Visual Tracking System for Welding Seams

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Abstract – **To track the narrow butt welding seams in container manufacture, a visual tracking system based on smart camera is proposed in this paper. A smart camera is used as the sensor to detect the welding seam. The feature extraction algorithm is designed with the consideration of the characteristics of the smart camera, which is used to compute the error between the welding torch and the welding seam. Visual control system based on image is presented, which employs a programmable controller to control a stepper motor to eliminate the tracking error detected by the smart camera. Experiments are conducted to demonstrate the effectiveness of the vision system.**

Key words – *visual tracking*; *smart camera*; *Welding Seams*; *tracking error*

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1 Introduction

During the production process of a container, welding technique plays the most important role. Most of container production lines used in workshop have no adaptive ability. During the welding process, the worker adjusts the welding torch manually. It's difficult and unhealthy, and at the same time, the welding efficiency and quality can not be guaranteed. It is meaningful to explore the seam tracking system that can be used in container manufacture.

Many efforts have been made in seam tracking field, and many seam tracking systems have been developed. In these systems, many kinds of sensors have been used to detect the welding seam. In Ref. [1,2], arc sensor was employed to detect the welding seam. In Ref. [3,4], ultrasonic sensor based seam tracking systems were developed. Vision sensor[5-8] has been proved to be more promising than other sensors due to its no contact, high speed, and high accuracy. However, the vision systems mentioned above are not fit for the narrow seam in container manufacture. In Ref. [9], a visual tracking system was developed for the container welding. However, it was a PC based system. Its big volume made it inconvenient for the industrial applications.

The smart camera[10] brings great conveniences to industrial applications. It can capture and process images without the help of computers. In addition, smart camera based systems are more robust than PC based vision systems. A visual tracking system based on smart camera in container manufacture is developed in this paper.

In a position-based visual servoing system, the input is computed in 3-D Cartesian space. In an image-based visua servoing system, the input is computed in 2-D image space. In a hybrid visual servoing system, the input is computed in part in 3-D Cartesian space and in part in 2-D image space. Generally, image-based visual servoing is more robust with respect to camera and robot calibration errors. In this paper, image-based visual servoing method is adopted to design the controller.

Programmable controller is popular as the low-cost and high-performance controller for a wide variety of devices in the industries. In the proposed system, a programmable controller is employed as the main controller. The combination of smart camera and programmable controller make the vision system suitable for industrial applications.

The rest of the paper is organized as follows: Section 2 describes the structure and principle of the system. Image processing algorithm and approaches of improving the system reliability are detailed in section 3. Section 4 introduces the controller design. Section 5 gives the experimental results. Conclusion is made in Section 6.

2 The structure and the principle of the system

The visual tracking system is composed of a special welding machine, a smart camera, a programmable controller, a touch screen, a stepper motor, a stepper motor driver, an electric welding machine and some other welding related devices.

The smart camera is mounted about 150 millimeters front of the welding torch. And its optical axis is perpendicular to the planar surface of the workpiece. The touch screen, the stepper motor driver, the programmable controller, and the power sources of the programmable controller and the camera are contained in the control box.

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Fig. 1 shows the diagram of the system. Before welding, the torch is aligned to the initial welding position manually. The smart camera is used to capture and process images of the welding seam during the welding process. The reference image feature point (u_r, v_r) is determined at the beginning of the welding. After that, the image feature point (u, v) is detected in real time. e is the image error in u -axis between the current feature point and the reference feature point, and it is transferred to the programmable controller by the smart camera. The input of the visual controller, e_o , is determined by the output error calculation algorithm. Then the controller outputs the control signals to the stepper motor l driver, finally, the stepper motor adjusts the welding torch to make sure the welding torch follow the welding seam during the whole process.

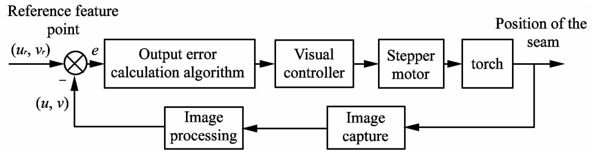

Fig. 1 Diagram of the system

Serial communication is adopted as the communication method between the smart camera and the programmable controller.

3 Image processing and approaches of improving the system reliability

3.1 Image processing

Image processing algorithm is one of the most important parts of the visual tracking system. The size of the captured image is 640×480 in pixel. Here, image "and" operation, seam line extraction, and image feature point selection are detailed.

1) Image "and" operation

The technology of CO_2 gas shielded arc welding is adopted in the production of the container. And many splashes are generated during the welding process. The first step of the image processing algorithm is to eliminate these splashes. Because of the instantaneity of the splash, most of splashes generated in one sampling period will disappear in the next period. By employing this fact, image "and" operation is used to eliminate the influences of the splashes. Eq. (1) shows the "and" operation.

$$I(i,j) = \min(I_1(i,j), I_c(i,j)), \tag{1}$$

Where $I_1(i,j)$, $I_c(i,j)$, $I(i,j)$ are the gray values of pixel point (i,j) in the last period image I_1 , the current period image I_c and output image I. i, j are integers and $0 < i < 641$, $0 < j < 481$.

Fig. 2 gives the effect of the image "and" operation. Fig. 2(a), (b) and (c) show the current period image, the last period image and the output image, respectively. It can be seen that there are many splashes in the current period image. But after the "and" operation, most of the splashes in the current image disappeared. Only a small number of them remained in the output image. And the next step of the image processing can be carried out smoothly.

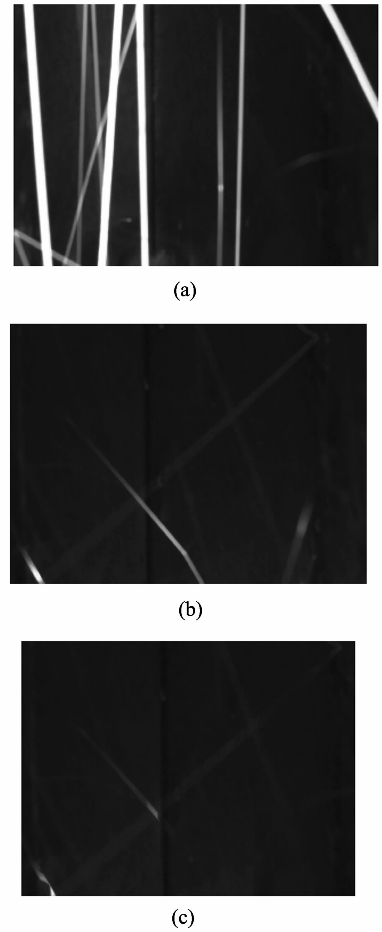

Fig. 2 The effect of the "and" operation: (a) the current period image; (b) the last period image; (c) the output image

2) Seam line extraction

Three steps are employed to extract the seam line: get the profile of the welding seam, Hough Transform and Least-square fitting method.

The profile of the welding seam should be obtained before Hough Transform. In most situations, the pixels in the welding seam are darker than others along rows of the under processed image. It is obvious that the lowest valley in the current image is the pixel point of the welding seam in that row.

Based on this fact, the seam's profile can be acquired by searching the image row by row with consideration of the gray distribution of the welding seam.

Hough Transform is a classical algorithm to detect straight lines in images. It is applied to the profile of the welding seam to get the seam line. The resolution of parameter θ in R-θ plane is set to 1 degree to accelerate the algorithm, and the range of θ is limited between $0 \sim 10$ and $170 \sim 180$ degrees by considering the fact that the seam is approximately parallel to v -axis of the image.

Least-squares linear fit technique is used to get the accurate seam line. If the distance from a pixel point of the seam profile to the line obtained by Hough Transform is less than a preset threshold l_{th}, it is accepted as the candidate pixel point. Least-squares linear fit technique is applied to these candidate pixel points. Equation (2), (3), (4), and (5) show the line detection process.

$$\begin{cases} \bar{u} = \sum_{i=1}^{f} u_i, \\ \bar{v} = \sum_{i=1}^{f} v_i. \end{cases} \tag{2}$$

$$\begin{cases} u_2 = \sum_{i=1}^{f} \exp(u_i - \bar{u}), \\ uv = \sum_{i=1}^{f} (v_i - \bar{v}) * (u_1 - \bar{u}). \end{cases} \tag{3}$$

Where (u_i, v_i) is the image coordinate of the i -th candidate pixel point; $(\bar{u}, \bar{v})$ is the average image coordinate of the candidate pixel points; f is the number of candidate pixel point; u_2, u_v are intermediate variables. If u_2 is greater than zero, the straight seam line will be calculated as shown below.

$$\begin{cases} m = \frac{uv}{u_2}, \\ n = \bar{v} - m * \bar{u}. \end{cases} \tag{4}$$

Where m and n are slope and intercept of the straight seam line, respectively. If u_2 is equal to zero, the function of the straight seam line will be in the form of equation (10).

$$u = \bar{u}. \tag{5}$$

3) Image feature point selection

The selection of the feature point is very important. Here, the midpoint of the extracted seam line is selected as the feature point. Fig. 3 shows the selection of the feature points.

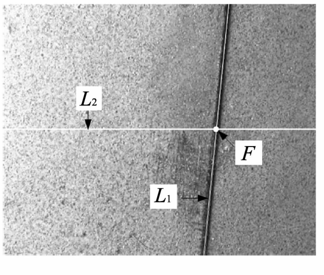

Fig. 3 Selection of the image feature point

In the figure, straight line L_1 is the detected welding seam, L_2 is the straight line $v = 240$. Point F, the intersection point of line L_1 and L_2, is selected as the feature point. The calculation of the current image error is given in

$$e = u_r - u. \tag{6}$$

Where u_r is the u -coordinate of the image reference feature point. u is the u -coordinate of the current image feature point. e is the image error in u -axis between the current feature point and the reference feature point.

3.2 Approaches of improving the system reliability

High Reliability is required for industrial applications. Some approaches are taken to improve the reliability of proposed system.

1) The calculation of the reference feature point

It is very important to determine the reference feature point. The reference feature point will be unchanged during a welding process once it is determined. A wrong reference feature point will result in failure of the welding. It is not reasonable to calculate the reference feature point according to an image. Actually, in our system, a group of images is used to get the reference feature point reliably. The flow chart shown in Fig. 4 explains the steps of calculating the reference feature point. 20 images are used to get a reliable result. These images are not randomly selected. They should contain at least one obvious straight line. After the selection of these images, the parameter of the reference seam line (R_r, θ_r) is determined in the final step.

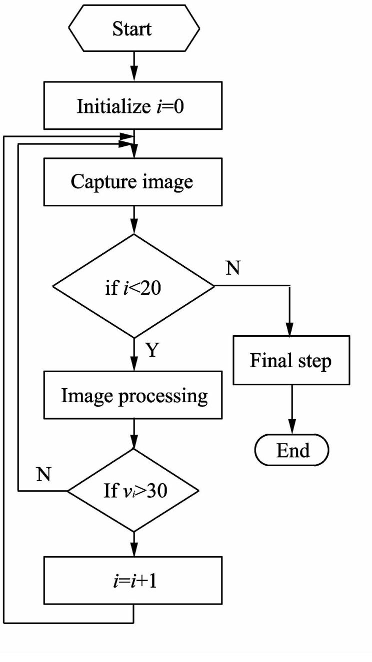

Fig. 4 The flow chart of the calculation of the reference feature point

Denote (R_i, θ_i, V_i) as the Hough parameter of the i -th captured image, i is an integer and $0 < i < 21$. (R_i, θ_i) is the polar coordinate of the seam line and V_i is the voting number of that line. After the selection of these 20 images, 20 triples can be obtained. Denote S as the set which is made up of these 20 triples. Denote S_1, $S_2, \cdots, S_j$ as the j subsets of S, j is an integer and $0 < j < 21$. These subsets are determined according to the distribution of θ_i. The elements in a subset have the same θ_i. Denote $S_k (0 < k < 21)$ as the subset which contains the maximum number $(n_m, 0 < n_m < 21)$ of elements and the reference feature parameter will be selected from it. Suppose (R_a, V_a, V_a) is the element of S_k with the maximum voting number V_a. (R_a, θ_a) is considered to be the parameter of the reference seam line L_r. And the midpoint of L_r is the reference feature point.

2) Test of the detected line

Arc welding is a very complex process where many noises are produced. It brings difficulties to the image processing. In many situations, the extracted lines are not the real seam lines. And they should be tested first to protect the system and avoid damages. Eq. (7) is employed to test the detected straight lines. Lines which don't satisfy the inequation are eliminated.

$$\begin{cases} | R_i - R_r | \leqslant \Delta R, \\ | \theta_i - \theta_r | \leqslant \Delta\theta. \end{cases} \tag{7}$$

Where R_i, θ_i are the parameters of the seam line in i-th captured image; ΔR is the distance threshold and $\Delta\theta$ is the angle threshold. In a control period, if the detected seam is eliminated, no adjustments are taken to the welding torch.

3) Output error calculation algorithm

The image error obtained according to equation (6) can not be input the controller directly. It should be processed first to get the suitable error, which is called output error in this paper.

A data array D is created to save the latest 10 image errors. The 10 errors are sorted according to their time index, and $D(10)$ is the image error of current sampling period. These 10 data are processed to get the output image error of the current period. There are two steps: eliminate the gross error and filtering.

The gross error brings damage to the welding and it should be eliminated first. The variances of the image errors in the data array are calculated as shown in equation (8) and (9).

$$A = \frac{1}{11}\sum_{j=1}^{i=10} D(j), \tag{8}$$

$$V(g) = \frac{1}{11}\sum_{j=0}^{j=10} [D(j) - A]^2. \tag{9}$$

Where A is the average of the data array D, $A(g)$ is the variance of $D(g)$, $g = 1,2,\cdots,10$. Suppose $V(m) = \max(V)$, $0 < m < 11$. The output image error is given as shown in equation (10) and (11).

$$S_f = \sum_{j=1}^{j=10} f(j), \tag{10}$$

$$e_o(r) = \frac{1}{S_f}\sum_{j=1}^{j=10} f(j)D(j). \tag{11}$$

Where $f(j)$ is the filter coefficient and $f(m) = 0$, s_f is the sum of the filter coefficient, $e_o(r)$ is the output image error.

4 Controller design

Image-based visual servoing method is adopted to design the controller because of the system configuration. The plate is nearly parallel to the image plane during the welding process, and the height between the image plane and the plate plan is fixed. Conclusion can be made easily that there is no need to adjust the welding torch in normal direction of the plate plane. In the proposed system, the welding torch is adjusted only in the left-right direction.

P_1 and P_2 are two points on the seam, Δl is the distance between them in the left-right direction. Denote Δu as this distance in image plane. Equation (12) is satisfied according to pinhole model.

$$\Delta u = a_u \Delta l, \tag{12}$$

where a_u is the scaling coefficient.

The pulse number needed for the stepper motor to remove an image error of one pixel can be obtained by calibration. A PID controller is designed. Equation (13) shows its expression.

$$u(r) = K_p e(r) + k_i \sum_{i=0}^{r} e(i) + K_d(e(r) - e(r-1)), \quad r = 1,2,\cdots,n. \tag{13}$$

Where $u(r)$ is the output of the PID controller in the r-th sampling period. $e(r)$ is the output image error of the period. K_p, K_i and K_d are the proportional, integral and differential gains, respectively.

Denote s_w as the adjustment quantity of the welding torch during the whole welding process of a plate. Generally, s_w is no more than 30 mm because of the configuration of the special welding machine and the welding seam. Suppose there are n_a sampling periods in the process. It can be got that the adjustment quantity of the welding torch is no more than s_w/n_a mm in each period. To protect the system and improve the system reliability, software limitation is carried out as shown in

$$p = \sum_{i=1}^{i=r} u_o(i-1). \tag{14}$$

Where $u_o(r)$ is the output image pixels in the r-th sampling period. p is the sum of $u_o(1)$, $u_o(2)$, $\cdots$, $u_o(r)$. n_l and s_l are the limited pulse number for one control period and the whole process, respectively.

5 Experiments

The experimental system was tested in a workshop. A programmable controller (Omron CP1H) and a smart camera (vc4018) were used to establish the system. A butt welding seam with 0.5 mm width and 2 000 mm length was employed. The calibration result shows that the Cartesian space resolution of a pixel in image space in experimental system was about 0.06 mm/pixel, and about 118 pulses are needed to remove an image error of one pixel. The velocity of the welding vehicle was 1 300 mm/minute. n_l and s_l were set to 100 and 3 000, respectively. The image coordinate of the refer feature point was (305, 240).

Fig. 5 shows the experimental results. Fig. 5(a) shows the tracking errors. Fig. 5(b) shows the welding results. The experimental results indicate that the seam tracking system can meet the requirement of container welding.

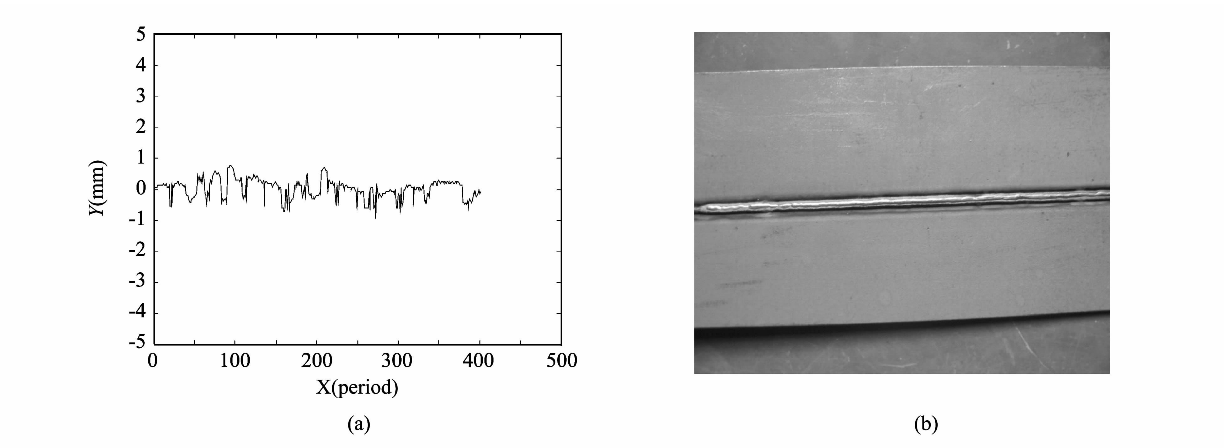

Fig. 5 The experimental results: (a) The seam tracking error; (b) The welding result

6 Conclusion

A visual tracking system based on smart camera, which is used to weld the narrow butt seams of thin plates in container manufacture, is designed. A smart camera is used to detect the welding seam. A programmable controller is employed to control the motor. Image based visual servoing strategy is adopted to design the controller. Experimental results verify the validity of the system. The proposed system, which can improve the efficiency and quality of the container production, has a high potential of being applied to manufacture industry.

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