A Study on Optimal Algorithms to Find Joint Tracking in GMA Welding

Jong-Pyo Lee, Qian-Qian Wu, Min-Ho Park, Cheol-Kyun Park and Ill-Soo Kim

Abstract—The GMA welding, which is also called Metal Inert Gas (MIG) welding, has been an important component in manufacturing industries. A major concern among the key technologies of welding automation is seam tracking technology, which is critical to improve the process performance and welding accuracy.

The goal of this study is to set up intelligent and cost-effective algorithms for image processing in Gas Metal Arc (GMA) welding based on the laser vision sensor. Weld seam images were captured from the CCD camera and then processed by the proposed image processing to track weld joint location. To improve the processing performance, algorithms that common used at the present stage were verified and compared to obtain the optimal one for each step in image processing. Moreover, taking the advantages of simple interactive environment and abundant toolboxes, MATLAB was utilized to realize those algorithms, which offer a sample for engineers to achieve the goal of algorithm development by this new but easier approach. Finally, validity of the proposal algorithms was examined by using weld seam images obtained with different welding environments for image processing. The results proved that the proposed method was quite excellent in getting rid of the variable noises to extract the feature points and centerline for seam tracking in GMA welding and could be used for general industrial application.

Index Terms—GMA welding process, Image process, Laser vision sensor, Seam tracking.

I. INTRODUCTION

GMA welding is one of most widely used metaljoining process and plays an important role in manufacturing industries. To enhance welding automation, it’s required to be one of the main research directions to improve seam tracking technology in the area of industrial robots [1].

To realize automatic welding seam tracking, one of the key technologies is the sensor. Sensor is critical to overcome noises from complex welding environment and provide corrections to the robot controller if the joint deviates from the trajectory. Therefore, the use of sensor can improve seam tracking precision. With the rapid development of sensor technology, the laser vision sensors present to contain a large number of weld seam information, high sensitivity and precision, strong anti-jamming ability that are widely used for automatic seam tracking. Studies on the application of LVS (Laser Vision System) were carried and it’s proved that the implement of laser vision sensor was adequate for the purpose of weld quality inspection [2].

Another required key technology to perform the weld seam tracking is the image processing. As shown in the Figure 1, the original image goes through the pre-processing which represented noise filtering, contrast enhancement and image binarization and post-processing which includes centerline extraction and feature points detection.

Fig 1 Flow chart of image processing procedure
It’s a hard job to develop optimal algorithms for every step of image processing and meet the requirements of overall performance at the same time. Filters were developed to remove impulsive and nonimpulsive noises in image [3, 4, 5]. The mean and median filters are the most common and fundamental noise filters in industry [6]. Contrast enhancement was used to enhance the weld seam information in the image, which can be seen in work by Gil [7], Jankowski [8], etc. Auto-thresholding techniques are the hot issue in image binarization, among which the Ostu’s method [9] is the most famous. For centerline extraction, the earlier Sun and Bolson algorithms were well-known [10], and in the recent years, the studies were mainly focus on the development of skeleton methods [11, 12]. Detection of feature points is essential for weld seam tracking since it provide input data for further operation [13].

For real time GMA welding, an accurate, efficient and fast image processing is required to decrease the welding error. However, during the past decades, studies were focused on one step of image processing for specific case that there are limitations for general applications. Therefore, it’s necessary to verify their effect when employed in image processing for GMA welding.

The objective of this study is to develop optimal algorithms for image processing in seam tracking system for GMA welding. An industrial GMA welding systems with DST-G85 LVS seam tracking system was employed. Common algorithms in image processing were investigated step by step to get the optimal algorithms for seam tracking purpose. The Mean Square Error (MSE), Root Mean Square Error (RMSE), Peak Signal-to-Noise Ratio (PSNR) and Signal-to-Noise Ratio (SNR) were utilized to qualify the algorithm effectiveness. Finally, an optimal image processing model was set up in MATLAB for V type seam tracking system in GMA welding.

II. DESCRIPTION OF GMA WELDING WITH AUTOMATIC SEAM TRACKING SYSTEM

The experimental system is employed for V shape butt seam welding as shown in Figure 2. The head was firstly moved to the centre of the weld seam and the set it to the origin of the probe coordinate. As the welding process started, the head captured the seam image and transmitted it to a host computer of the LVS System for image processing. Seam position or corrected torch position was exported to the robot controller. According to the given result, robot controller transmitted the command to welding controller to move the torque. To track the weld seam, a CCD camera is needed to capture the real-time image of GMA welding process. As shown in Figure 3, an optical head which consists of digital camera, laser, and optical filter is employed. To get the best experimental results, the optical disposable lens is installed to protect the permanent lens from smoke, spatter and other sources of damage. Air-flow is also supplied to the head to provide a good protection and cooling in a normal level since the complexity of factory environment.

In this study, the welding was performed on SM490A steel which is mainly used in marine pressure vessel required specification on the manual welding condition. Table 1 represents welding details based on standard Welding Specification Procedure (WPS) and manual welding conditions based on preliminary experiments to drive a stable bead area. The configuration of V type butt welding specimen is shown in Figure4.
Table 1 The welding conditions based on WPS

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Type</td>
<td></td>
</tr>
<tr>
<td>Groove Angle</td>
<td>70°</td>
</tr>
<tr>
<td>Base Metal Grade</td>
<td>SM490A</td>
</tr>
<tr>
<td>Thickness</td>
<td>9.5mm</td>
</tr>
<tr>
<td>Welding Wire</td>
<td>CSF-71T</td>
</tr>
<tr>
<td>Shielding Gas</td>
<td>CO2 99%</td>
</tr>
<tr>
<td>Root Gap</td>
<td>2mm</td>
</tr>
<tr>
<td>Welding Length</td>
<td>610mm</td>
</tr>
<tr>
<td>Evaluation Item</td>
<td>Welding Condition (Amp/Vol/Speed/Weaving)</td>
</tr>
</tbody>
</table>

III. DEVELOPMENT OF OPTIMAL ALGORITHM FOR PRE-PROCESSING

Image processing, using computer algorithms to perform image processing on digital figures, is the key technology in seam tracking system based on vision sensor. The results for precision of image processing are depend on choice of algorithms in the image processing that it’s quite important for algorithm determination. Therefore, common used algorithms in image processing were carefully investigated with the original image taken from the CCD camera as shown in Figure 5.

To perform image process, first of all is to reduce the noise of the welding image. Because of the complexity of welding environment, there are a lot of noises in the welding image which may affect the experimental results a lot, even lead to the weld seam tracking failure. Thus, developing suitable noise filters for image processing is necessary. With proper developed algorithms, the weld seam tracking system could have excellent intelligence to overcome the influence of variety of welding environment. In this study, the Gaussian filter [4] and median filter [5] were used according to the analysis on the noise in the welding process.
Gaussian filter is commonly used to blur images and remove Gaussian noise which usually has certain locations, but the distribution of the noise amplitude is normal distribution (the average value is 0). In other words, Gaussian removes “high-frequency” components from the image. Thus, Gaussian filtering is more effective at smoothing images. The Gaussian filter uses a Gaussian kernel to blur the image, whose function for the two dimensions is:

\[ G(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \]  

where \( x \) is the distance from the origin in the horizontal axis, \( y \) is the distance from the origin in the vertical axis, and \( \sigma \) is the standard deviation of the Gaussian distribution.

Median filter is selected while the noise in the image is dotting randomly but has a certain value in the image, such as “salt and pepper” noise which appearance as white and black dots superimposed on an image. The algorithm replaces the value of a pixel by the median of the gray levels in the neighborhood of the pixel. The filter window or neighborhood may be chosen as rectangle, circle, cross or cirque. Suppose that the pixel values in neighborhood are put into a sequence \( d_1, d_2, d_3, \ldots, d_n \) and it becomes \( d_1 \leq d_2 \leq d_3 \ldots \leq d_n \) after sorted in ascending order or in \( d_1 \geq d_2 \geq d_3 \ldots \geq d_n \) in descending order, then its median value is:

\[ D_{\text{median}} = \text{Med} \{d_i\} = \begin{cases} 
\frac{d_{[(n+1)/2]}}{2} & \text{.} \ n \ \text{is odd} \\
\frac{1}{2} \left[ d_{[(n/2)]} + d_{[(n/2)+1]} \right] & \text{.} \ n \ \text{is even} 
\end{cases} \]  

Figure 6 shows the results of the Gaussian and median filter process. Gaussian filter is found to blur the image without remove the noise effectively. However, the median filter is proved to superior to Gaussian filter since the filtered image shows clearer laser band with less noise. Thus, median filter was selected.

To evaluate the filters effectiveness quantitatively, four main statistical measures [14] were used: MSE, RMSE, PSNR and SNR. If the values of the MSE and RMSE are smaller and the values of the PSNR and SNR are higher, normally the enhancement effect of that particular filter is better than others [15]. As shown in Figure 7, it can be found that the median filter has lower MSE and RMSE values than that of Gaussian filter and the values of the PSNR and SNR are higher. So the median filter can be considered to have a better enhancement effect than the Gaussian filter.
After noise filtering, spot noise, relatively low-intensity line and area noise were removed. The line noise due to spatter in the orthogonal direction against the laser line was merged into spot noise. So the contrast of laser band with background is not so clear. Therefore, erosion, dilation, opening and closing filters [7] are used to completely remove the remaining noise and to strengthen the laser lines.

The results of the image contrast enhancement by these morphological transformations are shown in Figures 8 and 9. It can be found that the enhanced results by Erosion and Dilation filter didn’t satisfy the application requirement. Either the laser band was over eroded or blurred. In order to overcome this problem, opening and closing were carried out. It is worth to mention that image transformations employing iteratively applied dilations and erosions are idempotent, that is, their reapplication effects no further changes to the previously transformed results. The practical importance of idempotent transformations is that they comprise complete and closed stages of image analysis algorithms because shapes can be naturally described in terms of under what structuring elements they can be opened or can be closed and yet remain the same. Their functionality corresponds closely to the specification of a signal by its bandwidth. Morphologically filtering an image by an opening or closing operation corresponds to the ideal non-realizable band pass filters of conventional linear filtering. Once an image is ideal band passed filtered, further ideal band pass filtering does not alter the result. The image contrast enhancement results by opening and closing are shown in Figures 8(c) and (d). It also show that even though laser
band is enhanced and the noise was suppressed, the width of laser band is also enlarged which is not good for the reminder of the processing with opening filter. However, image filtered by closing filter presents a clearer and thinner laser band, indicating that it’s a proper algorithm in image contrast enhancement processing. The evaluated results of the comparison among those four algorithms showed that the closing filter has an MSE value less than other filters, and the values of the PSNR and SNR are larger, so the closing filter can be considered to have a better enhancement effect than the other filters. Thus, the closing filter was selected for contrast enhancement.

The final goal of pre-processing for image is to get the real weld information. To get clearer edge of the laser band in the filtered image, image segmentation is common used after image contrast enhancement in the image processing. Image segmentation is one of the principal approaches of image processing. Binarization is a simple but effective tool for separating the laser band from the background. The strategy of binarization is first to set a threshold \( T \) to separate the gray values in the image. After that, the gray level of pixels in the image will be set to 0 and 1 once the values are larger or smaller than the threshold. Therefore, it’s very important to set a proper threshold in the binarization processing. A threshold survey done by Sahoo [16] pointed out that the method proposed by Nobuyuki Otsu was quite outstanding and was involved in this study.

According to the Otsu’s method, the threshold is determined where the variance of the pixel has the maximum value, i.e.

\[
2 \sigma^2(t) = \frac{\sum_{i=0}^{L-1} (f(i) - \bar{f})^2}{\sigma_t} \times \frac{\sum_{i=0}^{L-1} f(i) (f(i) - \bar{f})^2}{\sigma_t} = 0
\]  

where \( f(i) \) is the gray level of a pixel in the image, and \( L \) is the range of gray level \( t \). The binarized result \( Y(x, y) \) of image \( f(x, y) \) will be then obtained as follows:

\[
Y(x, y) = \begin{cases} 
1, & f(x, y) \geq T \\
0, & \text{Otherwise} 
\end{cases}
\]  

Following the Otsu’s method, the threshold \( T \) of this image is 0.4314. The binarization result is shown in Figure 10(c). To illustrate the influence of the threshold on the binarization result, thresholds of 0.35 to 0.45 are used to compare with that by Otsu’s method. Figure 11 presents the threshold by Otsu’s method has an MSE value less than others, and the values of the PSNR and SNR are larger, so this method was selected for image binarization.
There are two main methods in the centerline extraction for this study: Skeleton [16] and contour on average methods [17]. Skeleton is often used for the description of basic topological characteristics of a 2D object. Another method is contour on average method. In a small circulation, the gray scales of the pixels was scanned from top to the bottom, and the center point will be located at the coordinate of the center point in a continue area which have the same grayscale.

The centerline detection results are shown in Figure 12. Burrs occur in the skeleton centreline extraction, and contour on average method is proved to have smoother centerline which satisfies the experimental requirement. Further evaluation results shown in Figure 13 also proved that Contour on average algorithm has a better effect than the Skeleton algorithm.
Harris proposed to solve the problem of the discrete shifts and directions with the help of the autocorrelation function and increased the accuracy of the localization [13]. The extracted lines by the previous step were actually not straight but contained a lot of very short lines that the above methods may find the unwanted points and could not get the useful point for seam tracking. Therefore, according to the given weld image, the slope detection algorithm was proposed in this study.

The results for feature point detection are shown in Figure 14. The Harris algorithm is quite sensitive to the detected line and the extracted lines were not actually straight that no expected results can be achieved. Therefore, this method needs more improvement for application in weld seam tracking system, and slop detection algorithm is the ideal one.

V. QUALITY EVALUATION OF THE PROPOSED IMAGE PROCESSING

It is worth to mention that coordinates in the image should be converted into LVS coordinates by means of mapping for industrial application. In the image, the origin (0, 0) is the coordinate in the upper left of the image and the coordinate in the lower right is \([\text{width}-1, \text{height}-1]\). In this study, the size of image is 387 in width and 290 in height, while the actual area is 59.92 m². The experimental setup included CCD camera is shown in Figure 15(a).

After adjusting, and when we start welding, the center point of seam was located in the center of image as shown in the right picture of Figure 15(b). Assume that the coordinate of a point in image is \((x, y)\), and the corresponding offset from the center \(\Delta Y\) in LVS coordinate can be expressed as:

\[
\Delta Y = \sqrt{\frac{A_l}{\frac{B_i}{2}}} \left( x - \frac{M}{2} \right)
\]

where \(A_l\) is the actual area on the workpiece(seen the dash line area in Figure 15(a) and \(B_i\)is the image size of \(M\timesN\). \(M\) and \(N\) are the width and height of the captured image, respectively.
This image was captured at the beginning of a welding process that the experimental $\Delta Y_0$ is 0.0000mm. The corresponding $\Delta Y_1$ by image processing is -0.0116mm. The accuracy of the image processing result is defined as:

$$\zeta = 1 - \frac{|\Delta Y_0 - \Delta Y_1|}{\Delta Y_0} \times 100\%$$

where $\Delta Y_0$ and $\Delta Y_1$ indicate offset by image processing and by experiment, respectively. SG stands for the seam gape which is given by experiment and its value is 16.11mm. Thus, the accuracy of image processing is as high as 99.928%, which is highly accepted for industrial implement.

To enhance the reliability of proposal algorithm, a variety of weld seam images captured from different head locations and welding surroundings were processed by proposed image processing. The captured images and the results are shown in Figures 16 and 17, respectively. It can be concluded that the proposed method has high possibility of adapting to variable welding environment and extract the feature points for weld seam tracking efficiently.
Effects of common algorithms in image processing were investigated in this study. According to above discussion, following conclusions were drawn:

1. Based on the laser vision sensor, noises captured from the CCD camera were mainly impulse noise, or salt and pepper noise. Median filter was proved to performed better and was selected to remove or reduce the noise within the captured images in the first step of pre-processing. And the closing operator was proved to be the most efficient to remove the remaining noise completely and to strengthen the laser lines.

2. Otsu’s method was quite powerful in automatic thresholding for image binarization to reinforce the contrasts of the intensity. To detect the binarized image, both Canny and LoG algorithm were used and Canny algorithm presented to has lower MSE value and higher SNR value that it was considered to be better than LoG algorithm.

3. Skeleton algorithm was sensitive to object outline and was not good for weld seam centreline extraction since burrs may be generated. Conversely, smoother centreline was exported by contour on average algorithm which satisfies the experimental requirement. The weld joint point position (0.016mm average error) can be detected by proposed slop based algorithm, while the Harris’s method failed.

4. The quality evaluation results through the optimal algorithms for image processing presented to have considerable high accuracy (99.928%) and the proposed method was quite robust in welding environment.

Overall, the optimal algorithms for image processing increased the precision and reliability for tracking the weld joint and seam edge at the same size of the precious laser vision sensor. Furthermore, detected results of environment dependency analyses prove that the optimal algorithms performed well in complex welding background and are accepted for industrial application.

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