A Novel 3D Measurement Method of welding workpiece for Robot off-line Programming

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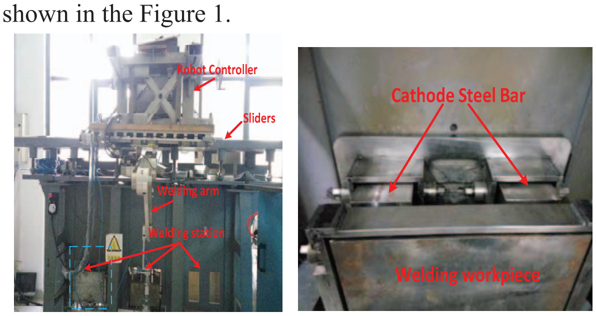
Abstract: In the narrow and dangerous working environment, the welding robot is an important way to guarantee the welding quality and improve the welding efficiency. During the process of the welding, the robotic abilities of environment perception and 3D measurement are the premise of robotic automatic planning and automatic control, especially in the narrow environment. Because the laser sensor has the characteristics of compact structure, non-contact measurement and high precision, the laser sensor is used to design a new 3D measurement system of welding workpiece combined with the practical application requirements of aluminum electrolytic cell. This system combines off-line programming mode of the special welding robot in the virtual environment to achieve semi-automatic batch welding tasks. At the same time, a calibration method based on monocular vision is designed to calibrate the laser sensor. Through the experimental verification, the system can well realize the 3D measurement of welding workpiece. Meanwhile, the angle measurement error is lower than 0.5 degree. And the results meet the actual welding demand through the actual welding experiment verification.

Key Words: narrow space; aluminum reduction cell; laser sensor; pose; monocular vision;

1 INTRODUCTION

In the modern manufacturing industry, the welding robot plays a key role in ship manufacturing, electrolytic metallurgy, petrochemical and other narrow and dangerous working environment[1]. The welding working environment of narrow spaces often appears in the industrial production, and these spaces also have high temperature, high radiation, strong electromagnetic interference and other complex features. Conventional manual welding is difficult to achieve these welding tasks. Therefore, the automatic welding robot technology is the key technology to ensure the person safety and production quality. This technology is also a typical representative of intelligent manufacturing technology[2]. Aimed at the automatic welding tasks of electrolytic aluminum cell in the metallurgical industry, this paper designs a fast 3D measurement system of welding stations to realize batch semi-automated welding tasks.

In the environment of aluminum electrolytic cell, the entrance of welding position is underground and the space of entrance is very narrow. And the gap between the cathode steel bars and welding workpiece is only about 20mm and the welding depth usually above 250mm. The picture of the welding station is shown in the Figure 1. Meanwhile, many electrolytic aluminum cells which need to be welded are placed in parallel. So the conventional manual welding cannot guarantee the welding quality. Therefore, the special welding robot is designed to replace the manual work to finish the welding tasks and improve the welding efficiency. The structure of the special welding robot system includes welding robot controller, guide rail, welding manipulator and welding stations. In order to complete the welding task of much welding stations, the guide rail is designed for the translation between the welding stations. The picture of the special welding robot is shown in the Figure 1.



(a) (b)

Fig 1. a)The special welding robot, b)the Welding station

During the process of welding, the workers cannot perform real-time monitoring during the process of robot welding, even with the help of CCD/CMOS camera and other measurement device. Meanwhile, no available space can be used to install some related detection devices, so the robot's sensing programming is difficult to be applied in practical welding tasks because of narrow space[3]. In this case, the robotic off-line programming mode in virtual environment is applied in the welding task of aluminum electrolytic cell to replace the robot's sensing programming. However, the off-line programming mode is greatly dependent on the 3D reconstruction of the robot's working space, so it lacks the ability of autonomous adaptation to the environment change and it cannot adapt to the current batch welding task. Therefore, this paper designs a flexibility and high-precision 3D measurement platform to achieve rapid pose detection and correction of all the welding workpieces, which guarantees that positions of all the welding workpiece are unification. Combined with the robot off-line programming mode, the system can realize the semi-automatic batch welding task well and improve the work efficiency.

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At present, the common 3D measurement methods are monocular vision, binocular vision, laser structured light, coded structured light and depth camera. Monocular vision measurement method cannot be directly applied to robot measurement tasks because of lack of depth information, and it often needs to cooperate with force sensors to realize the robot's environment perception. Binocular vision belongs to a kind of passive optical triangulation method[4]. The working environment of industrial robot often has the characteristics of single texture and simple structure. The binocular vision is difficult to be applied in the industrial environment. As a kind of active vision measurement technology, laser structured light also belongs to the triangulation method[5]. The disadvantage of laser structured light is that the scanning speed is slow, so it is difficult to realize fast 3D measurement. The coded structured light method is used to replace a camera with the projector in binocular vision[6]. But the measuring device is often large and not suitable for narrow space measurement. The principle of Depth cameras is often based on TOF (Time-of-Flight)[7] to achieve 3D measurement[8]. The main disadvantage of this method is the low measurement accuracy[9], which cannot be applied to high-precision 3D measurement of welding workpiece. Aimed at these shortcomings of traditional optical measurement methods, a flexible real-time 3D measurement system using laser sensor is designed to realize real-time measurement and correction of welding workpiece.

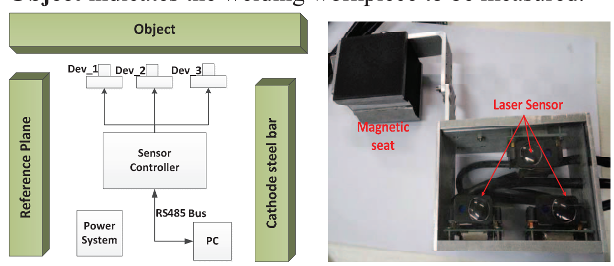
In this paper, aimed at the automation welding tasks in the electrolytic aluminum cell, a new 3D measurement system is designed to realize fast 3D measurement and correction of welding workpieces. The main contributions of this paper are described as follows. (1) Aimed at 3D measurement of much welding workpieces in the narrow space, the advantages and disadvantages of common 3D sensors are analyzed and a flexible 3D measurement system based on laser sensor is designed. (2) Aimed at parallelism calibration of lasers optical axis, the calibration algorithm based on monocular vision is designed to realize parallelism calibration of the laser measurement system. (3) Combined with the off-line programming of special welding robot, the system can realize the batch welding tasks automatically. This paper is organized as follows. The second part introduces the experimental platform. The third part introduces the principle of 3D measurement system and the fourth part is the parallelism calibration based on monocular vision. The fifth part is the experimental results and analysis. Finally, the last part is the conclusions.

2 SYSTEM PLATFORM

2.1 3D Measurement System

In the welding environment of aluminum electrolytic cell, a welding station is composed of two cathode steel bars and the welding workpiece. The cathode steel bar has the characteristics of large volume and heavy weight. And all of the cathode steel bars are installed in parallel in the fixed position. In this paper, the objective of 3D measurement system is mainly to measure the position of the welding workpieces in the 3D space and correct the position of the workpieces to ensure that they are in a unified position. So the cathode steel bars are set as the benchmark to adjust the pose of the welding workpiece.

According to the real measurement needs of aluminum electrolytic cell, a new 3D measurement system is designed combined with high-precision laser sensors to realize 3D measurement of all the welding workpieces. The whole measurement system includes laser sensors, laser controller, PC, magnetic seat and power system. The real picture of the measurement device is shown in the Figure 2. In the whole measurement system, the laser sensors are used for high-precision distance measurement. At the same time, the laser controller is used to control the data acquisition and data reading. In order to ensure the stability and convenience of the measurements, the magnetic seat is used to fix the device on the special position point of the cathode steel bars to realize the 3D measurement. And the software program on PC is to realize the data acquisition, processing and 3D display. The software program communicates with the laser sensor controller through RS485 bus. The specific structure of the 3D measurement system is shown in the Figure 2. In the left of the Figure 2, **Dev_x** $(\mathbf{x}=\mathbf{1},\mathbf{2},\mathbf{3})$ indicates three laser sensors and the **Object** indicates the welding workpiece to be measured.



(a) (b)

Fig 2. a)The structure of the measurement device, b) the real picture of the device

In order to realize the miniaturization of the measurement system, three laser sensors are used to construct the 3D measurement system. Based on the principle of three-coordinate measurement, the system can realize the real-time 3D position measurement of welding workpieces. The specific system measurement methods are shown in the third part of this paper.

2.2 Laser Sensors

In the measurement task of aluminum electrolytic cell, the laser sensor is used to build a fast and high-precision 3D measurement system. Compared with traditional methods, such as CCD/CMOS, depth camera and so on, the laser sensor has the advantages of small volume, high precision and high speed[10]. Laser sensor is a kind of high precision distance sensor, which has many advantages than other devices, such as strong anti-interference ability, small measurement point and so on. So it can be widely applied in the measurement of object contour, thickness measurement and so on. The distance measurement principle of laser sensor is realized by phase method principle, so the relationship between the measurement distance and the phase of the optical signal can be expressed as:

$$L=\frac{1}{2}ct \tag{1}$$

$$t=\frac{\emptyset}{w}=\frac{2\pi N+\Delta\emptyset}{2\pi f}=(N+\frac{\Delta\emptyset}{2\pi})\frac{1}{f} \tag{2}$$

Combined with the formula (1) and formula (2), the following formula can be obtained as follows.

$$L = \frac{1}{2}ct = \frac{c}{2}\left(N + \frac{\Delta\emptyset}{2\pi}\right)\frac{1}{f} = \frac{\gamma}{2}\left(N + \frac{\Delta\emptyset}{2\pi}\right) \quad (3)$$

In the formula (3), c is the propagation velocity of light wave; $\Delta\emptyset$ is phase difference; f is the modulation frequency of signal; γ is the wavelength of modulated wave; L is the measurement distance between laser sensor and the object to be measured. Therefore, the distance measurement can be converted to the measurement of the phase difference between the received signal and the emitted signal. The phase difference is the sum of the phase of the full wavelength and half wavelength. So the form of the measurement distance can be simplified as follows. And the specific measurement principle is shown in the Figure 3.

$$L = \frac{1}{2}ct = \frac{\gamma}{2}(N + \Delta N) \quad (4)$$

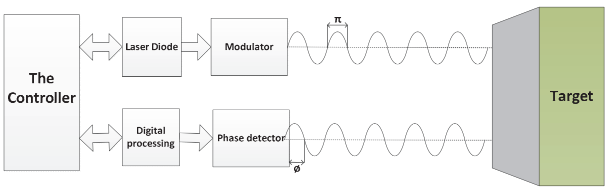


Fig 3. The principle of the distance measurement

3 THE PRINCIPLE OF 3D MEASUREMENT

3.1 Position Measurement

Three-coordinate measurement principle is to determine the X, Y and Z value of the measurement point relative to the origin point of the coordinates system. So this principle can determine the space position of the object and the surface model of the object. And it can be applied in many applications, such as the roughness detection of the target surface and pose measurement. In this paper, in the narrow working environment of the aluminum electrolysis cell, the three-coordinate measurement system is constructed by three laser sensors. According to the three-coordinate measurement principle, the coordinate system is established in the Figure 4.

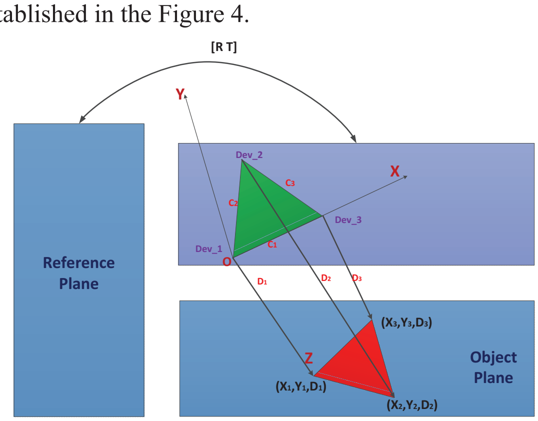


Fig 4. The coordinates system of the aluminum electrolysis cell

In the above coordinate system, the Reference Plane and Object plane represent cathode steel bars and welding workpieces to be measured. The Sensor Plane represents a fitting plane by optical center of three laser sensors and $Dev_{\_i}(i = 1\sim3)$ indicates the three laser sensors. The optical center of the laser sensor is set as the origin of the coordinate system. The direction of laser sensor light emitting direction is set as the direction of the Z axis. And the selection of X axis is the direction of connection line between the two sensors. The symbol of $D_i(i = 1\sim3)$ is the measurement data of laser sensors. The symbol of $c_i(i = 1\sim3)$ is the distance between optical center of laser sensors and the value of c_i can be calculated through parallelism calibration. The coordinate value of $X_i(i = 1\sim3)$ and $Y_i(i = 1\sim3)$ can be calculated based on the value of $c_i(i = 1\sim3)$.

The Least squares method is a common mathematical optimization technology through minimizing the sum of squares of error to find a best function matching, and it usually can be applied for curve fitting and plane fitting. Therefore, in this paper, the least square method is used to complete the fitting of the welding workpiece plane. For a series of points, $\sigma_i(i \in (1,2,\dots,n))$ represents the error value of each point and (a_0, a_1, a_2) represents the parameters of the plane, so the error equation expression of the plane and objective function can be defined as follows.

$$\begin{cases} z_1 - (a_0 + a_1x_1 + a_2y_1) = \sigma_1 \\ z_2 - (a_0 + a_1x_2 + a_2y_2) = \sigma_2 \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ z_n - (a_0 + a_1x_n + a_2y_n) = \sigma_n \end{cases} \quad (5)$$

$$s = \min \sum_{i=1}^{n}(a_0 + a_1x_i + a_2y_i - z_i)^2 \quad (6)$$

In the formula (6), the objective function can be transformed into the normal equation and it can be expressed in another form as follows. Combined with the Least squares method, the plane parameters (a_0, a_1, a_2) can be solved.

$$\begin{cases} a_1\sum x_i^2 + a_2\sum x_iy_i + a_0\sum x_i = \sum x_iz_i \\ a_1\sum x_iy_i + a_2\sum y_i^2 + a_0\sum y_i = \sum y_iz_i \\ a_1\sum x_i + a_2\sum y_i + a_0n = \sum z_i \end{cases} \quad (7)$$

In the actual process of 3D measurement, the position between the cathode steel bars and measuring device is fixed. So the position relationship T between the cathode steel bars and measuring device can be deduced based on the CAD model of the device. The transformation matrix can be expressed as follows.

$$T = \begin{bmatrix} r_1 & r_2 & r_3 & t_x \\ r_4 & r_5 & r_6 & t_y \\ r_7 & r_8 & r_9 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

Through this relationship, the 3D position of the object workpieces and the cathode steel bars can be determined and it can be used to guide the installation of the object workpieces. The simulation experiment is shown in the Figure 5

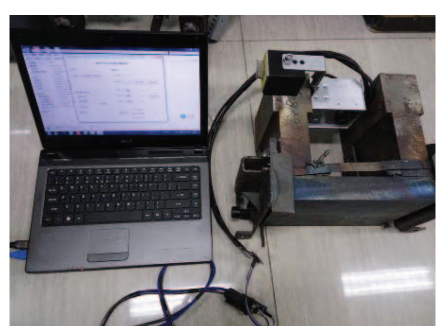


Fig 5. The simulation experiment of 3D Measurement

3.2 Angle Measurement

In the actual installation process of welding workpiece, real-time graphical 3D measurement results can directly show the relative position between the cathode steel bars and welding workpiece, but the measurement results lack of specific parameter information to evaluate measurement results. Therefore, in order to better reflect the position relationship between the welding workpiece and the cathode steel bars, the angle information is used to evaluate the results[11].

Combined with three coordinates of three laser points, the plane of the normal vector can be expressed as follows.

$$\begin{cases} A = (y_2 - y_1)(z_3 - z_1) - (y_3 - y_1)(z_2 - z_1) \\ B = (x_3 - x_1)(z_2 - z_1) - (x_2 - x_1)(z_3 - z_1) \\ C = (y_3 - y_1)(x_2 - x_1) - (x_3 - x_1)(y_2 - y_1) \end{cases} \tag{9}$$

And the angle value is determined by the normal vector. The special relationships are as follows.

$$\emptyset = \pi - \arccos\left(\frac{\overrightarrow{n_1}.\overrightarrow{n_2}}{|\overrightarrow{n_1}|*|\overrightarrow{n_2}|}\right) \tag{10}$$

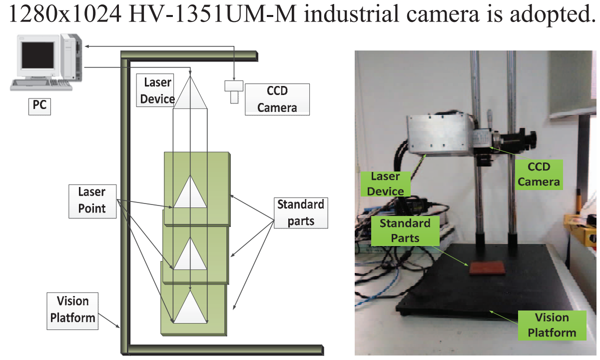
In the above formula, $\emptyset$ represents the angle between the plane of cathode steel bars and the plane of welding workpiece. The symbols of $\overrightarrow{n_1}$ and $\overrightarrow{n_2}$ indicate the normal vectors of the planes and the normal vectors are composed by (A, B, C). Combined with the graphical 3D measurement results, angle information and distance information of the laser sensors, all the welding workpieces can be adjusted to a unified position. With the help of the robot off-line programming in virtual environment, semi-automatic batch welding task of aluminum electrolytic cell can be finished.

4 THE PARALLELISM CALIBRATION

In the 3D measurement system, the laser projection direction is determined as the Z axis of the coordinate system. Therefore, the accuracy of the parallelism calibration of the laser optical axis determines the accuracy of the 3D coordinates of the measuring points. In order to realize the 3D coordinate calibration of the measurement system, with the help of high-precision vision platform and standard workpieces, the parallelism calibration of laser sensors is realized by the principle of monocular vision. When the laser axis is parallel and perpendicular to the reference plane, the triangle formed by three laser points is the same at different heights.

In this paper, a parallelism calibration method based on monocular vision is put forward. The basic steps of parallelism calibration are described as follows. (1) Three lasers project laser points to standard workpieces in turn, and CCD camera captures the image with laser points. (2) The triangle formed by three laser points is measured by computer program. (3) Repeat the above steps and complete laser projection in three different standard workpieces. At the same time, the positions of the laser sensors are adjusted to ensure that the three edges of the triangle at different heights are equal and the parallelism calibration is finished. To finish the parallelism calibration, the function of computer measurement software includes image acquisition, image preprocessing, the Canny edge detection, round fitting and the calculation the center and radius of the circle. The specific calibration principle and platform are shown in the Figure 6.

According to the principle of the parallelism calibration, a platform based on monocular vision is designed. The picture of the platform is shown in the Figure 6. The calibration system includes a high-precision vision experimental platform, CCD camera, standard parts and 3D measurement system to be calibrated. The calibration system platform is shown as follows. The adjustable vision platform is used to fix CCD camera and 3D measurement system. The standard parts are used for parallelism calibration. The CCD camera captures standard parts images with laser points and this image is processed by computer program. In this paper, the cost-effective 1280x1024 HV-1351UM-M industrial camera is adopted.



(a) (b)

Fig 6. a)The Sketch Map of parallelism calibration, b)calibration platform

4.1 Camera Calibration

The camera calibration is the key of 3D measurement. Due to the distortion of camera lens and Approximation error, the traditional camera calibration method is not suitable for high-precision calibration. Therefore, in this paper, the camera calibration method based on plane vision is adopted.

$$Z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} a_x & o & u_0 \\ 0 & a_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} \tag{11}$$

In the formula (11), $(u, v, 1)$ is the Image coordinate. (a_x, a_y, u_0, v_0) is the intrinsic parameters of the camera. (X_c, Y_c, Z_c) is the coordinate value in the camera coordinate system. Combined with the relationship between the camera coordinate system and world coordinate system, the following formulas can be deduced as follows.

$$Z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} a_x & o & u_0 \\ 0 & a_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{X_w}{d} \\ \frac{Y_w}{d} \\ \frac{Z_w}{d} \end{bmatrix} \tag{12}$$

Combined with the formula (12), the following formulas can be deduced as follows.

$$\begin{cases} u - u_0 = \frac{a_x}{d} X_w \\ v - v_0 = \frac{a_y}{d} Y_w \end{cases} \Rightarrow \begin{cases} u_2 - u_1 = \frac{a_x}{d}(X_{w2} - X_{w1}) \\ v_2 - v_1 = \frac{a_y}{d}(Y_{w2} - Y_{w1}) \end{cases} \tag{13}$$

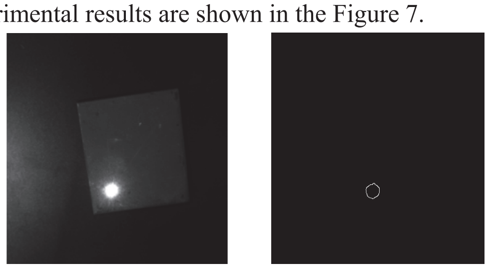
$$\begin{cases} k_x = \frac{u_2 - u_1}{X_{w2} - X_{w1}} \\ k_y = \frac{v_2 - v_1}{Y_{w2} - Y_{w1}} \end{cases} \tag{14}$$

The symbols of k_x and k_x are the ratio coefficients between the pixel distance and real distance which need to be calibrated. Therefore, the standard parts are used to calibrate the ratio coefficients.

4.2 Spot Center Extraction

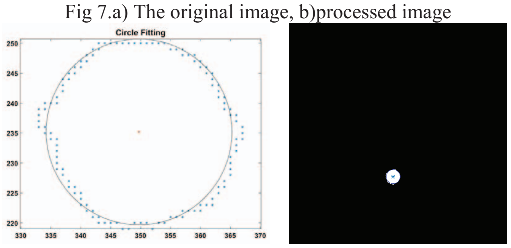
In the process of 3D measurement, the fast and accurate extraction of facula center is the basis of 3D measurement. At present, the common methods of spot center location include gray centroid method, the paraboloid fitting method[12] and so on. The gray centroid method has the disadvantage of weak anti-noise ability and limited precision, while the anti-noise ability of paraboloid fitting method is improved, but the precision of paraboloid fitting method is limited. In this paper, a method with the least squares method and Canny edge detection method is provided to realize the spot center extraction.

Because of the existence of noise information, it inevitably brings interference to the image. Image preprocessing must be performed before the spot center extraction. The adaptive Ostu method uses the statistical method to determine the optimal value and it can maximize the image gray level distinction. Meanwhile, the contrast of the laser point image and background of the target image is very large, so the Ostu method is used to realize image binaryzation. Then the Canny edge detection method is realized to realize the spot center extraction and the specific experimental results are shown in the Figure 7.



(a) (b)

Fig 7.a) The original image, b)processed image



(a) (b)

Fig 8. The results of the spot center extraction

Through the experimental results of the Figure 7, it can be seen that the combination method of the Ostu method and Canny operator can extract contour information of laser point formation well. In order to obtain the coordinates of the center, the least square fitting method is used for calculating the coordinates of the center.

In order to realize the circle fitting of laser point, the general equation of the circle can be expressed as follows.

$$R^2 = (x - A)^2 + (y - B)^2 \quad (15)$$

The square of the distance from the point to the edge of the circle can be defined as follows:

$$\delta^2 = (x_i - A)^2 + (y_i - B)^2 - R^2 \quad (16)$$

$$Q(A, B, R) = \sum \delta^2 = \sum[(x_i - A)^2 + (y_i - B)^2 - R^2]^2 \quad (17)$$

Based on the usual steps of the least squares, the following relationship could be acquired. Then the least square fitting method is used to complete the solution of A, B and R through optimization. The results of the circle fitting are shown as follows.

$$\begin{cases} \frac{\partial Q(A,B,R)}{\partial A} = 0 \\ \frac{\partial Q(A,B,R)}{\partial B} = 0 \\ \frac{\partial Q(A,B,R)}{\partial R} = 0 \end{cases} \quad (18)$$

Through the experimental results of the Figure 8, it can be seen that the spot center extraction of laser point is well realized. Then the pixel distances between the centers of the laser points can be calculated. With the results of the camera calibration, the actual length of the triangle formed by three laser points can be measured and the parallelism calibration could be finished.

5 Experiments

5.1 3D Position Display

According to the actual demand of aluminum electrolytic cell, this paper design a special 3D measuring device for the special structure of aluminum electrolytic cell to realize the 3D measurement of welding workpiece. During the measurement process, the 3D measurement device is fixed to a fixed point of the Cathode steel bars to ensure the consistency of the measurement results of all welding workpieces, and the simulation experiment and real experiment device are shown in Figure 9.

Fig 9. The experiments on the aluminum electrolytic cell

In order to test the effect of 3D measurement system, two sets of experiments are designed to verify the performance of the system. The experimental results are shown in the Figure10 and the Figure 11.

In the above experimental results, the Reference Plane and Object Plane represent the plane of the welding workpiece and the plane of the cathode steel bars. The three Dots indicate three laser welding points on welding workpiece. From the positive view and the top view of the measurement results, it can be seen that the 3D position of the cathode steel bars and the welding workpiece is well represented.

5.2 Angle Measurement

The Graphical position relationships can well show the positional relationships among workpieces, but this result lacks a direct representation form. In this paper, the angle information is calculated to evaluate the position relationship between the two parts.

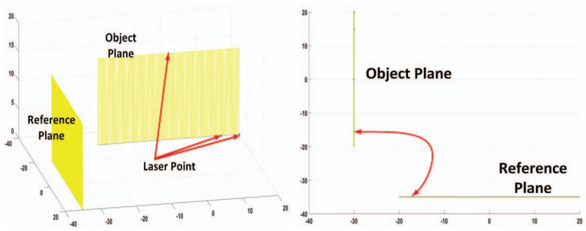


Fig 10. The Test results under 90°

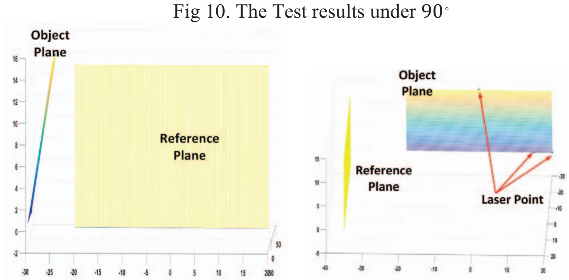


Fig 11. The Test results under 70°

In this experiment, through adjusting the position of two standard parts the accuracy of angle measurement is verified by the angle compare between measured value and actual value. In order to better verify the performance of the system and avoid the impact of random error, ten measurement experiments are done at each measurement point and these experiments take the intermediate value as measurement value. The specific test results are shown in the Table 1.

Table1. The results of angle measurement

Angle Setting	Measurement Angle	Measurement Error
60°	60.4°	0.4°
65°	64.8·	0.2°
70°	70.3°	0.3°
80°	80.3°	0.3°
85°	85.2°	0.2°
90°	90.4°	0.4°

Based on the Table 1, it can be seen that the measurement error of the system is lower than 0.5°. In order to better verify the performance of the system, the off-line programming of the robot in virtual environment is done. Combined with the 3D measurement system of all the welding workpieces, the system can well meet the actual demand after practical verification.

6 CONCLUSIONS

Aimed at the narrow and dangerous working environment, the special welding robot is designed to guarantee the welding quality and welding efficiency. However, the robotic sensing programming cannot be applied because of narrow space. To improve the efficiency of welding, a new 3D measurement system for welding workpieces is designed to keep the unified positions of all the welding workpieces. Combined with the off-line programming mode of robot in virtual environment, the system can realize the batch semi-automated welding tasks. Meanwhile, a calibration method based on Monocular vision is realized to complete the parallelism calibration of laser sensors. The experimental results show that the system can complete the position measurement and 3D display of the welding workpiece well, and the measuring precision of the angle between the welding workpiece and the Cathode steel bars is lower than 0.5 degree. Meanwhile, the 3D measurement system can meet the actual demand trough verification of real welding experiment. In the future, the function of the measurement device will be improved and the volume of device becomes smaller.

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