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A Novel 3D Seam Extraction Method Based on Multi-Functional Sensor for V-Type Weld Seam

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ABSTRACT To meet the current flexible modern manufacturing mode, based on the idea from coarse to fine, a novel three-dimensional(3D) seam extraction algorithm is proposed in this paper which includes the global rough extraction and the local fine positioning. Firstly, a multi-functional vision system based on Digital Light Processing(DLP) projector is designed to adapt different 3D measurement tasks. Secondly, a global sensor based on DLP projector is constructed which is used to acquire the whole weld seam. Meanwhile, a new feature extraction algorithm based on 3D information of work pieces is proposed. Thirdly, a line structured light sensor based on DLP projector is to serve as local sensor. Based on the results of rough extraction, the close-range laser scanning is to improve the measurement precision. Finally, the 3D path model and pose estimation of weld seam are done which could be applied into the 3D path teaching of welding robots. The experiments show that the proposed algorithm could well finish the high-precision 3D seam path planning through the ''Global-Local'' method.

INDEX TERMS Welding robot, seam extraction, DLP projector, ''global-local'' method, multi-functional sensor, point cloud processing.

I. INTRODUCTION

Nowadays, the welding robots have been widely working on intelligent manufacturing and automatic production lines. It could well improve the automation level of our nation manufacture equipments. Meanwhile, it could well guarantee the safety of workers and keep welding quality. The teaching-playback mode and the off-line programming(OLP) mode are the main working modes. Due to the complex working environment and changeable welding targets, these modes cannot perceive the working environment and lack certain flexibility to environment change. The intelligent welding robots [1]–[3] are the main research direction in the future.

The premise of the intelligent welding robots is the robot sensors. And it is used to get the image or location information about the welding work pieces. During the much research work, the common sensors include arc sensors [4]–[6], ultrasonic sensors [7], magneto-optical sensors [8], [9], infrared sensors [10], vision sensors [11]–[13]. Compared with other sensors, the vision sensors could obtain more details about weld seam. Meanwhile, it also has the advantage of high measurement precision. At present, the common vision sensors are passive and active light vision. Due to the characteristic of good robustness, the active light vision sensors have much applications on the intelligent welding robots. The common active light vision sensors are the laser structured light [14]–[16] and the coded structured light [17], [18]. The laser structured light has some advantages, such as good robustness and high precision. It is widely working on seam type identification and seam tracking. Due to its unique characteristics, it is just applied into local search applications. However, it cannot provide the global weld seam. The coded structured light sensors project some certain patterns to the work pieces and the seam extraction could be done by the processing of the distorted patterns. Due to larger working distance, it has limited measurement precision. Here, a multi-functional sensor is designed which integrates the merits of coded and laser structured light.

Recently, to realize intelligent welding, a considerable literatures have grown up around the theme of automatic

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3D seam extraction to replace the teaching-playback mode and OLP mode and improve the teaching efficiency of welding robot. The common 3D seam extraction methods include intelligent OLP mode, image-based methods, RGBD-based methods and laser structured light.

The conventional OLP modes provide such a solution of off-line path programming, which could upgrade the degree of automation and provide more efficient process and safer environment. However, it lacks the certain flexibility to environment change. The intelligent OLP mode is the upgrade of OLP mode which integrates the robot vision to OLP mode to enhance the ability of environmental perception. To overcome the shortcomings of OLP mode, Maiolino *et al.* [19] applied the RGB-D sensors to industrial robots to enhance the perception ability of welding robots. Through the registration of virtual environment and real point clouds based on 3D reconstruction, it could correct the results of OLP programming. It could well improve the measurement precision and the flexibility of the OLP mode. Nevertheless, the intelligent OLP mode also relies the construction of virtual welding environment. With the upgrade of modern manufacturing mode, the welding environment gradually presents unstructured characteristics which brings some challenges to the construction of virtual welding environment, and it will greatly affect the adaptability of the intelligent OLP mode.

Combined with the edge information of welding images, the image-based methods acquire the 3D seam path by the morphologic computation operator of welding images. Through the edge detection, Shah *et al.* [20] proposed an autonomous detection algorithm of the weld seam. And the proposed algorithm also defined some control points to realize the identification of seam type. Dinham and Fang [21] proposed a weld seam identification and localisation algorithm based on stereo vision [21]. To reduce the effect the background and determine the ROI area, a new searching algorithm was designed to locate the work piece. And the seam path was extracted by edge detection. However, the image-based method has poor robustness, due to the unique features of welding environment, such as weak contrast, reflections and the rust of work piece.

Compared with stereo vision and monocular vision, the RGB-D sensor could not only acquire the image about welding environment, but also depth inforamtion. Li *et al.* [22] proposed a 3D path extraction method based on RGB-D sensor. Fusion of spatial shape information of work piece, the seam path was detected by the image processing. And the depth information of seam path was detected by the registration of point cloud and welding image. In addition to the 3D seam path, it was also solved the 3D pose estimation of weld seam which could well determine the pose of welding guns. To acquire the seam path from the unorganized point clouds generated by RGB-D cameras, Ahmed *et al.* [23] proposed a novel edge and corner detection algorithm. Experiments showed that the proposed method could get better performance than 3D Harris operator. However, the RGB-D camera has disadvantages of limited measurement precision.

Due to the characteristics of high precision and good robustness, the laser structured light has been widely applied into the 3D measurement of welding robots. Zeng *et al.* [24] proposed a 3D path teaching method based on the laser structured light. Based on the characteristics of brightness loss in the narrow weld seam, the seam point could be extracted by the processing of laser stripe. And the 3D seam path could be acquired by the laser scanning. Meanwhile, the pose of weld seam was established according to the 3D information of laser scanning. To realize fast laser scanning, a seam extraction method based on kernelized correlation filters algorithm was proposed in our previous work [25]. Combined with the features of high speed and better extraction precision, the kernelized correlation filters algorithm was adopted to extract the seam points. The laser structured light is a local sensor and it can only perceive limited information. Therefore, the searching efficiency and measurement area of the laser structured light are low.

Based on the above research work, a novel 3D seam extraction algorithm based on the idea from coarse to fine is proposed. Combined with global rough extraction and the local fine positioning, the high precision seam extraction could be realized. The main contributions of this paper are as follows: (1) A multi-functional sensor based on the DLP projector is designed which could adapt different measurement task. (2) A new 3D seam extraction method is proposed based on the idea from coarse. (3) To perceive the whole weld seam, the global location method based on point cloud segmentation is proposed, which has better robustness to complex welding environment.

The rest of this paper is organized as follows: Section II describes the welding robot system and visual sensor. Section III is about the algorithm framework of this paper. Section IV describes the global rough seam extraction. Section V describes the local fine positioning of weld seam. Section VI introduces the experimental analysis. Finally, the conclusions and prospects are summarized.

II. SYSTEM CONFIGURATION AND SYSTEM ARCHITECTURE

A. EXPERIMENT PLATFORM

Here, an intelligent welding robot platform is designed to verify the performance of the proposed algorithm. The special system framework of the the experimental platform is shown in Fig.1. It mainly includes two parts: industrial robot platform and vision sensor. The industrial robot platform includes manipulator, teaching box, welding work pieces and manipulator controller. The vision system is used to perceive the global weld seam which is made up by industrial camera, optical projector and vision computer.

To construct the experimental platform, the Motoman UP6 manipulator is designed the welding robot platform. The high-performance industrial camera of MER-500-7UC with 2592(H)$\times$1944(V) resolution is adopted to design the vision sensor.

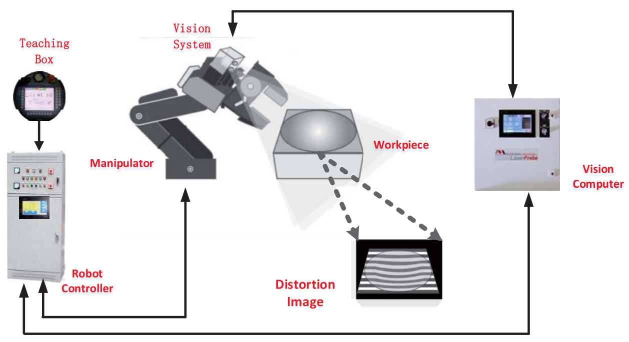

FIGURE 1. **The schematic diagram of the experimental system.**

B. VISION SYSTEM

The sensor system is the core part of the intelligent welding robots. Single sensor cannot get much information about welding environment and it is difficult to realize complex and high-precision welding task with a single sensor. At present, during much research work, multi-sensor fusion has been applied into the welding robots and it will get better performance than a single sensor on intelligent welding. However, much sensors will increase the complexity of actuators. Meanwhile, much sensors will bring the challenge to the limited installation space at the end of the manipulator. To better realized high-precision seam extraction, a multi-functional vision sensor is designed based on optical projector.

The DLP LightCrafter 4500 is used to design the vision sensor. The projector size is 122mm x 90mm x 48mm which has smaller size compared with commercial projectors, so it could well realize the miniaturization of robot sensor to adapt to the the limited installation space at the end of the manipulator. And it has high pattern switching rate up to 4225Hz. The sensor structure and size are shown in Fig.2.

To acquire 3D information of weld seam, combined with the DLP projector, the stereo cameras are adopted to design the stereo structured light sensor. And the 3D measurement is done combined with disparity model.

Meanwhile, in order to ensure synchronization between the DLP projector and the cameras, the input trigger of the DLP projector and the output trigger of the industrial camera are adopted. During the process of 3D measurement, the output trigger signal is generated by the camera exposure, which is used as the input trigger signal of the DLP projector to synchronize the pattern images switching and the camera acquisition. And the synchronization of stereo cameras is realized by program controlling.

C. SYSTEM ARCHITECTURE

To realize the high-precision and robust 3D seam path extraction, based on the idea from coarse to fine, a new "Global-Local" method is proposed based on the multi-functional vision sensors.

Based on the programmable DLP projector, the DLP projector separately generates the coded patterns and the line

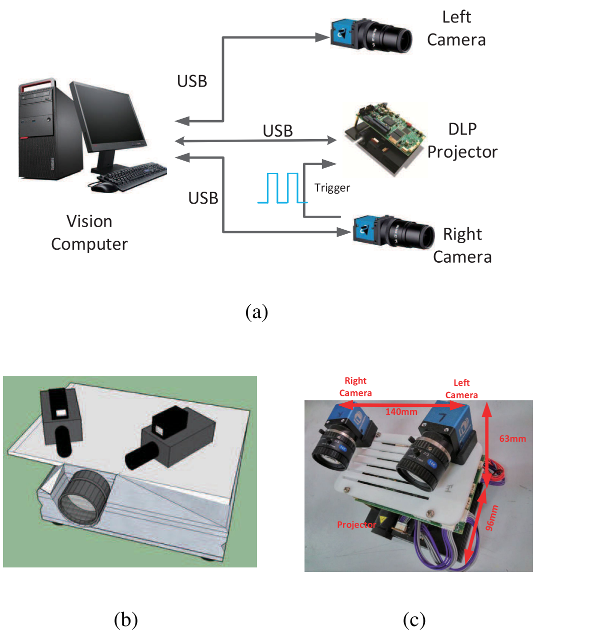

FIGURE 2. **The designed structured light sensor.**

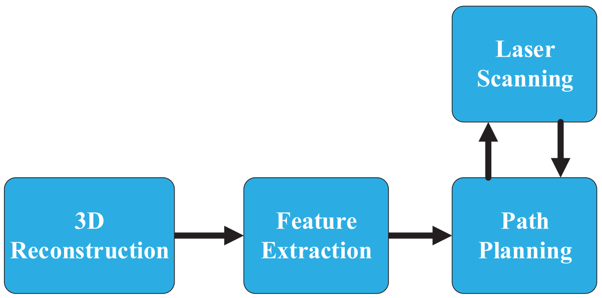

FIGURE 3. **The special architecture of the proposed algorithm.**

stripe. And the vision sensor separately acts as the coded structured light sensor and the line structured light sensor combined with the stereo cameras.

Through global seam extraction and local laser scanning, the precision seam extraction could be well realized, as shown in Fig.3.

1) The coded structured light is designed based on DLP projector as the global vision.
2) According to the results of 3D reconstruction, a global coarse extraction algorithm is proposed through point cloud processing.
3) The seam points by global coarse extraction is unsmooth, the path planning is needed to guarantee smooth and continuous seam path.
4) A line structured light is constructed to act as local vision. Based on the results of coarse extraction, the close-range laser scanning is used to improve precision of seam extraction.
5) The 3D path model and pose estimated of weld seam are done which could be used in the 3D path teaching.

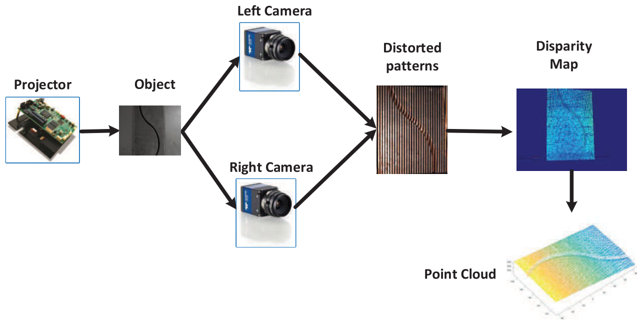

FIGURE 4. The diagram of 3D reconstruction.

III. GLOBAL SEAM EXTRACTION OF WELD SEAM

To realize robust global seam extraction of weld seam, a seam path extraction method is proposed based on point cloud processing. The key steps of global seam extraction includes 3D reconstruction, point cloud segmentation, feature extraction and path fitting.

A. 3D RECONSTRUCTION

3D reconstruction is prerequisite of the seam extraction in the proposed method. The digital fringe projection has been widely used in 3D reconstruction, reverse engineering and quality detection [26]. Compared with the stereo vision, shape form shading and laser scanning, this method has much good characteristic, such as fast measurement speed, good measurement precision and good robustness.

Most of the objects in the industrial environment are usually steel structure. Meanwhile, the industrial environment often presents the unique features of complex structure, weak texture and poor contrast. The digital fringe projection restores the 3D information by projecting patterns to object surface and it could well overcome the unique characteristics of industrial environment. The grid code is a common coding method which is adopted in this paper [27]. The diagram of 3D reconstruction is shown in Fig.4.

The weld seams with scratches and rusts are used to construct the experimental samples to test 3D reconstruction according to the flow chart of 3D reconstruction in Fig.5.

Fig.6 shows the experimental results of 3D reconstruction. The digital fringe projection has better accomplished 3D reconstruction of different work pieces. Meanwhile, it could well adapt to 3D reconstruction of scratches, rusts and weak texture. Therefore, it has good performance in industrial environment.

B. POINT CLOUD SEGMENTATION

To reduce the computation load of seam extraction, point cloud segmentation is proposed. Due to the simple shape of V-type butt joint, point cloud segmentation could realize the segmentation of the main plane and weld groove. Through the distance calculation form the weld groove to the main plane, the number of points involved in the calculation has been

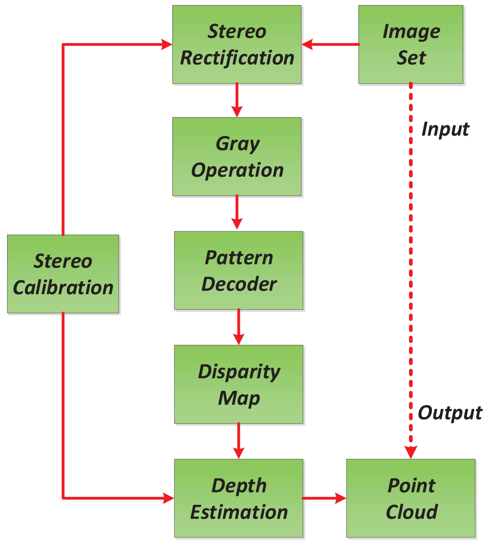

FIGURE 5. The flow chart of 3D reconstruction.

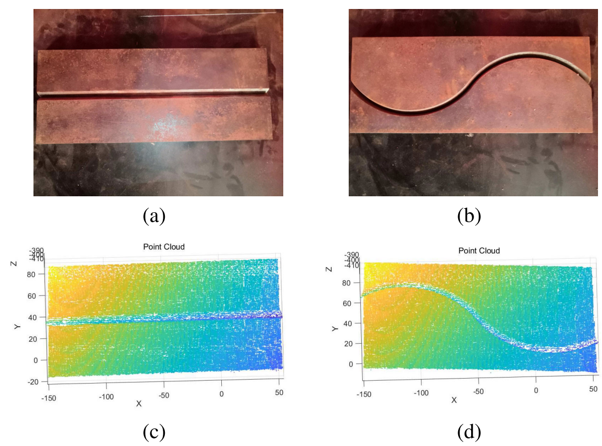

FIGURE 6. The results of 3D reconstruction.

greatly reduced and the computation load of seam extraction will reduce.

During the 3D reconstruction, there will be inevitably some noise. A robust plane fitting algorithm is necessary. RANSAC algorithm is a robust model fitting algorithm, which could accurately fit model from the data with outliers. So the RANSAC algorithm is used to fit the main plane of V-type work pieces.

Based on point clouds of work piece by 3D reconstruction, the results of point cloud segmentation are shown in Fig.7.

As shown in Fig.7, the planes of work pieces and grooves are well separated. And this geometric relation could well serve the seam extraction.

C. FEATURE EXTRACTION

During the actual industrial production, the V-type butt joint is a common weld seam. As shown in Fig.8, its structure and shape is simple. The valley line of the V-type butt joint is

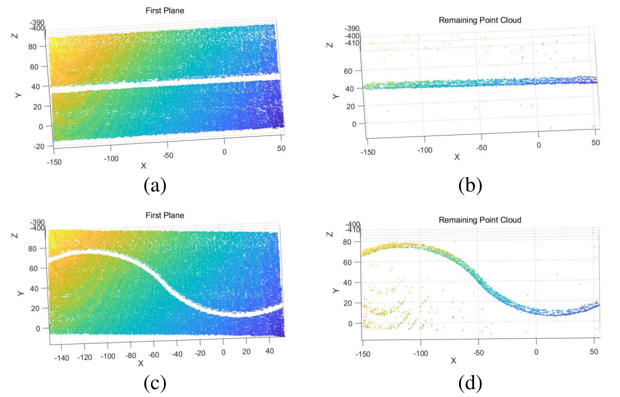

FIGURE 7. The results of point cloud segmentation. (a,c) The main plane of V-type butt joint; (b, d) Weld groove.

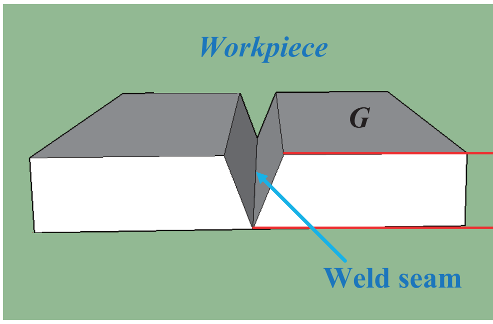

FIGURE 8. The model of the V-type butt joints.

weld seam. As we known, the distance from this valley line to the surface of work piece is certain and largest. Therefore, the distance information from the points in weld groove to the main plane is to serve feature extraction.

During the points of the weld groove, P_i is any point of weld groove. Its coordinates are (x_i, y_i, z_i). The distance from P_i to G is expressed as Eq.(1).

$$d_i = \frac{|a_0 + a_1x_i + a_2y_i - z_i|}{\sqrt{{a_0}^2 + {a_1}^2 + {a_2}^2}} \tag{1}$$

where (a_0, a_1, a_2) is the parameter of the main plane. Through the distance statistics between the points of weld groove and the main plane, the seam points could be acquired by maximum distance statistics.

The noise of point cloud will affect the follow-up seam extraction and an appropriate threshold is needed for feature extraction. Through experiment test, the threshold by some experiments is set as $0.92h_{\max}$. $h_{\max}$ is the maximum value from plane G to the points of weld grooves.

Based on the results of point cloud segmentation, Fig.9 shows the experiment results of the straight and curve weld seams.

The red points in point clouds are seam points. Its trajectory are consistent with the real seam paths. The proposed method could well finish feature extraction of point cloud with noise.

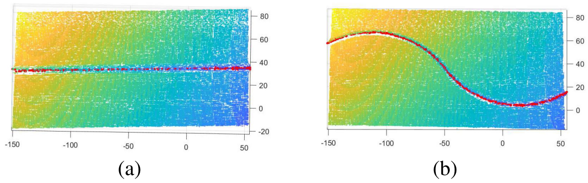

FIGURE 9. The experimental results of seam extraction.

D. PATH FITTING

This trajectory by seam extraction is un-smooth. The seam path by these feature points just could be only used to express the shape information of weld seam. So the path planning is an important link to guarantee smoothness and continuity of seam path.

Here, by separately fitting the X, Y and Z directions of seam points, the path fitting is expressed as Eq.(2).

$$\begin{cases} X_d = x(t) \\ Y_d = y(t) \\ Z_d = z(t) \\ 3D\_path = f(X_d, Y_d, Z_d) \end{cases} \tag{2}$$

By introducing the roughness penalty function, the smoothing spline function could realize the data fitting with noise. To better fit the weld seam, the smooth spline is adopted and its function is shown in Eq.(3)-Eq.(4).

$$\varepsilon = \sum_i w_i(y_i - s(x_i))^2 + m\int (\frac{d^2s}{dx^2})^2 dx \tag{3}$$

$$s(x) = \beta_1 f_1(x) + \beta_2 f_2(x) + \cdots + \beta_N f_N(x) \tag{4}$$

where ε is the fitting error. w_i is the weight.(x_i, y_i) is the data to be fitted. $f_i(x)$ is the basis function of the spline function. Here, the natural cubic spline function is adopted. $\beta_{(}i)$ is the coefficient of the basis function. m is the regulatory factor and its value is between 0 and 1. The value of m is shown in Eq.(5).

$$m = \frac{1}{1 + h^3/6} \tag{5}$$

where h is the average distance between points to be fitted.

To verify the fitting results of the smooth spline, Fig.10 shows the fitting results of different weld seams.

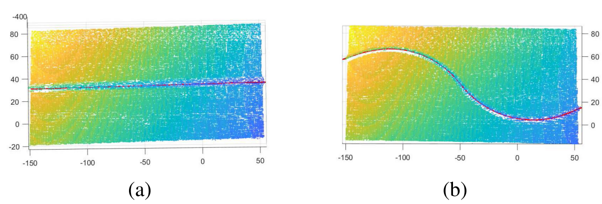

FIGURE 10. The experimental results of path fitting.

The fitting paths are in accord with the original weld seam. Therefore, the smooth spline could well keep smoothness and continuity of seam path. And it could well finish the path fitting with noise.

IV. LOCAL POSITIONING OF WELD SEAM

To acquire the whole weld seam and finish 3D reconstruction, the vision sensor works in a large distance and the global seam extraction algorithm could get high precision. Here, a line structured light is constructed to act as a local sensor to realize the close-range scanning. Through laser scanning, the "local positioning" of weld seam is done to improve measurement precision.

A. FEATURE EXTRACTION

To extract the feature points, the morphological image processing is adopted to finish seam extraction. This algorithm could be divided into four parts: image pre-processing, ROI extraction, center line extraction and feature extraction.

1) IMAGE PRE-PROCESSING

Inevitably, there are some noises in the weld images and it will affect the follow-up image processing. So image filtering is necessary. Median filter could prevent the image edge blur and maintain image details. It is used to done image filtering and the filtered image is used for subsequent ROI extraction.

2) ROI EXTRACTION

Large images will not only cause large computation, but also affect the real-time performance. To ensure algorithm performance, ROI extraction is done.

Because the stripe direction is nearly parallel with the image v-axis, the ROI area could be solved through the pixel value projection on image u-axis. The pixel value projection is solved in Eq.(6).

$$B_v(j) = \sum_{j=1}^{w} I(i, j) * i = 1, 2, \cdots, h \tag{6}$$

where $B_v(j)$ is the sum of the projection pixel value of the i-row image. w and h are the image width and image height.

And the ROI range could be determined by Eq.(7)-Eq.(8).

$$[u_{\min}, u_{\max}] = [1, w] \tag{7}$$

$$[v_{\min}, v_{\max}] = [v_c - 30, v_c + 30] \tag{8}$$

where $[u_{\min}, u_{\max}]$ and $[v_{\min}, v_{\max}]$ are the ROI area. And v_c is the row value with the greatest projection value. Fig.11 shows the results of ROI extraction.

3) CENTER LINE EXTRACTION

Generally, the stripe intensity values belong to Gaussian distribution, so the gray weighting method is used to obtain stripe center points. The stripe center point in every column is computed by Eq.(9).

$$L_s(j) = \frac{\sum_{i=v_s-30}^{v_s+30} i * I(i, j)}{\sum_{i=v_s-30}^{v_s+30} I(i, j)} \quad j = 1, 2, \cdots, w \tag{9}$$

where $L_s(j)$ is the center point in j-th column of weld images.

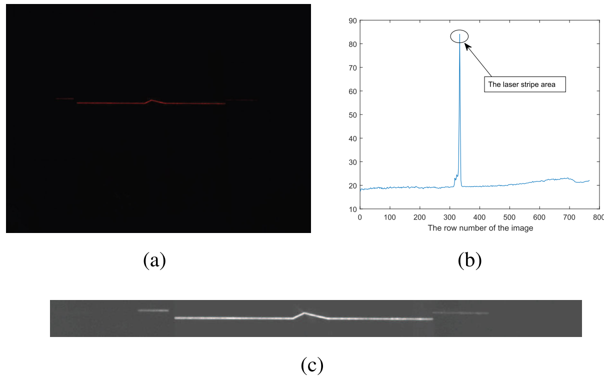

FIGURE 11. (a) The original image; (b) The sum of gray values of pixels in each row; (c) ROI extraction.

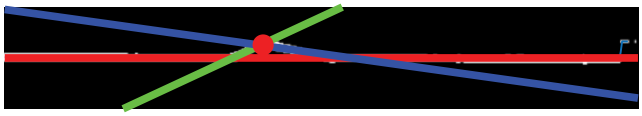

FIGURE 12. Feature extraction.

4) FEATURE EXTRACTION

In order to extract the feature points, Hough transform is adopted and its basic formula is expressed in Eq.(10).

$$r = u \cos\theta + v \sin\theta \quad \theta \in [0, 2\pi] \tag{10}$$

where θ is the angle from the Y-axis to the straight line. r is the distance between the origin point and this line. (u, v) is the image points in this line.

In the real experiments, the stripe direction is practically parallel to the Y direction of weld images. To detect the main axis of the stripe, the range of θ is set as [80,120].

And this line is fitted by the least square fitting as Eq.(11).

$$\begin{cases} \widetilde{k} = \dfrac{\sum_{i=1}^{n} x_i y_i - n\overline{xy}}{\sum_{i=1}^{n} x_i^2 - n\overline{x}^2} \\ \widetilde{b} = \overline{y} - k\overline{x} \end{cases} \tag{11}$$

where (x_i, y_i) are the inner points. $(\widetilde{k}, \widetilde{b})$ are straight line parameters. $\overline{x}$ and $\overline{y}$ are the mean values of (x_i, y_i). Meanwhile, based on the outliers, the other two lines is detected by Hough transform.

And the intersection of two straight lines is the feature points and its expression is shown in Eq.(12)-Eq.(13).

$$x_f = \frac{b_2 - b_1}{k_1 - k_2} \tag{12}$$

$$y_f = k_1 x_f + b_1 \tag{13}$$

where (x_f, y_f) is the feature point. (k_1, b_1) and (k_2, b_2) are the the slopes and intercepts of the two lines. Fig.12 shows the result of feature extraction.

Based on the results of feature extraction, according to the 3D measurement method [28], the 3D coordinates of feature points could be obtained by laser scanning. After the feature extraction, the smooth spline function in Section.III is to do path fitting to keep the seam path smoothing.

B. POSE ESTIMATION

The pose of welding guns is also an important factor to welding quality. Here, the seam pose is established to solve the pose of welding guns. To solve the pose of welding guns, Fig.13(a) shows the established seam pose. O is the origin point. According to the discrete seam pose in Fig.13(c), the pose of welding guns is solved as shown in Fig.13(b).

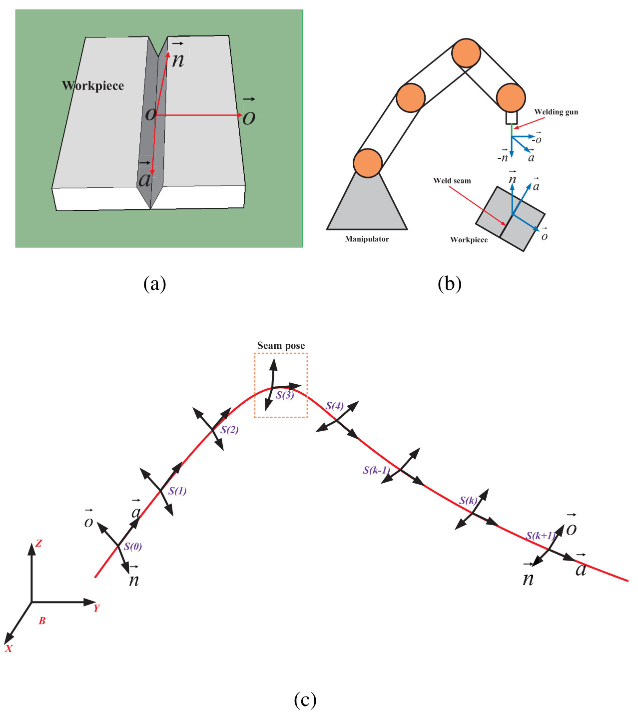

FIGURE 13. (a) The dynamic coordinate system; (b) The conversion schematic of seam pose and the pose welding guns; (c) The discrete seam poses.

During the real welding task, the welding robot could adjust the pose welding guns in real time to adapt complex work pieces.

The $\vec{a}$ is tangent vector which could be solved in Eq.(14).

$$\vec{a} = \frac{\frac{\partial x}{\partial t}i + \frac{\partial y}{\partial t}j + \frac{\partial z}{\partial t}k}{\left\| \frac{\partial x}{\partial t}i + \frac{\partial y}{\partial t}j + \frac{\partial z}{\partial t}k \right\|} \tag{14}$$

The normal vector is $\vec{n}$ and it is also the normal vector of work piece surface. The $\vec{o}$ could be solved based on right-hand rule as Eq.(15).

$$\vec{o} = \vec{a} \times \vec{n} \tag{15}$$

Combined with point cloud of work piece and seam pose, Fig.14 shows the pose of different weld seams.

Through the processing of point cloud, the established coordinate system of weld seam could solve the seam pose of different work pieces. According to the relationship in Fig.13(b), this pose could be converted to the pose of welding guns.

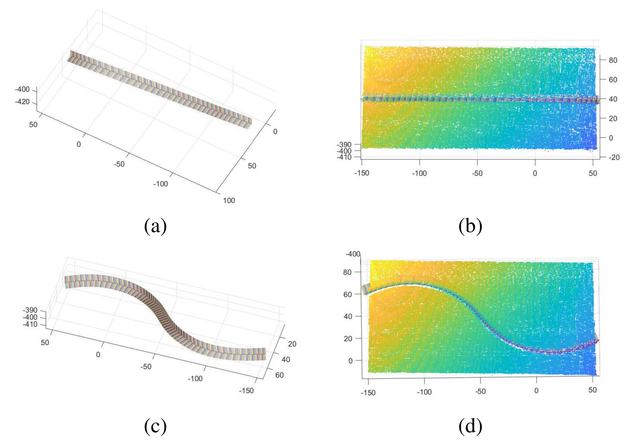

FIGURE 14. The pose of weld seams.

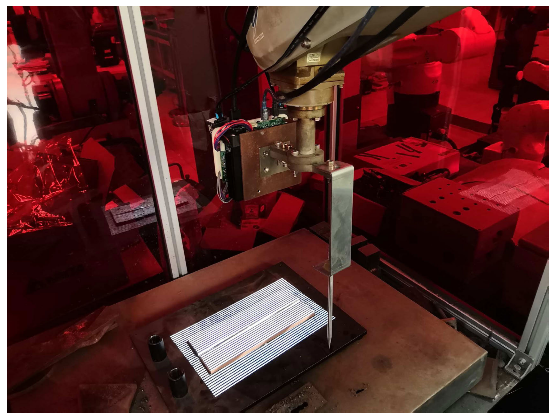

FIGURE 15. The special experimental platform.

V. EXPERIMENT

A. EXPERIMENT SETUP

To test the algorithm performance of this paper, Fig.15 shows the experimental platform based on UP6 Manipulator. And some related test experiments are done in this platform to verify the proposed method.

B. COARSE EXTRACTION OF ZIG-ZAG WELD SEAM

Here, algorithm generality of the proposed method is verified. The zig-zag butt joint is act as test sample to validate algorithm generality further. Fig.16 shows the results of coarse extraction of zig-zag butt joint.

The proposed algorithm based on point cloud segmentation could well finish the feature extraction of zig-zag butt joints. Therefore, the coarse extraction based on point cloud processing could solve different V-type work pieces. The smooth spline is used to do the path fitting in Fig.16(e). Fig.17 shows the results of path fitting of zig-zag butt joint.

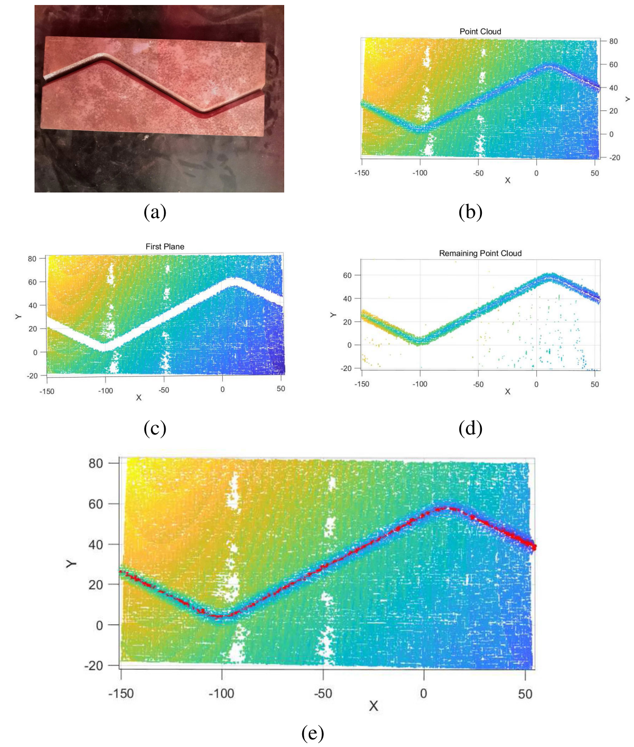

FIGURE 16. Coarse extraction of zig-zag butt joint.

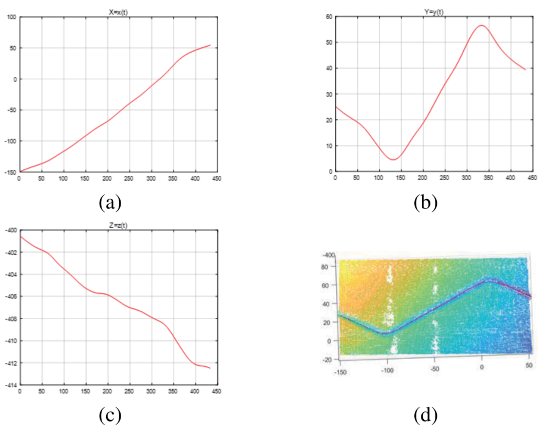

FIGURE 17. The path fitting of Zig-zag weld seam.

The smooth spline could well keep smooth seam path. Meanwhile, it could reduce the influence of noise. The fitted path could be used in subsequent local positioning.

Meanwhile, the computational efficiency of the proposed method is also tested and the special experimental results are shown in Table 1.

The time of 3D reconstruction is the longest during all the steps of the proposed method. During the process of image acquisition, camera and DLP projector need to keep sync. Due to the low frame rate of camera with 7Fps, the image acquisition takes a long time and the time of 3D reconstruction become larger. In the future work, the higher frame rate of camera will be selected to realize the fast 3D reconstruction.

TABLE 1. The running time of the proposed method.

Case	Link	Time(ms)
1	3D reconstruction	4703
2	Feature extraction	43
3	Path planning	87
4	The whole time	4832

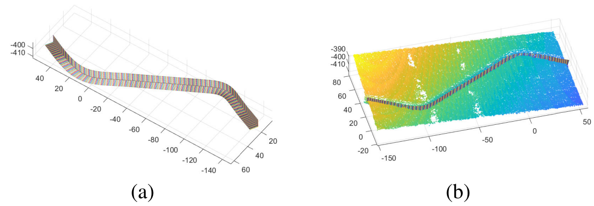

FIGURE 18. The pose of Zig-zag weld seam.

Although the whole time of the proposed method is a little larger, this method could get better result than the teaching-playback mode and the OLP mode. The proposed could well adapt to different V-type butt joints and improve working efficiency. Therefore, it could well meet the requirements of the flexible, accurate, fast manufacturing mode.

C. LOCAL POSITIONING OF ZIG-ZAG WELD SEAM

And the laser scanning is used to refine the 3D seam positions. Combined with the relocation seam path and point cloud of work piece, Fig.18 shows the results of the pose estimation of zig-zag butt joint.

The mathematical model of zig-zag butt joint could be well established. The seam pose could be converted to the pose of welding guns which could be used in real welding task.

D. ERROR MEASUREMENT

To test the measurement precision, the laser scanning has been widely applied into the robot welding which could get high measurement precision [29], [30]. Here, the results of laser scanning are set as benchmark data to verify the change of measurement precision of the coarse extraction.

Here, the maximum error(ME) and root mean square error($RMSE$) between local positioning and coarse extraction have been computed.

Table 2 shows the measurement errors of ME and $RMSE$. It could been seen that the measurement precision has been

TABLE 2. The measurement error of butt joints.

Case	Weld seam	Error(mm)	X	Y	Z
1	Straight butt joint	ME	1.45	1.71	2.05
2	Straight butt joint	RMSE	0.72	0.65	0.71
3	Curved butt joint	ME	1.82	1.75	1.98
4	Curved butt joint	RMSE	0.65	0.61	0.73
5	Zig-zag butt joint	ME	1.59	1.69	1.91
6	Zig-zag butt joint	RMSE	0.67	0.75	0.81

greatly improved. Combined with coarse extraction and local positioning, the proposed method could well solve the 3D position and pose of seam path. It has good flexibility and it could avoid complex artificial 3D path teaching.

VI. CONCLUSION

Based on the idea from coarse to fine, a "Global-Local" algorithm based on multi-functional robot sensor is proposed. The purpose of this paper is to improve the teaching precision of weld seams. Based on the proposed algorithm, the 3D path mode of V-type butt joints could be robustly solved. Meanwhile, the pose of weld seam is also established. The main conclusions are drawn as follows.

1) In order to realize the perception of welding environment, a multi-functional vision sensor based on DLP projector is constructed to adapt to different 3D measurement tasks.
2) Based on the idea from coarse to fine, A new "Global-Local" seam path extraction method is proposed in this paper. Through global seam extraction and local laser scanning, the precision seam extraction could be well realized.
3) To realize robust seam extraction, fusion of spatial information of weld seam, a new feature extraction algorithm based on the 3D information of work pieces is proposed which could well overcome the influence of poor contrast, reflections and rust.
4) To adapt to complex work pieces, the pose estimation of work pieces is done based on the discrete coordinate system of weld seam and it could be well solved the pose of welding guns.

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REFERENCES

[1] Y.-K. Liu and Y.-M. Zhang, "Supervised learning of human welder behaviors for intelligent robotic welding," *IEEE Trans. Autom. Sci. Eng.*, vol. 14, no. 3, pp. 1532–1541, Jul. 2017.
[2] Y. K. Liu and Y. M. Zhang, "Model-based predictive control of weld penetration in gas tungsten arc welding," *IEEE Trans. Control Syst. Technol.*, vol. 22, no. 3, pp. 955–966, May 2014.
[3] Y. Liu and Y. Zhang, "Iterative local ANFIS-based human welder intelligence modeling and control in pipe GTAW process: A data-driven approach," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 3, pp. 1079–1088, Jun. 2015.
[4] W. Li, K. Gao, J. Wu, T. Hu, and J. Wang, "SVM-based information fusion for weld deviation extraction and weld groove state identification in rotating arc narrow gap MAG welding," *Int. J. Adv. Manuf. Technol.*, vol. 74, nos. 9–12, pp. 1355–1364, 2014.
[5] Z. Zhang and S. Chen, "Real-time seam penetration identification in arc welding based on fusion of sound, voltage and spectrum signals," *J. Intell. Manuf.*, vol. 28, no. 1, pp. 207–218, 2017.
[6] Y. Xu, J. Zhong, M. Ding, H. Chen, and S. Chen, "The acquisition and processing of real-time information for height tracking of robotic GTAW process by arc sensor," *Int. J. Adv. Manuf. Technol.*, vol. 65, nos. 5–8, pp. 1031–1043, 2013.
[7] A. Kita and I. Ume, "Measuring on-line and off-line noncontact ultrasound time of flight weld penetration depth," *Weld. J.*, vol. 86, no. 1, p. 9, 2007.
[8] X. Gao, G. Huang, D. You, C. Lan, and N. Zhang, "Magneto-optical imaging deviation model of micro-gap weld joint," *J. Manuf. Syst.*, vol. 42, pp. 82–92, Jan. 2017.
[9] X. Gao, L. Mo, Z. Xiao, X. Chen, and S. Katayama, "Seam tracking based on Kalman filtering of micro-gap weld using magneto-optical image," *Int. J. Adv. Manuf. Technol.*, vol. 83, nos. 1–4, pp. 21–32, Jul. 2016.
[10] S. Chokkalingham, N. Chandrasekhar, and M. Vasudevan, "Predicting the depth of penetration and weld bead width from the infra red thermal image of the weld pool using artificial neural network modeling," *J. Intell. Manuf.*, vol. 23, no. 5, pp. 1995–2001, 2012.
[11] Z. Zhang, G. Wen, and S. Chen, "Audible sound-based intelligent evaluation for aluminum alloy in robotic pulsed GTAW: Mechanism, feature selection, and defect detection," *IEEE Trans. Ind. Informat.*, vol. 14, no. 7, pp. 2973–2983, Jul. 2018.
[12] Y. Xu, H. Yu, J. Zhong, T. Lin, and S. Chen, "Real-time seam tracking control technology during welding robot GTAW process based on passive vision sensor," *J. Mater. Process. Technol.*, vol. 212, no. 8, pp. 1654–1662, Aug. 2012.
[13] Z. Fang, D. Xu, and M. Tan, "A vision-based self-tuning fuzzy controller for fillet weld seam tracking," *IEEE/ASME Trans. Mechatronics*, vol. 16, no. 3, pp. 540–550, Jun. 2011.
[14] D. Wu, H. Chen, Y. Huang, Y. He, M. Hu, and S. Chen, "Monitoring of weld joint penetration during variable polarity plasma arc welding based on the keyhole characteristics and PSO-ANFIS," *J. Mater. Process. Technol.*, vol. 239, pp. 113–124, Jan. 2017.
[15] X. Li, X. Li, S. S. Ge, M. O. Khyam, and C. Luo, "Automatic welding seam tracking and identification," *IEEE Trans. Ind. Electron.*, vol. 64, no. 9, pp. 7261–7271, Sep. 2017.
[16] A. F. Villán, R. G. Acevedo, E. A. Alvarez, A. C. López, D. F. García, R. U. Fernández, M. J. Meana, and J. M. G. Sánchez, "Low-cost system for weld tracking based on artificial vision," *IEEE Trans. Ind. Appl.*, vol. 47, no. 3, pp. 1159–1167, May/Jun. 2011.
[17] Y. Liu, W. Zhang, and Y. Zhang, "Dynamic neuro-fuzzy-based human intelligence modeling and control in GTAW," *IEEE Trans. Autom. Sci. Eng.*, vol. 12, no. 1, pp. 324–335, Jan. 2015.
[18] Y. Liu and Y. Zhang, "Toward welding robot with human knowledge: A remotely-controlled approach," *IEEE Trans. Autom. Sci. Eng.*, vol. 12, no. 2, pp. 769–774, Apr. 2015.
[19] P. Maiolino, R. Woolley, D. Branson, P. Benardos, A. Popov, and S. Ratchev, "Flexible robot sealant dispensing cell using RGB-D sensor and off-line programming," *Robot. Comput.-Integr. Manuf.*, vol. 48, pp. 188–195, Dec. 2017.
[20] H. N. M. Shah, M. Sulaiman, and A. Z. Shukor, "Autonomous detection and identification of weld seam path shape position," *Int. J. Adv. Manuf. Technol.*, vol. 92, nos. 9–12, pp. 3739–3747, 2017.
[21] M. Dinham and G. Fang, "Autonomous weld seam identification and localisation using eye-in-hand stereo vision for robotic arc welding," *Robot. Comput.-Integr. Manuf.*, vol. 29, no. 5, pp. 288–301, Oct. 2013.
[22] J. Li, F. Jing, and E. Li, "A new teaching system for arc welding robots with auxiliary path point generation module," in *Proc. 35th Chin. Control Conf. (CCC)*, Jul. 2016, pp. 6217–6221.
[23] S. M. Ahmed, Y. Z. Tan, C. M. Chew, A. Al Mamun, and F. S. Wong, "Edge and corner detection for unorganized 3D point clouds with application to robotic welding," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2018, pp. 7350–7355.
[24] J. Zeng, B. Chang, D. Du, G. Peng, S. Chang, Y. Hong, L. Wang, and J. Shan, "A vision-aided 3D path teaching method before narrow butt joint welding," *Sensors*, vol. 17, no. 5, p. 1099, 2017.
[25] L. Yang, E. Li, T. Long, J. Fan, and Z. Liang, "A high-speed seam extraction method based on the novel structured-light sensor for arc welding robot: A review," *IEEE Sensors J.*, vol. 18, no. 21, pp. 8631–8641, Nov. 2018.
[26] B. Li, Y. An, D. Cappelleri, J. Xu, and S. Zhang, "High-accuracy, high-speed 3D structured light imaging techniques and potential applications to intelligent robotics," *Int. J. Robot. Autom.*, vol. 1, no. 1, pp. 86–103, 2017.
[27] L. Yang, E. Li, T. Long, J. Fan, and Z. Liang, "A novel 3-D path extraction method for arc welding robot based on stereo structured light sensor," *IEEE Sensors J.*, vol. 19, no. 2, pp. 763–773, Jan. 2018.

[28] J. Fan, S. Deng, F. Jing, C. Zhou, L. Yang, T. Long, and M. Tan, "An initial point alignment and seam tracking system for narrow weld," *IEEE Trans. Ind. Informat.*, to be published.

[29] A. Rout, B. B. V. L. Deepak, and B. B. Biswal, "Advances in weld seam tracking techniques for robotic welding: A review," *Robot. Comput.-Integr. Manuf.*, vol. 56, pp. 12–37, Apr. 2019.

[30] K. Zhang, M. Yan, T. Huang, J. Zheng, and Z. Li, "3D reconstruction of complex spatial weld seam for autonomous welding by laser structured light scanning," *J. Manuf. Process.*, vol. 39, pp. 200–207, Mar. 2019.

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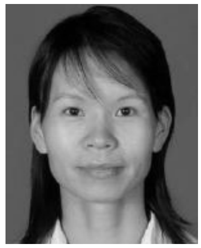

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