Development of an Autonomous Mobile Robot with a Visual Sensor for Welding of Pipe : Butt Welding of Thin Wall Stainless Steel Pipes

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Development of an Autonomous Mobile Robot with a Visual Sensor for Welding of Pipe

—Butt Welding of Thin Wall Stainless Steel Pipes—

Koichi OGAWA* and Yasuo SUGA**

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An autonomous mobile robot system with a visual sensor for automatic welding of pipe is constructed. The robot developed can move along a pipe autonomously and detect a weld line to be welded by means of its visual sensor. The robot can confirm automatically whether the line detected is a weld line to be welded or not. Moreover, the tracking of the weld line at a constant welding speed and butt welding of the pipes are executed automatically. Generally, the recognition of a butt weld line of thin plates is difficult in welding because of the brightness of the welding arc. In this system, in order to recognize it stably, a special lighting system and some image-processing methods are applied. The effectiveness of the system constructed is confirmed through experiments on automatic weld line tracking.

1. Introduction

Recently, the mechanization and robotization of the operations in the extreme condition, that is underwater, space or nuclear environment, are desired. Accordingly, the robotics are studied widely and a lot of intelligent robots which have various functions have been developing[1−3]. Especially, because the welding operation is often dangerous and hard work for operators, the various welding robots are developed and used. Already, teaching play back robots are used for the spot welding in industries. Recently, the intelligent welding robots with arc sensing system are developed and begin to be used practically in the production system of heavy industries[4−6]. But it is difficult to apply the arc sensing system to welding of thin plates. Accordingly, in order to develop more flexible welding robot, a robot system with visual sensor is remarked[7−12]. Therefore, in this study, in order to make possible to weld pipes automatically in an extreme condition, for example in nuclear constructions, the development of intelligent welding robot for butt welding of thin wall pipes is tried. In this paper, the effects of lighting system and image processing on the recognition of the weld line of thin wall stainless steel pipes and function of the basic robot system developed were discussed.

* College of Integrated Arts and Sciences, University of Osaka Prefecture.
** Faculty of Science and Technology, Keio University.

2. Hardware of the robot system

Figures 1 and 2 show the arrangement and appearance of the welding robot which is controlled by two personal computers. The hardwares are made mainly of two systems, one is the system for recognizing a weld line by a visual sensor and the other is the system for making the welding torch track on a weld line. That is to say, the robot system is made by cylindrical-coordinate robot body, CCD camera fixed at the rotary head of the robot, TIG welding apparatus, image processor, monitoring display and 16 bits personal computer (Epson PC286) and so on. As the pipe, SUS304 stainless steel pipes which was finished by an emery paper (#800) were used. Its diameter is 60.5mm and wall thickness is 1.65mm.

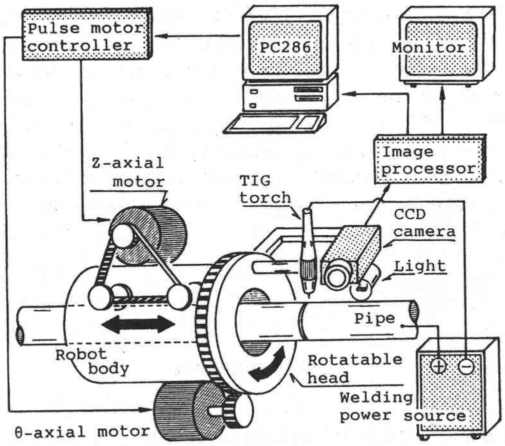


Fig. 1 Arrangement of equipment

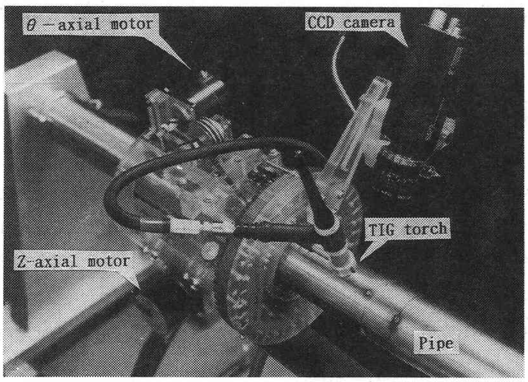


Fig. 2 Appearance of mobile robot

Figures 3 and 4 show the illustrations showing the function of the robot schematically and the flow chart of the function. As shown in Fig. 3(a), the robot runs autonomously along the pipe and detects the weld line. When the robot finds the weld line, it stops running. Then the robot head rotates somewhat and tracks the line in order to confirm whether the line found is truly the weld line or not, as shown in Fig. 3(b). If the line is judged not to be a weld line, the robot begins to search weld line again. When the robot judges it to be a weld line, the robot can ask the operator watching monitor whether the judgment was right or not. Then the robot prepares to perform welding of the pipes. That is to say, the robot memorizes the weld line position data from the starting point of welding up to the sensing point when the TIG torch comes to the start point. After that, the TIG torch is moved to the starting point of welding. Then arc is ignited by touch starting method and the welding of the pipes are performed automatically.

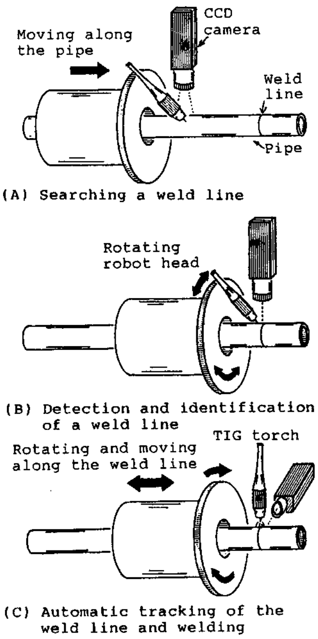


Fig. 3 Schematic illustration showing function of mobile robot

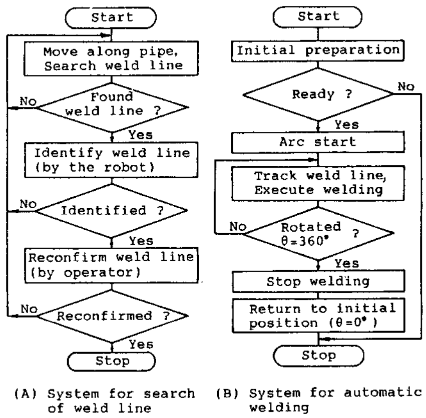


Fig. 4 A block diagram for recognition of weld line position and automatic tracking

3. Principle of recognition and automatic tracking of a weld line

Figure 5 shows a schematic illustration of the system for recognition and automatic weld line tracking. At first, the image of a weld line is taken into a CCD camera.

The image data are transformed to 64 steps digital data by an image-processor and recorded in an image-memory (256×256, 8bits). It takes 1/30s to take one flame. After the image data is taken into computer, brightness distributions on some scanning lines selected are processed and analyzed. When a remarkable point on the brightness distribution, for example the lowest or the highest point of the brightness, is detected, it is used for the detection of the weld line position. The difference between the weld line position detected and torch position was calculated, and then pulse motor of Z and θ axes are driven. The output pulses to the motors are controlled so as to keep the welding speed constant.

After the position of the weld line was detected in the first control cycle, weld line tracking was executed as follows. In the Fig.5, *R-O-Z* indicates an absolute coordinates and *X-O-Y* a relative coordinates, which move with CCD camera on the surface of the pipe ($R=R_o$). The axes X and Z are set to be parallel each other.

When the control cycle is indicated by T_i(i=1,2, ⋯,n) and θ-direction displacement of torch per one control cycle ΔL, the distance from the torch to detecting point of the weld line is set to be $n\Delta L$ in order to depress the influence of arc light. Accordingly the detected point of the weld line will be welded after nth control cycle (after ΣT_i).

Automatic tracking was performed as follows. At first the image is taken by CCD camera. According to the control data memorized in the memory of the computer, Z and θ axes pulse-motor were driven. During the robot is moving, the computer performs the data processing as follows. That is to say, relative position of weld line X_n is determined using the image data taken by CCD camera. From the data X_n, the absolute weld line position ($Z_n=Z_o+X_n$), which will be welded after nth cycle, is calculated. Weld line position data memorized already in memory are renewed as $Z_i=Z_{i+1}$. Then these operations are repeated. In order to keep the welding speed V constant, the moving speed of torch along the Z and θ directions, V_z and V_θ, must be controlled as $V=SQR(V_z^2+V_\theta^2)$.

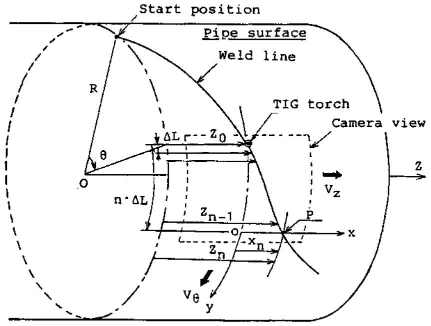
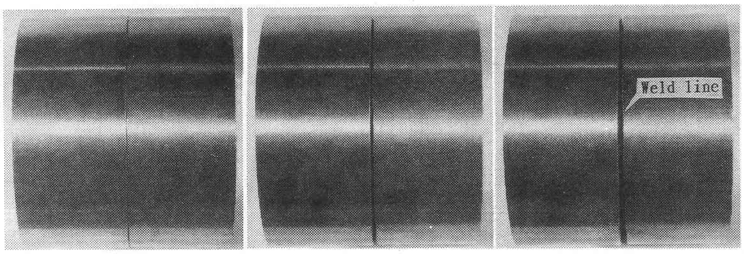


Fig. 5 Schematic illustration showing principle of automatic weld line tracking

4. Recognition of weld line

In order to perform automatic welding stably and obtain a sound weld, it is necessary to prevent misjudgment in recognition of weld line. Therefore the effects of root gap, surface condition of pipe, F number of camera, lighting and image processing on the recognition of weld line were investigated.

Figure 6 shows the effect of root gap, g, of the butt joint. In case g=0mm, the misjudgment was occurred sometimes. On the contrary, when the gap was more than 0.5mm, the weld line could be recognized stably.



(A) g=0mm (B) g=0.5mm (C) g=1.0mm

Fig. 6 Effect of root gap on recognition of weld line (with lighting, F16)

Figure 7 shows the effect of lighting on the recognition of weld line, in case the surface of the pipe was machined by a lathe. In the figure, when the lighting is relatively dark (a), the brightness distribution has a tendency to fluctuate remarkably. In this case, although it is posible to recognize the weld line position from the brightness distribution, if the lighting condition or surface condition changes, the misjudgment may occur. On the contrary, when the lighting is applied in front of the CCD camera and scanning line is set in the bright area of the pipe surface by the reflection of lighting (b), the noises of brightness distribution are eliminated and as the result the weld line can be recognized easily as the darkest position on the brightness distribution.

Figure 8 shows the arrangement of CCD camera, lighting, TIG torch and cover to shade the welding arc. Figure 9 shows the effect of F number of camera on the images of the pipe surface at a joint part (g=0.5mm). The arc current was DC 50A. These photographs are shown by color display and the numbers in the pictures indicate the brightness level. As shown in pictures (a) and (b), around the arc the brightness level indicates No.1, and it shows that the brightness of the area is very high. However, the brightness decreases with increasing the distance from the arc, because the pipe has a curved surface. When the F number is 16.5 as shown in (c), the bright area by the arc light decreases considerably. Moreover, when the cover shading the arc light is used (d), the influence of the arc light can be almost eliminated. From these photographs, it is clear that the influence of the arc light on the recognition of the

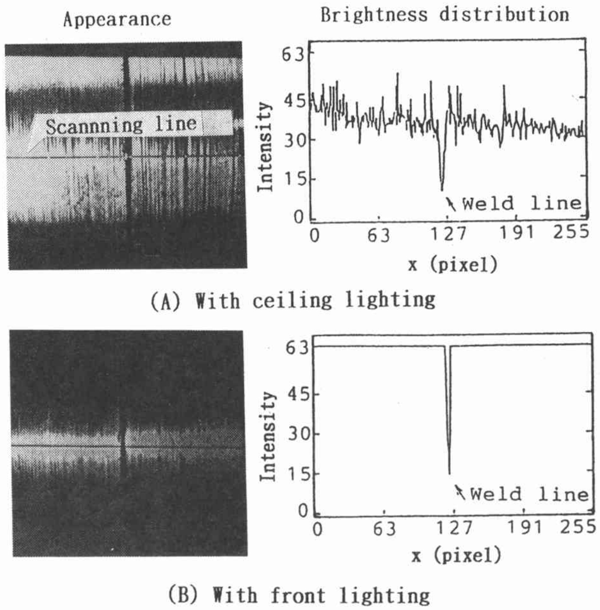


Fig. 7 Appearance and brightness distribution of pipe surface machined by a lathe (g=0.5mm)

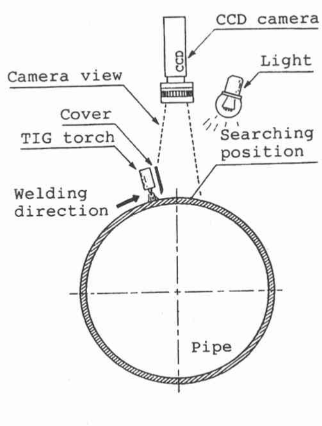


Fig. 8 Schematic illustration showing position of camera, torch and light

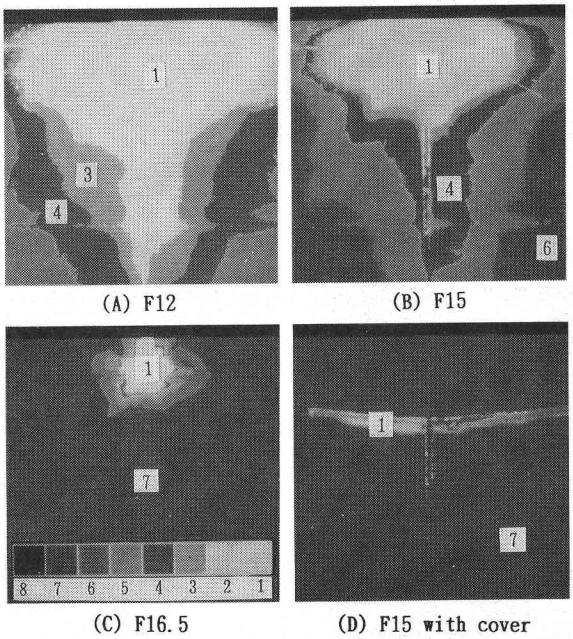


Fig. 9 Effect of F number on recognition of weld line in arc light (color display)

weld line can be eliminated by selecting the proper F number, using cover and setting the scanning line at the position far from the arc. Therefore the scanning line is set at the 200th from upper side of the CRT in this robot system.

Figure 10 shows the brightness distributions by color display in the case of F number of 16. In the figure, (a) shows the brightness distribution obtained without lighting, (b) that with lighting and (c) that with lighting and shade cover. From the figure, it is confirmed that, when the lighting is applied, the weld line can be recognized clearly as a dark line in the bright area reflecting the lighting. Especially, the influence of the arc light is eliminated completely in case the lighting and the shade cover are used. As the result, it is confirmed that the stable recognition of weld line is possible using the lighting system stated above.

5. Image processing to prevent misjudgment

5. 1 Differential and smoothing process

The robot moves along the pipe and searches the weld line autonomously. However, if the surface conditon of the pipe is not good or an unexpected lighting comes into

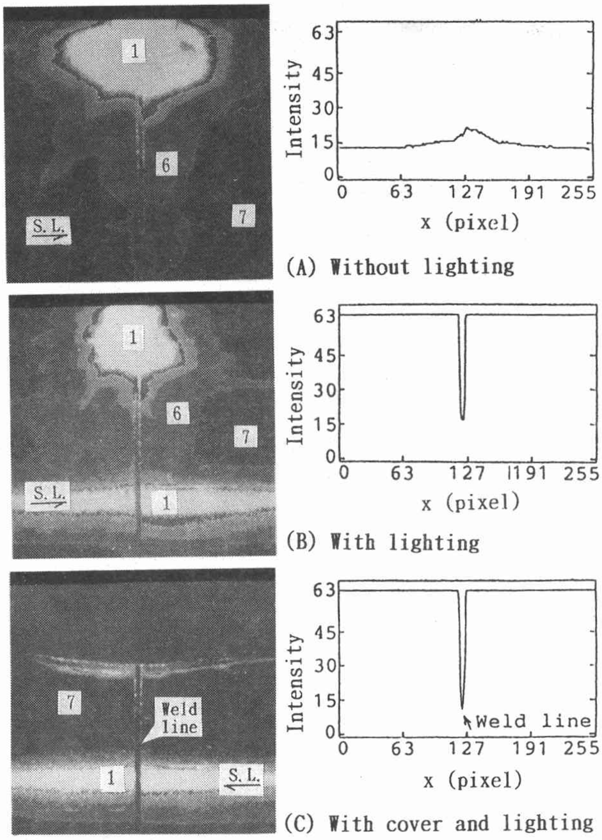


Fig. 10 Effect of lighting and cover on the brightness distribution

the view area of the camera, the robot may make a misjudgment in the recognition of the weld line. Figure 11 (A) shows an example of a brightness distribution on a scanning line. In this case, the position of the weld line can not detect by the algorithm, in which the weld line is detected as the darkest point on the brightness distribution. Therefore, a data processing method differentiating the brightness distribution was tried. The differential db/dx of the brightness $b(x)$ at a pixel of x can be obtained by the following formula.

$$db/dx = \{-b(x \times 2) + 8b(x+1) - 8b(x-1) + b(x-2)\} /12$$

The distribution shown in Fig. 11 (B) was obtained by differentiating the brightness distribution (A) and then by smoothing the differential (three points). From the figure, the long range variation of the distribution shown in (A) was eliminated by the differentiation. Besides, maximum and minimum values appear near the position of weld line. Accordingly, the positon of the weld line can be recognized clearly as the center position between these minimum and maximum pixels.

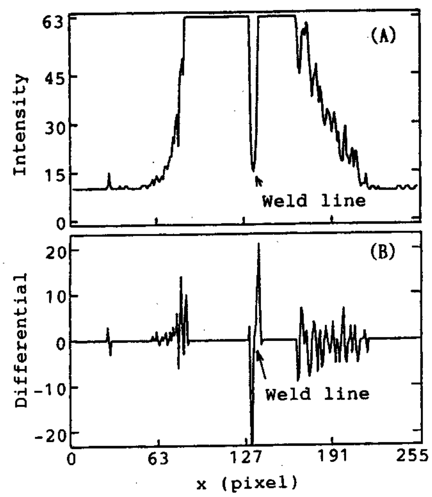


Fig. 11 Effect of differentiation of brightness distribution on the recognition of weld line

5. 2 Multi-scanning lines method and window process

Some experiments of automatic tracking of weld line were tried using the visual sensing system developed. As the result, when the welding arc exists, misjudgments were often occur. Observing one of these images, it was found that the weld line was often disappeared by the reflection of the strong arc light. Accordingly, the multi-scanning line method was developed. That is to say, although in the conventional method only one scanning line is used to detect the weld line, in the new method several scanning lines (N lines) are used as shown in the Fig. 12. In this system, if the weld line can be detected by one of these plural lines at least, the robot does not make a misjudgment. As the result, the reliability of the system increases remarkably.

For example, let us explain the recognizing method of a weld line by the three-scanning lines system. When the three points can be detected by the three scanning lines, the weld line position was determined as the average value of the three points. When the only one point can be detected by a scanning line, the point was determined to be weld line position. When the two points can be detected by two scanning lines including the main scanning line SL_0, the main point was determined to be weld line position. When the positions detected by two lines SL_1 and SL_{-1}, the average value was used.

As the weld line can be considered to be a cotinuous line, the weld line position should be near the weld line detected just before. Therefore the scanning line need not to be too long. When the scanning line length is reasonable, the probability to get noises and calculation time to detect weld line may decrease. As the result, the mis-

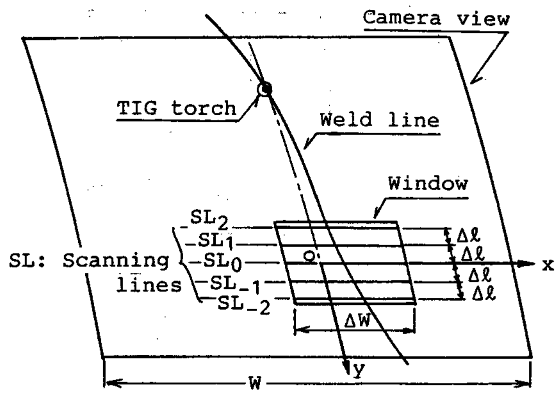


Fig. 12 Illustration showing weld line detecting method by multiscanning lines process

judgment of the robot will decrease. Therefore, a window, in which the plural scanning lines were set, was established in a image taken by the CCD camera. The window process is effective not only to prevention of misjudgment by noises, but also to a decrease of image data to be processed.

6. Experimental results of automatic tracking

In order to confirm the effectiveness of the data processing method constructed, automatic tracking of a weld line model, which is drawn by a broken line on a white paper, was tried. The length of the dash is 2mm and the gap between the dashes of the broken line is 1mm. As the multi-scanning lines method, three scanning lines method was adopted in this case. The experimental results of tracking are shown in Fig. 13. In the figure (A), the distance between scanning lines $\Delta \ell$ was set to be 0 pixel (that is one scanning line), (B) 3 pixels and (C) 5 pixels. The experiments were done 30 times respectively, and positions, at which misjudgment was occurred, were plotted in the figure. In the figure (A), the misjudgment occurs just after the tracking starts. Accordingly, it is seen that the tracking of a broken line is impossible by the one scanning line method ($\Delta \ell = 0$). On the contrary, in case the distance between scanning lines is 5 piexls(=0.84mm), no misjudgment occurred and stable tracking was performed. From the result, the effectiveness of the system constructed was confirmed.

Figures 14 and 15 show the result of automatic tracking of the weld line, when the pipes were cut at a angle of 10°, 30° as shown in the figures, (A) shows result of tracking, (B) normal component of error and (C) change of welding speed respectively. From the figures, it is seen that the welding torch tracks the weld line stably and the maximum tracking error is about 0.5mm and the average error 0.25mm. Moreover, from the figure (C), the welding speed is kept at 16.3 cm/min approximately. Accordingly, it is confirmed that the system constructed is effective in the automatic tracking of the weld line.

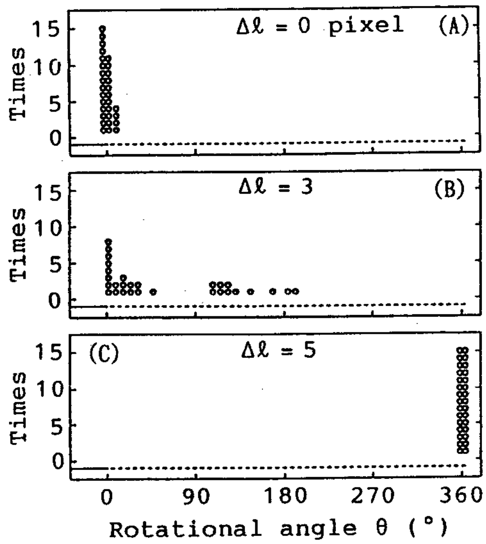


Fig. 13 Relation between ℓ and position of missing weld line

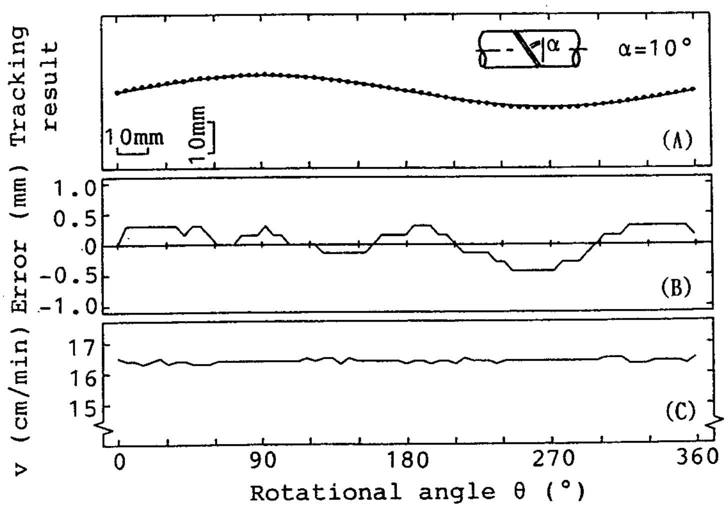


Fig. 14 Results of weld line tracking

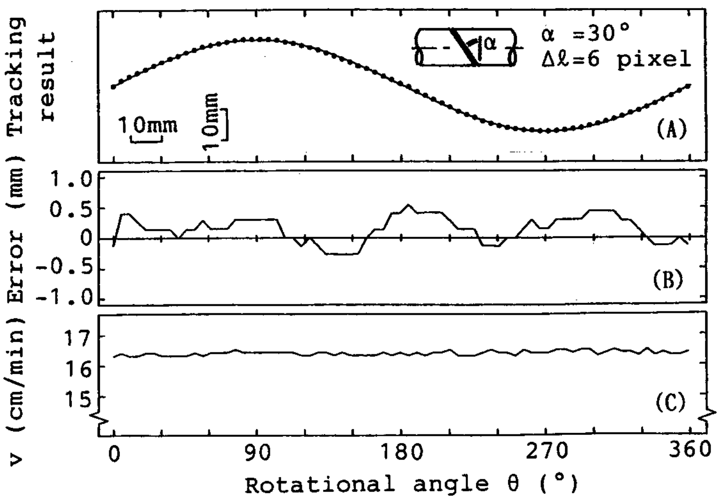


Fig. 15 Results of weld line tracking

7. Conclusions

Main results obtained are summarized as follows:

1) Applying proper lighting, butt weld line of pipes which have relatively rough surface condition can be detected.

2) Applying a lighting in front of CCD camera and setting the scanning lines on the bright area, the weld line was recognized stably regardless the arc light and surface condition of pipes.

3) Applying the differentiation process, smoothing process and window process to image data taken by CCD camera, the position of the weld line can be detected stably in butt welding of pipes. Moreover, multi-scanning lines process was proposed and its effectiveness was confirmed.

4) As the result of automatic tracking experiment, the torch tracked the weld line stably regardless noises, and the average tracking error was about 0.25mm. Therefore, it is confirmed that the pipe welding robot system is effective to automatic weld line tracking.

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