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基于小尺度测量的双目立体视觉系统误差分析

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摘　要:将小型双目立体视觉系统应用于小尺度测量,分析了CCD像素的不连续性对测量准确度的影响,探讨了系统结构参量基线距、焦距以及物距与测量误差之间的关系.当考虑像素不连续性时,视差值与测量距离之间呈阶梯状曲线关系,测量误差随基线距以及焦距的增大而减小,随物距的增大而增大.此外在实际测量中系统测量准确度达98.89%.该研究可为双目立体视觉小型系统的设计及搭建提供参考和指导.

关键词:双目立体视觉;距离测量;误差分析;像素不连续性;结构参量
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Error Analysis of Binocular Stereo Vision System Applied in Small Scale Measurement

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Abstract: A compact binocular stereo vision system was used for measurement in small scale. This paper analyzed the influence of CCD pixel discontinuity on the measurement accuracy and then built the relationship between structural parameters (baseline, focal length and object distance) and distance measurement errors. When considering the discontinuity of pixels, the relationship curve about measuring distance and disparity was of a stair-step shape. The measurement error decreased with the increase of the baseline and the focal length, while it gradually increased along with the object distance. The measurement accuracy of our system can reach 98.89%. Our valuable theory can be offered for optimization design of the binocular stereo vision system which is applied in small scale measurement.

Key words: Binocular stereo vision; Distance measurement; Error analysis; Pixel discontinuity; Structural parameters
OCIS Codes: 110.1758; 330.1400; 150.5670; 150.3040; 120.2830

0 Introduction

Three-dimensional (3D) morphology of the object is one of the most important features[1]. As a significant 3D measurement method, binocular stereo vision measurement technology has been researched extensively[2-5]. Binocular stereo vision measurement technology is a kind of high efficient detection technology and can achieve 3D information of an object similar to the way that human visual system does. It has many advantages, such as convenient operation, high measurement precision and rapid measurement speed. In addition, binocular stereo vision measurement technology can be used in a variety of complex and harsh conditions owing to its characteristic of non-contact measurement[6]. Therefore, the technology has been widely applied in object recognition, robot navigation, traffic monitoring,

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industrial inspection and so on[7-10].

However, in current industry, binocular stereo vision measurement technology is usually only used for large scale measurement which its effective measuring range is larger than 100 millimeter[11-13]. For example, Bumblebee binocular stereo system produced by the well-known Canadian company Point Gray has a high performance, but it is not applied when the distance between object and camera is too close, because in this condition small objects cannot be imaged in the two cameras simultaneously. For small scale or micro scale 3D measurement, laser scanning is usually the traditional measurement method[14]. There is no doubt that laser scanning measurement technology is highly efficient and accurate when detecting stationary objects. But it is limited when used to dynamic objects for the reason that scanning process takes time. To make up this deficiency, binocular stereo vision measurement technology may be a perfect choice. It can meet the requirement of real-time measurement due to its non-scanning imaging[15-17]. Especially for product real-time online monitoring field, binocular stereo vision measurement technology has its incomparable superiority. Thus, the research on measurement technology of binocular stereo vision applied in small scale measurement is quite necessary and valuable. Nowadays most of the binocular stereo systems are built base on artificial experience, only a few theoretical principles can be used for reference. Moreover, these theoretical principles are usually researched in the large scale measurement. For example, Ref. [5] analyzes the measurement errors of 3D coordinates of binocular stereo vision for tomatoes at the distances from 300 to 1000 mm, while Ref. [13] builds the model of measuring system whose measuring range is about 400 meters and then performs error analysis to show influence of every parameter on the measuring system error. Therefore, it is necessary to make a comprehensive error analysis of the binocular stereo vision system applied in small scale measurement, not only to improve the measurement accuracy, but also to promote the application

In this paper, we discuss the condition that a compact binocular stereo vision system is used for measurement in small scale whose measuring distance is about 10 millimeter. We present the measurement principle of binocular stereo vision. Then the influence of pixel discontinuities on the measurement accuracy is analyzed. Finally we describe the relationship between structural parameters and the measuring distance error.

1 Measurement principle of binocular stereo vision

Binocular stereo vision is an important branch of computer vision. According to the principle of stereo disparity, binocular stereo vision system can achieve 3D space coordinates of an object from its two different view pictures captured at one time. As illustrated in Fig. 1, O_L and O_R is the optical centers of the left and right camera. The two cameras are placed horizontally and modeled by the well-known linear pinhole model. They have the same focal length F. The distance between optical center O_L and O_R is baseline denoted by B. O_LO_l and O_RO_r individually express the optical axes of the left and right camera which are parallel to each other. P (X, Y, Z) is an object point in the world coordinate system. It is projected through the projection center of the lens to the point $P_L(x_l, y_l)$ and $P_R(x_r, y_r)$ in the image plane, where two image coordinates of the cameras are denoted by $O_l - X_lY_l$ and $O_r - X_rY_r$. Set the original point of the world coordinates in the optical center O_L. Then through this simple mathematical model we can get the expression of 3D world coordinates: $O_L(0,0,0)$, $O_R(B,0,0)$, $P_L(x_l, y_l, F)$, $P_R(x_r+B, y_r, F)$. For any P, P_L and P_R have the same y value, i. e. $y_l = y_r$.

$$Z=\frac{FB}{x_l-x_r} \tag{1}$$

Z is the coordinate value of the object point P along z axis in the world coordinates, expressing the distance between object and camera.

So if we can recognize the corresponding points between the left image and the right image, the measuring distance Z can be easily calculated by the Eq. (1).

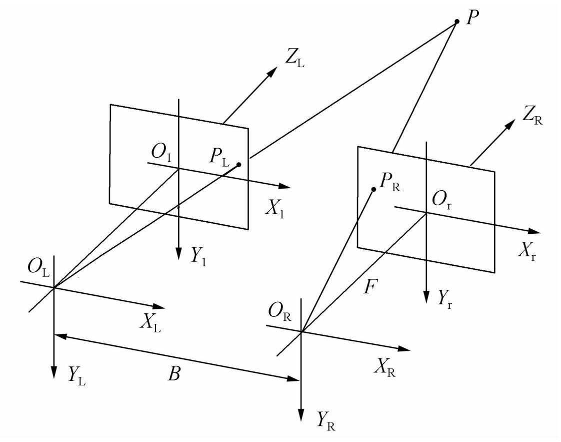

Fig. 1 Binocular stereo vision model

2 The influence of pixel discontinuities on the measurement error

The difference between P_L and P_R in x axis is disparity denoted by D. For the reason that the value of D achieved from stereo matching is the number of pixels, it's necessary to convert the image coordinate system into the pixel coordinate system.

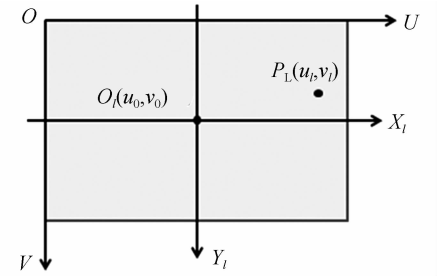

Fig. 2 Left image plane

As shown in Fig. 2, $O_l-X_lY_l$ is the left image coordinate system whose original point O_l is set in the main point of left camera. In the pixel coordinate system $O-UV$, suppose (u_0, v_0), (u_l, v_l) are the pixel coordinates of O_l and P_l respectively. The transformation between them can be given by

$$\begin{cases} u_l=\dfrac{x_l}{a}+u_o \\ v_l=\dfrac{y_l}{b}+v_o \end{cases} \tag{2}$$

where (a, b) is the size of CCD pixel in direction U and V.

On account that u_l and v_l can only be integers, we should do a little change about Eq. (2) as below

$$\begin{cases} u_l=\left[\dfrac{x_l}{a}\right]+u_o \\ v_l=\left[\dfrac{y_l}{b}\right]+v_o \end{cases}$$

Here the symbol $[t]$ indicates the minimum integer which is not less than t.

Similarly, for the point P_R in the right image plane, we can get

$$u_r=\left[\frac{x_r}{a}\right]+u_0$$

Therefore, the disparity D is also an integer.

$$D=u_l-u_r=\left[\frac{x_l}{a}\right]-\left[\frac{x_r}{a}\right]$$

$$Z=\frac{FB}{aD} \tag{3}$$

Based on the structural parameters of a compact binocular stereo vision system built by ourselves, which $F=2$ mm, $B=1.2$ mm, $a=0.003$ mm, the actual relationship between measuring distance Z and disparity D can be obtained immediately. To meet the requirement of small size, the measuring distance is about 10 millimeter. So Fig. 3 represents the result when D increases from 60 to 110. We can see that if the discontinuity of pixels is not considered, the curve is smooth, while if considering the discontinuity of pixels, a stair-step curve is achieved.

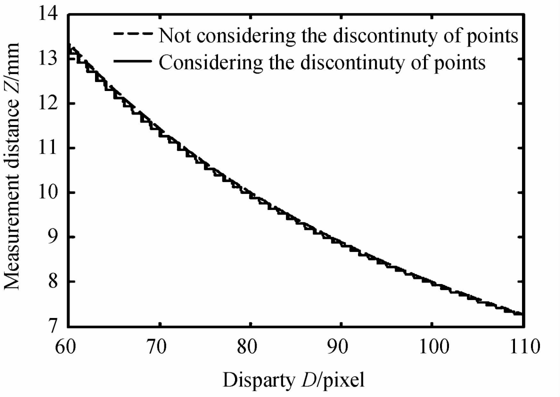

Fig. 3 Relationship between measuring distance Z and disparity D

Because each pixel in CCD has a certain size, the location of an ideal point cannot be detected accurately. Thus image recognition error is produced when considering the discontinuity of pixels. It will lead to a small error in disparity and then affect the measurement precision. Suppose the image recognition error is δ. Its maximum value is one pixel obviously, i.e. $\delta=1$. In addition, the influence of disparity D on the measurement accuracy comes from not only the image recognition error but also stereo matching error. Different stereo matching method has different matching performance. Suppose the error threshold of stereo matching is ε pixels, then we can get the total disparity error $\Delta D=\delta+\varepsilon=1+\varepsilon$. Due to the existence of ΔD, the distance we actually measured is

$$Z'=\frac{FB}{a(D+\Delta D)}$$

Therefore, we can get the distance measurement error and the error distribution curve.

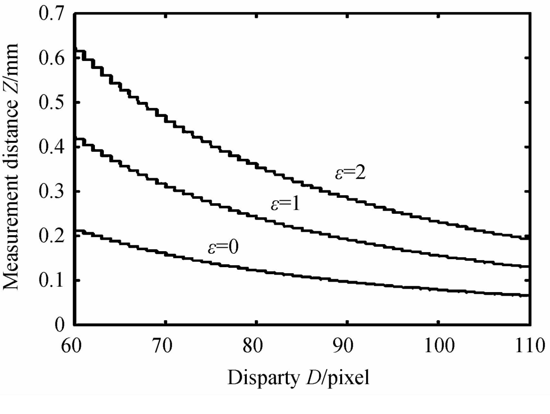

Fig. 4 Error distribution curve with the disparity

$$\Delta Z=Z-Z'=\frac{FB}{aD}-\frac{FB}{a(D+\Delta D)}=\frac{FB}{aD}-\frac{FB}{a(D+1+\varepsilon)}=\frac{FB(1+\varepsilon)}{aD(D+1+\varepsilon)}$$

As illustrated in Fig. 4, for larger value of disparity D, the measurement error is smaller. When disparity D is fixed, the measurement error will increase along with stereo matching error. $\varepsilon=0$ is a special situation, in this case, the result of stereo matching is considered to be perfect. With the value of ε increasing by 1, the measurement error will be nearly doubled.

3 The relationship between structural parameters and the measurement error

Measurement accuracy will result in changes when measurement system selects different structural parameters. In order to facilitate analysis process, suppose the result of stereo matching is perfect, i. e. , ε =0, then the measurement error is

$$\Delta Z=\frac{FB}{aD(1+D)} \tag{4}$$

Contact $D = FB/aZ$ with Eq. (4), then measurement error can be expressed as follows

$$\Delta Z=\frac{Z^2 a}{FB+Za} \tag{5}$$

3.1 The influence of baseline on the measurement error

As an important parameter, the baseline B describes the mutual position of two cameras in visual system. In order to analyze the influence of baseline on the measurement accuracy, other parameters such as focal length and object distance should be fixed. For small scale measurement, suppose $F = 2$ mm, $Z = 10$ mm, $a = 0.003$ mm. Using Eq. (5), the error distribution curve can be shown as Fig. 5.

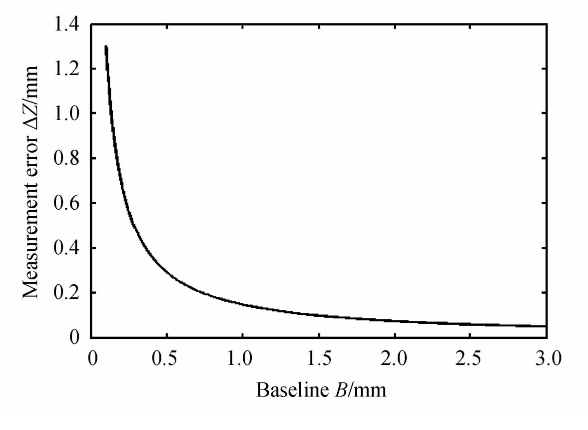

Fig. 5 Error distribution curve with the baseline

As we can see, the measurement accuracy will increase along with the baseline B. When baseline increases from 0 to 1, the measurement error will decrease sharply. When baseline is greater than 1, the downtrend becomes slower and slower. In the compact binocular stereo vision system, $B = 1.2$ mm, the measurement error is about 0.123 mm.

3.2 The influence of focal length on the measurement error

By analyzing the influence of focal length on the measurement accuracy, suitable cameras can be selected for the visual system. Suppose $B=1.2$ mm, $Z=10$ mm, $a=0.003$ mm, then we can get the error distribution curve in Fig. 6.

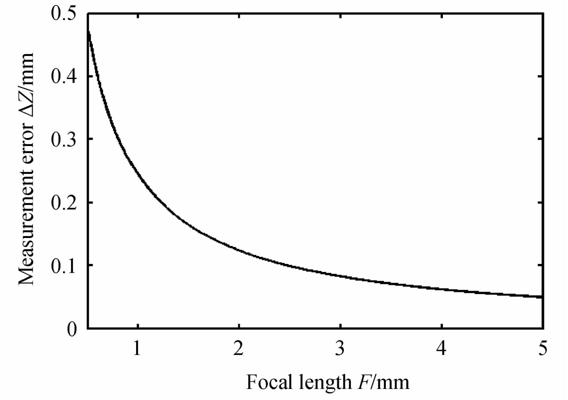

Fig. 6 Error distribution curve with the focal length

When baseline B and object distance are fixed, the longer the focal length is, the smaller the measurement error.

3.3 The influence of object distance on the measurement error

When the distance between object and camera is too close, objects cannot be imaged in the two cameras simultaneously. In order to apply the technology of binocular stereo vision in small scale measurement, it's significant to study the relationship between object distance Z and the measurement accuracy. Suppose there are 320 pixels in direction U of the CCD imaging plane. According to Eq. (3), the effective measuring range is from $FB/320a$ to FB/a as shown in Fig. 7. The dotted lines stand for the optical axis of each camera respectively. The common field of view of the two cameras is SMN.

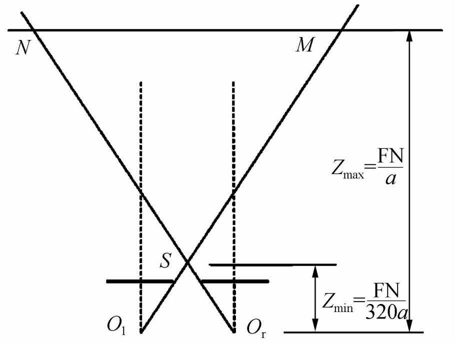

Fig. 7 Effective measuring range

Fig. 8 shows the error distribution curve when $F=2$ mm, $B=1.2$ mm, $a=0.003$ mm. If fixing other structural parameters, the measurement error will gradually increase along with object distance Z. In favor of the improvement of measurement accuracy, we should place the object as close as possible to the cameras. Of course, this distance must be within the effective measuring range.

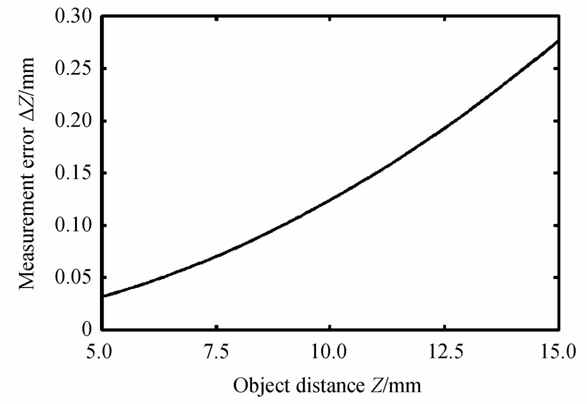

Fig. 8 Error distribution curve with the object distance

4 Experimental verification

In order to verify the validity of our theory, we conducted an experiment to measure the height of a small component. The actual value of the height obtained by vernier caliper was 1. 98 mm. If the measurement error was required to be less than 5%, according to our theory, the baseline should be greater than 1 mm, the focal length should be greater than 2 mm, and the object distance should be less than 10 mm. Therefore we built a compact binocular stereo vision system with $B=1.253$ mm, $F=2.071$ mm. The object distance was set near 9 mm. In addition, we marked 3 pairs of points on the component in order to reduce the manual error.

After obtaining the stereo images as shown in Fig. 9, we first estimated the disparity values of the 6 points through stereo matching. Then the world coordinate values of 6 points were calculated. And finally the distance between each pair of points can be achieved, $h_1 = 1.985$ mm, $h_2 = 1.926$ mm, $h_3 = 1.962$ mm. The average value was 1. 958 mm. Then we can get the measurement accuracy: $1.958/1.98 \times 100\% = 98.89\%$ Obviously it met the requirement. The experimental results demonstrated that our theory is valuable and can be offered for optimization design of the binocular stereo vision system which is applied in small scale measurement.

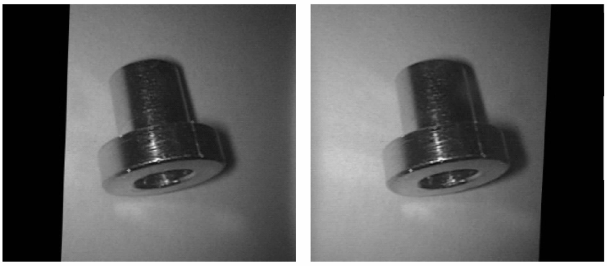

Fig. 9 Stereo images after rectification

5 Conclusion

As a significant 3D measurement method, binocular stereo vision measurement technology has incomparable superiority, especially for product real-time online monitoring field. In this paper, we analyze the influence of pixel discontinuity on the measurement accuracy as well as the relationship between structural parameters and distance measurement errors when a compact binocular stereo vision system is used for measurement in small scale. The valuable theoretical principles can be offered for optimization design. Utilizing our theory, the parameters of the system can be preliminarily determined based on the requirement of the measurement accuracy, or the measurement accuracy of the system can be estimated if given the relevant parameters. Our research can broaden the application areas of binocular stereo vision measurement technology in small scale measurement, such as 3D detection applied to MEMS devices.

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