A Study on the Comparison of Algorithms Seam Tracking in Gas Metal Arc Welding

이정익 (컴퓨터응용자동화과)
Jeong-Ick Lee (Dept. of Computer Aided Automation)

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ABSTRACT : There have been continuous efforts in automating the joint tracking system. Automation plays an important role in the usage of the vision sensor. The vision sensor on a robot is used for weld seam tracking on welding fabrication. Real time seam tracking plays an important role in the vision process technique. Vision process includes filtering and gap filling, segmentation processing, feature extraction and recognition. In this paper, the performance comparison results of seam tracking for real time rootpass on gas metal arc welding are shown. It can be concluded that the presently developed algorithm is superior to the previous algorithm in terms of seam tracking for rootpass of gas metal arc welding.

요약 : 용접선 추적 시스템을 자동화하려는 노력은 계속되어 왔다. 자동화에는 비전센서의 사용이 중요한 역할을 한다. 로봇에 장착된 비전센서는 용접구조물의 용접선 추적을 위해서 사용되었다. 실시간 용접선 추적은 비전처리 기술에 있어 중요하다. 비전처리에는 필터링과 갭충진, 분할선 처리, 특징점 추출 및 인식과정 등이 포함된다. 이 논문에서는, 실시간 GMA 초층용접을 위한 용접선 추적의 수행결과를 나타내고 있다. 그 결과, GMA 용접에서는 초층용접을 위한 용접선 추적에서 현재 개발된 추적알고리즘이 이전의 추적 알고리즘에 비해 추적성능이 우수한 것으로 결론지을 수 있었다.

1 Introduction

It is important to perform precise seam tracking to obtain the width and penetration of bead through good weld bead. Efforts for application on seam tracking by vision sensor have been made by precedent researchers. Clocksin[1] presented an algorithm defining the weld joint type by handling information of the laser line in MIG welding. Agapakis[2-3] proved a geometrical imaging information and real-time welding control algorithm and applied it on robots for welding. Huber[4] used laser vision as a method of detecting position and gap, and applied it to pipe welding. Nakata[5-6] studied upon the optimal geometrical formation by experimenting through light source, camera position and resolution, camera exposure and by He-Ne laser, band pass filter, and CCD camera. This research is promoted on designing seam information 3mm in front of the pool and constructing a seam tracking automation system.

Through reviewing what the researchers mentioned above, it can be said that the purpose of this research paper is focusing on performance comparison results of seam tracking for real time rootpass seam tracking on gas metal arc welding. The results showed that the presently developed algorithm(an application algorithm of segment splitting method) is better than the previous algorithm (iterative averaging technique) in the performance of seam tracking. That is became that the presently developed algorithm showed more robustness in sensor and arc noise than the previous algorithm.

2. Seam tracking

2.1 The principle of vision sensor

Optical triangulation is popularly used in measuring the distance to object by triangulation method because of its short image processing time and simple structure. Optical triangulation can be divided into two parts depending on the operational principle and light source, thus, by a structured light pattern type and scanning beam type. Generally, the scanning beam type is superior to structured light type in terms of noise. Laser vision sensor of scanning beam type is used in this paper.

2.2 Vision processing

Generally, intensity image or range image is used for vision processing. Intensity image is the gray level of each pixel and range image is the range information of each pixel. Range information is needed in seam tracking and is used more frequently than intensity image. The range image that comes from the vision sensor is transformed into a value in the camera coordinate to obtain needed information. Range image shows coordinates in the cross section of material. From this, information necessary to seam tracking is obtained. For this operation, the following steps are operated recursively.

(a) Data obtained from the noise reduction process and vision sensor includes various noise such as arc light, spatter, specular reflection and multiple reflection. Therefore, filtering operation of the image is necessary.

(b) For extracting features in the measured shape from segmentation and filtering, it is necessary to simplify the line segment by extracting of break points.

(c) From break points after extraction of break point and segmentation processing, information on the feature points and break points of V-grooved can be produced.

2.2.1 Vision preprocessing

Vision preprocessing means image processing, such as the promoting of image quality, transforming adequately for special application purposes etc.

This vision preprocessing includes image operation such as smoothing, sharpening, high frequency separation, and low frequency separation. Raw profile which is obtained from sensor calibration data by vision system is expressed (y, z) into the coordinate of 256. Y is defined as the bead width in the welding operation and Z is defined as the bead depth direction in the welding operation. In replacing image values into the mean value of the neighboring values, median filtering as a nonlinear operation technique is the most effective in noise reduction. This operation is done by removing noise elements without having major effects in high frequency elements. By changing the window size to 2 dimensions, the filtering range can be transformed. Because a considerably large 2 dimensional window can loose features of the profile such as the V corner, 2 dimensional window size which includes 3 or 5 neighboring profiles is suitable for image processing.

In this study, segmentation and feature extraction are used through vision preprocessing, and effects such as gap filling can be obtained by software in vision preprocessing.

2.2.2 Comparison of segmentation processing algorithm

The segmentation processing is done on the basis of finding considerably large directional change and approximating line segments. Significant data reduction effect can be expressed through this operation by storing the break points which are among the segments. Through this segmentation processing, two algorithms of segmentation processing are used in this paper to adequately express the break points. First, if the gradient difference is over tolerance, end points of those segments are considered break points in the previous algorithm[7] of segmentation processing. Though this algorithm is considerably simple, it has some difficulties in expressing various joint types. This algorithm is expressed as equation (1) and Fig. 1. To back-up the weak points of the previous algorithm of segmentation processing, a new algorithm of segmentation processing and extracting of break points is developed. Especially, as this new algorithm can be expressed in various joint types, this can be applied on not only to seam tracking but also to weld quality inspection. This new algorithm is expressed in equation (2) and Fig. 2. Equation 2 and Fig. 2 largely expressed the features of the laser stripe from vision sensor into 4 types. Z_i expresses z coordinate on i-th profile, and m_1, m_2, d_1, d_2 are designed to obtain the suitable length on the basis of segmentation processing by heuristic method for optimal conditions through experimental experiences. In this study, m_1 is used as 3, m_2 is used as 4, d_1 is used as 3 and d_2 is used as 6. The geometrical meaning of m_1, m_2, d_1, d_2 is that the 4types of joints or the general characteristics of the bead which form the basis of segmentation processing can be induced with z_i in the middle, according to the range depth magnitude of both sides, which is formed due to the distance of m_1 and m_2

. Profile data coordinate (y_i , z_i) which satisfies the condition is named as break points. The crossing point is between each line segment and is stored in memory.

$$\left| \frac{z_{i+1} - z_i}{y_{i+1} - y_i} - \frac{z_i - z_{i-1}}{y_i - y_{i-1}} \right| \geq \text{tolerance}, \quad i = 1, 2, \cdots, n \qquad (1)$$

$$\begin{aligned} & |z_i - z_{i-m_1}| \leq d_1 \text{ and } |z_i - z_{i+m_2}| \geq d_2 && \text{(a)} \\ \text{or, } & z_i - z_{i-m_2} \geq d_2 \text{ and } z_i - z_{i+m_2} \geq d_2 && \text{(b)} \\ \text{or, } & z_i - z_{i-m_2} \leq -d_2 \text{ and } z_i - z_{i+m_2} \leq -d_2 && \text{(c)} \\ \text{or, } & |z_i - z_{i-m_1}| \geq d_2 \text{ and } |z_i - z_{i+m_2}| \leq d_1 && \text{(d)} \end{aligned} \qquad (2)$$

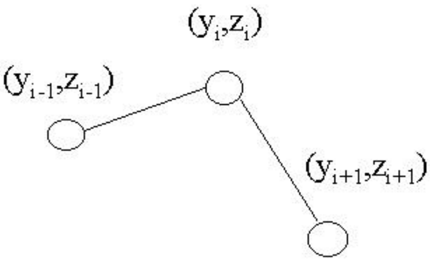


Fig. 1 Line segment of the profile

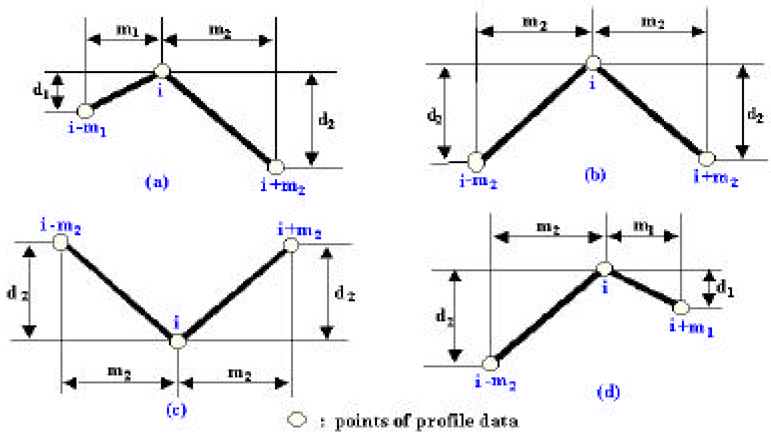


Fig. 2 Description of the segmentation processing

2.2.3 Feature point extraction and root point tracking by iterative averaging technique

Through the previous segmentation processing (equation (1), Fig. 1), features which have a meaning can be extracted as a next step.

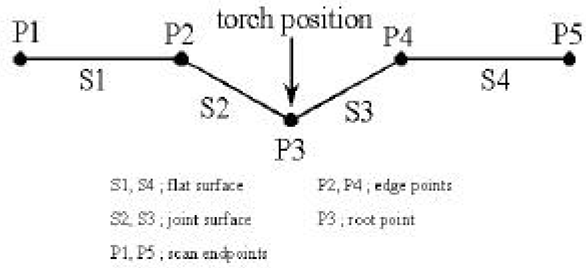


Fig. 3 Characteristic features of a V-grooved weld joint

To induce a joint type or general characteristic of weld bead on the basis of segmentation processing, a general characteristic is shown in Fig. 3. Feature extraction is a job of finding formation on feature points and feature lines. After this job is done, the information acquired is used to determine the weld tracking point. The feature extraction and root point tracking algorithm of V-groove which is used in this study is a modified version of the V-groove detection algorithm, which was formally changed by Smati, Smith and Yapp[8] who made it adaptable on range image. This feature extraction algorithm is based on iterative averaging technique. $\overline{z_o}$ is given by averaging all values of z axis. Left reference point(P2) and right reference point(P6) centering on P4 are found in Fig. 3 by using the V-groove detection algorithm in the middle of break points. The tolerance band is changed according to the magnitude of the joint and resolution of the laser camera. Next, an algorithm for finding a left reference point(L:P2), right reference point(R:P6) and center reference point(P6) is expressed in Appendix 1. As this iterative averaging technique is developed under the assumption that the left and right flat surface line centering on V-groove in Fig. 3 hardly changes during welding, this method shows comparatively superior time reduction to the new suggested algorithm for finding root tracking point. Sensor noise and arc light can deeply influence seam tracking, as vision data for seam tracking can be lost. Thus, these phenomena can effect the results of seam tracking.

Appendix 1 An algorithm in finding right and left reference point and center reference point by averaging iterative technique

Where, n: data number on profile, N: break point number on profile

z_i: z coordinate on i-th profile, Z_i : z coordinate of i-th break point on profile

2.2.4 Feature point extraction and root point tracking by an application algorithm of segment splitting method

In this study, feature point algorithm of V-groove was applied on the segment splitting method. The maximum distance points from the reference line were extracted as feature point. Fig .4 shows range image, break point and location of left and right reference point.

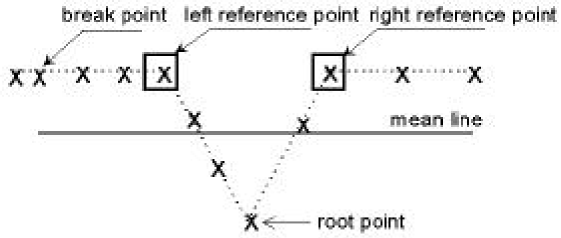


Fig. 4 Characteristic of break points and right and left reference point

Fig. 4 shows the typical shape of a V-groove. Here, the mean value of all z axis values are given as $\bar{z}$. From this reference line, mean line for finding a welding point is made in the part representing the V-groove. Through segmentation processing, the reference point is placed at both end points, thus, the left and right edge points of V-groove to left and right reference point in the middle of approximated break points. The left reference point is the farthermost point from the straight line that connects the first point of distance and the crossing point of the mean line and the left line of V-groove. Fig. 5 shows a method for finding the reference point. The principle for finding the right reference point is the same method. Equations (3) - (12) show an algorithm for finding the mean value, two crossing values of V-groove and mean line, and right and left reference point. A break point is found in the lowest point of the V-groove, which is named the center reference point. The precise welding position is extracted from this reference point.

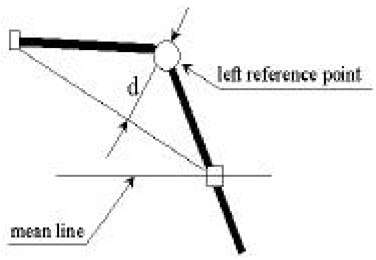


Fig. 5 Detection method of left reference point

Equation (8) shows an algorithm for finding a center reference point. A large amount of noise is made due to specular reflection near the seam tracking position. This reason causes a loss of the welding point. Furthermore, the point Z_K in equation 8 may not be an exact center point in joint surfaces due to noise and multiple reflection. Therefore, a back-up operation is necessary. First of all, the front and back break points of Z_K such as Z_{K-1} and Z_{K+1} should be found, and the absolute distance of $\overline{Z_L Z_{K-1}}$ and $\overline{Z_{K+1} Z_R}$ in equation 11 should be compared. According to the direction of two lines, the location of Z_K can be found in joint surfaces(left or right). After the location of Z_K is recognized, the two break points of Z_K (the front and the back break points) and two left and the right reference points should be connected to the lines. This process is called the least square error method. Thus, this crossing point of two lines is called the tracking point for rootpass welding. Equation 12 shows an algorithm for finding the rootpass welding point.

First average (mean value)

$$\bar{z} = \frac{1}{n}\sum_{i=1}^{n} z_i \tag{3}$$

Find m_1 when $z_{m_1} > \bar{z}$, $z_{m_1+1} < \bar{z}$, $m_1 = 1, 2, \cdots, n-1$ (4)

Find m_2 when $z_{m_2} > \bar{z}$, $z_{m_2-1} < \bar{z}$, $m_2 = n, n-1, \cdots, 2$ (5)

(where, m_1 and m_2 are crossing point of mean value line and V-groove)

Left reference point:

$$a = \frac{(z_1 - z_{m_1})}{(y_1 - y_{m_1})} \qquad b = z_{m_1} - a \times y_{m_1}$$

$$d = \frac{|\, a \times Y_L - Z_L + b|}{\sqrt{a^2+1}}, \quad L = 1, 2, \cdots, M_1 - 1, M_1 \tag{6}$$

Find L, d is maximum value.

Right reference point:

$$a = \frac{(z_n - z_{m_2})}{(y_n - y_{m_2})} \qquad b = z_{m_2} - a \times y_{m_2}$$

$$d = \frac{|\, a \times Y_R - Z_R + b|}{\sqrt{a^2+1}}, \quad R = M_2, M_2+1, \cdots N-1, N \tag{7}$$

Find R, d is maximum value.

Center reference point: (to find a minimum break point within joint surfaces)

Find K when Z_K is minimum value, $L \le K \le R$ (8)

Preparation for least square error method

Find Z_{K-1}, Z_{K+1} when Z_K is minimum value, $L \le K \le R$ (9)

Find D($\overline{Z_L Z_{K-1}}$), D($\overline{Z_{K+1} Z_R}$) (D: distance) (10)

If D($\overline{Z_L Z_{K-1}}$) > D($\overline{Z_{K+1} Z_R}$) (Z_K is situated on left)

Then D($\overline{Z_L Z_{K-1}}$) < D($\overline{Z_{K+1} Z_R}$) (Z_K is situated on right) (11)

Else then D($\overline{Z_L Z_{K-1}}$) = D($\overline{Z_{K+1} Z_R}$) (Z_K is situated on center)

Rootpass welding point: (the general expression of the least square error method)

$$z_L = a_L \times y_L + b_L, \qquad z_R = a_R \times y_R + b_R$$

$$y_{root} = \frac{b_R - b_L}{a_L - a_R}, \qquad z_{root} = a_L \times y_{root} + b_L \tag{12}$$

Where, $\bar{z}$; mean value of z coordinate,

z_i ; range image on i-th, n; number of range image,

m_1 , m_2 ; left and right value which crosses the V-groove and mean line,

N ; number of break point on range image,

z_i ; i-th range image on z coordinate,

Z_i ; i-th break point of range image on z coordinate,

y_i ; i-th range image on y coordinate,

Y_i ; i-th break point of range image on z coordinate,

M_1 , M_2 ; m_1 -th and m_2 -th of range image

2.3 Tracking signal processing of seam line

To promote tracking reliability in seam tracking, the tracking point that was recognized in each profile is used, and it is necessary to refer to the precedent tracking point. As a method of improving the reliability of the seam tracking trend used in this study, the present data is applied. By using this improved method, a weighted moving average, which is a kind of exponential smoothing method, is used in tracking signal processing.

$$y_a(n) = (1-m)y_a(n-1) + my(n) \tag{13}$$

$$z_a(n) = (1-m)z_a(n-1) + mz(n) \tag{14}$$

Where, m ; weighted value,

$y_a(n-1)$, $z_a(n-1)$; the precedent moving averaging value,

$y(n)$, $z(n)$; the tracking point at on-line tracking,

$y_a(n)$, $z_a(n)$; the moving averaging value at on-line

Weighting value has different value according to the welding process and welding condition. When m is given a value of 0.25, which was obtained by the experiment in this study, seam tracking was well performed.

3. Experiment

3.1 System configuration

The experimental system is divided into welding system parts and vision system parts. The welding system consists of 3 axis cartesian robots, CO_2 gas arc welding machine (maximum 350A inverter welding machine), wire feeder, water cooler and motion controller, and 1.2mm diameter wire were used. Vision system parts consist of vision controller and laser camera.

Vision control system is an adapted industrial PC embedded CPU (75MHz Pentium CPU) which is made up of camera control system with embedded DSP, and this is used on vision processing, laser power scanning control and camera control system with embedded DSP. The resolution of vision camera was 0.05mm. Vision camera (camera head or range finder) is used as laser vision sensor(dimension: 110mm width X 60mm depth X 48mm thickness). An auto-synchronized method is adapted as a range measuring system which applies the active optical triangulation principle to measure the depth. The light ray which is produced from the laser is projected on the object by forming a light surface. The receiver lens which is slantingly located in the light path is projected on the photosensitive detector which is reflected on an object surface. Because the photosensitive detector consists of a CCD of 2D, the sectional profile of the object is organized on CCD. The profile that is measured is separated by software and the position of each point on section is calculated. For the light source, 40mW, visible laser diode of amplitude 680 nm is used. Fig. 6 shows a system configuration.

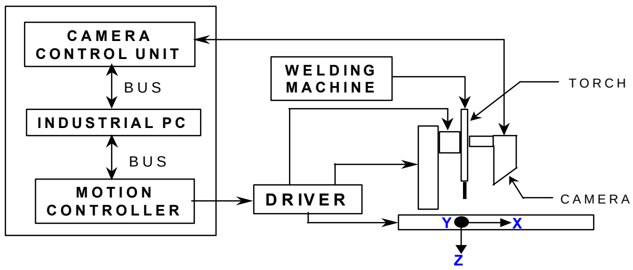


Fig. 6 System configuration for joint tracking

3.2 Experiment method

After two pieces of welding specimen (70mm width X 200mm depth X 16mm thickness)are tagged, butt welding is performed. For displacement of welding and good seam tracking of vision system, adaptable jig for butt welding is used. The V-groove of butt welding has a value of 60 degrees and groove angle for experiment has a root face of 3mm. A 1.2 mm solid wire, and shielding gas made of pure CO_2 gas, with a flow rate of 15 $l/\min$ is used. CTWD is kept at 15mm. Welding condition is performed in 180A welding current, 26 V welding voltage and 5mm/sec welding speed. the laser camera was located in front of welding torch, and the position of the tracking line can track range information in front of the look-ahead distance of 26mm.

The experiment was performed in the following procedure. After capturing data, noise removal and segmentation processing, feature extraction of V-grooved and recognition of feature points are processed. The algorithm of segmentation processing process(equation (1) and equation (2)) and the algorithm of V-groove feature extraction and rootpass tracking (the iterative averaging technique and an application algorithm of segment splitting method) are compared to tracking results. In this paper, two methods of seam tracking algorithm, the previous algorithm(equation (1) and the iterative averaging technique), and the present developed algorithm(equation(2) and the application algorithm of segment splitting method) are compared. The extracted feature point is transformed into coordinates which must be moved. The tracking point is given as the calibration of the next tracking point by weighted moving average method. By doing these repetitive operations, real-time seam tracking is performed. Fig. 7 shows a flow chart of joint tracking in tracking mode.

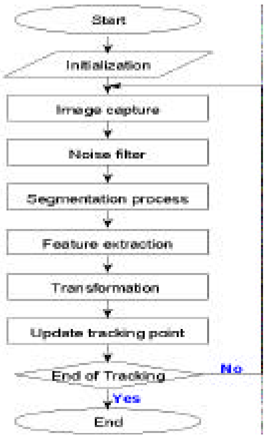


Fig. 7 Flow chart of joint tracking in tracking mode

To estimate the tracking performance, tracking experiment is performed to inspect whether the deviation degree could be tracked and also be changed in various degrees on the reference line using a 3 axis cartesian robot. Furthermore, as HANGUL (Korean Language) GUI(Graphic User Interface) program is developed for easy seam(weld line) tracking and real-time tracking, this system is made for on-line monitoring of each parameter and profile etc. Fig. 8 shows an example of Graphic User Interface in joint tracking program

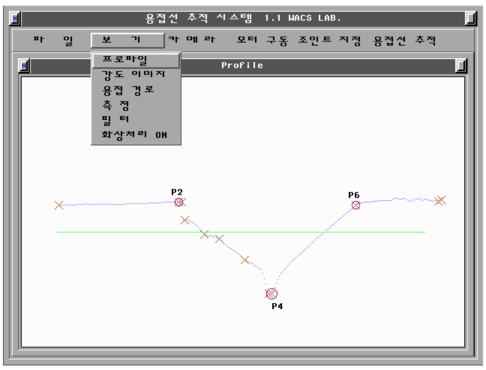
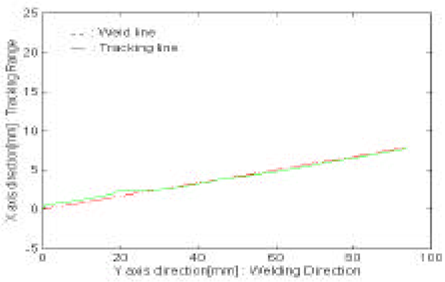


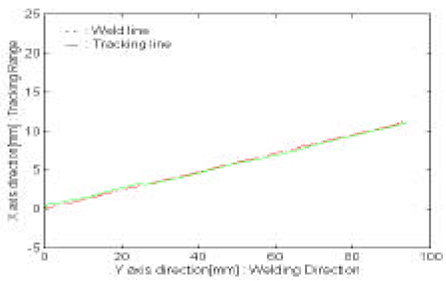
Fig. 8 Example of GUI in joint tracking program

3.3 Experiment result

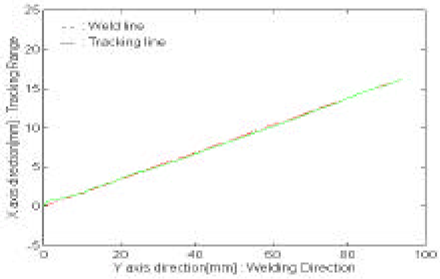
By applying seam tracking on the previous algorithm and the present developed algorithm, the deviation degree of three cases weld line tracking on 5, 7, 10 shows the following results. In case of 5degree deviation, maximum error showed a small difference. In case of mean error and standard deviation, error by previous algorithm which is given a suitable allowance, capturing left and right reference points and finding a center reference point(root point) shows a small error. As the deviation degree is increased, tracking error on maximum error, mean error and standard deviation are shown to have a small difference in the previous algorithm in comparison to the presently developed algorithm. Because the maximum error shows a value of below 0.7 mm near 10 degree deviation of both seam tracking algorithms, maximum error of tracking shows a small value if the fact that the wire is 1.2mm in diameter is considered and thus, superior tracking performance is proven. Therefore, as the degree increases, the presently developed algorithm shows rapid tracking performance and a smaller error deviation than the previous algorithm. The presently developed algorithm shows good results in tracking accuracy and tracking performance in on-line tracking. Fig. 9 and Fig. 10 show the tracking results of the previous algorithm and the presently developed algorithm. Table 1 and Table 2 show tracking results of maximum error, mean error and standard deviation. Mean error is the absolute value of the mean value of error on the tracking line and reference line, and standard deviation shows the whole trend of seam tracking.



(a) 5 degree

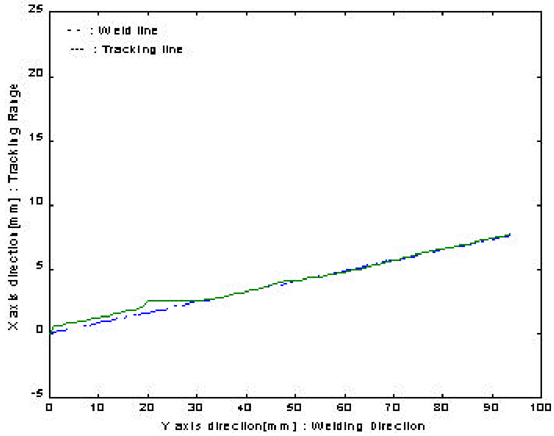


(b) 7 degree

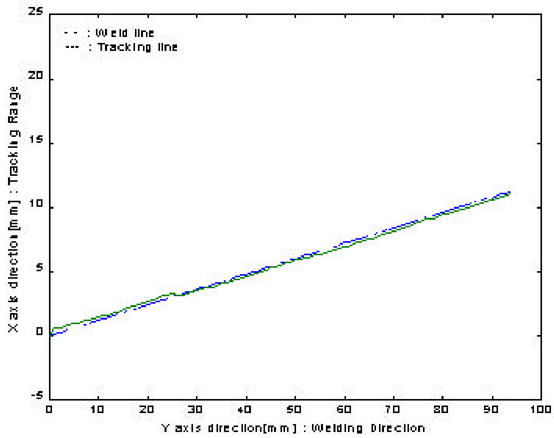


(c) 10 degree

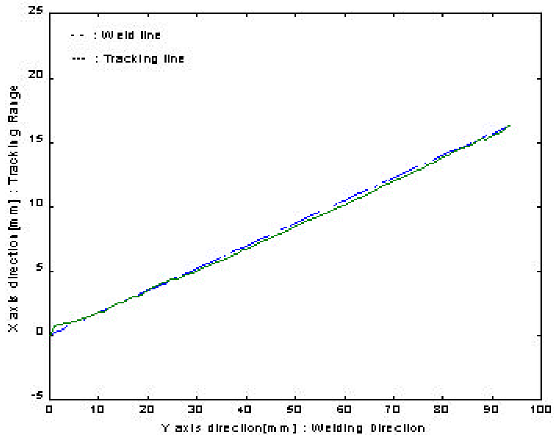
Fig. 9 Seam tracking results by the previous algorithm



(a) 5 degree



(b) 7 degree



(c) 10 degree

Fig. 10 Seam tracking results by the present developed algorithm

Table 1 Seam tracking results of V-groove on 5, 7, 10 degree by the previous algorithm

error (mm) / deviation	mean error	maximum error	standard deviation
5 degree	0.08	0.24	0.27
7 degree	0.16	0.44	0.29
10 degree	0.33	0.68	0.42

Table 2 Seam tracking results of V-groove on 5, 7, 10 degree by the present algorithm

error (mm) / deviation	mean error	maximum error	standard deviation
5 degree	0.15	0.14	0.28
7 degree	0.07	0.33	0.23
10 degree	0.14	0.35	0.23

4. Conclusion

As a research of GMA welding automation by vision sensor, real-time seam tracking results by two different algorithm(the previous algorithm and the presently developed algorithm)are compared in various deviation angles, and are discussed.

1. The new segmentation processing algorithm for precise seam tracking is suggested in two comparative algorithms. The new algorithm is superior to the previous segmentation processing algorithm in representing various joint types.
2. Seam tracking by the previous algorithm and the presently developed algorithm showless maximum error values below the wire diameter, thus showing satisfactory tracking result.
3. Seam tracking results of the presently developed algorithm shows similar tracking results compared to the previous algorithm in the deviation degree of seam where the discrepancy was small. As deviation degree increases, the presently developed algorithm is shown to have superior tracking performance to the previous algorithm.
4. The two segmentation processing algorithms did not show a discrepancy in tracking performance. In comparison of feature point extraction and root point tracking, an application algorithm of segment splitting method is shown to have superior robustness in arc and sensor noise to iterative averaging technique. As a result, it is considered that the robustness noise can effect the performance of seam tracking.

* Appendix 1

* Algorithm for average (mean value),

$$\overline{z_o} = \frac{1}{n}\sum_{i=1}^{n} z_i$$

Find L when $Z_L > \overline{z_o}$, $Z_{L+1} < \overline{z_o}$, $1 \le L \le N$ (L: Left side of Fig. 2 profile)

Find R when $Z_R > \overline{z_o}$, $Z_{R-1} < \overline{z_o}$, $1 \le R \le N$(R: Right side of Fig. 2 profile)

Left reference point: $\overline{Z} = \overline{z_0}$

Repeat

1. $If\ (Z_k < (\overline{Z} + tolerance))$, $k = L \ldots 1$

Then L = k

2. $\overline{Z} = \frac{1}{L}\sum_{i=1}^{L} Z_i$ Until $Z_k \ge (\overline{Z} - tolerance)$, $\forall k \in [1, L]$

Let: Left reference point = L

Right reference point: $\overline{Z} = \overline{z_0}$

Repeat

1. $If\ (Z_k < (\overline{Z} + tolerance)), \quad k=R \ldots N$

Then R = k

2. $\overline{Z_0} = \frac{1}{N-R+1}\sum_{i=R}^{N} Z_i$ Until $Z_k \geq (\overline{Z} - tolerance), \quad \forall k \in [R,\ N]$

Let : Right reference point = R

Center reference point:

Find k when $Z_{k+1} < Z_{k,} \quad k=L \ldots R$

Let : Center reference = k

Where, n ; total data number on profile, N; break point number on profile,

z_i : z value of profile on i-th, Z_i ; z value of break point in profile on i-th

References

(1) Clocksin, W. F., 1985, An implementation of model-based visual feedback for robot arc welding of thin sheet steel, The International Journal of Robotics Research, Vol. **4, No.**1, pp.13-26.

(2) Agapakis, J. E., 1990, Approaches for recognition and interpretation of workpiece surface features using structured lighting, The International Journal of surface Robotics Research, Vol. **9, No.** 5, pp. 3-16.

(3) Agapakis, J. E., 1986, Joint tracking and adaptive robotic welding using vision sensing of the weld joint geometry, Welding Journal, Vol. **65, No.** 11, pp. 33-41.

(4) Huber, C. & Boderie, E., 1988, A vision system for automatic welding of thin stainless steel plates, Proc. Int. Conf. Robot Vision and Sensory Controls, pp. 31-38.

(5) Nakata, S. & Jie, H., 1989, Construction of visual sensing system for In-process control of arc welding process and application in automatic weld line tracking, Japanese Welding Journal, Vol. **7, No.** 4, pp. 467-472.

(6) Nakata, S., 1989, Determination on geometrical arrangement of optical equipment and photographic parameters for construction of visual sensing system, Japanese Welding Journal, Vol. **7, No.** 3, pp. 358-362.

(7) Ramesh, J., Rangachar, K., Brain, G.S., 1995, Machine vision, McGraw-Hill, Inc., pp. 28-31.

(8) Smati, Z., Yapp, D., Smith, C. J., 1984, Laser guidance system for robots in Proceeding of 4th Intl Conf. on Robot Vision and Sensory Controls, pp. 91-101.