The Compensation of Machine Vision Image Distortion

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Abstract

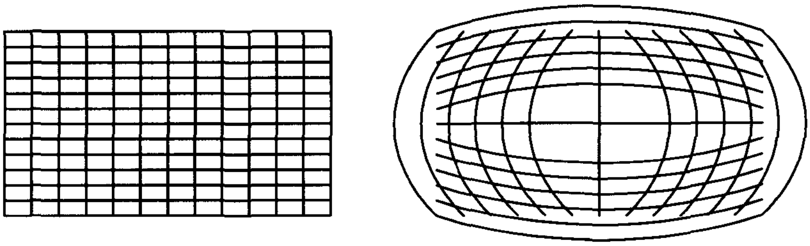
The measured values of a same object should remain constant regardless of the object's position in the image. In other words, its measured values should not vary as its position in the image changes. However, lens' image distortion, heterogeneous light source, varied angle between the measuring apparatus and the object, and different surroundings where the testing is set up will all cause variation in the measurement of the object when the object's position in the image changes. This research attempts to compensate the machine vision image distortion caused by the object's position in the image by developing the compensation table. The compensation is accomplished by facilitating users to obtain the correcting object and serves the objective of improving the precision of measurement.

Key Words: Machine Vision, Image Distortion, Compensation Table.

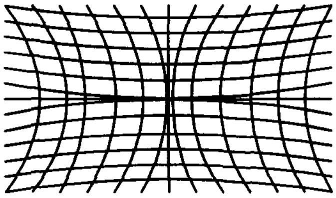
1. Introduction

A widespread application of industrial measuring apparatus is to use CCD (Charge Coupled Device), touch-free measuring equipment, as the image import tool for measuring the physical properties of the object in study, for instance, position, dimension, and defect. The application of such touch-free equipment can be found in the positioning, ID identification, and defect disposal of Wafer manufacturing process, the print circuit board (PCB) fiduciary positioning, and component examination and mounting on SMD machinery, the external examination and control of various medicines and food, either in high-tech electronic industry or in consumer goods production. From structure perspective, image-measuring system can be divided into image system and control system. Control system includes various hardware control units like mechanic arm, X-Y-Z platform, motion control, and I/O control etc. Image system is comprised of image development system and image editing unit. Image development system includes CCD, frame grabber, and optic equipment like lens and light source. Image editing unit further edits the image by recognizing borders, position, and defect after the image is captured.

The precision of image measuring system is determined collectively by the above-mentioned image system and control system. In this paper, we will not discuss precision control of hardware control system. The focus of this paper is how to improve the accuracy affected by image distortion given an image system not how to select a better image system. Image distortion can be caused by the geometrical distortion of lens or light source. As shown in Figure 1, lens' geometrical distortion has two types, one is Pincushion distortion and the other is Barrel distortion. Uneven light source will also cause variation in measuring results as the object moves its position.



Normal Image **Pincushion Distortion**



Barrel Distortion

Figure 1. Normal Image versus Distorted Images

The objectives of this research can be summarized as follows:

1. To explore the impact of lens on image;
2. To reduce distortion attributable to lens or light source by compensation;
3. To analyze research results and make proposals on how to improve the measurement accuracy of high-precision image.

2. Research Scope and Limitations

1. The specification of CCD image is RS170, size 640x480 pixels, and gray. The general frame grabber is used along with attached driver to capture the image.
2. Image computation code is Win32 written by Visual C^{++}6.0 on Windows 98 operating system, applying image capture function of frame grabber. All the other image-related computations are accomplished by self-running code instead of the library attached to frame grabber.
3. In order to avoid the flashing effect of light source, this study uses the dynamic measuring results for confirmation to reduce the variation in measured values caused by movement of light source.
4. This study selects the standard circle on a standard piece of glass as a correcting unit. The following testing is based on the different circles on the piece of glass.
5. The external geometrical properties of an object include point, line, circle, and arc. Except for point, which can be obtained directly for further application, all the other properties need to be calculated. For related computation formulas, please refer to Reference [1].

3. Research Methodology

The primary premise of this research is that the measured values of a same object should remain constant regardless of its position in the image, in other words, should not be any different as the object's position changes. However, in actual image measuring, different positions of the object usually result in varied values measured. This is mainly attributed to the image distortion caused by lens and the uneven light source. We have the option to choose lens with minor distortion, but due to price consideration, still lens with greater distortion are often seen in general applications. In such a case, users are required to place the object to be measured in the center of the image to reduce the impact of image distortion. However, as a matter of fact, even when the object is placed right in the center, the values of the positions farther away from the center still incur greater variance or distortion due to image distortion effect. The compensation is represented in two ways in this research:

1. Designate individualistic actual physical value corresponding to each and every pixel, that

is, the actual physical value of every pixel on the picture varies as the position shifts.

2. Convert every pixel to a value relative to the central pixel in the image, that is, the central pixel is given a value of 1, and the surrounding pixels could value at 0.9 or 1.1 pixel. The values are calculated based on the actual compensation result.

In the first way, while the accurate correcting unit is available, image distortion compensation and actual physical value computation can be accomplished simultaneously. Since this research is focused on the compensation for image distortion, the second way of representation is employed. Whenever an accurate correcting unit exists, the first way of representation can be applied to without modification needed. In this research, 8mm and 25mm lens are selected; the image is equally diced up to n segments; the variation in measured data at different positions is studied and then further used as the basis for compensation; finally the object is measured again and the post-compensation values are compared to the pre-compensation values.

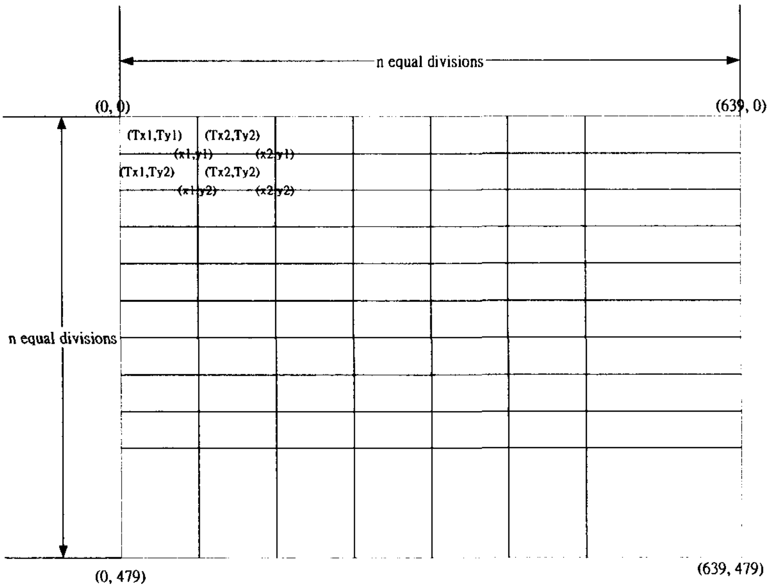


Figure 2. Image Partition for Compensation

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 2. 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]):
$$X = ((\mathrm{XPerUnit} \times \mathrm{CenterRight}) - 319.5) \times \mathrm{Calibration}[\mathrm{CenterLeft}][\mathrm{Ymin}] + \sum_{i=CenterRight}^{X\,\min-1} (\mathrm{XPerUnit} \times \mathrm{Calibration}[i][\mathrm{Ymin}]) + (X - X\,\mathrm{min} \times \mathrm{XPerUnit}) \times \mathrm{Calibration}[X\,\mathrm{min}][\mathrm{Ymin}] + 319.5$$

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]):

$$X = 319.5 - ((319.5 - (XPerUnit \times CenterLeft)) \times Calibration[CenterLeft][Ymin] +$$

$$\sum_{i=X\max}^{CenterLeft-1}(XPerUnit \times Calibration[i][Ymin]) +$$

$$(X\max \times XPerUnit - X) \times Calibration[X\min][Ymin])$$

The new Y coordinate is:

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

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

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

$$Y = ((YPerUnit \times CenterRight) - 239.5) \times Calibration[Xmin][CenterLeft] +$$

$$\sum_{i=CenterRight}^{Y\min-1}(YPerUnit \times Calibration[Xmin][i]) +$$

$$(Y - Y\min \times YPerUnit) \times Calibration[X\min][Ymin] + 239.5$$

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

$Y=239.5-(239.5-Y)\times Calibration[Xmin][CenterLeft]$

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

$$Y = 239.5 - ((239.5 - (YPerUnit \times CenterLeft)) \times Calibration[Xmin][CenterLeft] +$$

$$\sum_{i=Y\max}^{CenterLeft-1}(YPerUnit \times Calibration[Xmin][i]) +$$

$$(Y\max \times YPerUnit - Y) \times Calibration[X\min][Ymin])$$

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:

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

$$(X - X\min \times \text{XPerUnit}) \times \text{Calibration}[X\min][\text{Ymin}] + 319.5$$

2. When X<=319.5:

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

$$(X\max \times \text{XPerUnit} - X) \times \text{Calibration}[X\min][\text{Ymin}])$$

Then, the new Y coordinate is:

1. When Y>239.5:

$$Y = \sum_{i=CenterY}^{Y\min-1}(\text{YPerUnit} \times \text{Calibration}[\text{Xmin}][i]) +$$

$$(Y - Y\min \times \text{YPerUnit}) \times \text{Calibration}[X\min][\text{Ymin}] + 239.5$$

2. When Y<=239.5:

$$Y = 239.5 - (\sum_{i=Y\max}^{CenterY-1}(\text{YPerUnit} \times \text{Calibration}[\text{Xmin}][i]) +$$

$$(Y\max \times \text{YPerUnit} - Y) \times \text{Calibration}[X\min][\text{Ymin}])$$

4. Experiment Structure

The structure of the experiment in this research is: (1) to obtain the measured values in correcting unit for all regions; (2) to adjust the compensation values for all regions based on measured results; (3) to build compensation table. Later in actual computation, when the value of a line or point of the object is asked for, the compensation table can be used to calculate the new coordinates for lines and points. The computation of a circle as shown in Figure 3 is used as an example to explain how the new computation formula works.

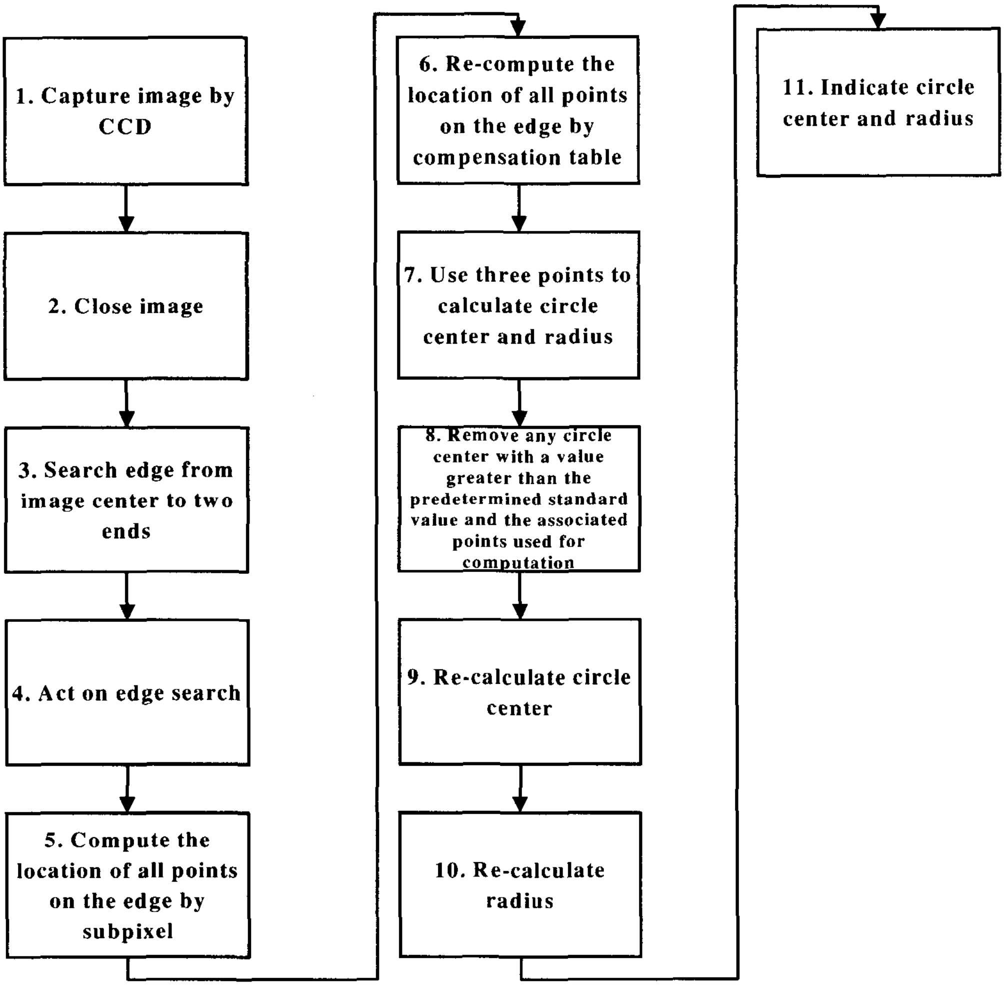


Figure 3. Computation Method for Circle Center and Radius

In this research, the lines and points are calculated by Subpixel, which is described in References [2, 3, 4].

5. Experiment Results and Discussions

The experimental items are shown in Table 1 as below:

Table 1. Experimental Item Grouping

8mm Lens				25mm Lens			
3x3 Grouping		5x5 Grouping		3x3 Grouping		5x5 Grouping	
Pre-Compensation	Post-Compensation	Pre-Compensation	Post-Compensation	Pre-Compensation	Post-Compensation	Pre-Compensation	Post -Compensation
A	B	C	D	E	F	G	H

Results are obtained for 9 subgroups in 3x3 Grouping (as shown in Figure 4), 25 subgroups in 5x5 Grouping (as shown in Figure 5). Therefore, A, B, E, F have 1~9 subgroups and C, D, G, H have 1~25 subgroups. For example, B8 is the post-compensation measurement of Position 8 in 3x3 Grouping for 8mm lens. Computation is done 100 times for every subgroup.

1	**4**	**7**
2	**5**	**8**
3	**6**	**9**

Figure 4. 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 5. The Position of Each Group in 5x5 Grouping

5.1. Experiment Results for 8mm Lens

5.1.1. 3x3 Grouping

Table 2. Experiment Results of 3x3 Grouping for 8mm Lens

	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
A1	109.2488	109.1843	109.2869	1.1875	1.1495	1.2521
A2	110.356	110.3378	110.3796	0.0803	0.0568	0.0986
A3	109.315	109.2933	109.3365	1.1214	1.0999	1.1431
A4	108.9642	108.9424	108.9916	1.4722	1.4448	1.494
A5	110.4364	110.4218	110.4512	0	-0.0148	0.0146
A6	109.0989	109.0891	109.1127	1.3375	1.3237	1.3473
A7	104.434	104.4087	104.4605	6.0024	5.9759	6.0277
A8	105.7239	105.6923	105.7524	4.7125	4.684	4.7441
A9	104.5814	104.5478	104.6115	5.855	5.8249	5.8886
Average	108.0176	107.9908	108.0425	**2.418756**	2.393856	2.445567
Maximum	110.4364	110.4218	110.4512	6.0024	5.9759	**6.0277**
Minimum	104.434	104.4087	104.4605	0	-0.0148	0.0146
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
B1	110.4596	110.4259	110.493	0.0322	-0.0012	0.0659
B2	110.5745	110.5499	110.6008	-0.0827	-0.109	-0.0581

B3	110.4046	110.3863	110.4354	0.0872	0.0564	0.1055
B4	110.4882	110.4535	110.5192	0.0036	-0.0274	0.0383
B5	110.4918	110.448	110.5245	0	-0.0327	0.0438
B6	110.3935	110.3677	110.4146	0.0983	0.0772	0.1241
B7	110.866	110.8324	110.9707	-0.3742	-0.4789	-0.3406
B8	110.6098	110.5795	110.6355	-0.118	-0.1437	-0.0877
B9	110.9485	110.9168	110.9935	-0.4567	-0.5017	-0.425
Average	110.5818	110.5511	110.6208	**-0.09003**	-0.129	-0.05931
Maximum	110.9485	110.9168	110.9935	0.0983	0.0772	0.1241
Minimum	110.3935	110.3677	110.4146	-0.4567	**-0.5017**	-0.425

5.1.2. 5x5 Grouping

Table 3. Experiment Results of 5x5 Grouping for 8mm Lens

	(1)	(2)	(3)	(4)	(5)	(6)
C1	81.4022	81.3806	81.4204	1.1414	1.1232	1.163
C2	81.6797	81.6329	81.7592	0.864	0.7844	0.9107
C3	81.9926	81.9599	82.0106	0.5511	0.533	0.5837
C4	81.7125	81.6909	81.7323	0.8311	0.8113	0.8527
C5	81.1131	81.0819	81.1704	1.4305	1.3732	1.4617
C6	81.9395	81.9229	81.9583	0.6041	0.5853	0.6207
C7	82.4617	82.4512	82.4725	0.082	0.0711	0.0924
C8	82.8294	82.8136	82.8423	-0.2858	-0.2987	-0.27
C9	82.4681	82.4564	82.486	0.0755	0.0576	0.0872
C10	81.7399	81.7158	81.7565	0.8037	0.7871	0.8278
C11	81.5305	81.5058	81.5573	1.0132	0.9863	1.0378
C12	82.1079	82.0952	82.1326	0.4358	0.411	0.4484
C13	82.5437	82.5307	82.5598	0	-0.0162	0.0129
C14	82.1988	82.1843	82.2117	0.3448	0.3319	0.3593
C15	81.2946	81.2874	81.3038	1.249	1.2398	1.2562
C16	80.0761	80.0545	80.1013	2.4675	2.4423	2.4891
C17	80.5332	80.5136	80.5482	2.0105	1.9954	2.03
C18	80.8021	80.7889	80.8188	1.7416	1.7248	1.7547
C19	80.56	80.5404	80.592	1.9836	1.9516	2.0032
C20	79.7723	79.7529	79.8014	2.7714	2.7422	2.7907

C21	77.9298	77.8954	77.9576	4.6139	4.586	4.6482
C22	78.0771	78.0535	78.1045	4.4666	4.4391	4.4901
C23	78.3328	78.3057	78.3655	4.2108	4.1781	4.2379
C24	78.0838	78.059	78.1164	4.4598	4.4272	4.4846
C25	77.5697	77.5228	77.6208	4.9739	4.9228	5.0208
Average	80.83004	80.80785	80.85601	**1.7136**	1.687592	1.735752
Maximum	82.8294	82.8136	82.8423	4.9739	4.9228	**5.0208**
Minimum	77.5697	77.5228	77.6208	-0.2858	-0.2987	-0.27
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
D1	82.5349	82.5008	82.5998	0.0125	-0.0524	0.0467
D2	82.7232	82.7062	82.7431	-0.1757	-0.1956	-0.1587
D3	82.6715	82.6441	82.7095	-0.1241	-0.162	-0.0966
D4	82.6328	82.6214	82.6422	-0.0853	-0.0947	-0.0739
D5	82.6544	82.6014	82.6997	-0.107	-0.1522	-0.054
D6	82.7565	82.7447	82.7784	-0.2091	-0.2309	-0.1972
D7	82.6017	82.5904	82.6125	-0.0542	-0.065	-0.0429
D8	82.6253	82.6142	82.6391	-0.0779	-0.0916	-0.0667
D9	82.6104	82.5861	82.6294	-0.0629	-0.0819	-0.0386
D10	82.5623	82.5549	82.5711	-0.0148	-0.0237	-0.0074
D11	82.4231	82.4103	82.4376	0.1243	0.1099	0.1372
D12	82.5029	82.4905	82.5156	0.0445	0.0319	0.057
D13	82.5475	82.5334	82.5584	0	-0.0109	0.0141
D14	82.4482	82.4372	82.4597	0.0992	0.0878	0.1103
D15	82.5633	82.5587	82.5728	-0.0159	-0.0254	-0.0113
D16	82.5073	82.5037	82.5107	0.0401	0.0368	0.0438
D17	82.4245	82.4113	82.4437	0.1229	0.1038	0.1362
D18	82.6122	82.5939	82.6373	-0.0648	-0.0898	-0.0464
D19	82.4279	82.414	82.4437	0.1195	0.1038	0.1335
D20	82.8834	82.8477	82.911	-0.3359	-0.3635	-0.3002
D21	82.7469	82.7002	82.7999	-0.1994	-0.2524	-0.1527
D22	82.4143	82.3879	82.4351	0.1332	0.1124	0.1596
D23	82.4153	82.3711	82.473	0.1321	0.0745	0.1764
D24	82.3783	82.3486	82.4752	0.1692	0.0723	0.1989
D25	82.3537	82.3003	82.3998	0.1938	0.1476	0.2472
Average	82.56087	82.53892	82.58793	**-0.01343**	-0.04045	0.008572
Maximum	82.8834	82.8477	82.911	0.1938	0.1476	0.2472
Minimum	82.3537	82.3003	82.3998	-0.3359	**-0.3635**	-0.3002

5.2. Experiment Results for 25mm Lens

5.2.1. 3x3 Grouping

Table 4. Experiment Results of 3x3 Grouping for 25mm Lens

	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
E1	104.54	104.3397	104.6373	-1.4479	-1.5452	-1.2476
E2	104.0129	103.7337	104.247	-0.9209	-1.1549	-0.6416
E3	104.1752	103.9507	104.4594	-1.0831	-1.3673	-0.8586
E4	103.9736	103.7876	104.1453	-0.8816	-1.0532	-0.6955
E5	103.0921	102.9085	103.2802	0	-0.1881	0.1836
E6	102.8025	102.6323	102.936	0.2895	0.1561	0.4598
E7	103.342	103.1972	103.4665	-0.2499	-0.3744	-0.1051
E8	103.0753	102.9386	103.2327	0.0167	-0.1406	0.1535
E9	103.0471	102.8632	103.2164	0.0449	-0.1243	0.2289
Average	103.5623	103.3724	103.7356	**-0.47026**	-0.64354	-0.28029
Maximum	104.54	104.3397	104.6373	0.2895	0.1561	0.4598
Minimum	102.8025	102.6323	102.936	-1.0831	**-1.3673**	-0.8586
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
F1	103.0411	102.8573	103.2014	-0.1434	-0.3038	0.0403
F2	103.2094	102.956	103.3972	-0.3117	-0.4996	-0.0584
F3	102.8317	102.4249	103.0319	0.066	-0.1343	0.4727
F4	102.4767	102.2857	102.6331	0.4209	0.2645	0.6119
F5	102.8976	102.7039	103.046	0	-0.1484	0.1937
F6	103.1474	102.9487	103.3051	-0.2497	-0.4075	-0.0511
F7	103.1084	102.7977	103.3716	-0.2107	-0.474	0.0999
F8	103.0262	102.8291	103.2036	-0.1286	-0.306	0.0685
F9	103.1393	102.9692	103.2943	-0.2416	-0.3967	-0.0716
Average	102.9864	102.7525	103.1649	**-0.08876**	-0.26731	0.1451
Maximum	103.2094	102.9692	103.3972	0.4209	0.2645	**0.6119**
Minimum	102.4767	102.2857	102.6331	-0.3117	-0.4996	-0.0716

5.2.2. 5x5 Grouping

Table 5. Experiment Results of 5x5 Grouping for 25mm Lens

	(1)	(2)	(3)	(4)	(5)	(6)
G1	51.9265	51.7846	52.0318	-1.5015	-1.6068	-1.3596
G2	51.731	51.5368	51.8546	-1.306	-1.4296	-1.1118
G3	51.571	51.4657	51.6849	-1.146	-1.2599	-1.0407
G4	51.544	51.3716	51.6886	-1.119	-1.2636	-0.9466
G5	51.64	51.4589	51.796	-1.215	-1.371	-1.0339
G6	51.1288	50.9562	51.2548	-0.7038	-0.8298	-0.5312
G7	50.8983	50.7663	51.067	-0.4733	-0.642	-0.3413
G8	50.7758	50.6611	50.8987	-0.3508	-0.4737	-0.2361
G9	50.7403	50.645	50.9055	-0.3153	-0.4805	-0.22
G10	50.829	50.64	50.9883	-0.404	-0.5633	-0.215
G11	50.8147	50.6906	50.9341	-0.3897	-0.5091	-0.2656
G12	50.6435	50.5499	50.7588	-0.2185	-0.3338	-0.1249
G13	50.425	50.3041	50.552	0	-0.127	0.1209
G14	50.4514	50.2157	50.6325	-0.0264	-0.2075	0.2093
G15	50.5723	50.4501	50.6778	-0.1473	-0.2528	-0.0251
G16	50.8694	50.7455	50.982	-0.4444	-0.557	-0.3205
G17	50.6851	50.4908	50.9075	-0.2601	-0.4825	-0.0658
G18	50.5854	50.4621	50.7109	-0.1604	-0.2859	-0.0371
G19	50.6365	50.5343	50.7592	-0.2115	-0.3342	-0.1093
G20	50.6582	50.5274	50.7801	-0.2332	-0.3551	-0.1024
G21	51.6083	51.4384	51.7104	-1.1833	-1.2854	-1.0134
G22	51.4326	51.3447	51.5702	-1.0076	-1.1452	-0.9197
G23	51.3428	51.2557	51.4314	-0.9177	-1.0064	-0.8307
G24	51.2988	51.135	51.4455	-0.8738	-1.0205	-0.71
G25	51.3368	51.212	51.4641	-0.9118	-1.0391	-0.787
Average	51.04582	50.9057	51.17947	**-0.62082**	-0.75447	-0.4807
Maximum	51.9265	51.7846	52.0318	0	-0.127	0.2093
Minimum	50.425	50.2157	50.552	-1.5015	**-1.6068**	-1.3596

	(1)	(2)	(3)	(4)	(5)	(6)
H1	50.5123	50.39	50.5764	0.13	0.0659	0.2523
H2	50.545	50.4039	50.6364	0.0972	0.0059	0.2384
H3	50.4855	50.3032	50.7313	0.1568	-0.089	0.3391

H4	50.4509	50.3104	50.6053	0.1914	0.037	0.3319
H5	50.4787	50.3244	50.6721	0.1636	-0.0298	0.3179
H6	50.5504	50.4414	50.6418	0.0919	0.0005	0.2009
H7	50.4481	50.2526	50.5625	0.1942	0.0798	0.3897
H8	50.4553	50.2385	50.6264	0.187	0.0159	0.4038
H9	50.4783	50.3144	50.6628	0.164	-0.0205	0.3279
H10	50.4987	50.2966	50.658	0.1436	-0.0157	0.3457
H11	50.4793	50.3135	50.6275	0.163	0.0148	0.3288
H12	50.5451	50.4073	50.6536	0.0972	-0.0113	0.235
H13	50.6423	50.5287	50.7422	0	-0.0999	0.1136
H14	50.4999	50.3262	50.6371	0.1424	0.0052	0.3161
H15	50.5254	50.413	50.5989	0.1169	0.0434	0.2293
H16	50.593	50.4215	50.7528	0.0493	-0.1105	0.2208
H17	50.5025	50.3785	50.5928	0.1398	0.0495	0.2638
H18	50.4959	50.3367	50.6439	0.1464	-0.0016	0.3056
H19	50.3881	50.2063	50.493	0.2542	0.1493	0.436
H20	50.551	50.3776	50.7114	0.0913	-0.0691	0.2647
H21	50.5902	50.448	50.7109	0.0521	-0.0686	0.1943
H22	50.5861	50.4574	50.6787	0.0562	-0.0364	0.1849
H23	50.4815	50.3756	50.5806	0.1608	0.0617	0.2667
H24	50.4174	50.3059	50.5179	0.2249	0.1244	0.3364
H25	50.5783	50.4301	50.7019	0.064	-0.0596	0.2122
Average	50.51117	50.36007	50.64065	**0.131128**	0.001652	0.282232
Maximum	50.6423	50.5287	50.7528	0.2542	0.1493	**0.436**
Minimum	50.3881	50.2063	50.493	0	-0.1105	0.1136

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.

5.3. Discussion of Experiment Results

From the results of 3x3 Grouping for 8mm lens (as shown in Table 2), the post-compensation (Group B in experiment) maximum distortion was reduced by 5.526 pixels from pre-compensation (Group A in experiment) maximum distortion of 6.0277 pixels to -0.5017 pixels. The average distortion declined from 2.418756 pixels to -0.09003 pixels. Based on the results of 5x5 Grouping for 8mm lens (as shown in Table 3), the post-compensation maximum distortion was -0.3635 pixels, a decrease of 4.6573 pixels from pre-compensation maximum distortion of 5.0208 pixels. The average distortion dropped from 1.7136 pixels to -0.01343 pixels.

From the results of 3x3 Grouping for 25mm lens (as shown in Table 4), the post-compensation (Group B in experiment) maximum distortion was reduced by 0.7554 pixels from pre-compensation maximum distortion of -1.3673 pixels to 0.6119 pixels. The average distortion declined from -0.47026 pixels to -0.08876 pixels. Based on the results of 5x5 Grouping for 25mm lens (as shown in Table 5), the post-compensation maximum distortion was 0.436 pixels, a decrease of 1.1708 pixels from pre-compensation maximum distortion of -1.6068 pixels. The average distortion dropped from -0.62082 pixels to 0.131128 pixels.

6. Conclusions and Recommendations

6.1 Conclusions

The following conclusions are drawn from the experiment results mentioned above:

1. The image distortion effect is not negligible. According to the experiment results obtained above, the different position of a same object in the image results in material variation in measured values. This effect is usually not explained to operators in detail. Therefore, the inappropriate placement of the object by operators causes distortion in measuring.
2. The compensation method proposed in this research reduces the distortion to be less than 1 pixel, that is, the difference in measurement of the same object for varying positions in the image can be controlled within 1 pixel. This provides a greater degree of freedom in

positioning the object without impact on the measurement accuracy.

3. The greater number of equalized segments the image is divided into, the more controllable the measured values of the object at different positions. However, more equal segments require more time on building compensation tables, so the users should determine the number of equal segments by the accuracy required.
4. The image distortion of the lens and the angle between the lens and the object also affect the measured results. Hence, users should avoid inappropriate lens and incorrect setup. For example, the image distortion of 8mm lens in experiment is far more significant than that caused by 25mm lens.

6.2 Recommendations

The only measuring unit considered in this research is pixel. The measured results can be converted to actual metric with the help of correcting unit. The image measuring itself requires not only optic and image control but also integration with hardware platform. The precision control of hardware platform is not an intended topic of this research. The discussion requires integrated mechanic and electronic professional knowledge. This research is focused on how to improve the measurement accuracy of current system, so the topics involve selection of lens and so on. Nevertheless, as a matter of fact, comprehensive considerations in image measuring are a prerequisite for high accuracy and high speed.

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