Ying-qiao KONG, Jian-kang ZHAO*, Xuan XIA, Cheng-guang ZHU

Research on High-precision Calibration and Measurement Method based on Stereo Vision

Abstract: In stereo vision measurement system, distortion caused by the optical system makes images of targets deviate from theoretical imaging points, which results in measurement error of the system. In order to improve the measurement accuracy of the system, a quartic polynomial on the whole image plane is obtained through fitting the pixel resolution of each angular point on calibration board, the coefficient of which is proportional to the distance from the object to the camera. Then, we utilize binocular vision technology to calculate the distance of the detected object, and monocular vision to measure its transverse dimension. Experimental results show that, when the distance between the object and the camera is within 10m, the distance error can be reduced to less than 5%. And when the object is 1 meter away from the camera, the measuring error of the transverse width of the object is within 0.5mm, which approaches to the theoretical highest resolution.

Keywords: calibration; pixel resolution; distortion equation; fitting; measuring distance by binocular model; measuring size of monocular vision

1 Introduction

As an emerging test technology, computer vision measurement technology utilizes some functions of the optical or electronic device, based on the biological vision, to obtain the information of the detected object, and complete the real-time measurement of three-dimensional information of the object. With the development of modern science and technology, vision inspection technology has been more important in the field of non-contact measurement, and widely adopted in various fields such as industry, medical industry and aviation.

Measurement accuracy is an important factor in weighing measurement technology which is related to many factors, such as calibration error of the camera and the selected measurement method [1-10]. In recent years, many domestic and overseas scholars have been trying to improve the measurement accuracy. The traditional calibration method [5,6] has the advantage of high precision, while with a complicated process. Self-calibration method [7,8] relies on the relationship between

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corresponding points of some images, which is flexible but has strong robustness. Calibration method upon active vision [9,10] solves parameters through controlling the camera to move by the given way, which calculates simply and has strong robustness, but requires using high-precision mobile platforms.

Hereby, this paper proposes a measurement method based on stereo vision. We will establish a new type of camera calibration model, which utilizes binocular vision technology to calculate the distance of the object, and monocular vision to measure its transverse dimension. And the calibration template uses the conventional liquid crystal display, which does not need professional production and can be placed and adjusted easily.

2 Measurement model

2.1 Binocular Vision Model

Binocular vision model [11] is shown in Figure 1: two cameras which image planes are exactly coplanar with each other, with exactly parallel optical axes that are a known distance apart, and with equal focal lengths. And the paper has assumed that the principal points- c_x^{left} and c_x^{right} have been calibrated and have the same pixel coordinates in their respective left and right images. Usually, the center of an image is not on the optical axe, so we use c_x and c_y to imitate the shift of the center.

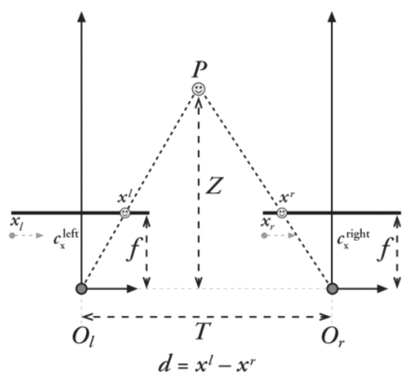

Figure 1. Binocular vision model of parallel transverse mode

For describing the model quantitatively, we define the world coordinate system, the camera coordinate system and the pixel coordinate system [12]. A world coordinate system is defined as a spatial 3D coordinate. The camera coordinate system takes the optical center to the coordinate origin, and usually defines the optical-axis direction as Z-axis which is perpendicular to the image plane. And we take the point O- the intersection of the optical axis of the image plane to the main point. A pixel coordinate system is a cartesian coordinate system on the image plane which is in pixels. The upper left corner is seen as the origin, and the pixel coordinate (x, y) represents the number of columns and rows of the point on the image.

Moving on, let's further assume a point P in the left and the right image views as p_l and p_r which have the respective horizontal coordinates x_l and x_r. And the coordinate of P in the world coordinate system is (X,Y,Z). Take the left camera coordinate system to the world coordinate system O-XYZ, and the left pixel coordinate system is O_l-$x_l y_l$, while the right is O_r-$x_r y_r$. The disparity is defined simply by $d = x_l - x_r$. As the situation shown in Figure 1, we can easily derive the following formulas by using similar triangles:

$$x_l = f_x \frac{X}{Z} + c_x \tag{1}$$

$$x_r = f_x \frac{X-T}{Z} + c_x \tag{2}$$

$$\frac{Z-f}{Z} = \frac{T-(x_i - x_r)}{T} \rightarrow Z = \frac{fT}{x_l - x_r} \tag{3}$$

where f represents the focal length of the camera, and T is the length between two cameras.

According to Eq.(3), the depth is inversely proportional to disparity, and obviously there is a nonlinear relationship between them: when disparity is near zero, small disparity differences make for large depth differences. When disparity is large, small disparity differences do not change the depth by much. Therefore, the binocular vision system is with high precision when the object is relatively near the camera.

In the experiment, we adopt SAD [11] to find matching points between the left and right stereo rectified images. SAD means the sum of square of absolute error of accumulated data in the given window, which is shown as Eq. (4).

$$SAD(x,y) = Sum\{|Left(x,y) - Right(x,y)|\} \tag{4}$$

The window with the minimum value of SAD in the searching area is the best matching block of pixels in the left and right image.

2.2 Monocular Model of Measuring Width

As shown in Figure 2 is the schematic diagram of the perspective, and only objects among the area of W and Z can be precisely imaged on the photosensitive sheet sensor. The angle formed by WC and ZD is the maximum range to observe objects, and that is the perspective. The focal length is F mm, and the length of the photosensitive device is l mm. According to the triangular relations, the perspective can be calculated as

$$\tan\frac{\alpha}{2}=\frac{l/2}{F}\rightarrow\alpha=2\tan^{-1}\frac{l}{2F} \tag{5}$$

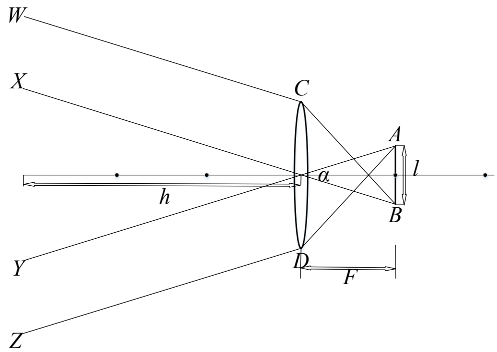

Figure 2. Range of single camera

In the meantime, the resolution accuracy which refers to the actual physical width of a pixel can be calculated as

$$s=\frac{2h\cdot\tan\frac{\alpha}{2}}{p}=\frac{2h\cdot\frac{l/2}{F}}{p}=\frac{hl}{pF} \tag{6}$$

where h is the real distance between the target and the camera, and p is the number of pixels on the photosensitive sheet in the longitudinal direction.

Moving on, let's process the target's image and count the number n of pixels ready to be measured, so the transverse width is

$$W=ns=n\cdot\frac{hl}{pF} \tag{7}$$

3 Error analysis

In visual detection system, measurement accuracy is a key indicator which runs through the design process of the system. The application field and worth of the system depend on the level of its measurement accuracy. Measurement accuracy of the system is influenced by various factors. Figure 3 mainly analyzes several key steps in the image processing process and the main factors that affect the accuracy of the transverse width and longitudinal distance.

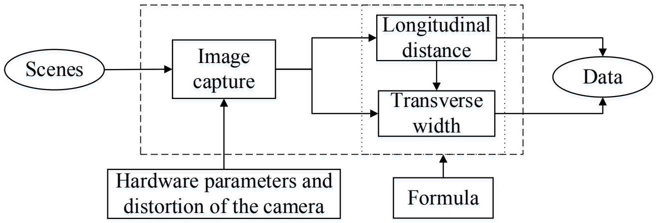

Figure 3. Image processing and factors affecting the accuracy of detection

As can be seen from the above figure, followings are the factors affecting measurement accuracy of the camera [13]:
The natural parameters of the object itself or the changes of characteristics.
- Various factors in the process of capturing images, which mainly refer to the influence of camera hardware parameters, including distortion, installation accuracy of the camera, physical focal length, baseline, as well as the size and resolution of CCD.
- Different measurement methods and calculation formulas.
- Interference caused by noise or something else in processing and analyzing image.

In the meantime, according to Eq. (7), the horizontal width of the object is directly proportional to the actual distance between the object and the camera. Therefore, the measurement accuracy of the distance also significantly affects the transverse measurement accuracy.

As seen from the above analysis, the main factors affecting the accuracy of the measurement system originate in both hardware and software. Among them, natural parameters of the object itself or changes of characteristics are not controllable. Then, we will focus on optimizing the calibration model and measurement method. Some hardware parameters of the camera, such as distortion and accuracy of installing the camera, and some noise caused by the software will not be discussed in this paper.

4 High-precision camera calibration and measurement

4.1 Pixel Resolution Calibration

The classic binocular camera calibration, such as the calibration method proposed by Zhang [5], is a process to determine the mapping matrix of points from three-dimensional to two-dimensional space. The projection matrix is determined by the internal and external parameters obtained by the camera calibration. Internal parameters refer to distortion coefficients of the camera, while external parameters indicate rotation coefficients and offset coefficients of the camera coordinate system relative to the world coordinate system. In object vision measurement, since the calibration template and the measured object are not in the same image plane, online fine adjustment needs to be carried out respectively in calibration and measurement so as to make the imaging clearer. Because the system is adjusted in measurement, parameters of the camera need to be calibrated again which is difficult to maintain the consistency of calibration results of the lens. Moreover, the calibration is tedious and complex.

Image processing based on machine vision is to convert actual size of the object through the number of pixels. Therefore, the calibration model proposed in this paper will directly calibrate the pixel resolution of the camera, namely the relationship between the pixel and the actual size. The measurement result is the superposition of the resolution of each pixel. The accuracy of the measurement results can be greatly improved through accurate calibration of pixel resolution.

The calibration and measurement process throughout the experimental system is shown in Figure 4.

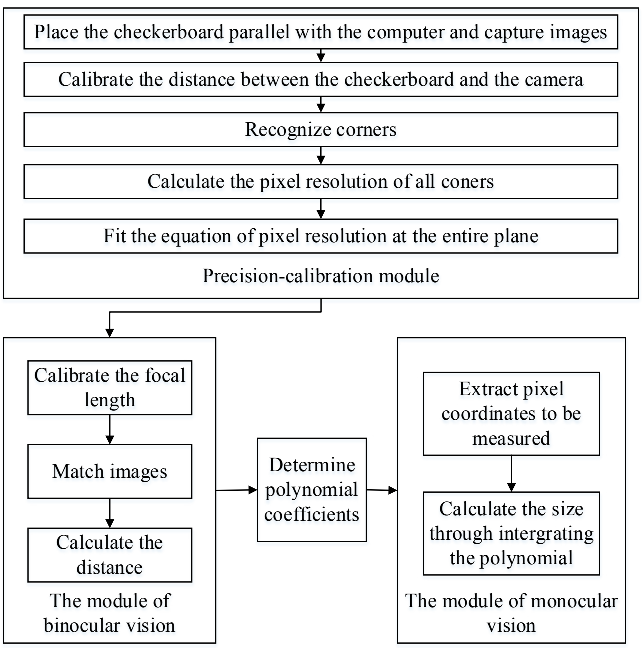

Figure 4. The process of experimental calibration and measurement

4.2 Fitting the Calibration Model

The optimum fitting of a plane can be interpreted as the minimum sum of errors' squares of existing data. When a polynomial is defined as the fitting surface, the polynomial least square fitting can be carried out [14,15]. Theoretically, the selected order of the polynomial is arbitrary. However, high-order polynomial will lead to poor numerical characteristics. Furthermore, with the increase of the order of polynomial, the fitting surface will become not smooth enough. Therefore, polynomial of which the order is higher than the required should not be selected. Generally speaking, the precision of cubic polynomial established through the calibration proposed by Zhang [5] is limited. Consequently, this paper will establish a quartic polynomial fitting model for the measured data, which is shown as Eq. (8).

$$f(x,y) = k(\sum p_{ij}x^i y^j)(i+j \le 4) \tag{8}$$

According to Eq. (6), it can be known that the resolution of pixel points is not only related to hardware parameters of the camera, such as the focal length, the number of pixels on the photosensitive sheet, and the length of sheet, but also proportional to the actual distance from the camera to the object to be measured. Therefore, the proportionality coefficient between the distance from the object to the camera and the calibrated standard distance is the coefficient k required to be multiplied by the pixel resolution equation at this distance.

4.3 Calibration of Focal Length of the Camera

As shown in Figure 5, l is a resolution fitting curve when image coordinate y and depth Z are fixed. c_x represents offset of original point in the image. x_1 is the pixel coordinates of point X on the imaging plane. Take into account the distortion of the camera, the rectified pixel coordinate x can be obtained when the areas of quadrangle $ABCD$ and $ABFE$ are equal.

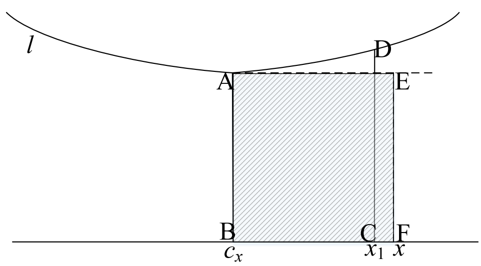

Figure 5. The correction of pixel coordination

The focal length of the camera can be calculated according to the model of pinhole camera proposed above. The rectified pixel coordinates of points on the image can be denoted as (x, y), the depth of standard template as Z, the actual length as (X, Y) and the offset of the origin point in the actual image as (c_x, c_y), so the focal length f_x and f_y of the camera on x and y direction can be calculated, as shown in Eq. (9). Moreover, c_x and c_y are just the coordinates of the central point in the fitting model.

$$f_x = Z \cdot \frac{x - c_x}{X}, f_y = Z \cdot \frac{y - c_y}{Y} \tag{9}$$

5 Experimental scheme and result

5.1 Resolution Model

The experiment is implemented with two aims. Firstly, it aims to verify the feasibility of the proposed detection method in the scheme. Secondly, it purposes to analyze the measurement accuracy of the method. The experimental system consists of a group of binocular cameras, with the resolution of 1920*1080, the focal length of 15mm, the photosensitive sheet's length of 7.52mm, and the length between two cameras of 200mm. The experiment shows that the targeted accuracy of the system in distance measurement is for 5%, while the transverse dimension measurement for 0.5mm.

The checkerboard is placed 100cm away from the camera to capture images. Make sure that the checkerboard is filled with the entire imaging plane, as shown in Figure 6. The camera is calibrated based on the method which has been described, with the fitting model shown in Figure 7. And the calibration result of the focal length is 4345 pixels.

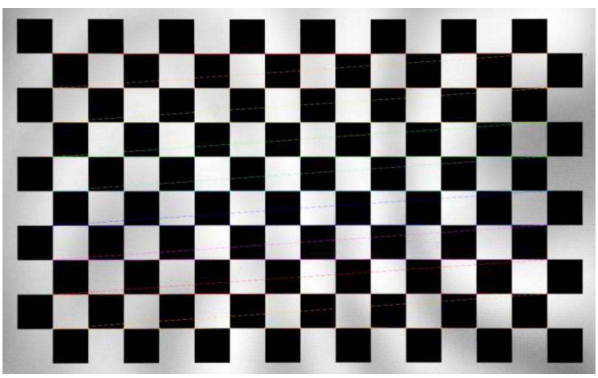

Figure 6. The calibration image

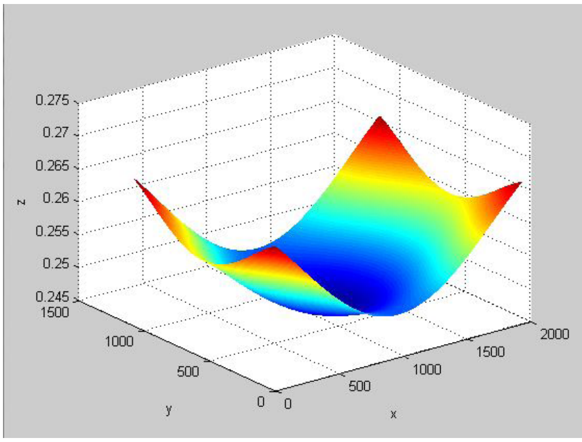

Figure 7. The fitting model of pixel resolution

5.2 Distance Measurement by Binocular Vision

In order to maintain whether the system can calculate the target distance accurately, the distance of the object will be calculated by binocular vision, comparing with the actual distance while the object is 1m to 5m away from cameras. The measurement results are shown in Table 1. A relative error curve is gained based on the results in Table 1, from which the measurement error is within 5% when the object is away from the camera within 10 m.

Table 1. Measure results of distance

True distance/m	Measured result/m	Error/m	Relative error
100	99.5	-0.5	0.5%
150	147.75	-2.25	1.5%
200	195.96	-4.04	2.02%
250	243.75	-6.25	2.5%
300	291.48	-8.52	2.84%
350	338.8	-11.2	3.2%
400	386.2	-13.8	3.45%
450	432.9	-17.1	3.8%
500	479.75	-20.25	4.05%

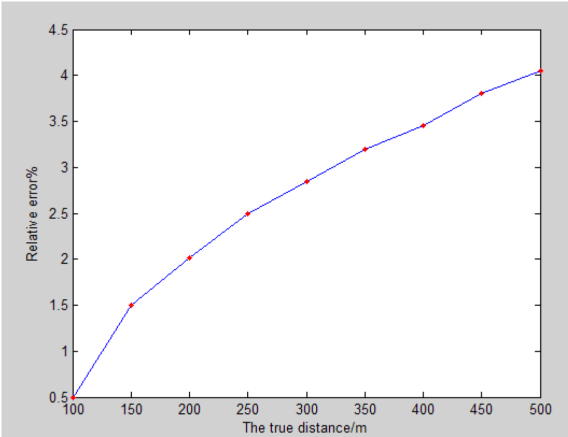

Figure 8. Relative error curve of the distance by binocular system

5.3 Width Measurement by Monocular Vision

In order to test the accuracy of transverse dimension measurement by the system, the length of any section of a scale will be measured to be compared with the actual size. For eliminating the influence of the distance on the transverse width, we will fix the distance between the scale and the camera of 100cm, which is the standard distance when calibrating. Therefore the proportionality coefficient of the quartic polynomial will be 1. The pixel coordinates of the two ends of the scale are adopted to calculate the length by means of the integration for the quartic polynomial which has been fitted.

The theoretical pixel resolution accuracy of the experimental system based on Eq.(6) is 0.245mm. Any section of the measurement scale is taken to be measured, and the result is shown in Table 2 where (x_1,y_1) and (x_2,y_2) represent respectively pixel coordinates of the two end points in any section of the scale.

Table 2. Measurement results of transverse width

x1	y1	x2	y2	Measured width/mm	True width/mm	Error/mm
60	412	213	412	39.7620	40	-0.238
213	412	409	412	50.2449	50	0.2449
409	415	608	415	50.3446	50	0.3446
608	415	808	415	50.1071	50	0.1071
808	396	1009	396	50.1609	50	0.1609
1009	398	1210	398	50.2492	50	0.2492
1210	401	1407	401	49.6186	50	-0.3814
1408	422	1602	422	49.4122	50	-0.5878

5.4 Analysis on the Experimental Results

From above, it can be seen that the measurement accuracy obtained by the two methods is high.

When measuring the distance, calculating the disparity has consumed lots of time. In order to improve the efficiency of the system, the resolution of the camera should be lowered and the disparity parameter should be adjusted. However, a pixel deviation might correspond to long distance in the actual situation. Theoretically, the system will measure the distance more accurately with higher resolution of the camera. Obviously, it is necessary to maintain a balance between the accuracy of the distance measurement and the operation time of the algorithm.

As can be observed from Figure 8, with the distance of the object from the camera increasing, the measurement error of the system is also constantly increasing. It can be seen that the error appears an approximately parabolic relationship with the distance, which is related to the principle of distance measurement by the binocular vision. The distance of the object is inversely proportional to its pixel deviation in two photos. When the object is far away from the camera, a great distance movement corresponds to just a small deviation of pixels, so the system is not so sensitive to remote objects. In addition, the resolution of the camera is not high enough, leading to the difficulty of measuring remote objects.

In testing the transverse accuracy of the system, the measurement error is about 0.3mm within 0.8m to 1.5m away from the camera, which has achieved the target precision of 0.5mm. It can be found that the error in the system mainly comes from three aspects:

– The measurement of the distance

The distance between the object and the camera determines the coefficient of the fitting equation, so if we don't measure the distance accurately, the polynomial will change.

– Error itself of the fitting model

Firstly, the resolution of individual pixel is calculated by adopting the average distance of two points. What's more, a certain amount of optimization in the fitting model is possible to cause some errors. In order to decrease the error, the more accurate calibration boards are supposed to apply, and more images should be captured to cover all pixels when calibrating. And we have to look for the better curve fitting method.

– Camera Pixels

In the experiment, the pixel coordinates of the end points of the scale are manually extracted, and a pixel shift may correspond to a certain width deviation. Therefore, it is necessary to improve the accuracy of extracting pixel coordinates.

6 Conclusion

In this paper, fitting a polynomial is adopted to propose a new model of high-precision camera calibration. And establishing the general equation for the resolution of the entire field has been written into the program for real-time measurement. We will calculate the distance through binocular system as well as the monocular system to measure the transverse dimension of the object. While the calibration template uses the conventional liquid crystal display, which does not need professional production and can be placed and adjusted easily. The experimental results show that the four fitting equation can effectively improve the accuracy of the object measurement. In the meantime, further improvement of extracting pixel coordinates and measuring remote objects has an important role in high-precision measurement, and we will make further exploration in the future studying.

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