1. INTRODUCTION

The heavy industries are recently faced with the increase in the average age of employees, shortage of skilled workers and upcoming environmental problems in the welding workplace. Furthermore, it is difficult to implement automated welding fabrication system in the heavy industries, because there are serious conditions including huge, complicated various workpieces, variation of gap size and misalignment of fit-up.

Thin workpiece used in this study consists of straight part and corrugated part (hereafter, corrugations) by turns. The size of workpiece is about 3.5m by 1.5m with 8 small corrugations and 9 large corrugations.

The sensors used for automatic seam tracking are two types generally as follows.
- a contact type: tactile probe
- a non-contact type: through-the-arc sensor, laser vision sensor

The contact sensor is easy to implement, however, difficult to maintain and repair because of collision with objects during operation. Furthermore, its reliability highly depends on the condition of object shape and surface. In this study because of good condition of the workpiece surface, two tactile sensors are used to keep a constant torch height and a given torch angle.

The commercial laser vision sensor is widely used to track the weld seam in the welding automation areas[1,2]. In the case of seam tracking systems, the optical triangulation method using the structured light has been used in robotic welding[3,4,5] and a noise rejection for joint configuration detection in arc welding was proposed[6]. Sometimes there are several restrictions to apply a commercial vision sensor into the curved surface inspection of the herring roe[7] and into the welding for a specific workpiece type such as thick plate and 3-dimensional corrugated workpiece.

In order to implement the automated welding fabrication system for corrugated workpiece in the ship building industry, the automatic welding carriage system with vision sensor for seam tracking was developed in this study.

The automatic welding carriage system and the automatic weld seam tracking system are controlled by the PLC and the IPC based on the embedded OS respectively.

In section 3 the developed sensor system is introduced including image processing algorithms and exception handling on the corrugated workpiece.

In section 4 the control scheme is discussed with regard to distant based path plan and regulating of welding torch height and its angle.

Finally, the results of test to show the feasibility and performance of the proposed algorithm are described.

2. SEAM TRACKING SYSTEM

A schematic diagram of overall control systems is shown in Fig. 1, which includes a single torch, mechanized carriage with five axes, a clamp device, a main control unit including carriage motion control and the laser vision sensor, a plasma welding machine and its peripheral devices to weld a workpiece such as Fig. 2.

Fig. 1 Configuration of the overall system.
The automatic welding carriage system and the automatic weld seam tracking system are controlled by PLC and the IPC equipped with embedded OS independently. The interlock signals between the controllers are exchanged by digital input and output.

The workpiece consists of straights and corrugations with lap-joints. The workpiece size is about 3.5m x 1.5m with 8 small corrugations and 3 large corrugations.

The five-axis welding carriage system consists of a driving axis(X-axis), an up and down axis(Y-axis), a rotation axis(R-axis), a traversing axis(Z-axis) and an axis for AVC (automatic voltage control). The AVC axis is used to keep the constant distance between workpiece and end of torch.

Two tactile sensors are used to track the contour of corrugation. PLC reads the analog signals from two linear potentiometers and calculates the inclined angle of the corrugation panel to keep a torch pose perpendicular to corrugation surface. PLC controls 3-axis(X, Y, and R-axis) simultaneously for sound weld results.

We have developed the GUI software for easy operation. The software is compiled by the Microsoft Visual C++, developing tool available for Win32 platform, and running on the embedded XP®.

The IPC based seam tracking system equipped with sensor head, frame grabber, motion board, and digital in/out board controls Z-axis to track weld seam line.

Delta Tau’s Mini-PMAC controller as a motion control is used. PMAC is based on the Motorola’s digital signal processor(DSP) and can provide a wide various application as a general purpose controller. The frame grabber based on PCI bus is used to acquire an image from CCD camera.

To improve the reliability of controller based on IPC, we used a flash disk instead of HDD to prevent data corruption from external shock and adopted Windows XP® embedded to create an own OS image based on the requirements of embedded system hardware and software. Target Designer is a tool to customize run-time images using components selected from the database and then to assemble the actual run-time image. After building run-time image, target image size is about 240MB. It takes about 50 sec for the run-time image to boot.

3. THE SENSOR SYSTEM

3.1 Sensor head design

Fig. 4 shows the structured vision sensor head equipped with a CCD camera, a lens, and diode laser. The object is illuminated by a laser stripe generated from the 10mW non-Gaussian(uniformly illuminated) diode laser structured light projector. And CCD camera detects the stripe through the band pass filter, which provides 670nm wavelength and 10nm full width at half maximum(FWHM).

Table 1 The specification of vision sensor.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand-off distance</td>
<td>74mm</td>
</tr>
<tr>
<td>Angle, ( \alpha )</td>
<td>16°</td>
</tr>
<tr>
<td>Look-ahead distance</td>
<td>400 mm</td>
</tr>
<tr>
<td>Resolutions</td>
<td></td>
</tr>
<tr>
<td>Z-direction</td>
<td>0.0115 mm/pixel</td>
</tr>
<tr>
<td>Y-direction</td>
<td>0.022 mm/pixel</td>
</tr>
<tr>
<td>Weight</td>
<td>680g</td>
</tr>
</tbody>
</table>

3.2 Image processing algorithms

The size of vision sensor head is 70mm(length) x 86mm(height) x 29mm(depth). The specification of the laser vision sensor is outlined in Table 1.
The process of acquiring and analyzing the image is divided into the following steps.

- Image acquisition
- Stripe extraction
- Feature points extraction
- Exception handling

First, a gray-scale image of a laser stripe illuminated on the workpiece is acquired from a CCD camera and then digitized into the computer memory through a PCI frame grabber board. The image has the data depth of 8 bits per pixel. The data type of the image is internally unsigned and the originate, (x, y) = (0,0), is located at the top left corner.

Second, the stripe location has to be extracted. Fig. 5 shows the process of laser stripe extraction. After threshold processing, the center of the laser stripe was found at start position, x(0) to x(A), which was calculated by the center of gravity method. To reduce processing time a searching window was used, which is pre-defined and three times as thick as laser stripe thickness. The center of searching window is the same of previous the center of stripe. If actual stripe thickness is lower than a predefined thickness of laser stripe within searching window, current center of stripe regards as abnormal case and is taken from previous one. This information how many times current center is replaced by previous one was used to recognize an existence of tack bead.

The next step is to search feature points on the stripe found from the process of the stripe extraction. In this study welding is done on the lap joint type. Fig. 6 and Fig. 7 show an example of actual joint type and its feature points, respectively.

The feature points could be edges of lap joint that each plate overlaps. Because gray level does not change along the stripe, it is hard to find these points as using the existing algorithm which finds min/max values by taking second derivative of gray level along the stripe in the x-direction. There is another way to find feature points which is chosen by taking spatial second derivative along the stripe in the x-direction. In this case, however, because second derivative is very weak to noise and strongly depends on the interval, x(i) to x(i+1), its reliability is decreased.

For this reason, to overcome the above mentioned problem, a reliable and simple feature extracting algorithm is proposed like Eq. (1).

\[
\sum_{i=1}^{k} y(i) - y(l) \geq D,
\]

where \( l = k + LAD \), k and LAD represents an arbitrarily x value on the stripe and a look ahead distance from torch to sensor head, respectively, and D is a design factor and picked as 13 pixels through the test.

3.3 Exception handling

Tack welding is done to fit-up the workpiece before carrying out welding. These tack beads and scratches work as disturbances to detect normal feature points automatically. Exception handling process plays a most important role in these cases to increase the sensor reliability.

Exception process items are as follows.

1) Algorithm to recognize tack bead automatically
Laser stripe is distorted if meets with tack bead like a Fig. 8. At this time a special processing routine to certainly recognize it to be tack bead is necessary. If thickness (H) of the laser stripe is smaller than standard thickness, current y(i) is replaced by the prior y(i-1). As count of the case that took a prior y(i-1) is W in the x direction, it is judged that a tack bead is if this W is larger than predefined value(30 pixels) in case of Fig. 9.

2) A case when feature points got out of the region of interest(ROI)
There is a case for center position of the feature point that is
out of ROI if the vision sensor head was abnormally installed, or it was distorted on operation. In this case, it was composed to be able to give warning to operator automatically.

3) A case when the vision sensor entered a corrugated section

When the vision sensor head enters a corrugated section, the center position of the torch changes rapidly in the y direction. The laser stripe disappears out of field of view (FOV) finally (called blind zone). And it is appear into the FOV again at the spot where the corrugated section is over. This process is extremely normal phenomenon. The deviation counts between the current center and the prior center on the beginning of section is calculated, and then it is recognized as the beginning of corrugation in the case that this value is larger than predefined value for every sampling time. When stripe enters within FOV again at the end of corrugated section, it is judged normal condition if counts are larger than predefined value. It is designed that a specific path of welding torch was generated in advance and welding torch to track it for the blind zone.

4. CONTROL SCHEME

4.1 Path plan

Generally the vision sensor head is attached at front of welding torch and the distance between torch and sensor is fixed as shown in Fig. 9. That is, welding torch and vision sensor head move by the same speed, and keep the same direction.

A relational expression between vision sensor head and welding torch is shown in Eq. (2).

\[ T[k] = V[k + N], N = \frac{\text{LAD}}{\text{SPEED} \times T_s} \]  

where \( k \) is current time, \( \text{LAD} \) is distance between torch and vision sensor, \( \text{SPEED} \) is welding speed, and \( T_s \) is the sampling time. \( T[k] \) and \( V[k] \) represent tracking values of torch and calculated value of vision sensor, respectively. That is, the tracking data of torch is generated about time under the constant speed condition (called time-delay method).

The corrugation panel is composed of straight part and curved part. A driving speed (X-direction) is equal to welding speed in the straight part, but not welding speed in the corrugation part, because the driving speed is not constant in the X direction to implement the constant welding velocity in a tangent line of the curve. Welding condition is different, moreover, by a section on the corrugation part. As for this, it is continuously played an image processing with non-constant interval from the vision sensor point of view. Fig. 10 shows the position of sensor head related to torch position according to time.

Because torch arrives at the position that vision sensor recognized after passing a specific sampling time in the case of constant welding speed, seam tracking is possible by time-delay method. But torch doesn't reach the position that vision sensor recognized even if the specific sampling time is passed in the case of varying welding speed. Therefore, seam tracking becomes impossible by time-delay method in the case of varying welding speed.

![Fig. 10 A case when welding speed is varied.](image)

In this paper to overcome this matter, a distant based path planning is proposed, first, tracking data vision sensor recognized is rearranged with distant-base path planning, and then torch is traced by these trajectories. That is, tracking is realized by linear interpolation method shown in Eq. 3.

\[ Y(X_m) = Y(X_{T(n)}) - Y(X_{T(n-1)}) \times \frac{X_m - X_{T(n-1)}}{X_{T(n)} - X_{T(n-1)}} + Y(X_{T(n-1)}) \]  

where \( Y(X_{T(n)}), Y(X_{T(n-1)}) \) : tracking data at a sampling time

\( X_{T(n)}, X_{T(n-1)} \) : X position at a sampling time

\( Y(X_m) \) : tracking data by linear interpolation output

\( X_m \) : X position in random

The above formula corresponds to only a straight line part but for the corrugation part torch moves according to the predefined path as mentioned at the end of previous section. The predefined path of the corrugation part is generated by using weld seam line information in start point and end point of corrugation, which is received from photo sensor.

4.2 Welding torch height and angle control

Height and angle control of welding torch are very important to get good weld result in plasma welding process. Welding torch should keep the offset distance from torch to workpiece and the specific working angle. As shown in Fig. 11, two tactile sensors are used at the side of torch to realize
these goals.

Eq. (4) is applied to straight part and corrugation part, which is used for torch height control. And Eq. (5) is used to keep the specific working angle.

\[ y(k) = D_1(k-1)\cos\theta(k-1) \]  
\[ \theta(k) = \arctan\left(\frac{D_3(k-1)}{D_0}\right) \]

where \[ D_3 = D_1 - D_2 \] and \[ D_0 = |D_1 - D_2| \].

The position control as well as the velocity control of welding is realized by the following Eq. (6) and Eq. (7).

\[ V_x(k) = V_w\cos\theta(k-1) \]  
\[ V_y(k) = D_1(k-1)\cos\theta(k-1) \]

5. EXPERIMENTAL RESULTS

Welding test is done on the corrugated workpiece with 3 SC and 1,030mm length. As shown in Fig. 13, look-ahead distance, from torch to vision sensor head, is 400mm.

The automatic welding carriage system with seam tracking function has been developed and applied for corrugation panel fabrication in the shipbuilding.

The features of this system can be summarized as follows:
1) The five axes automatic welding carriage to track the contour of curved workpiece and an automatic weld seam tracking system using vision sensor.
2) The algorithm to keep the torch pose perpendicular to corrugated surface constantly.
3) The reliable and robust image processing algorithm for straight weld line seam tracking.
4) The embedded operating system by using Microsoft Windows XP Embedded.

REFERENCES