The autonomous detection and guiding of start welding position for arc welding robot

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Emerald Article: The autonomous detection and guiding of start welding position for arc welding robot

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Research article

The autonomous detection and guiding of start welding position for arc welding robot

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Abstract

Purpose – The recognition and positioning of start welding position (SWP) is the first step and one of the key technologies to realize autonomous robot welding. The purpose of this paper is to describe a method developed to accomplish successful autonomous detection and guiding of SWP.

Design/methodology/approach – The images of workpieces are snapped by charge coupled device (CCD) cameras in a relative large range without additional light. The recognized methods of SWP are analyzed according to the given definition. A two-step method named "coarse-to-fine" is proposed to recognize the SWP accurately. The first step is to solve the curve functions of seam and workpieces boundaries by fitting. The intersection point is regarded as initial value of SWP. The second step is to establish a small window that takes the initial value of SWP as centre. Then, the SWP is obtained exactly by corner detection in the window. Both the abundant information of original image and the structured information of recognized image are used according to given rules, which takes full advantage of the image information and improves the recognized precision.

Findings – The detected results show that the actual and calculated positions by first step of SWP are identical for regular seam, but different for the irregular curve seam. The exact results can be calculated by the two-step method in the paper for both regular and irregular seams. The typical planar "S-shape" and spatial arc curved seams are selected to carry out autonomous guiding of SWP.

Originality/value – The experimental results are given based on the introduction of 3D reconstructed and guided method. The guided precision is less than 1.1 mm, which meets the requirements of practical production. The proposed two-step method recognizes the SWP rapidly and exactly from coarse to fine.

Keywords Arc welding, Robotics, Production processes

Paper type Research paper

1. Introduction

High efficiency, digital control, intellectualization, and robotization have been the developing trend for arc welding, which is integrating artificial intelligence, computer vision, digital processing, and robot into welding technology (Tarn *et al.*, 2007; Cullison, 1995; Shafi, 2004). The application of modern technologies in the traditional welding manufacturing makes it shine vigour. Industrial robots binding with computer vision and artificial intelligence can influence the conventional rigid welding manufacturing form and make it possible to realize flexible and intelligent welding (Tarn *et al.*, 2007; Chen *et al.*, 2005).

Intelligent arc welding robots should have some intelligent functions like welder, such as finding start welding position (SWP), adjusting the welding path and parameters according to the changing work environment. The corresponding technologies include autonomous guiding of SWP, path-plan, seam tracking, control of weld quality, etc. However, most of the welding robots serving in production, mainly the "teaching and playback" and off-line programming type, have no ability to adapt to environment changing in welding process (Chen *et al.*, 2005; Gini, 1987). The main differences between general and intelligent welding robot are that the latter has the ability of self-adapting and self-determination. It is an effective way to develop and improve intelligent technologies for welding robots by vision sensors. Humans get more than 80 percent information by vision, welders are not exception. The welders would adjust the welding path and parameters to adapt the change of welding conditions. The development of inexpensive on-the-shelf charge coupled device (CCD) camera with good performance and small size makes it possible to install "welder eyes" on robot.

Many works have been done to realize intelligent functions in arc robot welding, such as seam tracking, seam information

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computing, weld quality control (Tarn *et al.*, 2007; Chen *et al.*, 2005; Ge *et al.*, 2005; Wei *et al.*, 2005). However, few works focus on the autonomous guiding of SWP. The positioning and guiding of SWP is one of the key technologies and the first step in the robot welding, it is also the precondition of seam tracking. At present, the main method to realize guiding of SWP is by teach and playback, which depend on the operator's experience, break the degree of intellectualization and the whole automatic welding procedure. On the other hand, the robot cannot adapt to the changes of work conditions, such as the change of workpieces' position. It needs to be taught and playback again when position changes. Some enterprises and institutes have paid attention to this problem (Chen *et al.*, 2006; Seijin, 1998; Makoto, 1994; Guo Zhenmin *et al.*, 2003). Seijin (1998) detected the SWP by touches the workpieces or groove using contact sensor, which is also used in some companies. However, this method needs to know the position of SWP in advance, it is only suitable for seams with obvious detectable seam edges such as L, V, T type grooves, which must be easy to touch. Positioning of SWP by the contact sensor, the robot should be moved close with the SWP, which needs much bigger work spaces, and is hard to realize the autonomous finding of SWP in a large range. Laser sensor is also used to detect the SWP by some robot manufactures. This method can find the right position exactly, its disadvantage is that the sensor costs much comparing with robot itself, and sensor size is bigger, size of laser spot also limits its application in some types of seams. Guo Zhenmin *et al.* (2003) report on the guiding of initial welding position with visual servo control method, but the error is about 30-50 mm, and a special white mark is needed in order to recognize the SWP, which cannot meet the requirements of practical production. The research provides us a good idea to realize the autonomous guiding of SWP. Zhu *et al.* (2005) put the steel workpieces on a board with special color background, it recognizes the initial welding position using pattern matching technology and realizes the guiding of SWP with one camera, its computing error is about 5 mm. The author (Chen *et al.*, 2006) gives a practical method to locate the SWP with visual technology, which is the foundation to realize the guiding of initial weld position, which is used for planar (2D) aluminum alloy seam, not for the spatial seam, its error is less than 3 mm. All these researches make some progress in the field of autonomous detection and guiding of SWP and provide us with some good methodologies, but its precondition and big error limit its application in real production. A further research in real welding environment with less error in this field is needed.

In this paper, we imitate the action of skilled welder, fix two CCD cameras on the end-effector of welding robot to observe the welding environment to realize the autonomous detection and guiding of SWP. A stereo image pair of workpieces is snapped in a large-scale by the vision system. Based on the given definition and analysis of SWP, a two-step method, that is, from coarse to fine is proposed to recognize the SWP accurately. Then, the binocular vision is used to calculate three-dimensional (3D) coordinates of the SWP. The experimental results are given at last. The method accomplishes the autonomous detection and guiding of SWP successfully.

2. Experimental system and definition of SWP

2.1 Binocular vision system

We fixed two same CCD cameras on the end-effecter of the welding robot, which formed a binocular vision system, as shown in Figure 1. The robot we used is Motoman XRC produced by YASKWA Company. The camera type is WATEC-902H, with a weight of 90 g, a size of 35.5(W) × 36(H) × 58(L) mm, and a focal length of 4.8 mm. Images are captured by image capture card CG-400 that produced by DaHeng Corporation in Beijing. The image is snapped with natural light.

2.2 Definition and analysis of SWP

There are two start welding points for a work-piece to be welded, which have bigger and smaller coordinate values according to X-axis in the image coordinate system for the sapped image. The point with bigger coordinate is regarded as the SWP in this paper. For the workpieces without obvious SWP, such as workpieces with close seam, a rule to ensure the SWP is needed. First, the image snapped by left camera is regarded as a reference whose center is selected as the referenced point. Second, the matched point of the referenced point can be found by stereo matching. The SWP we need is determined by the referenced point and its matched point.

The main joint types in welding engineering are butt, lap, fillet, and Tee weld joints. And many kinds of grooves are needed for butt joints according to actual welding conditions, such as V, U, X, and I grooves. There are also front, side, and oblique fillet joints. Tee joint can be regarded as one type of fillet. Figure 2 shows the main types of grooves. All of the grooves are shown as seam types of (a)-(c) in Figure 2, which we named as T, L, and V types, respectively. It is the main corresponding groove type blow these three seam types. The marked "1" in the figure is the work-piece boundary near SWP, "2" and black filled part denote the weld seam. Other types of seams can be included in these three types. For example, fillet joint can be seen as type (b), and if it is the oblique fillet joint, the work-piece boundary becomes the dashed line. All the seams can be analyzed like this.

The SWP can be seen as the intersection point of work-piece boundary (or groove "1") and seam, which corresponds with the concept of corner point in image processing. Thus, two methods can be used to get SWP, i.e. by interception point and corner point.

Figure 1 Binocular vision system

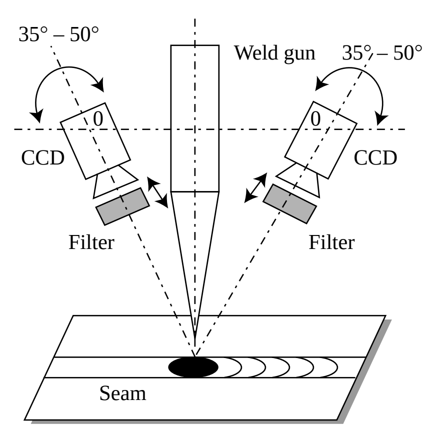
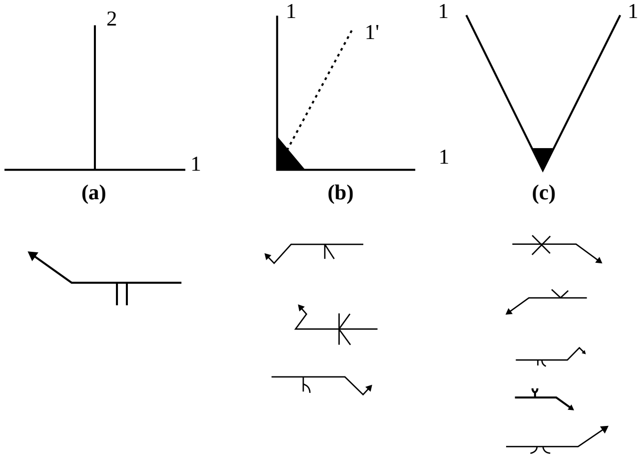


Figure 2 Seam type and initial weld position



It is easy to get the curve equations by curve fitting technology. Because the seams are two parallel curves, we can calculate two intersection points of the parallel seam edges and the same boundary (the SWP is on it). Thus, the midpoint of the two intersection points is the SWP we want. We can calculate exactly results by this method when the seams are line or regular curves with right equations. However, it is not effective for irregular seam because its exact curve equations cannot be obtained by fitting. The discontinuous points of seams would occur for some reason in the process of image recognition, which can be solved by fitting and point joining, but error will occur because of the fitted method or too many discontinuous points. All these reasons will affect the detection precision of SWP. If we detect SWP by corner detection directly, the inaccurate or wrong positioning results would be found because there are too many corner points in the image, such as the inflection point or corners of workpieces. Thus, a two-step method that takes full advantage of intersection and corner methods is proposed to detect the SWP.

3. Recognition of SWP

3.1 Recognition of initial SWP by edge intersection

The edges of seam and work-piece boundaries can be recognized and separated by image processing, whose procedure includes pre-processing, edge detection, post-processing, and so on, which can be found in the reference (Chen *et al.*, 2007). The position of SWP in image coordinate system is acquired by interception point of seam and boundary. Data fitting is a practical and easy way to carry out mathematical expression of seam and boundary. The fitting of curves and surfaces is an important content in numerical analysis. Least mean-square error rule is a usual method to calculate the best fitting function with some proper parameters. The selection of parameters is not related to problems and polynomial form, spline functions are often used in general.

We have gotten a point set of one edge by image recognition. The set is $(x_i, y_i), i = 1, 2, \ldots, n$, and the goal is to find a function to make its mean square deviation minimum, which can be expressed as follows:

$$\mathrm{MSE} = \frac{1}{2}\sum_{i=1}^{N}(y_i - f(x_i))$$

Polynomial form is selected here and its expression is $f(x) = a_0 + a_1x + a_2x^2 + \cdots + a_nx^n$. Curve fitting is a process to calculate the best parameters, which uses least square method. It can be expressed as a pseudo inverse problem by matrix form as follows:

$$\mathbf{Y} = \begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ . \\ y_n \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 1 & x_1 & \ldots & x_1^n \\ 1 & x_2 & \ldots & x_2^n \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ 1 & x_n & \ldots & x_n^n \end{bmatrix}, \quad \mathbf{A} = \begin{bmatrix} a_1 \\ a_2 \\ . \\ . \\ . \\ a_n \end{bmatrix} \tag{1}$$

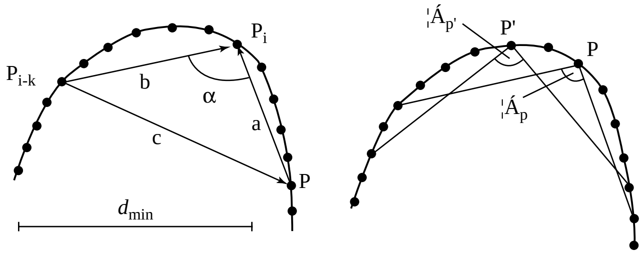
The error vector is $\mathbf{E} = \mathbf{Y} - \mathbf{BA}$, then we have $\mathrm{MSE} = (1/N)E^{\mathrm{T}}E$ and its optimal solutions are $A = (B^{\mathrm{T}}B)^{-1}B^{\mathrm{T}}Y$. Thus, we can solve the parameters of the polynomial, and the curve function is also obtained. The functions of edge and boundary form an equation, and the intersection point of seam and boundary is solved by this equation. It is the coordinates of SWP in image coordinates system, which is regarded as the initial value of SWP.

3.2 Accurate positioning of SWP by corner detection in local range

SWP has the character of corner that formed by seam and groove or boundary, so it can be obtained by corner detection. Corner is an important local character in image processing, and it has been used in many fields, such as object description, motion estimation, and target tracking. There are different methods to detect corner according to its definitions in image processing. Such as, corner is defined as "points with obvious curvature changes on image edges" (Zuniga and Haralick, 1983), "points with enough high curvature on image edge" (Smith and Brady, 1997), and "points that have discontinuous edge direction changes" (Sheu and Hu, 1996). The corner detection methods can be classified into two types: one is to judge corner by calculating the curvatures or inclination of recognized edge points, the other is to detect corner directly using grey information of images. The former takes advantage of structured information after image processing, faster but its precision depends on the quality of image processing. The latter detects corner by original image information directly, but it is sensitive to noise so as to have lower detection precision.

The value calculated in Section 3.1 is an initial value of SWP. We get a small window that takes the initial SWP as center, and the corner detection is carried out only in the local range, which accelerates processing speed and improves detection precision. The edge in the small window is an orderly point set $S = \{p_i : (x_i, y_i), i = 1, 2, \ldots, n\}$, where order means that the edge is scanned by clockwise or anti-clockwise. If P is a center, there are M points before, and after M, they form connected region. Here, front and after denotes the scanned points in searched region by clockwise and anti-clockwise. As Figure 3(a) shows, any point P_i and $P_{i\text{-}k}$, P_{i+k} in curve formed a triangle. As Figure 3 shows, $|P_i\ P_{i+k}| = a$, $|P_i\ P_{i-k}| = b$, $|P_{i-k}\ P_{i+k}| = c$. The angle between P_{i-k}, P_{i+k} is $\alpha \in [-\pi, \pi]$, thus we have:

Figure 3 Corner detection



(a) Selecting candidate corner points **(b)** Determining corner point

$$\alpha = \arccos\left(\frac{a^2 + b^2 - c^2}{2ab}\right) \tag{2}$$

The judged condition of candidate points for corner points is given as follows:

$$\begin{cases} d_{\min} \leq a \leq d_{\max} \\ d_{\min} \leq b \leq d_{\max} \\ \alpha \leq \alpha_{\max} \end{cases} \tag{3}$$

where:

$d_{\min}$, $d_{\max}$, $\alpha_{\max}$ Main parameters of the constraint condition.

$d_{\min}$ Determines the minimum value to get fine corners.

$d_{\max}$ Is necessary to avoid false sharp triangles formed by distant points in highly varying curves.

If the P is too far, the formed acute triangle would make wrong detection. In general, $d_{\max} = d_{\min} + 2$, the parameters in this paper are $d_{\min} = 3$, $d_{\max} = 5$, and $\alpha_{\max} = 150°$.

There would be many candidate points that satisfy the above constraint condition, just as shown in Figure 3(b). Similar to edge detection, a post-processing step is needed to select the strongest response by discarding the wrong points. There are two candidate points P and P' in Figure 3(b). P is discarded if it has a sharper valid neighbor $\alpha_p > \alpha_{p'}$. We can get the best point when there are many candidates by this discarding rule. Considering the vector product of $\mathbf{b} = (b_x, b_y)$ and $\mathbf{c} = (c_x, c_y)$, it is easy to see that the corner is convex if $b_x c_y - b_y c_x > 0$, otherwise it is concave.

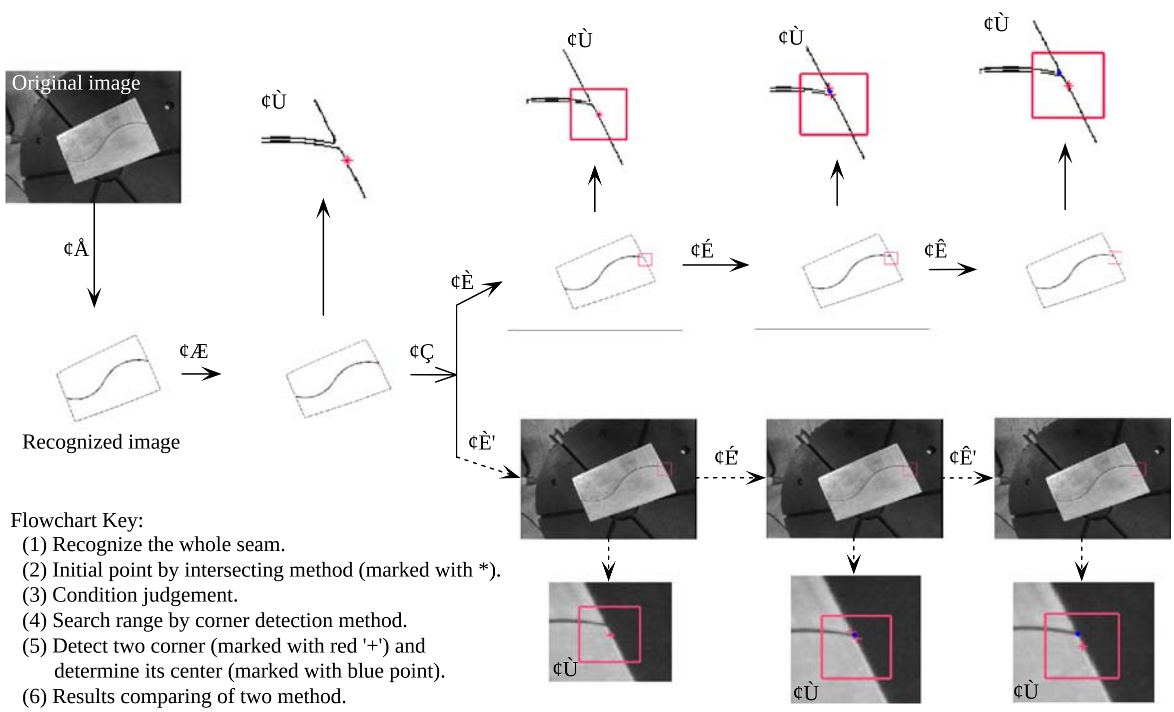
We can calculate the only right corner in the small window by the two-pass selection. A corner detector based on grey image is also used in this paper, the SUSAN corner detector (Smith and Brady, 1997) is selected here.

Thus, we accomplish the exact detection of SWP by a two-step recognized method. Figure 4 shows the whole recognition procedure.

The detailed procedure is described as follows according to Figure 4:

1 Recognize the whole seam and boundaries using edge detection technology. The Canny detector is adopted, whose detailed technology can be found in reference (Chen *et al.*, 2007). The curve function of seam edge and workpieces boundaries is solved by fitting technology. This corresponds to the procedure marked with "(1)" in Figure 4.
2 Initial point by intersecting method (marked with *) and search range. The two intersection points of two parallel seam edges and boundaries are solved using the curve

Figure 4 Flowchart for recognition of initial weld position



Note: ¢Ù amplificatory image in local range around initial weld position. Reproduced from the only available original

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functions, and the midpoint of these two intersection points is regarded as the initial value of SWP. This corresponds to the procedure marked with "(2)" in Figure 4.

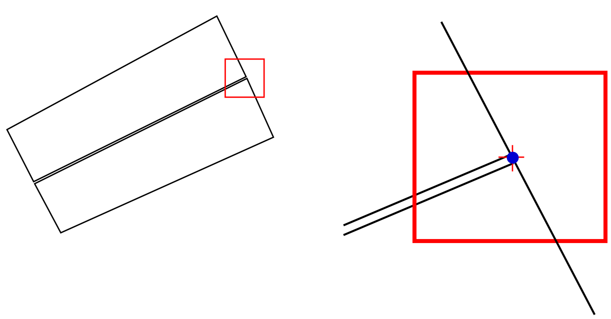
3 Taking the initial value as centre (red "*" in Figure 4), a small window with size M^*N (red pane in Figure 4) is set up in recognized image in procedure (1) or in original image, which corresponds to procedure (4) and (4)′ in Figure 4.

4 The two parallel seam edges and workpieces form two corners. These two corners are detected by corner detector in the small window that set in procedure (3), and their midpoint is the positioning result of SWP, which corresponds to procedure (5) and (5)′ in Figure 4.

There is a branch in procedure (3) in Figure 4, it is a rule to judge whether the recognized image or original image should be used when corner is detected. When the case is that recognized edge is disconnected, including that the disconnected distance is large than a threshold or the edge/boundaries is disconnected near SWP, we think the information that recognized structure image provided is not enough, thus the original image is choose to detect the SWP. The detection procedure is similar and here SUSAN detector is used.

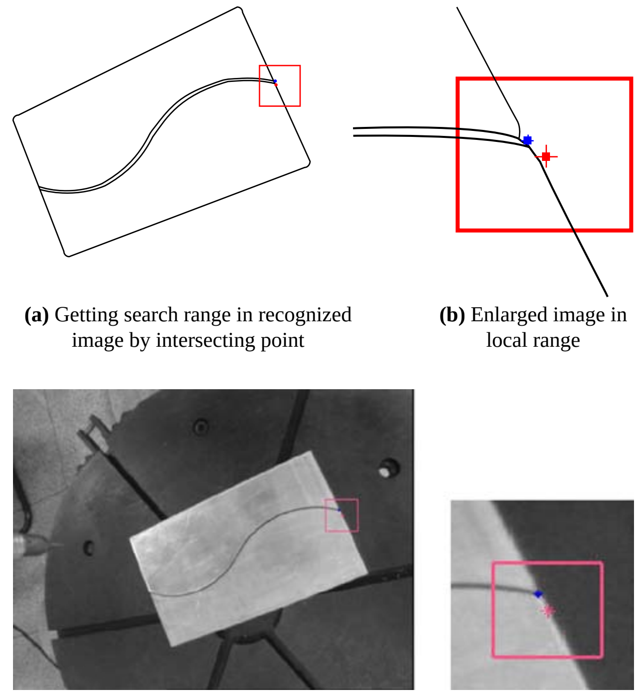
Procedure (6) in Figure 4 is comparison between results of SWP by intersection point and corner detection in local range. In order to illuminate the results further, Figures 5 and 6 are given. In these two figures, the SWP solved by the intersection of edge and boundaries marks with a red asterisk, the red rectangle frame is the window around the interception point. It is the SWP got by corner detection in small widow that marks with blue solid dot. Figure 4 is the results of recognition with line seam type. As line is a regular curve and its function can be got exactly by fitting, even if the recognized seam is disconnected, the results of SWP by intersection point method and corner detection in local range are the same. As shown in Figure 5, the red asterisk and blue solid dot is superposition, that is to say, both methods can get exact results for regular curve shaped seams. But for the un-standard curve seams, the SWP results from two methods are different, because the fitting curve function cannot express the un-standard curve exactly, as shown in Figure 6. In this case, result of SWP by corner detection in local range is exact, which is shown in the amplificatory image in Figure 6(b) and 6(d).

Figure 5 Case of same results by two methods (line seam)



(a) Method by intersecting point **(b)** Enlarged image in local range

Figure 6 Case for different results by two methods



(a) Getting search range in recognized image by intersecting point **(b)** Enlarged image in local range

(c) Getting search range in recognized image by intersecting point **(d)** Enlarged image in local range

Image positioning results of SWP using original image information is shown in Figure 6. We know that both methods can obtain good results in this figure. In principle, it is sensitive to noise using original image to detect the corner, but in the local range its detection precision is almost the same compared with recognized edge image. This shows that there is enough information in the recognized image in this case for corner detection. Without much disconnected points, the recognized image expresses the original image very well. When both the recognized image and original image can obtain good results, it is better to use the recognized image information base on edge, because it is structured information, which will simplify and accelerate processing procedure.

The method proposed in this paper detects SWP in a small region, which avoids the effect of all kinds of noises and locates the SWP rapidly. The given example also shows that it can be used for regular and irregular curves.

4. Calculation of 3D coordinates for SWP

The binocular vision is used to reconstruct the 3D coordinates of SWP, i.e. its spatial position in robot coordinates system. Camera calibration is necessary in order to reconstruct the 3D information. Here, the mature calibration method based on Zhang (2000) is adopted directly, and the calibration procedure is shown in Figure 7. Here, only the calibrated results are given. Table I shows the intrinsic parameters of two cameras, and the relationship between two cameras can be expressed as a rotation matrix and a translation vector:

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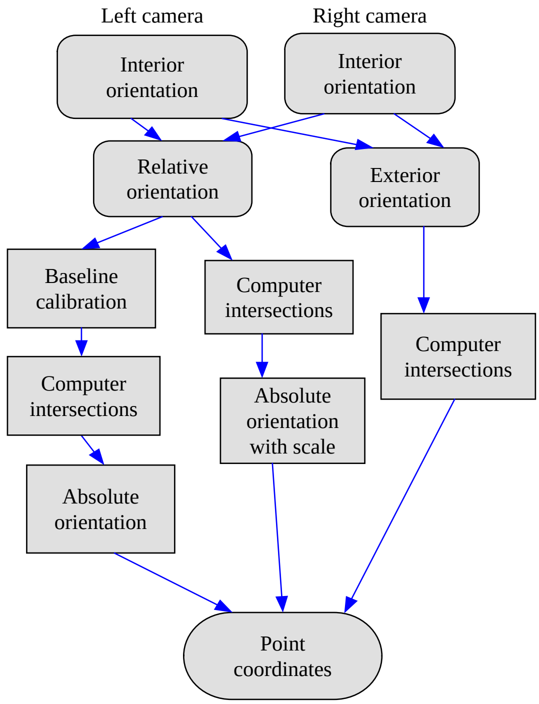
Figure 7 A diagram of the procedures for calibrating a binocular stereo system



Source: Jain *et al.* (2003)

$$\mathbf{R} = \begin{bmatrix} 0.9348 & -0.0629 & 0.3495 \\ 0.0680 & 0.9977 & -0.0025 \\ -0.3485 & 0.0261 & 0.9369 \end{bmatrix}$$

$$\mathbf{T} = [-229.94930, -3.30043, 45.28599]$$

Stereo matching is one of the key and difficult problems in binocular vision. But for the matching of SWP, it is an easy thing. We have gotten the exact results by the recognized method above, and the SWP in left and right images is unique. So, the recognized SWP in image coordinate system in left and right images are matching points.

A common model to reconstruct depth information is used here, whose detail can refer to Chen *et al.* (2005) and Jain *et al.* (2003). The principle is shown in Figure 8. Two matching image points p and p' are obtained by the recognized method above, and it is in principle straight forward to reconstruct the corresponding scene point by intersecting the two rays ROp and $R'O'p'$. However, the rays R and R' will never, in practice, actually intersect, due to calibration and feature localization errors. A reasonable approach to the reconstruction problem is adopted here. We choose to construct the line segment perpendicular to R and R' that intersects both rays: the mid-point P of this segment is the closest point to both rays and can be taken as the wanted spatial point. Thus, we get the 3D coordinates of SWP in the world coordinate system. In order to guide the robot to the SWP, this value should be transferred to the robot coordinate system. The relationship between robot and camera coordinate system are needed, which is so-called "hand-eye" relationship, and the calibration method is the same as ours in Chen *et al.* (2005) and Jain *et al.* (2003). The hand-eye relationship also can be expressed by a rotation matrix and a translation vector like two cameras' relationship as follows:

$$\mathbf{R}_{\text{hande-eye}} = \begin{bmatrix} 0.0009983778 & -0.9998731218 & -0.0158979088 \\ 0.9991480888 & 0.0003415087 & 0.0412671791 \\ -0.0412565139 & -0.0159255654 & 0.9990216596 \end{bmatrix}$$

$$\mathbf{T}_{\text{hand-eye}} = [-7.1811871084, -120.6327249800, -57.7479974776]$$

5. Experiments

5.1 Experimental system

Figures 9 and 10 show two typical stereo image pairs of a planar curve and spatial seam, which are also used as examples to show the experimental results. Although Figure 9 is similar to image used in Figure 4, their materials are different. Their material types are steel and aluminum alloy, respectively. Aluminum alloy reflects light strongly as steel does not. The recognized method is robust to the different conditions. The two experimental examples are two typical planar and spatial seam types with different typical materials. In the recognition process of SWP in Section 3, the image snapped by left camera is taken as an example, and SWP of right image can be recognized by the same method, which is not be repeated here.

MOTOCOM32 software is used to communicate and transfer data between robot controller and computer. RS232 and Ethernet are two typical communication types. The latter has faster transferred speed (the speed of it is about 10 Mbps, and the speed of RS232 is about 9,600 bps), and it can be used to multi-robots communication. Thus, Ethernet is selected as communication type. The TCP/IP is the communication protocol. Figure 11 shows the communication between robot and computer. We need connect the Ethernet I/F board which built in robot controller to network. After right connection and parameters setup, the robot would be controlled to move by computer. The movement can be increment type or point to point, and the former type is adopted here.

Table I Calibration results of intrinsic parameters

Parameters	Focal length f_u, f_v/pixels	Principal point (u_0, v_0)/pixels	Distortion (k_1, k_2, k_3, k_4)
Left camera	(595.7734, 593.9186)	(374.4609, 297.1968)	(−0.1867, 0.1477, 0.00064, −0.0031)
Right camera	(604.4058, 603.62116)	(371.0050, 77.4524)	(−0.2186, 0.1768, −0.0021, −0.00049)

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Figure 8 Reconstruction of spatial point

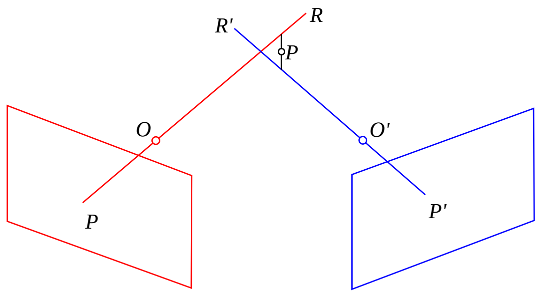
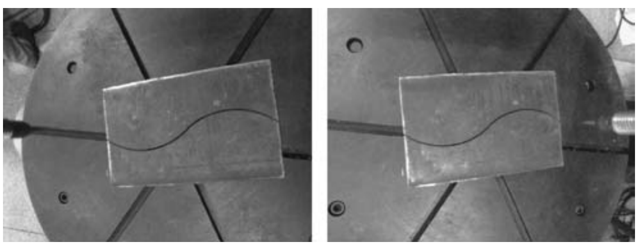
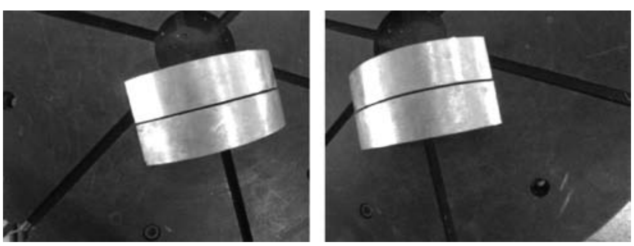


Figure 9 Stereo pair images of S-shape seam (steel)



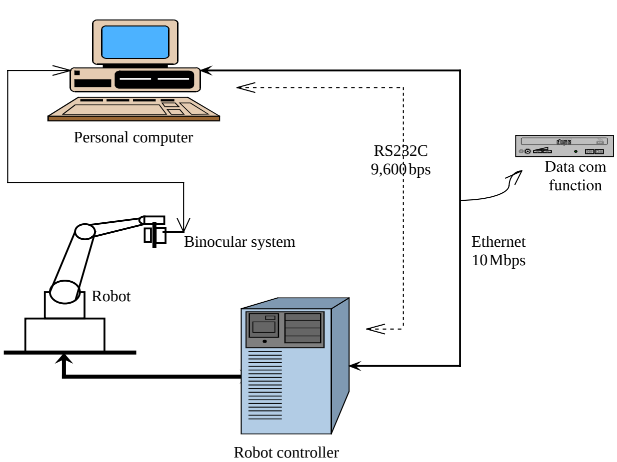
(a) Original left image **(b)** Original right image

Figure 10 Stereo pair images of spatial arc seam (aluminum alloy)



(a) Original left image **(b)** Original right image

Figure 11 Communication between robot and computer



5.2 Guiding method and experiments

With the method above, vision-guided experiments are performed without additional light. During the process, the robot was moved to ensure SWP within the view range of both CCD cameras. Two typical seams in Figures 9 and 10 are selected to prove the experiments.

The calculated 3D coordinates of SWP in robot coordinate system is transferred to robot controller by computer. The welding torch is guided to the SWP. The robot moves in a high speed when the torch is far away from work-piece, and moves in a lower speed when the torch is close to the SWP, which saves motion time and avoids collision between torch and workpieces.

The coordinates of SWP obtained by "teach and playback" function is regarded as the real position (the robot motion error is less than 0.08 mm), and the experimental error is obtained by comparing calculated and real position values. Two repeated experiments are designed to measure the error. One is to change pose where image is captured while the work-piece does not move. The other is to move the work-piece every time while captured pose is constant. The former is designed to test how robot movement precision and capture pose will affect experimental results, and the result shows the error is less than 1.1 mm (standard error is less than 0.54 mm) after repeated experiments for 18 times, which is not the importance in this paper. The detailed analysis will be published in another paper. The latter is like the practical production, and the experimental results are also given by this method. Figure 12 shows a SWP guiding scene captured from a guiding video screen, and it corresponds to workpieces in Figure 10.

Figures 13 and 14 show the experimental error in X, Y, and Z directions of planar "S-shape" and spatial arc seam, and the experiment repeated time is 25. Except for the 5th (1.2 mm) and 14th (1.4 mm), the experiment in Figure 13 and the 7th experiment (1.5 mm) in Figure 14, the error in three directions is less than 1.1 mm.

The experiments have more guiding error due to bad image capture pose. For example, the welding torch or wire feeding device occulted the SWP. Figure 15 shows such a situation, which affects the recognized precision of SWP. The two cases that have big error in Figure 13 are caused by the occlusion. For the regular seam, the occulted problem can be solved by

Figure 12 A captured screen of a guiding video

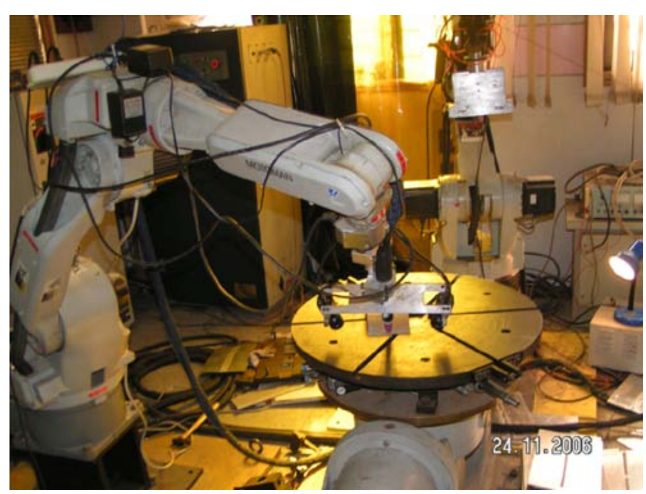


Figure 13 Guiding errors of planar S-shape seam

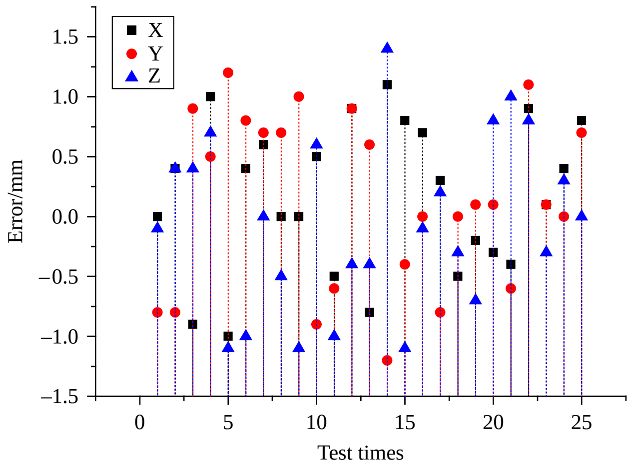


Figure 14 Guiding errors of spatial arc seam

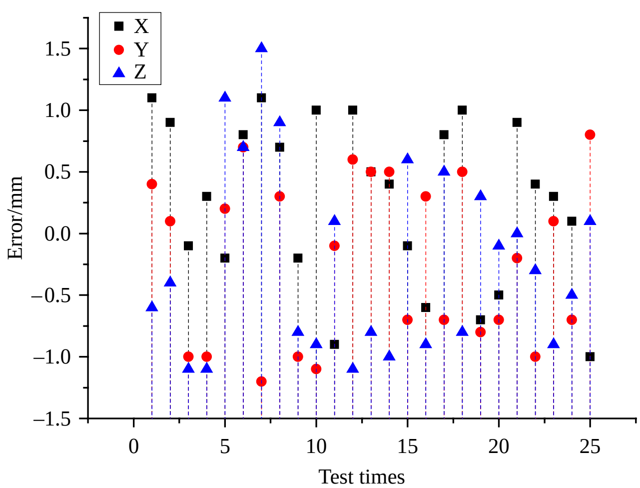
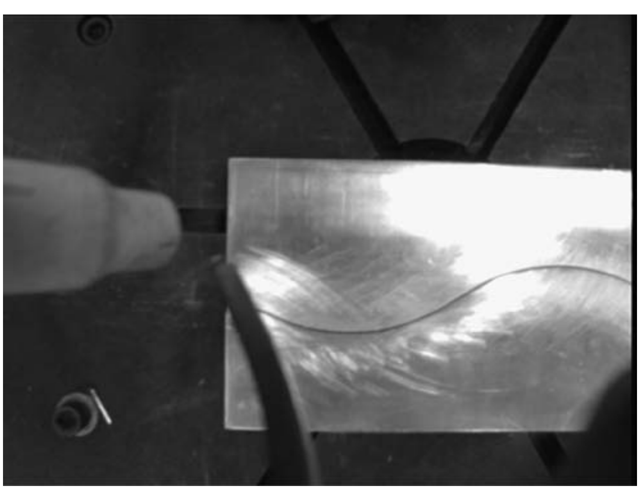


Figure 15 An occlusion case when SWP guiding



data fitting in Section 3.1. However, both the data fitting and corner detection in local range in Section 3 cannot solve the problem completely for the irregular curve seams, although it would improve positioning precision in some extent. The best way to solve this problem is to capture image in a right pose, and it is not difficult to find some proper poses. Light reflection also affects the guiding precision, which occurs in such kinds of material which has the "mirror" function and reflects light strongly as aluminum alloy. Case with big error in Figure 14 belongs to this situation. We should avoid the SWP in the reflected region by adjusting image captured pose. Thus, the guiding error is less than 1.1 mm when experimental conditions are qualified (no occlusion and light reflection).

Figure 16 shows the whole flowchart of the autonomous detection and guiding of SWP. The procedure with section line is not the work in this paper but a necessary step in autonomous welding.

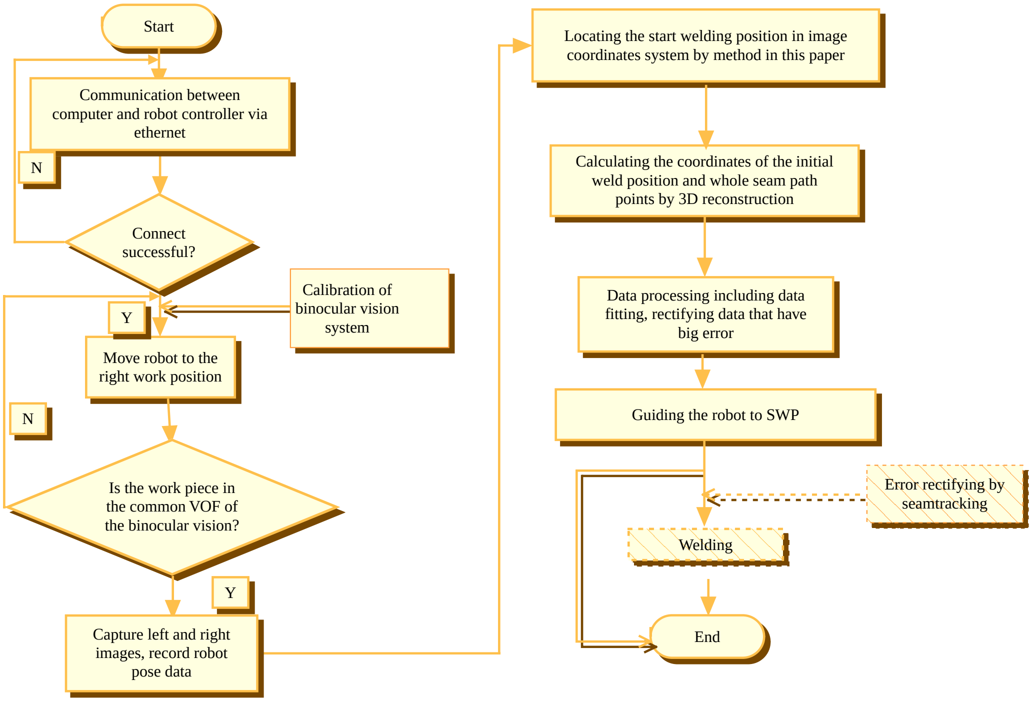
The welding robot also should be guided to leave the work-piece when welding task ends. For the recognition and guiding of the terminated welding position, the algorithm is the same as the SWP. The difference is that it is carried out after the welding process is finished, the image processing result would be affected inevitable by weld arc, and most of the time the right position of the terminated point would not be obtained. Thus, we do the job before start welding, just as the SWP, and transport the result to the master computer. When the value of position read from robot controller in real time equals to the stored data, we can confirm that the robot has arrived at the terminated position. Finally, the welding robot is guided to leave work-piece.

6. Conclusion and discussion

The autonomous detection and guiding of SWP is the first step in autonomous robotic welding system. The definition of SWP is given based on the analysis of seam type. The proposed two-step method recognizes the SWP rapidly and exactly from coarse to fine. The recognized algorithms take full advantage of abundant original image information and structured simple information after image recognition, which ensure the processing speed and precision. The method can be applied to regular and irregular curve seams, and the experiments show the fine recognized results. The typical planar "S-shape" and spatial arc seam are selected to carry out guiding experiments, and the results show that the guiding error is less than 1.1 mm when there are no occlusion and light reflection. The detection and guiding of SWP is the foundation and one of the key technologies to realize autonomous robot welding.

The detection and guiding of SWP is related closely to other automatic procedure. The guiding precision of SWP is improved compared with reference (Chen *et al.*, 2006; Guo Zhenmin *et al.*, 2003; Zhu *et al.*, 2005), which can be applied in practical production. It also should be combined with other autonomous welding technologies, such as path rectifying and seam tracking, which make it merge into the whole autonomous robot welding process. The calculated precision is related to many factors, such as image recognition, calibration, reconstructed method, and vision configuration. It should be analyzed in a full view as well as some experimental method should be designed to evaluate the precision, which we will research in another paper.

Figure 16 Flowchart of the autonomous detecting and guiding



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