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Investigating Two-dimensional (2-D) Coordinate Calibration for Object Measurement in Robotic Arms

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Abstract
Nowadays, robots play an essential role in automated production lines, gradually replacing humans in many stages of production, thereby increasing productivity, improving quality, and reducing product costs. Robots are typically pre-programmed to perform specific tasks; however, with advancements in technology, robots are increasingly integrated with machine vision systems, making them more intelligent. This paper investigates two-dimensional (2-D) coordinate calibration methods which are linear and quadratic transformations for machine vision systems integrated with robotic arms. These methods establish the relationship between image coordinates and the world coordinate system, enabling the robot to use world coordinate data for object manipulation. The calibration framework was built using a calibration paper that includes 13 black circles in the X-direction and 12 in the Y-direction, each with a radius of 28 mm. The distances between the centers of the circles are 62 mm in the X-direction and 48 mm in the Y-direction, respectively. Image processing methods were employed to determine the image coordinates of the calibration points. Results from this study demonstrate that the coordinate calibration methods are effective and sufficiently accurate for a robotic arm to determine object positions in space
Keywords: *coordinate calibration, machine vision, robot arm.*

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I. INTRODUCTION

Today, machine vision offers innovative solutions in industrial automation and provides significant benefits for various industrial applications. These applications span manufacturing of electronic components [2], textile production [3], metal products [4], glass manufacturing [5], machined products [6], printed materials [7], and automated optical inspection for granite quality [8], as well as advanced manufacturing of integrated circuits (IC) [9], among others. By enhancing both productivity and quality management, machine vision technology provides numerous advantages to industries.

Calibration is crucial for the performance of a machine vision system, as its effectiveness relies on the accuracy of the calibration process. Numerous studies have explored various calibration methods. In one study, Shin, K. Y. et al. [10] proposed a new calibration method for a multi-camera setup using a "wand dance" procedure. This method initially estimates 3-D frame parameters using the Direct Linear Transformation (DLT) method. These parameters are then refined through iterative nonlinear optimization with the wand dance procedure. Experimental results showed that this calibration method significantly enhances the DLT algorithm's accuracy and user convenience.

In another study, Y. Ji et al. [11] proposed an automatic calibration method for a camera sensor network utilizing a 3-D texture map of the environment. This approach introduced a novel image descriptor based on quantized line parameters in the Hough space (QLH), enabling a particle filter-based matching process between line features and 3-D texture map data. Similarly, Deng, Li, et al. [12] explored a calibration model for cameras by accounting for geometric parameters and lens distortion effects. Their algorithm demonstrated robust avoidance of local optimums and precise completion of visual identification tasks.

Additionally, You, X. et al. [13] presented a two-vanishing-point calibration method for roadside cameras. To improve calibration accuracy, they used multiple observations of the vanishing points and introduced a dynamic calibration method to adjust camera parameters. This method is particularly suited for outdoor applications.

In summary, the literature demonstrates that machine vision technology is widely applied across many fields, and calibration is a critical aspect of its effectiveness. Therefore, this study presents an investigation of coordinate calibration methods, specifically linear and quadratic transformations, for enhancing robot vision.

II. EXPERIMENTAL SYSTEM

To investigate coordinate calibration for the machine vision system, this study used a Logitech C525 CMOS camera, connected to a computer via USB. The camera specifications are shown in Table 1. Image processing and machine vision software were set up on the computer. Calibration paper, measuring 744 mm by 528 mm in the OX and OY directions, respectively, was used to establish the relationship between image and world coordinates. The calibration instrument, shown in Figure 1, includes 156 black circles with a diameter of 28 mm. The space between two black circles is 62 mm in the OX direction and 48 mm in the OY direction. The experimental system setup is illustrated in Figure 2.

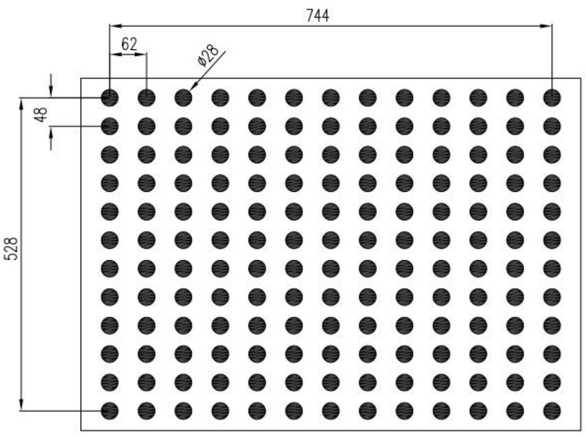

Figure 1: Calibration instrument.

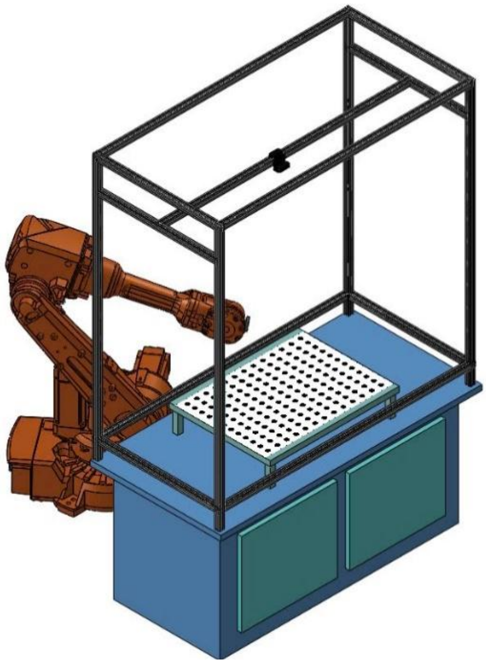

Figure 2: Diagram of experimental system.

Table 1. Specifications of CMOS Camera

No.	Specifications
1	HD video calling (1280 x 720 pixels) with recommended system
2	HD video capture: Up to 1280 x 720 pixels
3	Logitech Fluid Crystal™ Technology
4	Autofocus
5	Photos: Up to 8 megapixels
6	Hi-Speed USB 2.0 certified

III. RESEARCH METHODOLOGY

2.1 Linear transformation using regression

This method is used to determine the relationship between image coordinates and world coordinates. With this approach, a point is represented in two dimensions (2-D) by its coordinates (x, y). To accurately determine position information, the image coordinates of point I(x, y) must correspond to the world coordinates of point W(X, Y). The coordinate transformation from image coordinates to world coordinates must conform to a linear relationship, as shown in Equation 1. This relationship is fully established after obtaining the values of the factors a, b, c, e, f, and g using the coordinate data from three points.

$$\begin{cases} X = ax + by + c \\ Y = ex + fy + g \end{cases} \tag{1}$$

Where a, b, c, e, f, and g are transformation factors. In this method, the Cramer method and regression is used to determine these transformation factors.

2.2 Quadratic transformation method

In this method, the relationship between the image coordinates of point I (x, y) and the world coordinates of point W(X, Y) is described by Equation 2, as follows:

$$\begin{cases} X = a_1x^2 + b_1xy + c_1y^2 + e_1x + f_1y + g_1 \\ Y = a_2x^2 + b_2xy + c_2y^2 + e_2x + f_2y + g_2 \end{cases} \tag{2}$$

Where a_1, b_1, c_1, e_1, f_1, g_1 and a_2, b_2, c_2, e_2, f_2, g_2 are transformation factors. After completing conversion of the X, Y coordinates between the world coordinate system and the image coordinate system, the least squares method is represented by Equation 3.

$$\begin{cases} S_X = \sum_{i=1}^{n}[X - (a_1{x_i}^2 + b_1x_iy_i + c_1{y_i}^2 + e_1x_i + f_1y_i + g_1)]^2 \\ S_Y = \sum_{i=1}^{n}[Y - (a_2{x_i}^2 + b_2x_iy_i + c_2{y_i}^2 + e_2x_i + f_2y_i + g_2)]^2 \end{cases} \tag{3}$$

Where S_X and S_Y are summations of the squared errors with respect to the X and Y coordinates. To determine the transformation coefficients, we calculate the partial derivatives of S_X and S_Y with respect to each transformation coefficient.

2.3 Calibration method

In this section, the CMOS camera (C525) mounted above the working platform was used to capture images. The first step involved the camera capturing the calibration paper, after which the image data was sent to the computer. Using image processing technology, the centers and image coordinates of all circles on the calibration paper were determined. These centers were ordered from the 1st to the 156th, as shown in Figures 3 and 4. Subsequently, the image coordinate data and the corresponding world coordinates were utilized to determine the transformation coefficients. Finally, the relationship between the world coordinates and image coordinates was established, as detailed in Equations 1 and 2, concluding the calibration process.

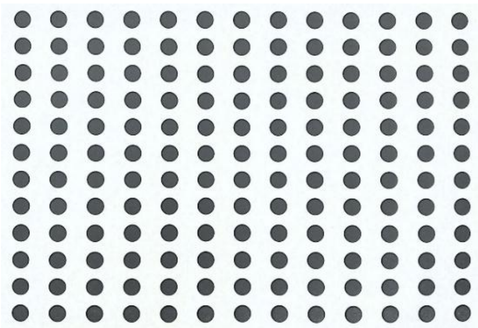

Figure 3: Binary image of calibration paper.

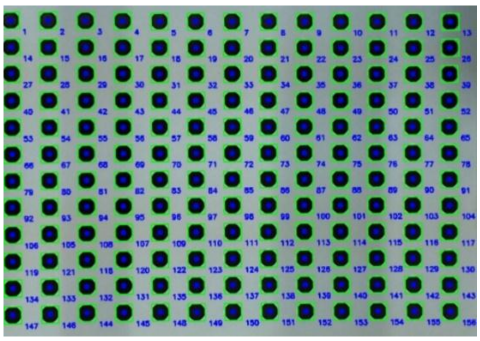

Figure 4: Recognized result.

IV. RESULTS AND DISCUSSION

2.2 Calibration result using linear transformation

To solve Equation 1, three points were selected from the calibration paper: the first point (1^{st}), the twelfth point (12^{th}), and the last point (156^{th}). These points are located within the workspace of the proposed system. Their image coordinates and the corresponding world coordinates are presented in Table 2.

Table 2: Coordinate table of three points.

Points	The world coordinate (mm)		Corresponding image coordinate (Pixel)	
	x	y	X	Y
1^{st}	0	0	129	64
12^{th}	682	0	569	67
156^{th}	744	528	600	404

Using the Cramer method, factors a, b, c, e, f, g in Equation 1 can be determined as following:

$$\begin{cases} X = 1.5479x + 0.0414y - 202.5645 \\ Y = -0.0107x + 1.5677y - 98.9570 \end{cases} \quad (4)$$

Using Equation 4, the relationship between the image coordinates (x, y) and the world coordinates (X, Y) for all points within the workspace of the proposed system can be calculated. However, calibration deviation of this method is high.

2.2 Calibration result using quadratic transformation

Using regression analysis, transformation factors (a_1, b_1, c_1, e_1, f_1, g_1 and a_2, b_2, c_2, e_2, f_2, g_2) can be obtained as follows:

$$\begin{cases} X = -0.000026629x^2 + 0.00011742xy - 0.000012468y^2 + 1.5665x - 0.018242y - 203.42 \\ Y = -0.000000065977x^2 - 0.0000026663xy + 0.00012098y^2 - 0.010728x + 1.5206y - 97.675 \end{cases} \quad (5)$$

From Equations (5), relationship between image coordinates (x, y) and the world coordinates (X, Y) can be determined.

2.3 Calibration result

Based on the experiment result, the quadratic transformation method was applied to determine the world coordinates, presented in Table 3. In Table 3, x and y represent the image coordinates, while X and Y denote the corresponding world coordinates. Additionally, ΔX and ΔY indicate the calibration deviations in the OX and OY directions, respectively. This table provides a comprehensive summary of the coordinate transformation accuracy, showing the effectiveness of the quadratic transformation method in minimizing calibration errors for precise positioning in the robot's workspace.

Using the quadratic transformation method with linear regression, the error analysis results are shown in Figure 5. These results indicate that the error in the OX direction ranged from 0.969 mm to -1.07 mm, with a total error of 2.039 mm. In the OY direction, the error ranged from 1.05 mm to -1.28 mm, with a total error of 2.33 mm. These results confirm the accuracy of the calibration method, indicating its suitability for precise object positioning required for the robot arm's manipulation tasks.

Table 3: Calibration work.

No.	x	y	X	Y	ΔX	ΔY
1	-0.5394	-0.5692	0	0	0.5394	0.5692
2	62.603	-0.5059	62	0	-0.603	0.5059
3	123.16	-0.60724	124	0	0.84	0.60724
4	185.65	0.49125	186	0	0.35	-0.49125
5	248.05	0.053654	248	0	-0.05	-0.05365
6	310.36	-0.38415	310	0	-0.36	0.38415
7	372.61	0.71352	372	0	-0.61	-0.71352
8	433.2	0.28614	434	0	0.8	-0.28614
9	495.26	-0.1524	496	0	0.74	0.1524
10	558.79	-0.60212	558	0	-0.79	0.60212
11	620.68	-0.5411	620	0	-0.68	0.5411
12	682.48	-0.4803	682	0	-0.48	0.4803
13	744.74	-0.6307	744	0	-0.74	0.6307
14	-0.5968	48.455	0	48	0.5968	-0.455
15	62.159	47.547	62	48	-0.159	0.453

No.	x	y	X	Y	ΔX	ΔY
145	62.794	528.53	62	528	-0.794	-0.53
146	123.33	528.46	124	528	0.67	-0.46
147	185.78	528.6	186	528	0.22	-0.6
148	248.16	528.14	248	528	-0.16	-0.14
149	310.45	527.68	310	528	-0.45	0.32
150	372.66	527.22	372	528	-0.66	0.78
151	434.81	528.37	434	528	-0.81	-0.37
152	496.86	527.91	496	528	-0.86	0.09
153	558.87	528.36	558	528	-0.87	-0.36
154	620.76	528.6	620	528	-0.76	-0.6
155	682.58	528.14	682	528	-0.58	-0.14
156	744.64	529.28	744	528	-0.64	-1.28

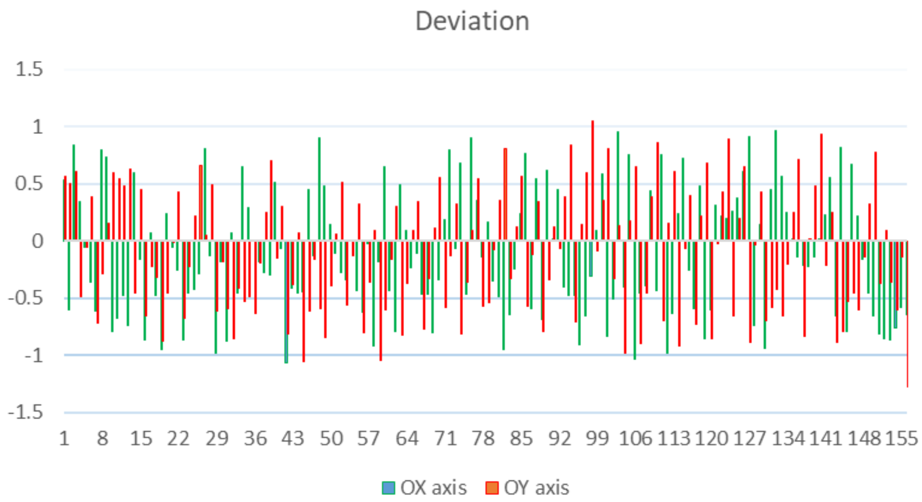

Figure 5: Calibration deviation in OX and OY directions.

V. CONCLUSIONS

This study investigated two calibration methods in two dimensional (2-D) space: linear transformation and quadratic transformation. These methods aim to establish general equations for converting image coordinates to world coordinates in two dimensions (2-D) for a machine vision system integrated with a robot arm. The methods were developed by determining the transformation coefficients using calibration paper. The calibration results were applied to identify the positions of objects in 2-D space which can be used for the manipulation of the robot arms. These methods are simple and easy to use. In the future, the accuracy of these methods could be enhanced by employing a higher-resolution camera and controlled lighting environments for the machine vision system.

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