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Self-calibration Method and Pose Domain Determination of Light-Pen in a 3D Vision Coordinate Measurement System

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Abstract: Light pen 3D vision coordinate measurement systems are increasingly widely used due to their advantages, such as small size, convenient carrying and wide applicability. The posture of the light pen is an important factor affecting accuracy. The pose domain of the pen needs to be given so that the measurement system has a suitable measurement range to obtain more qualified parameters. The advantage of the self-calibration method is that the entire self-calibration process can be completed at the measurement site without any auxiliary equipment. After the system camera calibration is completed, we take several pictures of the same measurement point with different poses to obtain the conversion matrix of the picture, and then use spherical fitting, the generalized inverse method of least squares, and the principle of position invariance within the pose domain range. The combined stylus tip center self-calibration method calculates the actual position of the light pen probe. The experimental results show that the absolute error is stable below 0.0737 mm and that the relative error is stable below 0.0025 mm. The experimental results verify the effectiveness of the method; the measurement accuracy of the system can meet the basic industrial measurement requirements.

Keywords: stylus tip center self-calibration; spherical fitting; pose domain; vision measurement system

1. Introduction

With the continuous development of human society, manufacturing has begun to flourish, and industrial measurement has become an extremely important link in the process of industrial development. With the development of industries that require high-precision real-time measurement in the automotive industry and aerospace industry, there are an increasing number of applications and requirements for workpiece measurement, and the requirements for workpiece measurement accuracy are increasing. At present, mainstream measurement technology is unable to keep up with ever-increasing measurement requirements. The traditional coordinate measuring machine (CMM)[1] cannot meet the online measurement requirements of some industrial sites due to its large size and limited measurement range. Indoor GPS, White light scanner[2, 3], optical laser trackers[4-6] and other common measurement equipment[7, 8] also have many shortcomings, such as low measurement efficiency, high cost, complex configuration, and poor portability. The shortcomings of modern measurement technology have limited the development of industry to a certain extent. Therefore, development of a new measurement technology has become a common expectation. Vision measurement systems[9] are mainly based on

computer vision, including measurement technology, electronic technology, image processing technology, etc., creating a new measurement structure frame, reducing measurement limitations, increasing flexibility and convenience, and allowing workpiece measurement from multiple angles. Its small size has met with favorable response in modern manufacturing fields such as aerospace and automobiles. The light-pen-type 3D vision measurement system[10] based on machine vision is increasingly widely used because of its small size, convenient portability, flexible assembly according to on-site measurement requirements, and good applicability, and related products have already been put into production[11]. Of course, many scholars have their own unique insights into visual measurement systems and have achieved notable results[12-15].

The actual coordinates of the center of the light pen stylus in the coordinate system directly affect the measurement accuracy of the three-coordinate measuring system. In practical applications, the center of the light pen stylus is mostly taken as a theoretical value when the light pen is used for processing. Due to the processing error of the light pen, the center value directly affects the measurement accuracy. When measuring various measurement objects, such as some deep holes and grooves, it is necessary to replace the light pen probe with other angles or add an extension rod for measurement. The difference in force and the loss of multiple uses of the light pen also cause small changes in the coordinates, so the self-calibration of the stylus tip center is particularly important. Liu optimized an objective function based on the principle of position invariance and the generalized inverse method of the least squares solution of the nonlinear equations and obtained the position of the stylus tip center in the coordinate system[16, 17]. Zheng proposed a two-step calibration method for the center of a plane target probe[18]. According to the principle of position invariance, the objective optimization function is established, and the optimized correction value of the stylus tip center in the X and Y directions in the target coordinate system is solved by the Levenberg–Marquardt algorithm. Then, the error of the stylus tip center in the Z direction is solved. Zhang also adopted the principle of position invariance and, based on this, gave error constraint parameters[19].

The work of this paper is divided into the determination of the pose domain and the self-calibration method of the probe center based on spherical fitting. The posture of the light pen is an important factor affecting accuracy. The pose domain of the light pen needs to be given so that the measurement system has a suitable measurement range to obtain more qualified parameters. Therefore, a threshold measurement device is designed according to the measurement system used in the experiment. The main body is composed of a light pen, connecting rod, base, motor seat, coupling and other parts. The transmission device is composed of a Siemens servo motor and the corresponding drive. The experiment was completed on the built measurement system[20]. After the motor parameters and program settings are completed, the experiment is driven by the motor to drive the device of the mechanical structure to make precise angle changes. For each rotation of 1° , the corresponding experimental image is collected to obtain the measurement error at this angle, and the data are sorted to obtain the pose that meets the requirements area. In the experiment of the self-calibration method, methods such as the principle of position invariance[17] are used. After the camera calibration is completed[21-24], the light pen probe collects multiple sets of images in different poses that meet the threshold measurement requirements under the CCD camera and uses the conversion relationship of each image to fit the same feature point on a sphere with the center of the probe as the center of the sphere, as shown in Figure 2. In this way, the actual position of the center of the probe is obtained.

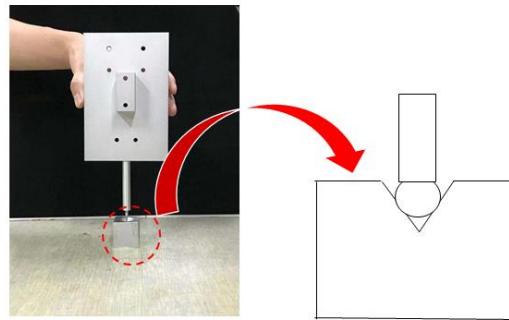


Figure 1. The principle of position invariance

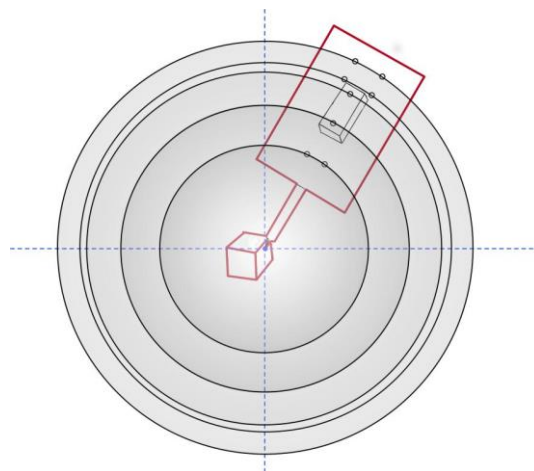


Figure 2. Schematic diagram of the self-calibration method

2. Self-calibration method of the stylus tip center

2.1. Light-pen-type 3D vision measurement system

The light-pen-type vision measurement system is mainly composed of three parts: a CCD industrial camera capable of imaging infrared rays, a computer and light pen, as shown in Figure 3. The light pen consists of 8 infrared LEDs and a detachable ruby ball probe. Figure 4 shows several types of probes. During the measurement, the light pen image is taken by the CCD industrial camera and transmitted to the computer for related calculations, and finally, the measurement result is obtained.

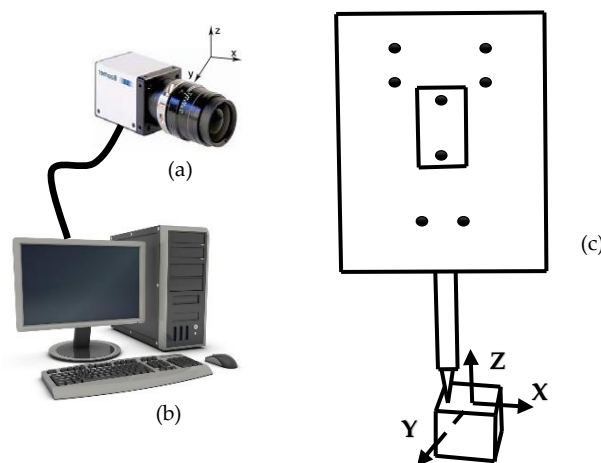


Figure 3. System composition diagram: (a)camera(b)computer(c)light pen



Figure 4. Light pen stylus

The measurement process of the measurement system is as follows: After the camera's internal parameters are calibrated[25], the user places the measured object and the light pen in the range that the CCD camera can shoot, the user presses the shooting button, the CCD camera takes a set of pictures, and the world coordinates of the measured object can be obtained. For the coordinates in the system, the distance between the two points can be measured by placing the light pen on another point in the same way.

2.2. Establishment of the coordinate system

The visual coordinate measurement system contains three coordinate systems:

1. Image coordinate system (O_0 -XY):

The coordinate system is established on the imaging surface of the CCD camera, with the center of the imaging surface as the coordinate origin. The x-axis and y-axis are respectively parallel to the horizontal and vertical imaging directions of the CCD camera, and parallel to the O_1UV plane (unit: pixel).

2. Camera coordinate system (O_1 -uvw):

The camera coordinate system is established on the industrial camera, and the origin of the camera coordinate system is the optical center of the industrial camera. The plane formed by the camera coordinate system is also parallel to the O_1UV plane (unit: mm).

3. Light pen coordinate system (O_2 -xyz):

The theoretical value of the center of the light pen stylus is the coordinate origin, and the direction of the light pen shaft is the y-axis; the lower plane perpendicular to the six characteristic points of the light pen is the z-axis, and the x axis is determined by the right-hand rule (unit: mm).

2.3. Parameter solving

Before measurement, the stylus tip center in the light pen coordinate system should be calibrated in advance. During the measurement, the images of the LED targets are captured by a CCD camera, and the computer processes the images to obtain the center coordinates of the center position of the target as a known quantity for calculating the rotation matrix R and the translation vector T [20]. The coordinates of the stylus tip center corresponding to the measured position in the camera coordinate system can be obtained by (1). Transformation from the camera coordinate system to the light pen coordinate system occurs as follows:

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} r_1 & r_2 & r_3 & t_x \\ r_4 & r_5 & r_6 & t_y \\ r_7 & r_8 & r_9 & t_z \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \quad (1)$$

Here, $\begin{bmatrix} r_1 & r_2 & r_3 \\ r_4 & r_5 & r_6 \\ r_7 & r_8 & r_9 \end{bmatrix}$ is the rotation matrix R of the image, and $\begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix}$ is the displacement matrix T of the image.

We establish the relationship between the camera coordinate system and the pixel coordinate system:

$$s \cdot \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & f \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix} \quad (2)$$

The conversion between the camera coordinate system and the pixel coordinate system is carried out by Equation (2); f is the focal length, $X = \frac{f}{w}u, Y = \frac{f}{w}v$;

We establish the linear equation set of the j -th feature point in the image:

$$s_j \cdot \begin{bmatrix} X_j \\ Y_j \\ 1 \end{bmatrix} = t_z \begin{bmatrix} a_1 & a_2 & a_3 & a_4 \\ a_5 & a_6 & a_7 & a_8 \\ a_9 & a_{10} & a_{11} & 1 \end{bmatrix} \begin{bmatrix} x_j \\ y_j \\ z_j \\ 1 \end{bmatrix} \quad (3)$$

$$\text{let } t_z \begin{bmatrix} a_1 & a_2 & a_3 & a_4 \\ a_5 & a_6 & a_7 & a_8 \\ a_9 & a_{10} & a_{11} & 1 \end{bmatrix} = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & f \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & f \end{bmatrix} \begin{bmatrix} r_1 & r_2 & r_3 & t_x \\ r_4 & r_5 & r_6 & t_y \\ r_7 & r_8 & r_9 & t_z \end{bmatrix}$$

$$s_j = r_7 x_j + r_8 y_j + r_9 z_j + t_z = t_z (a_9 x_j + a_{10} y_j + a_{11} z_j + 1) = t_z \zeta_j \quad (4)$$

$$\text{Equation (3) is equivalent to: } \zeta_j \cdot \begin{bmatrix} X_{cj} \\ Y_{cj} \\ 1 \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & a_3 & a_4 \\ a_5 & a_6 & a_7 & a_8 \\ a_9 & a_{10} & a_{11} & 1 \end{bmatrix} \cdot \begin{bmatrix} x_j \\ y_j \\ z_j \\ 1 \end{bmatrix} \quad (5)$$

After solving the linear equations, the parameters are separated to obtain the initial values of R and T.

In the ideal perspective imaging process, the solution obtained by the above formula is feasible because there is no error in the coordinate values of the object point and the image point in each coordinate system, and the calculated R satisfies the orthogonal system constraint. However, in the actual environment, due to various factors, such as the camera parameter calibration error, the image plane position extraction error of the control point center, and the coordinate value calibration error of the control point center in the coordinate system, the R matrix does not satisfy the orthogonal constraint relationship. Consequently, the matrix T also has a large error, so the initial values of R and T can be obtained by the linear equation solving method, and then the optimal solution of R and T can be obtained by the Newton–Gaussian iteration method[33].

2.4. Self-calibration method of the stylus tip center

After R and T are determined, because the distance between the characteristic point of the light pen and the actual position of the stylus tip center coordinate is a fixed value, according to the generalized inverse method of the nonlinear least square method, we can obtain:

$$(x_{ij} - x_0)^2 + (y_{ij} - y_0)^2 + (z_{ij} - z_0)^2 = d_{ij}^2 \quad (6)$$

Here, i represents the i -th image, and j represents the j -th feature point

The coordinate positions of the pictures in the coordinate system are different, but the distance from the actual position of the center coordinate of the probe is the same, so the same feature point of the n groups of pictures in the same spatial coordinate system (based on the probe and the actual position of the center coordinate) is the center of the sphere, and the constant distance between the characteristic point and the stylus tip center is the radius of the sphere. The $8n$ coordinates of n sets of pictures of the fitted 8 spheres are used to calculate the actual position of the center coordinates of the stylus.

We obtain the residual formula:

$$F = \sum_{i=1}^n [(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 - d^2]^2 \quad (7)$$

The corresponding partial derivatives are

$$\begin{aligned} \frac{\partial F}{\partial x} &= -4 \sum_{i=1}^n (x_i - x_0) [(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 - d^2] \\ \frac{\partial F}{\partial y} &= -4 \sum_{i=1}^n (y_i - y_0) [(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 - d^2] \\ \frac{\partial F}{\partial z} &= -4 \sum_{i=1}^n (z_i - z_0) [(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 - d^2] \\ \frac{\partial F}{\partial d} &= -4d \sum_{i=1}^n [(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 - d^2] \end{aligned} \quad (8)$$

We insert the coordinate values, set the partial derivative equal to zero, construct a system of equations, and solve it to obtain the actual position of the center coordinate of the probe.

2.5. Self-calibration steps

1. After the measurement system is built, use the spatial coordinates of the characteristic points of the light pen measured by CMM as the initial value.
2. Use the principle of position invariance to shoot images of different poses. In view of the particularity of the self-calibration method, the image pose should be changed as much as possible within the threshold range to make the result more accurate.
3. After obtaining at least 8 sets of pictures within the threshold range, calculate R and T corresponding to each image by Equations (1)-(5).
4. After R and T are determined, construct Equations (6)-(8), and solve them.
5. Obtain the actual position of the stylus tip center coordinate in the light pen coordinate system.

3. Experiment

3.1. Pose domain experiment

We performed the threshold measurement experiment according to the above method.

When rotating around the X-axis, the angle between the light pen and the positive half axis of the Y-axis (pitch) is $41^\circ \sim 159^\circ$, and there is a clear and recognizable image.

When rotating around the Y-axis, the angle between the light pen and the positive half axis of the X-axis (yaw) is $0^\circ \sim 180^\circ$, and there is a clear and recognizable image.

When rotating around the Z axis, the angle between the light pen and the positive half axis of the X-axis (roll) is $0^\circ \sim 45^\circ$ and $136^\circ \sim 180^\circ$, and there is a clear and recognizable image.

Due to the processing error of the mechanical device and the measurement error of the measuring equipment, we use 1° as the unit of the data under the premise of ensuring that the error does not affect the experimental results. The motor drives the light pen to the measurement position, takes a stable image, calculates the measurement accuracy, and then rotates one degree to take the image. Every time it rotates by one degree, the camera collects 15 groups of images within the angle, analyzes and processes the data, and compares the obtained measurement results with the real values to obtain a difference. The graphs are shown in Figures 5-7.

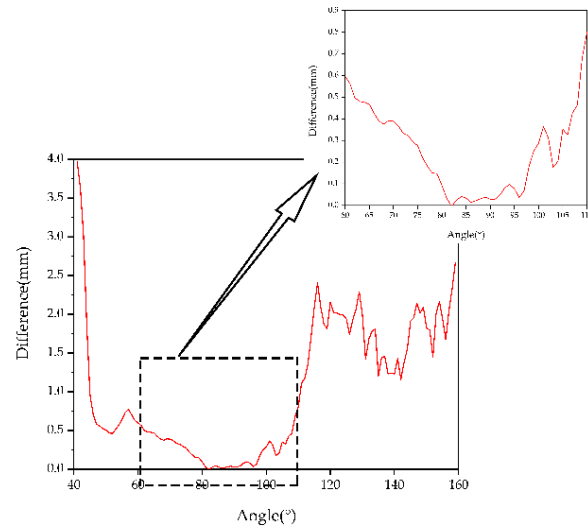


Figure 5. Pitch angle measurement results

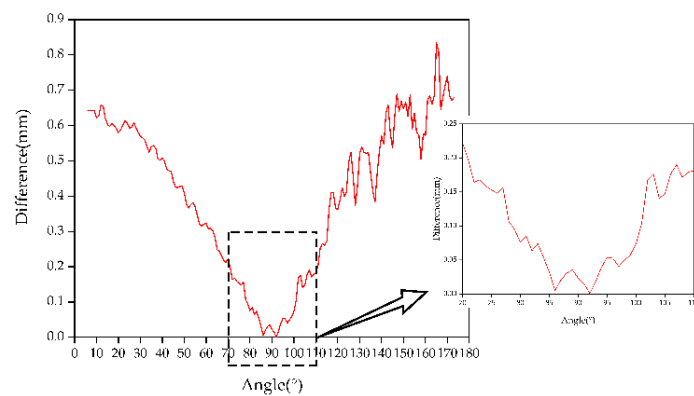
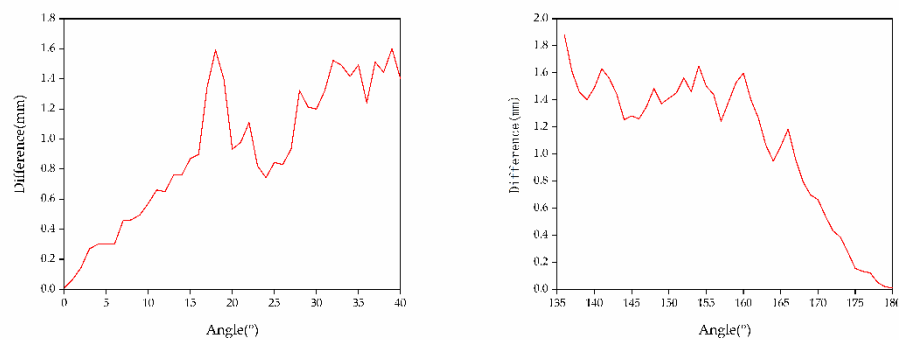


Figure 6. Yaw angle measurement results



(a) (b)

Figure 7. Tilt angle measurement results: (a) is the results of $0^{\circ}\sim 40^{\circ}$ (b) is the results of $136^{\circ}\sim 180^{\circ}$

When the pitch angle range is $80^{\circ}\sim 97^{\circ}$, the yaw angle is $80^{\circ}\sim 101^{\circ}$, and the tilt angle is $0^{\circ}\sim 2^{\circ}$ and $177^{\circ}\sim 180^{\circ}$, a certain measurement accuracy can be guaranteed to meet the measurement requirements. Satisfactory experimental results were obtained.

3.2. Self-calibration method

3.2.1. Self-calibration measurement experiment

We carried out the self-calibration experiment according to the method steps in this article. The self-calibration method was incorporated into the light pen measurement system for measurement comparison experiments, and each light pen performed 10 measurement experiments. Compare the measured value with the real value (30.0317mm) to get the absolute error and relative error. The measurement results are shown in Table 1.

Table 1. Self-calibration experiment

Stylus type	A	B	C	D	E
1	29.989	30.331	30.272	30.242	29.923
2	29.870	30.305	30.248	30.214	29.853
3	30.083	30.294	30.254	30.244	30.058
4	29.733	29.865	29.828	29.820	29.750
5	29.905	29.792	29.770	29.794	29.939
6	30.135	30.058	30.051	30.080	30.127
7	29.994	29.773	29.764	29.801	30.018
8	29.877	29.560	29.561	29.609	29.869
9	30.187	29.892	29.900	29.956	30.209
10	30.036	29.948	29.931	29.958	30.046
Average value	29.981	29.982	29.958	29.972	29.979
Absolute error	0.051	0.050	0.074	0.060	0.053
Relative error	0.17%	0.17%	0.25%	0.20%	0.18%

The measured values of the 5 light pen styluses are displayed on lines 2 to 11. The last three lines show the average, absolute error and relative error. The measurement results of each stylus in the ten images are represented by 1 to 10 lines. As shown in Table 1, the absolute error of the probe of each light pen is stabilized below 0.0737 mm, and the relative error is stabilized below 0.0025 mm. The experimental results meet the basic industrial measurement requirements, verifying the effectiveness of this method.

3.2.2. Single-point repeatability experiment

We put the light pen stylus in a standard cone, and under the premise of keeping the position of the light pen stylus unchanged, we rotate the position of the light pen to perform a single-point repeatability experiment.

Table 2. Single-point repeatability experiment

Test	1	2	3	4	5	6	7	8	9	10	AVE	STD	
A	u	78.995	78.995	79.014	79.004	78.997	78.997	78.983	79.002	78.990	78.995	78.997	0.008
	v	79.967	79.975	79.965	79.968	79.961	79.964	79.982	79.956	79.979	79.980	79.970	0.009
	w	790.029	789.994	790.040	790.026	790.047	790.030	789.965	790.083	789.986	789.948	790.015	0.041
B	u	79.061	79.074	79.054	79.066	79.068	79.071	79.056	79.064	79.068	79.047	79.063	0.008
	v	80.262	80.250	80.275	80.247	80.261	80.243	80.268	80.260	80.271	80.269	80.261	0.011

	w	790.209	790.262	790.205	790.261	790.220	790.271	790.236	790.277	790.216	790.219	790.238	0.028
	u	79.094	79.096	79.090	79.094	79.103	79.094	79.093	79.102	79.096	79.097	79.096	0.004
C	v	80.626	80.604	80.619	80.634	80.616	80.625	80.627	80.611	80.628	80.609	80.620	0.01
	w	790.286	790.298	790.263	790.222	790.283	790.235	790.231	790.302	790.250	790.289	790.266	0.03
	u	78.907	78.900	78.897	78.900	78.906	78.909	78.899	78.887	78.899	78.906	78.901	0.006
D	v	79.347	79.352	79.352	79.348	79.340	79.340	79.345	79.357	79.349	79.342	79.347	0.005
	w	789.472	789.444	789.425	789.474	789.508	789.518	789.481	789.404	789.467	789.509	789.470	0.037
	u	79.155	79.166	79.166	79.159	79.178	79.167	79.175	79.167	79.164	79.169	79.167	0.007
E	v	80.843	80.869	80.860	80.845	80.861	80.859	80.856	80.860	80.868	80.883	80.860	0.012
	w	790.859	790.855	790.882	790.908	790.881	790.845	790.909	790.907	790.864	790.843	790.875	0.026

The experimental results of 5 light pen styluses are shown in Table 2. The coordinates of the center point of each light pen stylus in the ten images are represented by columns 1 to 10. Single point repeatability is expressed by the standard deviation of ten center point coordinates. As shown in the previous column, the probe repeatability of each light pen does not exceed 0.041, which verifies the effectiveness of the self-calibration method.

4. Conclusions

This paper proposes a new self-calibration method, determines the pose domain of the measurement system through experiments, and describes the self-calibration process of the measurement system in detail. In the pose domain, the actual position of the light pen probe is calculated by a combination of spherical fitting, the generalized inverse method of the least square method, and the principle of position invariance. The experimental results are satisfactory, and the measurement accuracy after calibration is notably better than that before calibration. In future research, we plan to explore other factors that improve the measurement accuracy of the light-pen-type 3D vision measurement system.

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