value profile and their approximations by Gaussian line profile. (a) Original laser stripe image; (b) Gray, blue and corrected value of laser stripe and Gaussian line profile

The real image contains a significant amount of noise. Therefore, the first and second derivatives of an image $z(x)$ should be estimated by convolving the image with the derivatives of the Gaussian smoothing kernel.

$$g_\sigma(x) = \frac{1}{\sqrt{2\pi}\sigma}\mathrm{e}^{-x^2/(2\sigma^2)} \tag{8}$$

For the Gaussian line profile with noise, the line profile should be convolved with the derivatives of the Gaussian kernel. Then a smooth function is obtained as

$$r_g^{(n)}(x) = g_\sigma^{(n)}(x) * f_g(x) \tag{9}$$

Let $r(i)$ be the Gaussian smooth result at point i of the image that is obtained by convolving the image with the Gaussian kernels. In principle, the rough line in 1D can be located with the center of gravity.

$$\bar{x} = \frac{\sum_{i=x_1}^{x_r} ir(i)}{\sum_{i=x_1}^{x_r} r(i)} \tag{10}$$

However, this point $\bar{x}$ denotes the position of the line only with pixel accuracy. In order to overcome this, the second order Taylor polynomial of $z(x)$ is examined.

$$p(x) = r + r'x + \frac{1}{2}r''x^2 \tag{11}$$

where the derivatives r, r' and r'' of an image can be obtained by convolving the image with the corresponding Gaussian kernels. Then the position of the line p_x at a sub-pixel level is obtained with $p'(t) = 0$.

$$p_x = \bar{x} + t \tag{12}$$

where $t = -r'/r''$, and $t \in [-1/2, 1/2]$.

2.2 Detection of line profiles in 2D

Let $r(i, j)$ be the Gaussian smooth result at point (i, j) of the image that is obtained by convolving the image with the Gaussian kernels. In principle, the rough line in 2D can be located with the center of gravity.

$$(\bar{x}, \bar{y}) = \left(\frac{\sum_{i=x_1}^{x_r}\sum_{j=y_t}^{y_b}(ir(i,j))}{\sum_{i=x_1}^{x_r}\sum_{j=y_t}^{y_b} r(i,j)}, \frac{\sum_{i=x_1}^{x_r}\sum_{j=y_t}^{y_b}(jr(i,j))}{\sum_{i=x_l}^{x_r}\sum_{j=y_t}^{y_b} r(i,j)} \right) \tag{13}$$

The direction in which the second directional derivative of $z(x, y)$ takes its maximum absolute value is used as the direction $n(t)$. This direction can be determined by calculating the eigenvalues and eigenvectors of the Hessian matrix.

$$H(x, y) = \begin{bmatrix} r_{xx} & r_{xy} \\ r_{xy} & r_{yy} \end{bmatrix} \tag{14}$$

where the partial derivatives r_x, r_y, r_{xx}, r_{xy} and r_{yy} of an image can be obtained by convolving the image with the corresponding Gaussian kernels.

Let the eigenvector corresponding to the eigenvalue of maximum absolute value and the direction perpendicular to the line be given by (n_x, n_y) with $\|(n_x, n_y)\|_2 = 1$. This point can be obtained by inserting (n_x, n_y) into the

Taylor polynomial,

$$z(x, y) = z(tn_x, tn_y) = r + [tn_x \quad tn_y] \begin{bmatrix} r_x \\ r_y \end{bmatrix} + \frac{1}{2}[tn_x \quad tn_y] \begin{bmatrix} r_{xx} & r_{xy} \\ r_{xy} & r_{yy} \end{bmatrix} \begin{bmatrix} tn_x \\ tn_y \end{bmatrix} \quad (15)$$

The derivative of this expression is

$$\frac{\partial}{\partial t} z(tn_x, tn_y) = n_x r_x + n_y r_y + tn_x^2 r_{xx} + 2tn_x n_y r_{xy} + tn_y^2 r_{yy} \quad (16)$$

Hence, using the center of gravity $(\bar{x}, \bar{y})$ as the reference point, the sub-pixel coordinate of the line central point (p_x, p_y) can be expressed as

$$(p_x, p_y) = (\bar{x} + tn_x, \bar{y} + tn_y) \quad (17)$$

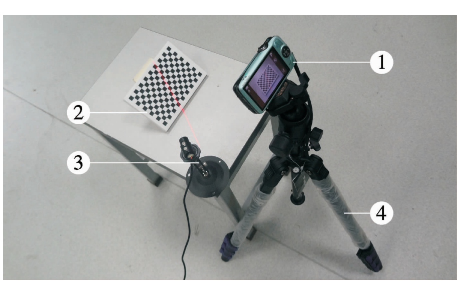
where

$$t = -\frac{n_x r_x + n_y r_y}{n_x^2 r_{xx} + 2n_x n_y r_{xy} + n_y^2 r_{yy}} \quad (18)$$

Again, $(tn_x, tn_y) \in [-1/2, 1/2] \times [-1/2, 1/2]$ is required in order for a point to be declared a line point.

3 Experiments and Results

The proposed algorithm, which is discussed in the previous section, is implemented with a PC processor of 1.73 GHz and 1 GB RAM in VC++ environment. The laser plane calibration system is composed of a 1 280 × 720 camera, a laser transmitter and a 16 × 10 calibration pattern, as shown in Fig. 3. The square marks on the pattern used for experiments are equally distributed with a size of 8 mm × 8 mm. Also, experimental images are captured by the Canon IXUS 200IS camera with the laser stripe falling onto the pattern positioned differently.

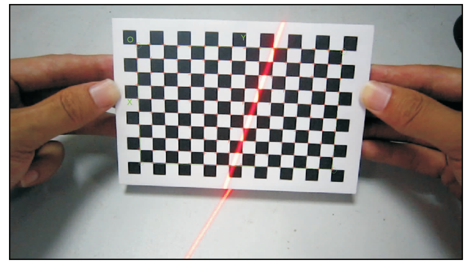


1—Camera; 2—Calibration pattern; 3—Laser transmitter; 4—Tripod

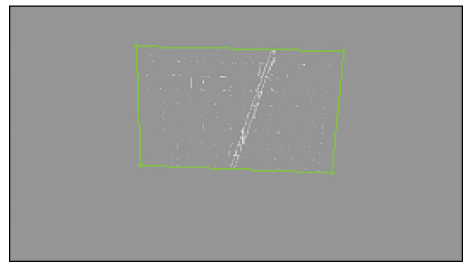
Fig. 3 Experimental equipment

3.1 Two-side edge detection experiment

After extracting four outer corner points on the pattern, laser stripes are constrained in the calibration pattern, so that the region of interest (ROI) is adopted for further image analysis, as shown in Fig. 4(a). For identifying the foreground edges to vote the accumulator, the color Canny edge detector is used to obtain the pattern and laser stripe edges in the ROI. After eliminating the pattern edges through the difference between their color components, the detected result, which primarily contains the laser stripe edges, is shown in Fig. 4(b).



(a)



(b)

Fig. 4 Color Canny edges detection. (a) Extracted corners on the distorted pattern image; (b) Detected color Canny edges on the undistorted pattern image

To vote the accumulator with supporting pixels using the PC angle, the two-side edge of laser stripe is detected by two peaks containing large pixel segments, as shown in Fig. 5(a), and the PCA ellipses used for reflecting the PC angles are displayed in Fig. 5(b) with rotation 90°. The 3D plot form of the voting map on PPHT and the proposed algorithm with supporting line segments are shown in Fig. 5(c) and Fig. 5(d), respectively, from which it can be observed that the useless votes are prevented by restricting the votes in the PC angle ranges. Finally, the average operating time for one frame of two-side edge detection is almost 29 ms.

3.2 Center line extraction experiment

By means of the detected two edges of laser stripes above, the widths of the laser stripe, calculated for further sub-pixel extraction, are located between 10 and 13 pixels, which correspond closely to the real laser stripe widths, as shown in Fig. 6(a). According to the 2D Taylor expansion using the detected laser stripe widths, the 2D center line of laser stripe is extracted at a sub-pixel level, which is closer to the real laser stripe center line than the gravity center line with pixel resolution, as shown in Fig. 6(b). Meanwhile, the average execution time for center line extraction is about 49 ms/frame.

For verifying the accuracy of the extracted sub-pixel center lines, the whole central points are reconstructed from 2D coordinates to 3D ones using camera parameters[15], as shown in Fig. 7(a). Each 3D reconstructed coordinate is located on the laser plane, so all these 3D coordinates are coplanar to each other, and the coplanar error indirectly

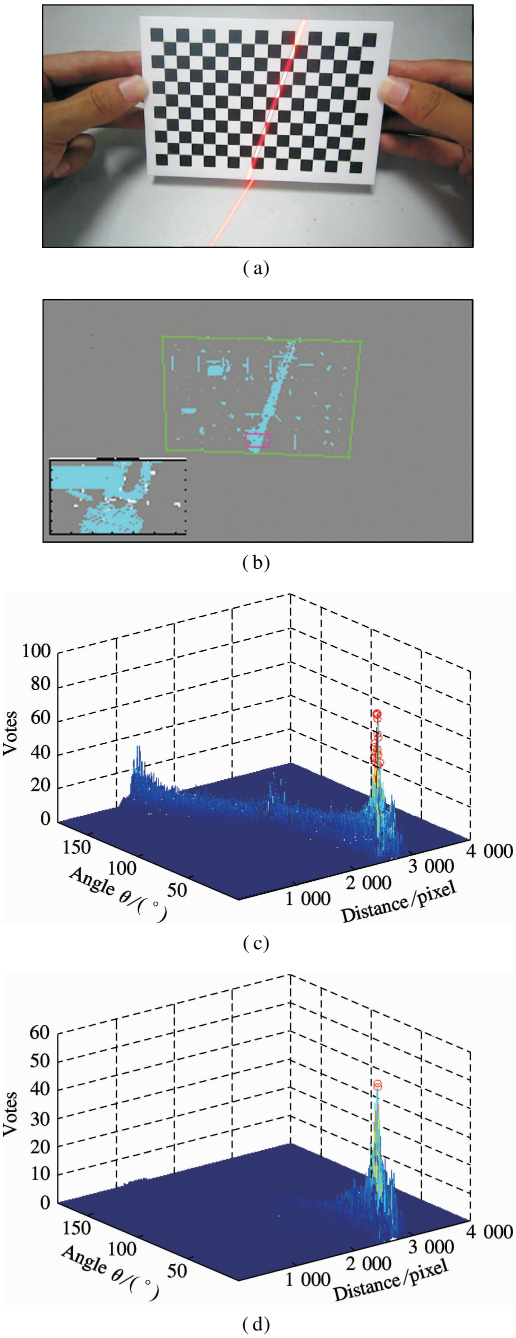


Fig. 5 Two-side edge detection using PC angle-based PPHT. (a) The detected two-side edge of laser stripe using PC angle-based PPHT; (b) The PCA ellipses rotated 90° indicating the PC angle; (c) The Hough space of the traditional PPHT algorithm without removing the pixels in the line segments; (d) The Hough space of the PC angle-based PPHT algorithm without removing the pixels in the line segments

reflects the accuracy of center line extraction. Finally, the laser plane parameters are calibrated by the least square method, as shown in Tab. 1.

By means of the laser plane equation above, the mean error of the reconstructed 3D coordinates can be defined as

$$\bar{m} = \frac{1}{N}\sum_{i=1}^{N} \left| \boldsymbol{n}^{\mathrm{T}}\boldsymbol{x}_i + d \right| \tag{19}$$

The relative position of the laser plane is displayed in a form of 3D plot, as shown in Fig. 7(a). Each error of

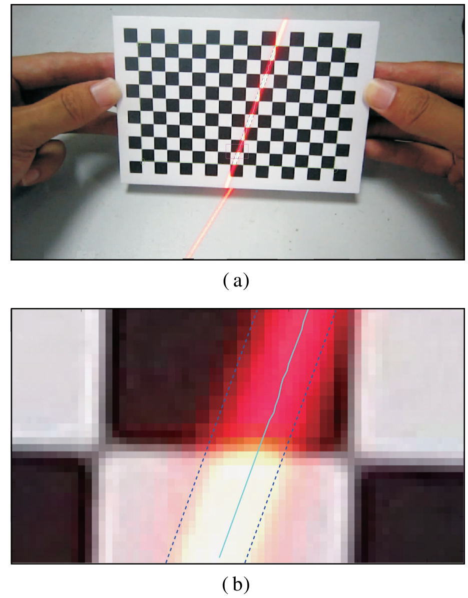


Fig. 6 Center line extraction using 2D Taylor expansion. (a) The extracted sub-pixel center line using 2D Taylor expansion; (b) Local enlarged image of Fig. 6(a)

Tab. 1 Laser plane calibration result

Parameter	n_x	n_y	n_z	d
Estimated value	0.877 7	0.377	0.295 8	53.281

these reconstructed coordinates, reflecting the distance from the corresponding point to the laser plane, is within 0.3 mm, as shown in Fig. 7(b). Furthermore, the mean error of these re-projected points is 0.063 mm, and it indirectly reveals that the extracted sub-pixel center lines have a high precision.

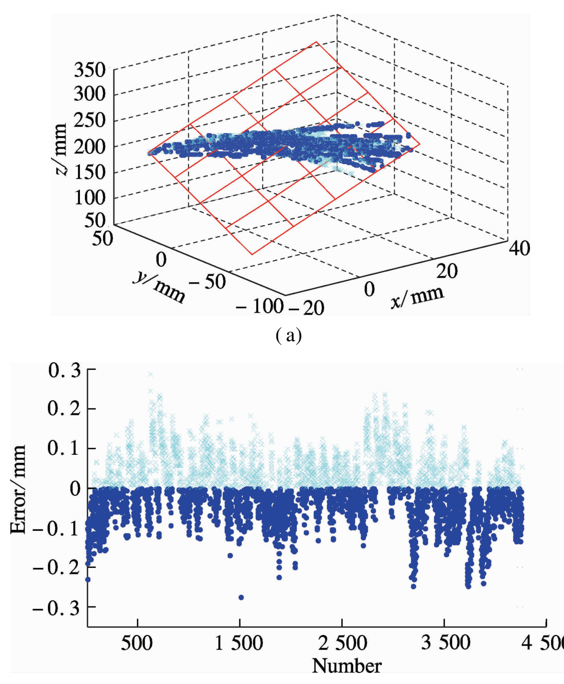


Fig. 7 Laser plane calibration and the corresponding error. (a) Laser plane in a form of 3D plot, the "x" points indicating above the laser plane and the "." ones indicating below the laser plane; (b) Each error of the reconstructed points to the corresponding plane

4 Conclusion

In this paper, a low-level approach to extracting the laser stripe with sub-pixel accuracy is presented for calibrating the laser plane to reconstruct a 3D shape. In practice, the PC angle-based PPHT algorithm is computationally efficient to detect the two-side edge of the laser stripe due to the elimination of the outlier pixels and the reduction of the vote scope. Meanwhile, only the first and second derivatives concerning 2D Taylor expansion, calculated by convolving the image with the derivatives of the Gaussian kernels, are adopted for extracting the center line of the laser stripe.

Theoretical and experimental results show that the proposed algorithm is effective for estimating the parameters of the laser plane with rapid speed and high precision. It can not only extract the laser stripe at a sub-pixel level for locating its position, but also calibrate the laser plane with low error for 3D shape measurement. So, the laser scanning system, comprising of camera, pattern and laser, is established by the intersection of the laser plane with the optical ray penetrating the optical center.

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亚像素级激光光条提取及其激光平面标定应用

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摘要: 为了标定激光平面以实现三维形貌测量,提出一种亚像素级精度激光光条提取算法. 该算法包括两侧边检测和中心线提取 2 个部分. 首先,利用基于主成分角的渐进概率霍夫变换检测 2 条侧边并依赖该两侧边的距离获取光条宽度; 然后,应用二维泰勒展式提取具有亚像素级精度的光条中心线并依据重建的三维坐标标定激光平面. 实验结果表明,所提算法光条中心提取速度较快,平均约为 78 ms/帧,光条平面共面误差较低,限制在 0.3 mm 以内. 因而所提算法能够满足提取光条的两侧边和中心线的需要,且快速可靠、精度高和抗干扰能力强.

关键词: 亚像素提取;中心线提取;激光平面标定;渐进概率霍夫变换;主成分角;二维泰勒展式

中图分类号: TP391.4; TN911.73