To Improve the Image Distortion and Machine Motion Accuracy in Machine Vision Measuring System

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Abstract

In general, machine vision measurement errors include image system errors and measuring platform errors. Image system errors include the errors due to the computation principle and imaging equipment, which will cause the measured results of the same object to vary with the position change of the object in image when the measuring platform is fixed. This is caused by lens distortion, uneven light sources, and the angle between the lens and the object. On the other hand, the measuring platform errors are produced by machine motion and positioning errors. This research attempts to study the variation in distortion and accuracy of machine positioning so as to establish a compensation table to compensate the variation caused by the different position of the object in image, and under the condition of providing convenience for users to obtain a calibration object, to complete compensation and thus improve the accuracy of measuring.

Keywords: Machine Vision, Distortion, Compensation Table

1. Introduction

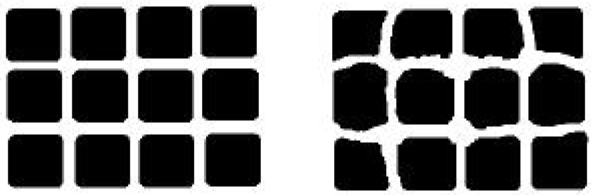
Dimension is a very important index in measuring. A great deal of physical measure is based on dimension. Without accurate dimension, any further physical measure can be affected. During production process, it is not possible to achieve 100% accuracy in engineering. Therefore, in order to prioritize production and control errors within a certain range based on the importance of dimension, the acceptable tolerance is graded according to the processing method and technology, in which way, the products can be guaranteed to fall within the allowance of dimension.

However, to determine if the dimension satisfies the specifications relies on measuring system. The non-contact measuring equipment uses charge coupled device (CCD) for image input and to further measure the physical properties of the object such as position, dimension, and defect inspection, which has become the most popular inspection apparatus for measuring system. No matter in the production of high tech like electronics industry or consumer products, this kind of non-contact measuring equipment is widely used. The other relevant applications can be found in reference literature [1].

In terms of system architecture, image measuring system can be generally divided into such two parts as image system and control system. The control system includes all hardware control units: for instance, mechanic arm, X-Y-Z platform, motion control, and I/O control. The image system contains image formation system and image processing unit. The image formation system comprises of CCD, frame grabber, and optical equipment such as lens and light sources. The image processing unit determines the location of boundaries and corner points, as well as the defects and impurities after the image is grabbed. The accuracy of image measuring system depends on both the image system and the control system mentioned above.

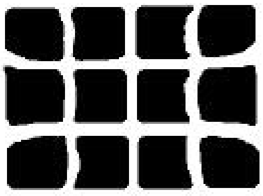
1.1 Image System Errors

Image distortion is caused by lens' geometrical distortion and light sources etc. The lens' geometrical distortion, as shown in Figure 1, can be classified as Pincushion distortion and Barrel distortion. The uneven light sources cause variation in lightness or darkness on the object when placed at different locations, which leads to different computations of the same object following boundary direction and thus different results measured.



Normal Image

Pincushion Distortion



Barrel Distortion

Figure 1: Normal image and distorted images

The lens' geometrical distortion can be represented by:

$$\text{Distortion } (\%) = \frac{\text{Actual Distance (AD)} - \text{Predicted Distance (PD)}}{\text{Predicted Distance (PD)}} \times 100\%$$

The distorted image is shown in Figure 2:

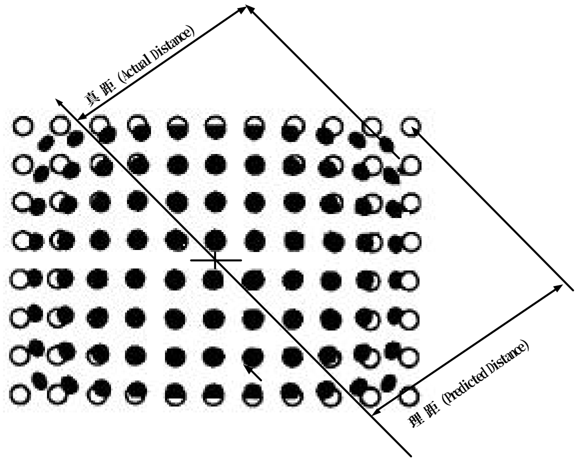


Figure 2: The object's predicted distance and actual distance in image

The image is composed of pixels. For example, in this research, the dimension is 640x480 pixels. In general measuring, a calibration action is taken by putting a standard unit (verified optical calibration film etc.) under lens for measuring, and computing the number of pixels of the physical measurement so as to obtain a conversion unit, that is, the equivalent actual dimension of one pixel. The number of pixels of the object is then converted to the actual dimension, as shown below:

The object's actual dimension = the object's pixel value measured in image system × (the actual dimension of the calibration unit / the pixel value of the calibration unit measured in image system)

As shown in Figure 2, at positions closer to the boundaries of the image, the difference between the theoretical and actual values is larger. On the contrast, as the position gets nearer the center, the actual value approximates to the theoretical value. Therefore, the actual value corresponding to every pixel in the picture varies. If the same conversion unit is used in computation, the resulting dimensions will vary with the position in the picture, causing errors in machine vision measuring. The errors in focusing the object in line with the lens and autofocusing [2, 3, 4, 5] are not the problems concerned in this research.

1.2 The control system errors

The control system errors refer to the errors that occur when the platform moves, which is related to the machine's motion and positioning accuracy including correction of machine's positioning and backlash errors, that is, the positioning accuracy of forward and reverse paths. Figure 3 displays the positioning results of an X platform repetitively measured by the laser interferometer. The positioning on forward path obviously differs from that on reverse path.

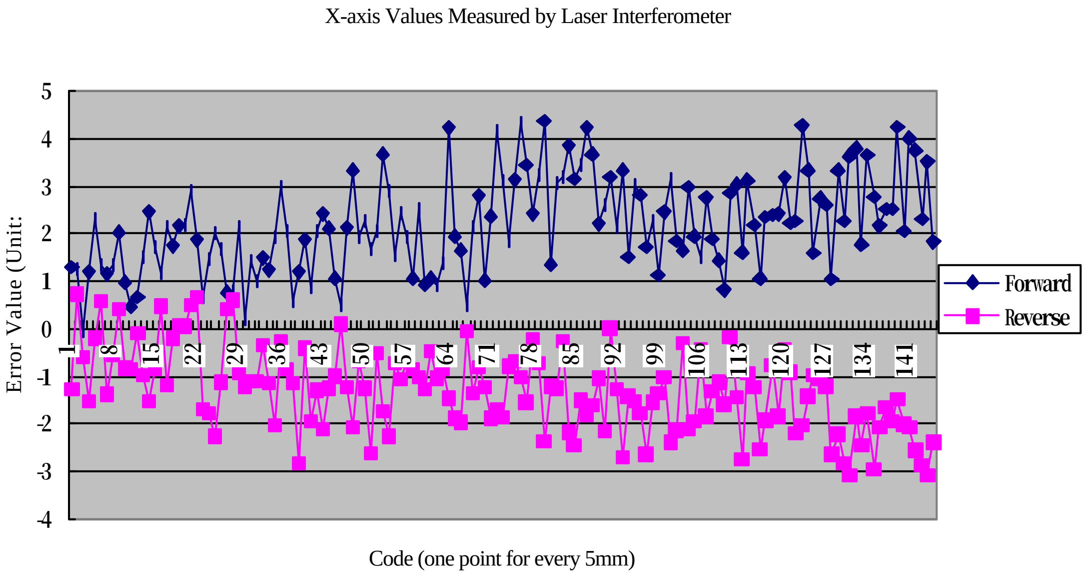


Figure 3: The backlash errors of the forward and reverse paths of the moving platform

In addition, since the image measuring system integrates the image system and the control system, even after both systems are verified, some other error factors still exist in Measured results. The angle between CCD and the object (as shown in Figure 4) can also affect the measured results, which relates to the flatness of the measuring platform.

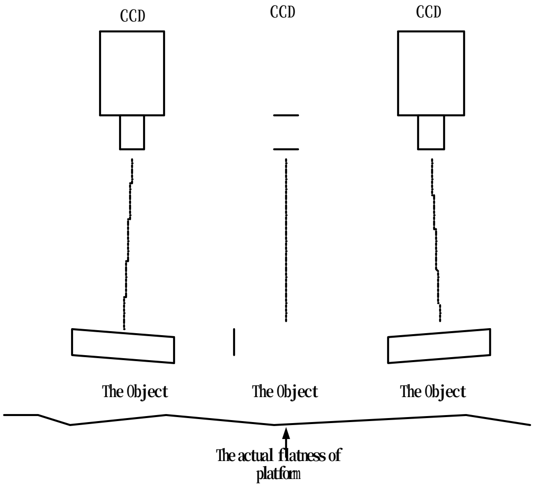


Figure 4: Different angles between CCD and the object at different locations on the platform

This research has five major objectives: (1) exploring the effects of lens on image; (2) applying compensation method to reduce errors caused by lens and light sources; (3) studying the effects of moving platform on measuring system; (4) using compensation method to reduce the measuring errors caused by the positioning errors of measuring platform; and (5) analyzing results and making recommendations for improving accuracy of precise image measuring.

2. Research scope and limits

The research scope and limits are defined as follows: (1) The image specification of CCD is RS170, and the dimension of image is 640x480 pixels in gray. The image is obtained by using common frame gabber and its driver. (2) The image computation program is Win32 written in Visual C^{++}6.0 on Windows 98 operating system only considering the picturing function of frame grabber. The remaining image computation is completed by self-executed program instead of the library accompanying frame grabber. (3) In order to avoid the effect of flashing light sources, this research uses the dynamic results measured for confirmation thus reducing the variation in measured values caused by flashing light sources. (4) In selecting calibration object, this research employs the standard circle of a standard piece of glass as a calibration unit. The subsequent tests are implemented with the different circles on this standard piece of glass. (5) The geometric configuration of the object can be described by point, line, circle, and arc. Except for points can be obtained and applied directly, the others must be obtained by further computation [6]. (6) The data of points can be obtained directly. However, due to the existence of distortion, the results obtained differ from the standard values, which in turn contribute to the differentials in distortion. Consequently, direct acquirement of data results in large errors. The method used in this research can reduce these errors. (7) The moving platform takes control through Parker AT6400 server control system, whose effective distance is 700 mm. (8) The subject of the moving platform is single X-axis. If a XY platform is in use, the compensation method proposed in this research will not be appropriate. (9) In selecting the calibration object for image measuring system, this research places the two ends of a compasses with a distance of 30mm on two standard pieces of glass, using the standard circle on the glass as calibration unit, and fix tight in moving. The compensation table is established every 5 mm. (10) In order to make sure that the object in motion keeps parallel to the moving direction of X-axis, a fixture is fixed on one side of the platform so that the object is moved parallel to the moving direction of X-axis.

3. Research Method

3.1 Compensation for image system distortion

The conception of this research is that for the same object at different positions in the image, the measured values should be consistent but not vary with the position; however, in actual image measuring, the measured values for the same object usually change with the position, which is mainly attributed to the lens distortion and uneven light sources etc. When selecting lens, we can choose the lens producing smaller distortion. But due to such concerns as price, the lens that cause larger distortion is usually used in general applications. Under such a circumstance, in image measuring, users should place the object right in the center of the image so as to reduce the effects of distortion. However, in reality, when the object is placed in the center, the pixel data for positions far from the center will have larger errors due to the effect of image distortion. The distortion compensation is represented in two ways: (1) the actual physical amount corresponding to every pixel is individually represented, that is, the actual physical amount represented by every pixel in the picture is given different values as the position changes; (2) use the pixel at the center of the image as a base to calculate relative value of every other pixel, that is, the pixel at the center is 1, then the pixel around may be 0.9 or 1.1, whose value is obtained from the actual compensation result. When the accurate calibration unit is available, the first representation approach can complete distortion compensation and obtain the actual physical amount at the same time. Since the focus of this research is compensation of distortion, only the second approach is used. When the accurate calibration unit exists, the results of this research can be applied to the first approach without modification. The 8.5 mm and 16 mm lens are selected in this research. After the picture is divided into *n* equal pieces, the variation in the data measured as the position changes is studied, and the data provides a basis for compensation. The object is then re-measured based on the compensation results for error comparison.

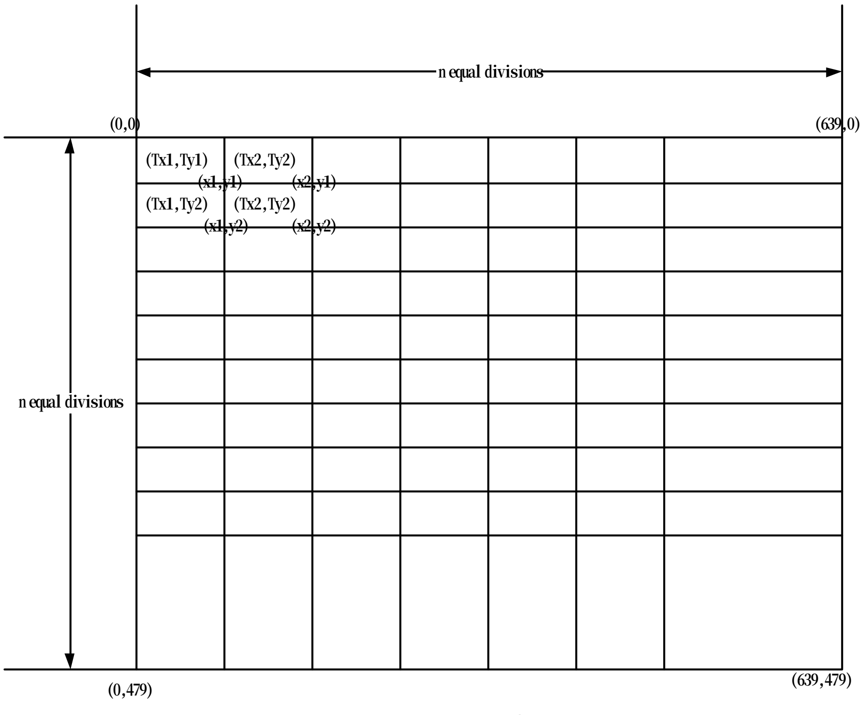


Figure 5: Image partition for compensation

This research uses a 640x480 pixels image as an example. The central location of the image is (319.5, 239.5). It is equally divided into *n* divisions in X direction, represented by Region_X, and again equally divided into *n* divisions in Y direction, represented by Region_Y, as shown in Figure 5. The relevant variables are defined as follows:

Region_X: Region_X belongs to{0,1,2,...,n-1}

Region_Y: Region_Y belongs to{0,1,2,...,n-1}

XPerUnit: equal to 640 / n.
YPerUnit: equal to 480 / n.
Result[Region_X][Region_Y]: the measured value when the calibration object is placed in Region-X and Region_Y.

Stand: the standard value of calibration object.

Calibration[Region_X][Region_Y]: the compensated value of every pixel in Region_X and Region_Y.

When *n* is odd, then:

CenterLeft = n/2 choose the minimum integer;
CenterRight = n/2 choose the maximum integer;
Hence, the standard value Stand = Result[CenterLeft][CenterLeft];
Calibration[Region_X][Region_Y] = Result[CenterLeft][CenterLeft] / Stand.

When measuring the pixel value for a location (x, y) after compensation:

Let
Xmin = the minimum integer of X/XperUnit;
Ymin = the minimum integer of Y/YperUnit;
Xmax = the maximum integer of X/XperUnit;
Ymax = the maximum integer of Y/YperUnit;

Hence, the new X coordinate is:

1. When X > 319.5 and X falls within the central region ([CenterLeft][Ymin]):
   X = (X-319.5) Calibration[CenterLeft][Ymin] + 319.5.

2. When X > 319.5 and X falls outside the central region ([CenterLeft][Ymin]):

$$\begin{aligned}X = {}&((\mathrm{XPerUnit} \times \mathrm{CenterRight}) - 319.5) \times \\ &\mathrm{Calibration}[\mathrm{CenterLeft}][\mathrm{Ymin}] + \\ &\sum_{i=\mathit{CenterRight}}^{X\min-1} (\mathrm{XPerUnit} \times \mathrm{Calibration}[i][\mathrm{Ymin}]) + \\ &(\mathrm{X} - \mathrm{X\,min} \times \mathrm{XPerUnit}) \times \mathrm{Calibration}[\mathrm{X\,min}][\mathrm{Ymin}] + 319.5\end{aligned}$$

3. When X <= 319.5 and X falls within the central region ([CenterLeft][Ymin]):
X = 319.5-(319.5-X) Calibration [CenterLeft][Ymin]

4. When X <= 319.5 and X falls outside the central region ([CenterLeft][Ymin]):

$$\begin{aligned}X = {}&319.5 - ((319.5 - (\mathrm{XPerUnit} \times \mathrm{CenterLeft})) \times \\ &\mathrm{Calibration}[\mathrm{CenterLeft}][\mathrm{Ymin}] + \\ &\sum_{i=X\max}^{\mathit{CenterLeft}-1} (\mathrm{XPerUnit} \times \mathrm{Calibration}[i][\mathrm{Ymin}]) + \\ &(\mathrm{X\,max} \times \mathrm{XPerUnit} - \mathrm{X}) \times \mathrm{Calibration}[\mathrm{X\,min}][\mathrm{Ymin}])\end{aligned}$$

The new Y coordinate is:

1. When Y > 239.5 and Y falls within the central region ([Xmin][CenterLeft]):

Y = (Y - 239.5) Calibration[Xmin] [CenterLeft] + 239.5.

2. When Y > 239.5 and Y falls outside the central region ([Xmin][CenterLeft]):

$$\begin{aligned}Y = {}&((\mathrm{YPerUnit} \times \mathrm{CenterRight}) - 239.5) \times \\ &\mathrm{Calibration}[\mathrm{Xmin}][\mathrm{CenterLeft}] + \\ &\sum_{i=\mathit{CenterRight}}^{Y\min-1} (\mathrm{YPerUnit} \times \mathrm{Calibration}[\mathrm{Xmin}][i]) + \\ &(\mathrm{Y} - \mathrm{Y\,min} \times \mathrm{YPerUnit}) \times \mathrm{Calibration}[\mathrm{X\,min}][\mathrm{Ymin}] + 239.5\end{aligned}$$

3. When Y <= 239.5 and Y falls within the central region ([Xmin][CenterLeft]):
Y = 239.5 - (239.5 - Y) Calibration[Xmin] [CenterLeft]

4. When Y <= 239.5 and Y falls outside the central region ([Xmin][CenterLeft]):

$$Y = 239.5 - ((239.5 - (\mathrm{YPerUnit} \times \mathrm{CenterLeft})) \times \mathrm{Calibration[Xmin][CenterLeft]} + \sum_{i=Y\max}^{CenterLeft-1} (\mathrm{YPerUnit} \times \mathrm{Calibration[Xmin][i]}) + (\mathrm{Y\,max} \times \mathrm{YPerUnit} - \mathrm{Y}) \times \mathrm{Calibration[X\,min][Ymin]})$$

When *n* is even, then:

CenterX = n/2 is an integer;
CenterY = n/2 is an integer;

Stand = (Result[CenterX-1][CenterY-1] + Result[CenterX][CenterY-1] + Result[CenterX - 1][CenterT] + Result[CenterX - 1][CenterY-1]) / 4.

Calibration[Region_X][Region_Y] = Result[CenterX][CenterY] / Stand.

When measuring the pixel value for a location (x, y) after compensation:

Let
Xmin = the minimum integer of X/XperUnit;
Ymin = the minimum integer of Y/YperUnit;
Xmax = the maximum integer of X/XperUnit;
Ymax = the maximum integer of Y/YperUnit;

Then, the new X coordinate is:

1. When X > 319.5:

$$X = \sum_{i=CenterX}^{X\min-1} (\mathrm{XPerUnit} \times \mathrm{Calibration[i][Ymin]}) + (\mathrm{X} - \mathrm{X\,min} \times \mathrm{XPerUnit}) \times \mathrm{Calibration[X\,min][Ymin]} + 319.5$$

2. When X <= 319.5:

$$X = 319.5 - (\sum_{i=X\max}^{CenterX-1} (\mathrm{XPerUnit} \times \mathrm{Calibration[i][Ymin]}) + (\mathrm{X\,max} \times \mathrm{XPerUnit} - \mathrm{X}) \times \mathrm{Calibration[X\,min][Ymin]})$$

Then, the new Y coordinate is:

1. When Y > 239.5:

$$Y = \sum_{i=CenterY}^{Y\min-1} (\mathrm{YPerUnit} \times \mathrm{Calibration[Xmin][i]}) + (\mathrm{Y} - \mathrm{Y\,min} \times \mathrm{YPerUnit}) \times \mathrm{Calibration[X\,min][Ymin]} + 239.5$$

2. When Y <= 239.5:

$$Y = 239.5 - (\sum_{i=Y\max}^{CenterY-1} (\mathrm{YPerUnit} \times \mathrm{Calibration[Xmin][i]}) + (\mathrm{Y\,max} \times \mathrm{YPerUnit} - \mathrm{Y}) \times \mathrm{Calibration[X\,min][Ymin]})$$

3.2 Compensation for the image measuring system

The underlying concepts are the same as in compensation for the image system distortion, that is, for the same object, the values measured by the final image measuring system should be consistent regardless of its location, in other words, should not vary with change of location. The image measuring system comprises image system and control system; therefore, the compensation mentioned here is not restricted to the control system but rather the compensation for the final results from the complete image system and control system. The compensation for the distortion caused by image system must be made before the results can be applied to further computation. A standard pair of compasses 30 mm long is selected in this research. At each end of the compasses a standard circle with a diameter of 5 mm is placed as the standard unit for length. The machine has to reset home before measuring. In order to ensure the accuracy of the machine's repetitive action, the distance of the circles at two ends of the standard unit is measured 100 times before and after compensation respectively, that is, 100 times from A to B and another 100 times from B to A (as shown in Figure 6) (due to the existence of backlash errors, the results from A to B differ from those from B to A). The results are used to ensure the repetitiveness of the measuring system and establish the compensation table. Moreover, the 8.5 mm lens used in early distortion compensation of image system is selected for further computation in this research.

Figure 6: Standard unit diagram

First of all, the machine's path is equally partitioned into *n* divisions. This *n* is not necessarily equal to the *n* defined in compensating the image system distortion. As shown in Figure 7, the standard value is set as the coordinates measured from the center of Circle A to the center of Circle B when *n* = 0. Since this research focuses on single axis motion, the data of X coordinate are used as the basis for compensation and judgment. When the moving direction is from A to B, the center of Circle A is fixed, the center of Circle B is measured by moving along from A to B, and its X coordinate is thus obtained. When the moving direction is from B to A, then the center of Circle B is fixed, the center of Circle A is measured by moving along from B to A, and its X coordinate is thus obtained.

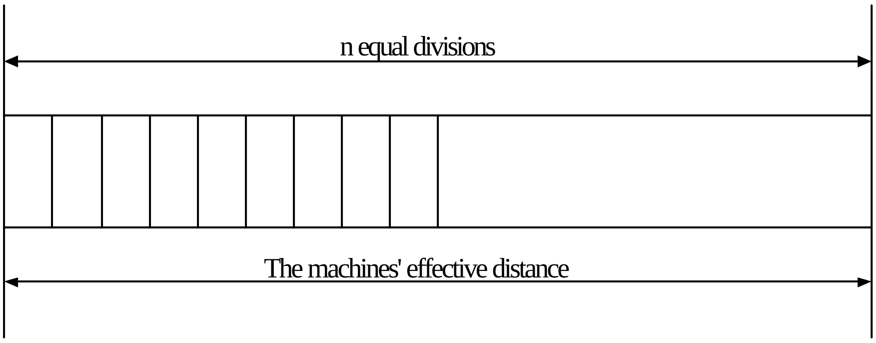


Figure 7: Partition of the machine's path for compensation

The relevant variables are defined as follows:

n: the number that equally divides the effective motion distance of the moving platform.

Forward path: the platform moves from A to B.

Reverse path: the platform moves from B to A.

Total Distance: the effective motion distance of the moving platform.

Motion Standard Distance: the machine's motion distance from A to B when n = 0, that is, the distance between the center of Circle A and the center of Circle B.

MotionRegion_X: MotionRegion_X belongs to {0,1,2,...,n-1}.

MotionXPerUnit: equal to TotalDistance / n.

Center_A_X: the X coordinate of the center of Circle A.

Center_B_X: the X coordinate of the center of Circle B.

Measure_A2B_Results_Pixels_B [MotionRegion_X]: the X coordinate of the center of Circle B when the calibration object is placed in MotionRegion_X and the moving direction is from A to B.

Meaure_B2A_Results_Pixels_A [MotionRegion_X]: the X coordinate of the center of Circle A when the calibration object is placed in MotionRegion_X and the

moving direction is from B to A.
Calibration_A2B[MotionRegion_X]:
the compensation value for every pixel in MotionRegion_X when the moving direction is from A to B.

Calibration_B2A[MotionRegion_X]:
the compensation value for every pixel in MotionRegion_X when the moving direction is from B to A.

When the measured direction is the forward path, the center of image should be focused on Circle A aiming the X coordinate of the center of Circle A at 319.5 Pixels; When the measured direction is the reverse path, the center of image should be focused on Circle B aiming the X coordinate of the center of Circle B at 319.5 Pixels.

(1) First, to obtain MotionStandardDistance: that is, place the standard unit at the position n = 0, compute the center of Circle A, and move the machine to the center of Circle A focusing the image center of CCD (319.5,239.5) on the center of Circle A. The X value sent back by the server control system for this moment is recorded as Position_0_X1. When the machine is moved to the center of Circle B and the image center (319.5, 239.5) is focused on the center of Circle B, the X value sent back by the server control system for this moment is recorded as Position_0_X2. MotionStandardDistance = |Position_0_X1 - Position_0_X2|, which is the motion distance ordered by the program every time.

(2) To build the preliminary data of Measure_A2B_Results[MotionRegion_X] and Measure_B2A_Results[Motion Region _X].

In MotionRegion_X, use the center of Circle A or B as origin. After the machine moves MotionStandardDistance, measure the coordinates of the center of Circle B or A.

When the moving direction is from A to B:
Measure_A2B_Results[MotionRegion_X] = Center_B_X.

When the moving direction is from B to A:
Measure_B2A_Results[MotionRegion_X] = Center_A_X.

(3) To build the compensation data for Calibration_A2B[MotionRegion_X] and Calibration_B2A[MotionRegion_X] :

Calibration_A2B[MotionRegion_X] = Measure_A2B_Results_Pixels_B [MotionRegion_X] - 319.5;
Calibration_B2A[MotionRegion_X] = Measure_B2A_Results_Pixels_A [MotionRegion_X] - 319.5.

(4) If the moving platform does not have any error, then the X coordinate of the center of Circle B measured from A to B should be right at the image center 319.5; likewise, the X coordinate of the center of Circle A measured from B to A should be right at the image center 319.5. However, compensation is needed when error exists. For instance, assume it is moved to Poistion_X, then the compensated distance for the image is:

(a) Determine the moving direction: forward or reverse. The compensation table of Calibration_A2B[MotionRegion_X] is applicable to forward direction, and the compensation table of Calibration_B2A [MotionRegion_X] is applicable to reverse direction.

(b) Compute which region of {0,1,2,...,n-1} that Poistion_X falls in, that is, the result from (Poistion_X / MotionStandardDistance) (Let it be the variable Region_X).

(c) Obtain the two values before and after compensation from the compensation table, and determine the compensated distance for the image by inserting:

(i) Forward:

The Compensated Distance for the Image =

$$\frac{\text{Poistion\_X} - (\text{MotionXPerUnit} \times \text{Region\_X})}{((\text{MotionXPerUnit} \times (\text{Region\_X} + 1)) - (\text{MotionXPerUnit} \times \text{Region\_X}))} \times$$

(Calibration_A2B[Region_X+1] - Calibration_A2B [Region_X])

(ii) Reverse:

The Compensated Distance for the Image =

$$\frac{\text{Poistion\_X} - (\text{MotionXPerUnit} \times \text{Region\_X})}{((\text{MotionXPerUnit} \times (\text{Region\_X} - 1)) - (\text{MotionXPerUnit} \times \text{Region\_X}))} \times$$

(Calibration_A2B[Region_X - 1] - Calibration_A2B [Region_X])

If Poistion_X falls in Region 0, then insert in Region 0 and Region 1. If it falls in the last region, then insert in the last region and the second to last region.

(d) The new measurement results are obtained by adding the compensated values to the prior measured coordinates of the image center.

4. Experimental results and discussion

4.1 Description of experiment

(1) Image system

Two types of lens (8.5 mm and 16 mm) are used in this experiment. For each type of lens, there are 3x3 groups and 5x5 groups, which refer to different positions in a picture. Figure 8 displays 3x3 groups for a 640x480 picture whereas Figure 9 illustrates 5x5 groups for a 640x480 picture. 3x3 grouping results in 9 groups and 5x5 grouping generates 25 groups. Hence, in A, B, E, F, there are 1~9 groups, and in C, D, G, H, there are 1~25 groups, as shown in Figure 10. B8 refers to the post-compensation measurement of No.8 position in 3x3 grouping for 8.5 mm lens. The computation is done 100 times within each group.

1	4	7
2	5	8
3	6	9

Figure 8: The position of each group in 3x3 grouping

1	6	11	16	21
2	7	12	17	22
3	8	13	18	23
4	9	14	19	24
5	10	15	20	25

Figure 9: The position of each group in 5x5 grouping

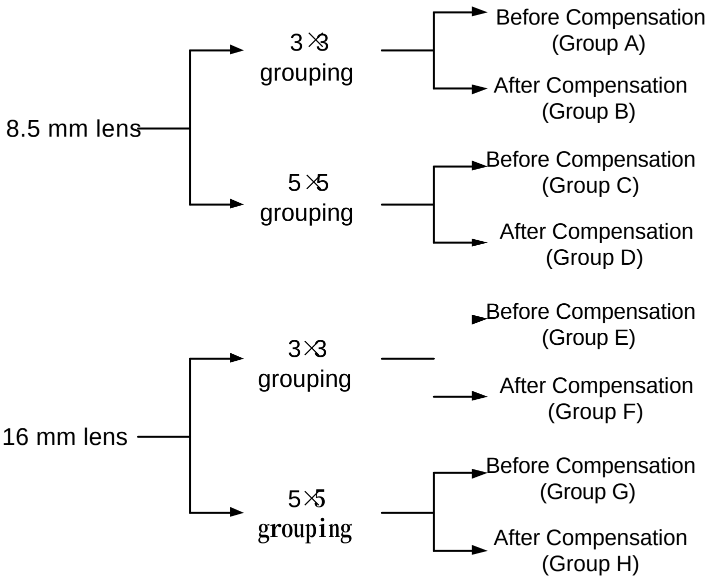


Figure 10: The grouping table for experimental items of image system

(2) Image measuring platform

The effective distance of the moving platform for experimental items is 700 mm (the effective length of optical gage and lead screw). Measuring is done every 5mm resulting in 140 groups. Since the length of the standard unit is 30 mm and the distance between the two circle centers is 25 mm, the forward path can actually reach as far as 675 mm and the reverse path can actually reach as far as 25mm. As a result, the actual number of applicable groups is 130, and the machine's feasible compensation range is 25mm~675mm. The motion distance of the platform in this experiment is 25mm~675mm, with 130 groups each including forward and reverse distance. The grouping is depicted in Figure 11.

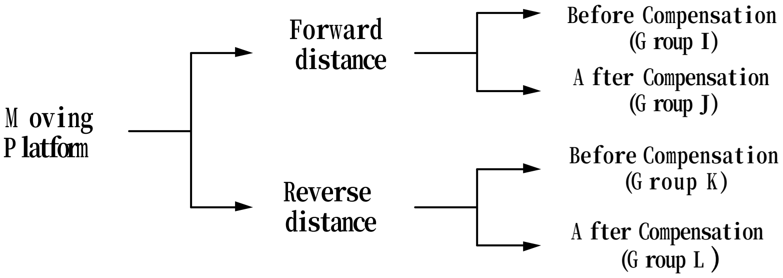


Figure 11: The grouping table for experimental items of X-axis measuring platform

4.2 Discussion of experimental results

(1) Image system

4.2.1 The results from 3x3 grouping for 8.5 mm lens (as shown in Table 1):

(a) Maximum error

The maximum error before compensation (Group A in experiment) is 6.0485 pixels;
The maximum error after compensation (Group B in experiment) is -0.3901 pixels.

(b) Average error

The average error has decreased from 2.554 pixels to -0.0815 pixels.

4.2.2 The results from 5x5 grouping for 8.5 mm lens (as shown in Table 2):

(a) Maximum error
The maximum error before compensation (Group C in experiment) is 4.9943 pixels;
The maximum error after compensation (Group D in experiment) is -0.3369 pixels.

(b) Average error

The average error has decreased from 1.7322 pixels to -0.0145 pixels.

4.2.3 The results from 3x3 grouping for 16 mm lens (as shown in Table 3):

(a) Maximum error

The maximum error before compensation (Group E in experiment) is -1.4574 pixels;
The maximum error after compensation (Group F in experiment) is 0.4079 pixels.

(b) Average error

The average error has decreased from -0.47856 pixels to -0.1005 pixels.

4.2.4 The results from 5x5 grouping for 16 mm lens (as shown in Table 4):

(a) Maximum error

The maximum error before compensation (Group G in experiment) is -1.4996 pixels;
The maximum error after compensation (Group H in experiment) is 0.2540 pixels.

(b) Average error

The average error has decreased from -0.6193 pixels to 0.1300 pixels.

(2) Image measuring platform

From the experimental results (as shown in Table 5), the maximum error on forward path before compensation is known 12.9116 pixels, and the average error 4.0048 pixels, whereas the maximum error after compensation is 4.2554 pixels and the average error 2.0506 pixels. On the reverse path, before compensation, the maximum error is 13.2300 pixels and the average error is 4.0374 pixels; after compensation, they are reduced to 5.4558 pixels and 1.9401 pixels respectively.

5. Conclusions and Recommendations

5.1 Conclusions

Based on the above experimental results, this research has reached the following conclusions:

1. Image distortion not only exists but also has a significant impact on the measured results. Based on the above experimental results, the different position of the same object in image causes considerable variation in measurement. The existence

of such variation is not negligible to precise measurement.

2. The compensation method proposed in this research can reduce this variation to be within 1 pixel, that is, the variation in measurement due to different position of the same object in image can be controlled within 1 pixel. Hence, in image measuring, a greater degree of freedom is allowed to place the object without affecting the accuracy of measurement.

3. As far as the number for equal division is concerned, the more equal divisions the distance is divided into, the easier to control the measured results of the object at different positions. However, the more equal divisions require more time in establishing compensation table. Therefore, the user should consider the accuracy required when determining the number of divisions to equally divide up the distance.

4. The lens distortion and the angle between the lens and the object also have effects on measured results. Therefore, when selecting and setting up the lens, the user should first identify and dispose of inappropriate lens and incorrect way to set up. As shown in experimental results, the distortion caused by 8.5mm lens is far more significant than 16mm lens.

5. The error of the moving platform can be corrected by image compensation, but there still exits variation of more than 1 pixel, which reflects the result from both image distortion and the final error of measuring platform.

6. The compensation method developed for moving platform in this research is based on the assumption that the standard object (i.e. standard unit) is easy to obtain. For higher accuracy, laser interferometer etc. equipment can be used for correction when establishing the compensation table, which will contribute to considerable improvement of accuracy in measuring.

5.2 Recommendations

In studying image distortion, pixel is the only unit in consideration. If the verified calibration film is also used, then the results and actual dimensions can be converted to each other without additional work required. In addition to optics and image processing, image measuring needs integration with hardware platform to do the job. This research is focused on the compensated results of measuring system. The precision control of hardware platform is the specialized topic of mechanics and electric beyond our research scope. This research concentrates on improvement of accuracy in measuring by current system, without involvement in such topics as selection of lens and motion system. However, in reality, image measuring requires comprehensive consideration in order to achieve high precision and high speed.

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Appendices

Appendix 1: Image System

The standard value for 3x3 grouping is the average of 100 times computation in A5, B5, E5, and F5; the standard value for 5x5 grouping is the average of 100 times computation in C13, D13, G13, and H13. (1), (2), (3), (4), (5), and (6) represent the followings respectively (the results are in pixel):

(1): represents the average value of 100 times computation;
(2): represents the minimum value in the 100 times computation;
(3): represents the maximum value in the 100 times computation;
(4): represents the average variation from the standard value for 100 times computation;
(5): represents the minimum variation from the standard value among the 100 times computation;
(6): represents the maximum variation from the standard value among the 100 times computation.

Experimental results for 8.5 mm lens

Table 1: Experimental results of 3x3 grouping for 8.5 mm lens

	(1)	(2)	(3)	(4)	(5)	(6)
A1	109.6499	109.4199	109.9764	1.5166	1.5026	1.5583
A2	110.5088	110.2992	110.5337	0.0362	0.0317	0.2010
A3	110.5185	110.4167	110.7717	1.5203	1.5073	1.5626
A4	109.6197	109.4958	109.8576	1.9216	1.9057	1.9760
A5	110.9626	110.8696	111.5486	0	-0.0258	0.0016
A6	109.9818	109.9292	110.2350	1.3720	1.3219	1.9451
A7	104.4492	104.2365	104.8033	6.0485	6.0083	6.3253
A8	105.4282	105.1048	105.5544	4.7197	4.6810	4.7430
A9	104.2289	103.9175	104.4629	5.8513	5.8217	5.8860
Average	108.3719	108.1877	108.6382	2.5540	2.5283	2.6888
Maximum	110.9626	110.8696	111.5486	6.0485	6.0083	6.3253
Minimum	104.2289	103.9175	104.4629	0	-0.0258	0.0016
	(1)	(2)	(3)	(4)	(5)	(6)
B1	110.5168	110.4849	110.5398	0.0331	0.0229	0.0456
B2	110.5008	110.4503	110.5845	-0.0778	-0.0788	-0.0316
B3	110.9427	110.8423	111.0285	0.0585	0.0573	0.0663
B4	110.8448	110.8241	110.9876	-0.0001	-0.0027	0.0132
B5	110.3959	110.3445	110.5210	0	-0.0060	0.0000
B6	110.3819	110.2853	110.4931	0.0714	0.0707	0.0855

B7	110.8223	110.7129	110.9164	-0.2975	-0.3003	-0.2760
B8	110.7896	110.6976	110.9004	-0.1312	-0.1351	-0.1075
B9	110.9135	110.7942	111.0026	-0.3901	-0.3925	-0.3766
Average	110.6787	110.6040	110.7749	-0.0815	-0.0849	-0.0646
Maximum	110.9427	110.8423	111.0285	0.0714	0.0707	0.0855
Minimum	110.3819	110.2853	110.4931	-0.3901	-0.3925	-0.3766

Table 2: Experimental results of 5x5 grouping for 8.5 mm lens

	(1)	(2)	(3)	(4)	(5)	(6)
C1	81.4222	81.4007	81.4411	1.1600	1.1434	1.1845
C2	81.6986	81.6531	81.7807	0.8828	0.8042	0.9311
C3	82.0119	81.9800	82.0317	0.5699	0.5531	0.6044
C4	81.7331	81.7119	81.7531	0.8506	0.8318	0.8732
C5	81.1318	81.1031	81.1910	1.4502	1.3935	1.4819
C6	81.9587	81.9431	81.9796	0.6231	0.6054	0.6412
C7	82.4809	82.4726	82.4936	0.1005	0.0920	0.1126
C8	82.8489	82.8339	82.8638	-0.2658	-0.2780	-0.2492
C9	82.4884	82.4764	82.5066	0.0945	0.0789	0.1089
C10	81.7594	81.7358	81.7766	0.8237	0.8077	0.8484
C11	81.5504	81.5268	81.5783	1.0325	1.0061	1.0576
C12	82.1281	82.1159	82.1529	0.4558	0.4318	0.4694
C13	82.5632	82.5513	82.5796	0	-0.0091	0.0338
C14	82.2183	82.2047	82.2321	0.3632	0.3521	0.3799
C15	81.3138	81.3088	81.3238	1.2689	1.2598	1.2769
C16	80.0951	80.0748	80.1224	2.4872	2.4631	2.5092
C17	80.5535	80.5345	80.5682	2.0299	2.0160	2.0499
C18	80.8222	80.8092	80.8391	1.7617	1.7449	1.7757
C19	80.5794	80.5601	80.6115	2.0037	1.9730	2.0235
C20	79.7918	79.7743	79.8215	2.7910	2.7620	2.8113
C21	77.9484	77.9156	77.9782	4.6338	4.6066	4.6692
C22	78.0964	78.0732	78.1249	4.4856	4.4606	4.5112
C23	78.3531	78.3263	78.3861	4.2304	4.1992	4.2585
C24	78.1034	78.0791	78.1370	4.4787	4.4474	4.5053
C25	77.5887	77.5431	77.6417	4.9943	4.9434	5.0402
Average	80.8496	80.8283	80.8766	1.7322	1.7076	1.7564
Maximum	82.8489	82.8339	82.8638	4.9943	4.9434	5.0402
Minimum	77.5887	77.5431	77.6417	-0.2658	-0.2780	-0.2492

	(1)	(2)	(3)	(4)	(5)	(6)
D1	82.5526	82.5189	82.6182	0.0119	-0.0520	0.0464
D2	82.7409	82.7245	82.7617	-0.1764	-0.1951	-0.1592
D3	82.6887	82.6622	82.7278	-0.1252	-0.1613	-0.0963
D4	82.6507	82.6405	82.6604	-0.0869	-0.0955	-0.0738
D5	82.6718	82.6198	82.7175	-0.1081	-0.1524	-0.0546
D6	82.7749	82.7628	82.7966	-0.2098	-0.2300	-0.1958
D7	82.6197	82.6091	82.6299	-0.0561	-0.0651	-0.0425
D8	82.6436	82.6333	82.6573	-0.0793	-0.0928	-0.0675
D9	82.6273	82.6053	82.6475	-0.0646	-0.0834	-0.0380
D10	82.5798	82.5720	82.5899	-0.0164	-0.0235	-0.0076
D11	82.4404	82.4285	82.4562	0.1230	0.1091	0.1360
D12	82.5209	82.5098	82.5342	0.0432	0.0319	0.0565
D13	82.5648	82.5520	82.5763	0	-0.0106	0.0138
D14	82.4664	82.4555	82.4784	0.0991	0.0881	0.1098
D15	82.5810	82.5768	82.5917	-0.0164	-0.0257	-0.0114
D16	82.5237	82.5228	82.5300	0.0392	0.0367	0.0430
D17	82.4418	82.4299	82.4623	0.1222	0.1044	0.1357
D18	82.6297	82.6122	82.6554	-0.0663	-0.0908	-0.0477
D19	82.4446	82.4319	82.4628	0.1176	0.1040	0.1335
D20	82.8994	82.8663	82.9281	-0.3369	-0.3637	-0.3005
D21	82.7641	82.7182	82.8193	-0.2006	-0.2527	-0.1531
D22	82.4324	82.4071	82.4541	0.1328	0.1124	0.1598
D23	82.4326	82.3891	82.4912	0.1312	0.0751	0.1763
D24	82.3963	82.3672	82.4934	0.1683	0.0721	0.1982
D25	82.3719	82.3192	82.4190	0.1928	0.1472	0.2471
Average	82.5784	82.5574	82.6064	-0.0145	-0.0405	0.0083
Maximum	82.8994	82.8663	82.9281	0.1928	0.1472	0.2471
Minimum	82.3719	82.3192	82.4190	-0.3369	-0.3637	-0.3005

Experimental results for 16 mm lens

Table 3: Experimental results of 3x3 grouping for 16 mm lens

	(1)	(2)	(3)	(4)	(5)	(6)
E1	100.5232	100.3236	100.6209	-1.4574	-1.5518	-1.2553
E2	99.9965	99.7186	100.2326	-0.9306	-1.1624	-0.6492
E3	100.1581	99.9353	100.4442	-1.0925	-1.3761	-0.8669
E4	99.9577	99.7711	100.1298	-0.8897	-1.0607	-0.7037
E5	99.0748	98.8930	99.2647	0	-0.1957	0.1746
E6	98.7858	98.6164	98.9203	0.2805	0.1478	0.4517
E7	99.3252	99.1816	99.4507	-0.2591	-0.3823	-0.1124
E8	99.0585	98.9236	99.2166	0.0071	-0.1478	0.1465
E9	99.0313	98.8477	99.2007	0.0356	-0.1321	0.2217
Average	99.5457	99.3568	99.7200	-0.4785	-0.6512	-0.2881
Maximum	100.5232	100.3236	100.6209	0.2805	0.1478	0.4517
Minimum	98.7858	98.6164	98.9203	-1.4574	-1.5518	-1.2553
	(1)	(2)	(3)	(4)	(5)	(6)
F1	99.0566	98.8741	99.2191	-0.1563	-0.3157	0.0284
F2	99.2256	98.9728	99.4156	-0.3242	-0.5123	-0.0707
F3	98.8471	98.4420	99.0485	0.0533	-0.1468	0.4600
F4	98.4928	98.3036	98.6500	0.4079	0.2524	0.5993
F5	98.9148	98.7214	99.0636	0	-0.1623	0.1807
F6	99.1646	98.9655	99.3228	-0.2630	-0.4192	-0.0639
F7	99.1254	98.8146	99.3906	-0.2243	-0.4866	0.0868
F8	99.0434	98.8456	99.2211	-0.1430	-0.3180	0.0557
F9	99.1563	98.9875	99.3132	-0.2548	-0.4091	-0.0841
Average	99.0030	98.7697	99.1827	-0.1005	-0.2797	0.1325
Maximum	99.2256	98.9875	99.4156	0.4079	0.2524	0.5993
Minimum	98.4928	98.3036	98.6500	-0.3242	-0.5123	-0.0841

Table 4: Experimental results of 5x5 grouping for 16 mm lens

	(1)	(2)	(3)	(4)	(5)	(6)
G1	71.9464	71.8055	72.0528	-1.4996	-1.6049	-1.3569
G2	71.7514	71.5569	71.8754	-1.3049	-1.4262	-1.1084
G3	71.5917	71.4871	71.7065	-1.1439	-1.2570	-1.0377
G4	71.5644	71.3939	71.7093	-1.1172	-1.2604	-0.9437
G5	71.6607	71.4802	71.8170	-1.2130	-1.3686	-1.0298
G6	71.1483	70.9770	71.2760	-0.7023	-0.8271	-0.5280
G7	70.9188	70.7872	71.0879	-0.4707	-0.6389	-0.3385
G8	70.7963	70.6824	70.9198	-0.3484	-0.4714	-0.2333
G9	70.7603	70.6670	70.9266	-0.3144	-0.4780	-0.2169
G10	70.8485	70.6612	71.0086	-0.4030	-0.5608	-0.2128
G11	70.8345	70.7116	70.9543	-0.3872	-0.5064	-0.2636
G12	70.6634	70.5716	70.7804	-0.2168	-0.3312	-0.1223
G13	70.4456	70.3245	70.5730	0	-0.1244	0.1243
G14	70.4712	70.2356	70.6543	-0.0251	-0.2041	0.2123
G15	70.5927	70.4709	70.6990	-0.1465	-0.2493	-0.0220
G16	70.8902	70.7660	71.0021	-0.4437	-0.5549	-0.3179
G17	70.7048	70.5115	70.9290	-0.2584	-0.4792	-0.0635
G18	70.6046	70.4828	70.7331	-0.1590	-0.2830	-0.0348
G19	70.6568	70.5547	70.7796	-0.2093	-0.3309	-0.1061
G20	70.6784	70.5477	70.8010	-0.2321	-0.3514	-0.1004
G21	71.6281	71.4604	71.7308	-1.1816	-1.2823	-1.0101
G22	71.4522	71.3645	71.5910	-1.0061	-1.1420	-0.9165
G23	71.3627	71.2761	71.4523	-0.9163	-1.0040	-0.8267
G24	71.3190	71.1570	71.4663	-0.8724	-1.0188	-0.7075
G25	71.3572	71.2330	71.4844	-0.9104	-1.0362	-0.7836
Average	71.0659	70.9266	71.2004	-0.6193	-0.7517	-0.4778
Maximum	71.9464	71.8055	72.0528	0	-0.1244	0.2123
Minimum	70.4456	70.2356	70.5730	-1.4996	-1.6049	-1.3569
	(1)	(2)	(3)	(4)	(5)	(6)
H1	70.6297	70.5083	70.6946	0.1295	0.0657	0.2521
H2	70.6622	70.5226	70.7546	0.0964	0.0059	0.2386
H3	70.6024	70.4219	70.8504	0.1555	-0.0892	0.3389
H4	70.5691	70.4297	70.7242	0.1896	0.0369	0.3309
H5	70.5951	70.4428	70.7907	0.1616	-0.0295	0.3173
H6	70.6678	70.5602	70.7601	0.0901	0.0008	0.2008
H7	70.5657	70.3708	70.6819	0.1922	0.0785	0.3895

H8	70.5722	70.3579	70.7451	0.1859	0.0168	0.4049
H9	70.5964	70.4337	70.7820	0.1628	-0.0214	0.3273
H10	70.6164	70.4144	70.7765	0.1426	-0.0158	0.3458
H11	70.5954	70.4327	70.7451	0.1625	0.0141	0.3286
H12	70.6625	70.5254	70.7716	0.0967	-0.0121	0.2349
H13	70.7602	70.6474	70.8614	0	-0.0999	0.1137
H14	70.6169	70.4436	70.7558	0.1406	0.0045	0.3163
H15	70.6426	70.5327	70.7170	0.1152	0.0431	0.2291
H16	70.7105	70.5401	70.8719	0.0491	-0.1106	0.2199
H17	70.6198	70.4970	70.7114	0.1382	0.0490	0.2634
H18	70.6136	70.4547	70.7621	0.1448	-0.0030	0.3050
H19	70.5056	70.3252	70.6112	0.2541	0.1490	0.4353
H20	70.6683	70.4960	70.8311	0.0909	-0.0705	0.2643
H21	70.7084	70.5664	70.8296	0.0512	-0.0676	0.1938
H22	70.7036	70.5760	70.7973	0.0549	-0.0362	0.1854
H23	70.5997	70.4937	70.6988	0.1600	0.0619	0.2660
H24	70.5347	70.4244	70.6366	0.2234	0.1253	0.3362
H25	70.6948	70.5495	70.8201	0.0628	-0.0587	0.2119
Average	70.6285	70.4787	70.7592	0.1300	0.0015	0.2820
Maximum	70.7602	70.6474	70.8719	0.2541	0.1490	0.4353
Minimum	70.5056	70.3252	70.6112	0	-0.1106	0.1137

Appendix 2: Image measuring

Table 5: The prior- and post- compensation results for forward and reverse paths of image measuring platform

	Position	I	J	K	L
1	25mm	1.6083	0.7155	1.4157	1.6247
2	30mm	0.5437	0.0801	1.1926	2.0630
3	35mm	1.6825	1.8988	0.9139	3.4928
4	40mm	1.7145	1.2772	0.7725	1.0874
5	45mm	1.8632	0.1598	1.0992	2.9310
6	50mm	2.1993	2.6745	1.0802	2.9650
7	55mm	0.7374	1.5320	1.4355	1.0699
8	60mm	1.4406	2.7853	1.4760	4.1058
9	65mm	1.6530	1.6378	1.6618	2.5817
10	70mm	1.2426	2.7429	1.7473	2.1093
11	75mm	1.5692	2.0324	1.4139	3.6917
12	80mm	0.8303	2.4636	1.0851	2.2626
13	85mm	2.0729	2.0526	1.8718	3.3895
14	90mm	0.7305	3.5740	1.2952	3.8781
15	95mm	1.4419	1.8325	1.6204	5.2640
16	100mm	0.0284	1.7246	1.5140	1.5981
17	105mm	1.7150	2.3372	1.2448	2.0890
18	110mm	1.2565	2.9857	0.9862	1.1981
19	115mm	2.1291	0.8501	0.7285	0.9905
20	120mm	1.5091	4.2554	1.5448	2.6149
21	125mm	2.6694	1.7694	3.6321	1.4648
22	130mm	0.7508	0.5156	4.0772	2.4752
23	135mm	3.1599	3.8636	1.2240	3.4622
24	140mm	1.6280	1.1026	2.2921	2.0405
25	145mm	3.6167	2.3082	3.5957	2.4201
26	150mm	1.6275	0.4845	2.5656	1.5823
27	155mm	2.4230	3.7442	2.4419	3.4403
28	160mm	2.4292	2.3749	2.4774	3.6444
29	165mm	3.0591	2.9524	1.9767	0.9390
30	170mm	2.4568	4.1439	2.4115	1.6809
31	175mm	2.4867	2.2574	1.8262	3.1768
32	180mm	2.7297	1.8022	2.2197	1.6372
33	185mm	1.1699	2.5146	4.7983	2.4795

34	190mm	1.5288	3.3167	1.3302	2.5129
35	195mm	3.6701	3.6975	2.4555	1.7101
36	200mm	2.3413	3.4986	4.6289	2.1553
37	205mm	2.9114	2.3866	2.9146	2.0834
38	210mm	3.4660	3.8091	3.2764	3.3691
39	215mm	3.0151	3.0968	2.1874	-0.5373
40	220mm	3.1148	1.7894	4.3839	1.0060
41	225mm	3.9226	1.1003	3.2992	2.0407
42	230mm	2.3940	2.1920	3.4392	1.0835
43	235mm	0.7914	3.2481	3.7525	3.4115
44	240mm	2.8478	1.2488	2.9278	1.2297
45	245mm	2.5832	2.1777	2.0952	0.7004
46	250mm	1.4538	1.7939	1.1218	2.2712
47	255mm	3.7994	-0.0175	3.4017	2.7293
48	260mm	3.3010	3.3079	2.3142	1.7338
49	265mm	2.0655	1.4000	2.8855	0.9544
50	270mm	2.8617	1.5330	3.7587	2.2325
51	275mm	3.2668	2.2310	2.9516	2.8918
52	280mm	0.4281	1.8165	2.4762	-0.9388
53	285mm	1.9710	3.0064	4.9063	2.9644
54	290mm	1.0981	2.5651	3.9416	2.8134
55	295mm	2.5032	2.2067	2.3661	0.9575
56	300mm	2.6473	2.0712	2.5372	0.7185
57	305mm	0.9943	2.1440	1.3324	2.0094
58	310mm	1.1637	2.8721	1.8044	0.3856
59	315mm	1.3173	2.5617	2.3205	-0.0792
60	320mm	5.6367	2.0286	2.7282	0.6714
61	325mm	1.4998	2.3130	2.0891	0.0699
62	330mm	3.0166	0.9189	3.0848	0.5040
63	335mm	1.8742	1.7911	1.5882	4.2163
64	340mm	3.3404	1.8813	0.3935	3.1697
65	345mm	2.7602	1.0991	1.9700	1.8299
66	350mm	1.2820	2.3993	1.8467	0.2181
67	355mm	4.0045	1.2138	4.3271	0.4134
68	360mm	2.7827	1.1746	2.8160	0.7572
69	365mm	1.0530	3.5566	1.5273	1.4931
70	370mm	3.8937	4.1795	3.6697	0.8990
71	375mm	5.7403	2.0582	5.2684	1.8170
72	380mm	7.7643	0.7311	3.6850	2.0791

73	385mm	6.7266	2.3852	7.6267	2.9146
74	390mm	6.0865	0.4772	6.9974	0.1403
75	395mm	8.7476	1.7874	5.2968	0.1412
76	400mm	7.4703	2.7837	5.9860	0.1446
77	405mm	4.3397	1.4672	5.3842	2.8879
78	410mm	12.9116	2.6679	4.1272	1.4074
79	415mm	6.2782	1.7350	3.0477	2.0218
80	420mm	7.8504	0.0305	4.4780	1.4967
81	425mm	5.5532	1.1835	6.9866	2.9429
82	430mm	5.4596	2.2448	6.9336	2.9193
83	435mm	9.0500	2.4603	6.2401	2.7696
84	440mm	3.7892	-1.0622	8.7273	2.7983
85	445mm	6.9505	3.2302	9.0466	2.0134
86	450mm	4.6050	1.9129	8.7591	1.8664
87	455mm	6.2595	0.1822	3.5549	3.1136
88	460mm	5.2219	3.1680	7.6305	2.7889
89	465mm	4.4162	3.2670	5.7071	1.3398
90	470mm	2.9881	0.5133	5.6740	1.7470
91	475mm	6.7444	2.6164	2.8274	0.8892
92	480mm	9.2225	0.9132	6.5720	1.8070
93	485mm	7.4346	1.9010	6.0657	2.2150
94	490mm	8.9546	1.0546	3.6604	5.4558
95	495mm	6.9367	2.1868	7.8101	2.1776
96	500mm	8.2372	2.1218	5.0773	1.6815
97	505mm	8.7692	1.2066	2.9699	0.1092
98	510mm	9.2752	2.1691	5.7403	2.0169
99	515mm	4.2557	2.2927	7.7643	1.5368
100	520mm	5.0977	1.0837	6.7266	3.4916
101	525mm	4.1218	2.7118	6.0865	0.3169
102	530mm	5.3922	1.9570	8.7476	0.1858
103	535mm	2.8672	2.0883	7.4703	0.5506
104	540mm	4.9676	1.6972	4.3397	1.8752
105	545mm	7.1369	1.7078	13.2300	2.9114
106	550mm	6.5250	2.2460	6.2782	2.7814
107	555mm	5.4031	1.2961	7.8504	1.9620
108	560mm	7.3665	0.7879	5.5532	2.5007
109	565mm	8.5430	2.4179	5.4596	1.6188
110	570mm	2.8802	1.4681	9.0500	1.6686
111	575mm	4.2366	2.5394	3.7892	1.4807

112	580mm	4.6103	2.1241	6.9505	0.7113
113	585mm	5.5020	1.4359	4.6050	2.7379
114	590mm	6.0299	1.6147	6.2595	2.1483
115	595mm	5.0875	2.2139	5.2219	1.5369
116	600mm	5.3713	1.6292	4.4162	2.0810
117	605mm	5.9912	3.1026	2.9881	1.2739
118	610mm	5.4679	2.3440	1.3296	0.9181
119	615mm	3.6718	2.3626	6.7444	3.0665
120	620mm	6.4035	2.1037	9.2225	2.0067
121	625mm	3.5821	3.9411	6.9367	1.6670
122	630mm	7.8459	0.7089	8.2372	1.3740
123	635mm	4.1931	2.0123	0.7692	3.0708
124	640mm	8.5385	1.4932	9.2752	1.8160
125	645mm	3.2077	1.3474	4.2557	2.3090
126	650mm	8.3684	2.2230	5.0977	-0.1446
127	655mm	8.9037	2.8445	6.3260	1.6144
128	660mm	5.7710	2.7470	7.3147	3.5777
129	665mm	5.3877	3.0166	6.2578	1.8415
130	670mm	3.3386	2.5692	5.9433	1.9183
Average		4.0048	2.0506	4.0374	1.9401
Maximum		12.9116	4.2554	13.2300	5.4558
Minimum		0.0284	-1.0622	0.3935	-0.9388