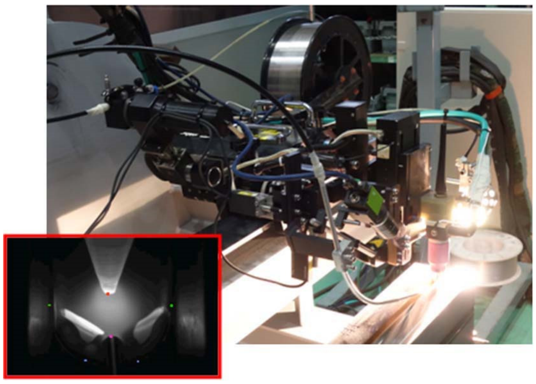
Automatic Welding Technique with the Skilled Welding Operators Technique Due to the Utilization of Image Processing Technology and Machine Learning Technology



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For welds of nuclear power plant equipment, high reliability is required to ensure stable operation. For this reason, the application of automatic welding has been promoted to reduce dependence on skilled welding operators. At the present time, however, constant monitoring and fine adjustment of welding positions is still carried out by welding operators and depends on their skill. Therefore, by applying image processing technology and machine learning technology, Mitsubishi Heavy Industries, Ltd. (MHI) developed an automatic welding technique featuring the skill of experienced welding operators and obtained the prospect of welding without depending on skill. In the future, we will promote further development toward the application of the welding technique to complex shapes.

1. Introduction

For welds of nuclear power plant equipment, welding operators still constantly monitor the welding operation and frequently intervene even during automatic welding, so the welding operation depends on the skill of the welding operators. **Figure 1** shows a schematic view of a reactor vessel head nozzle weld. In the case of welds between the reactor vessel head and the nozzle, the shape of the groove and the welding position change depending on the location, so the difficulty level of the welding is extremely high.

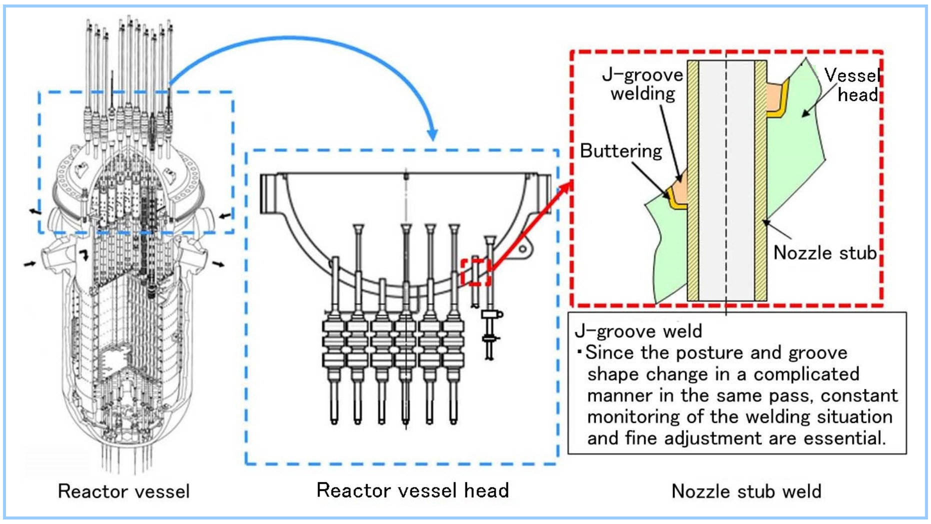

Figure 1 Schematic view of reactor vessel upper lid nozzle weld

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In order to carry out this extremely difficult welding, the welding operator identifies feature points for ensuring the welding quality based mainly on the visual information on the welding state and controls the electrodes and wire positions based on experience to achieve high-quality welding. Therefore, we are developing a method of automatic welding control that combines image processing technology and machine learning technology to identify feature points from the images obtained from the cameras and always maintains the characteristic points in their proper positions. As a preliminary step of applying automatic control to extremely difficult welding, we have developed automatic welding technology for one-pass straight narrow groove TIG welding. This paper describes the outline and future prospects of the developed automatic welding technology.

2. Conventional welding operator operation

Figure 2 is a situational diagram of conventional automatic TIG welding. **Figure 3** presents a schematic diagram of a welding operator's operation. Conventionally, a welding operator identifies the positions of feature points, which are the electrode, the weld pool, the wire, and the groove, based on an image of the area surrounding a weld acquired by the monitoring camera attached to the welding apparatus, and finely adjusts the electrode position and the wire position to appropriate positions in order to prevent welding defects such as incomplete fusion. The vertical position of the electrode is conventionally feedback-controlled so that the arc voltage becomes constant by utilizing the correlation between the arc length and the arc voltage.

In order to eliminate the intervention of a welding operator, it is necessary to develop a method to identify the feature points described above and to incorporate the operational expertise of a skilled welding operator into the automatic welding control logic.

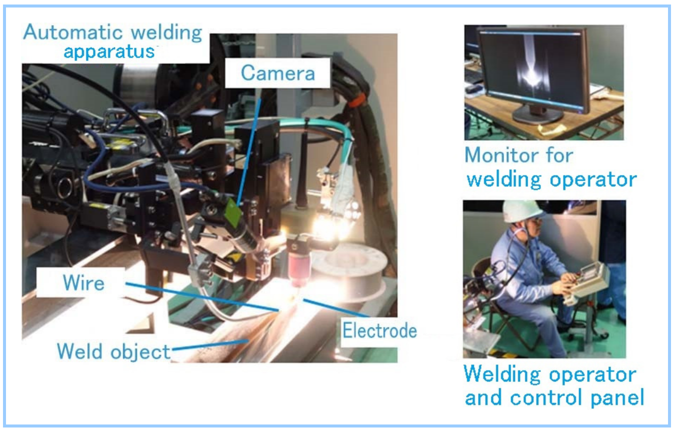

Figure 2 Situational diagram of conventional automatic TIG welding

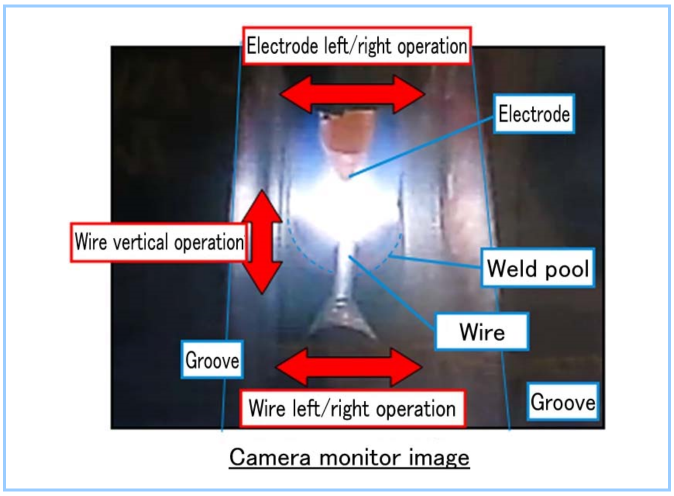

Figure 3 Summary of welding operator's operation

3. System configuration

Figure 4 shows the system configuration of an automatic welding apparatus. Image signals of the cameras installed in the vicinity of the electrodes and information on the welding apparatus are transmitted to the image control device sequentially and feature points such as electrodes and wire positions are detected in real time through image processing. The detected feature points are filtered and converted into the amount of deviation from the target position, and the control amount is calculated as necessary and transmitted to the welding apparatus. As a result, an automatic welding system that can cope with various welding situational changes is realized. **Table 1** shows the specifications of each device. In order to improve the visibility of weld pool shapes, the imaging device consists of a monochrome CMOS sensor and an infrared band pass filter, which can transmit high-pixel images at a high frame rate.

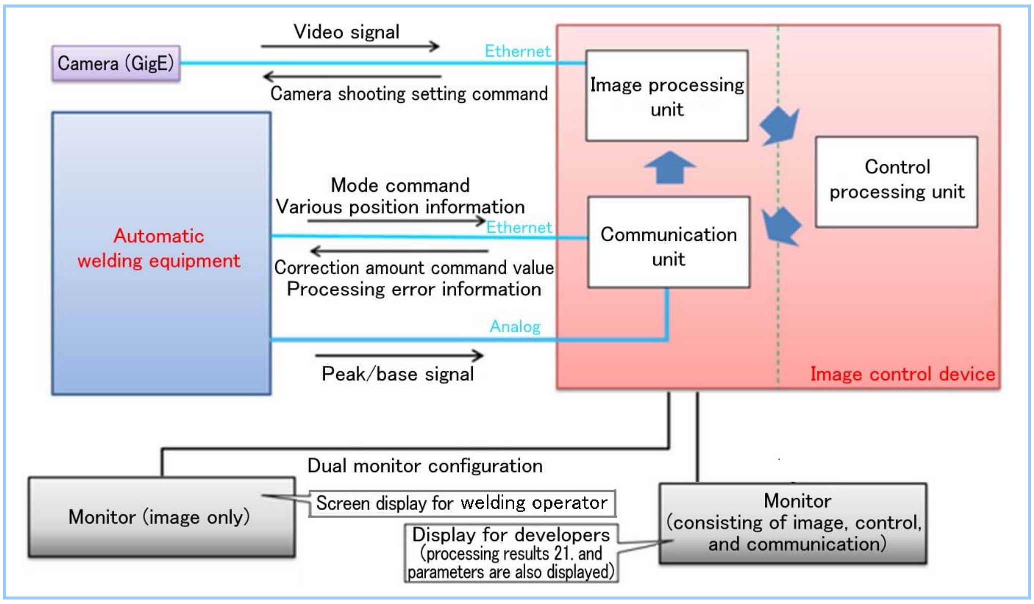

Figure 4 System configuration

Table 1 Specifications of each device

No.	Major item	Middle item	Specification
1	Imaging device	Camera	CMOS, 1936 x 1216 pixels
2		Frame rate	45fps
3		Transmission method	Gigabit Ethernet
4		Filter	Infrared bandpass
5	Image control device	CPU	Xeon 3.7GHz 4core
6		A/D converter	16bit 100Hz
7	Welding device	Welding power supply	Inverter control TIG welding power supply
8		Welding head	Self-traveling head

4. Outline of developed technology

4.1 Development of image processing technology

In order to realize automatic welding, it is necessary to use image processing to detect the positional relationship between the electrode, weld pool, wire, and groove that the skilled welding operator uses for determination. Therefore, in this research we developed the following two technologies.

(1) Multi-exposure photography

In TIG welding, the arc light energy generated from the electrode is large, and feature points such as the electrode and weld pool cannot be caught simultaneously by a single captured image. For this reason, light and dark images were alternately acquired using multi-exposure photography in which the shutter speed was switched in a short time. To prevent the brightness of the entire image from changing greatly when welding conditions such as the arc current and wire supply amount change, the exposure time is fine-tuned dynamically while successively monitoring the brightness. **Figure 5** is an example of an image captured by multi-exposure photography. This figure shows that in the case of an image captured with a short exposure time, the arc light is suppressed, and the tip positions of the electrode and wire are visible, and that in the case of an image captured with a long exposure time, the visibility of the groove and weld pool is high.

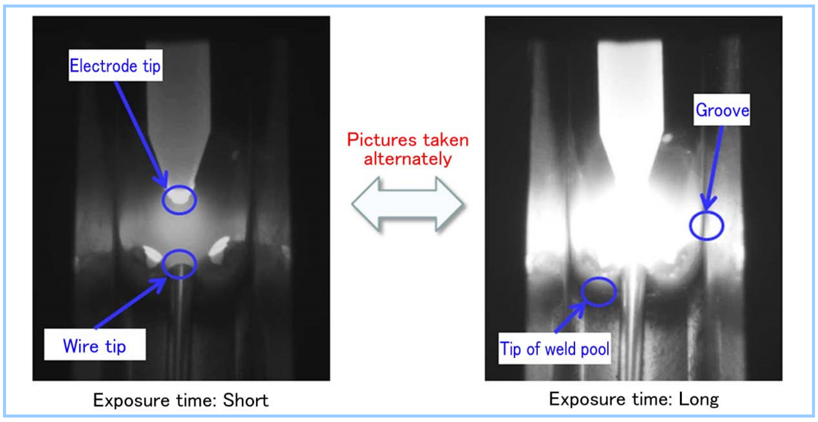

Figure 5 Example of image captured by multi-exposure photography

(2) Automatic feature point detection technology

In order to automatically detect the positions of the electrode, weld pool, wire, and groove from the captured image, we developed an algorithm combining binarization, filter processing and luminance profile search processing according to each feature. **Figure 6** outlines the developed algorithm. With regard to the electrode, because of the characteristics of its shape, the straight line component of the edge is first obtained to calculate the intersection point, and the final tip position is determined based on the intersection point using the luminance as an index. The groove needs to be detected on both the right and left sides. The profile of the luminance is acquired in the horizontal direction of the image from the vicinity of the previously obtained electrode position, and the minimum point, that is, a valley where the luminance falls, is detected. At this time, there are some cases where the minimum point cannot be found depending on the welding conditions, so the detection process is performed using both long and short exposure time images taken by multiple exposure photography and adopts the result with higher reliability. Since the actual diameter of the wire is known, the shape is directly extracted by the Min-Max filter, and its tip position is determined by binarization and labeling. With regard to the weld pool, the part which becomes a boundary line of luminance near the tip of the wire obtained previously is extracted, and finally the most advanced point in the welding direction is detected as the tip position.

All of the above processing is built on a general industrial computer, and the detection process operates in real time in response to the image data transmitted at 45 fps from the camera.

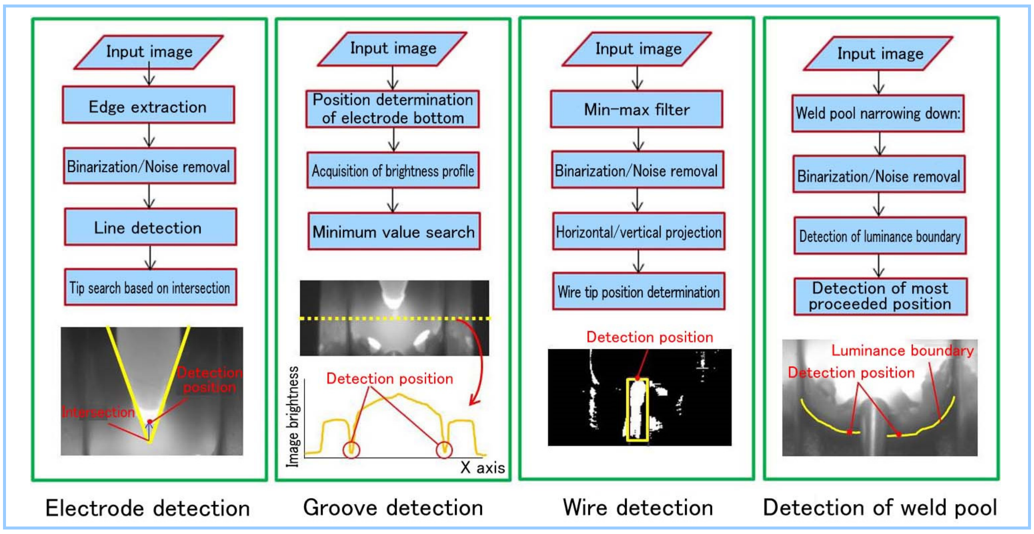

Figure 6 Image processing algorithm

4.2 Development of automatic control technology simulating operation of skilled welding operator

In order to simulate the operation of a skilled welding operator, the operation history of a skilled welding operator was machine learned, and the target value of the image feature point was identified. In this test, the welding was performed using a welding wire that had been bent beforehand to increase the frequency of the intervention of the welding operator and collect learning data in a short welding time. A classification model using image feature points as the input and the operation presence/absence label as the output was generated by a support vector machine (SVM) to identify the separation boundary between an area requiring operator intervention and an area requiring no such intervention in the space of feature points, and such an area where no intervention is needed was set as the target range of feedback control.

The number of collected learning data items for the presence of operation (e.g., lowering operation, raising operation) was less than that for the absence of operation. It is known that the discrimination performance of the SVM greatly deteriorates when the number of data items is biased in this way. In order to solve this imbalance, the classes were weighted based on the ratio of the number of data items. As a result, the problem of underestimation of the class for the presence of operation (for which the number of data items was less) was solved.

Figure 7 presents the results of learning the history of the wire height control operation. As a result of learning the relationship between the feature point obtained by the image processing and the operation history, wire height and weld pool height were extracted as the feature points to be noticed, and the separation boundary surface between the presence/absence of the operation was identified. Based on the identified separation boundary surface, it was found that a welding operator adjusts the wire height in response to a change in the weld pool position caused by varying welding conditions such as the welding speed. We developed an automatic control technology incorporating the operation expertise of the welding operator.

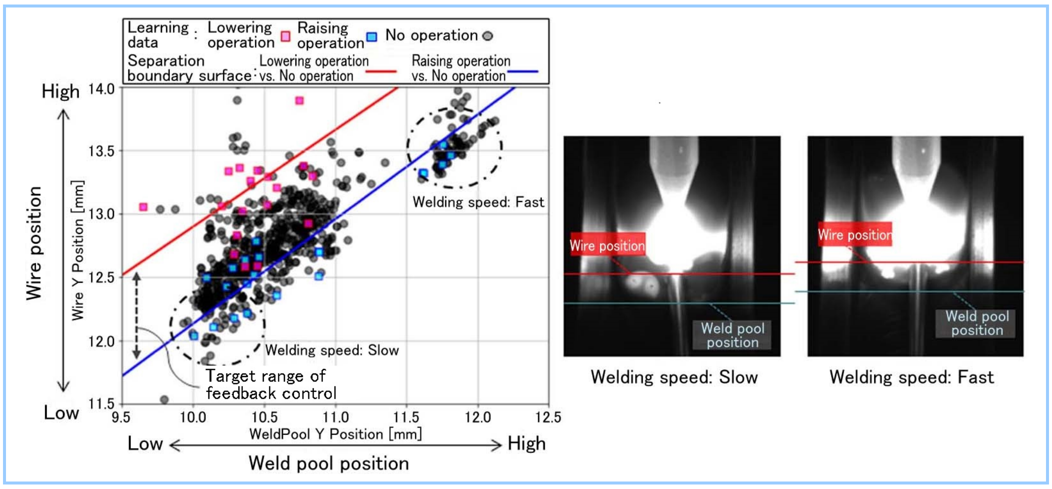

Figure 7 Results of learning the wire height control by SVM

4.3 Welding test simulating actual equipment

Using the developed equipment, a welding test was carried out with a one-pass straight narrow groove welding piece in order to verify that welding with sufficient quality can be performed without a welding operator's intervention. **Table 2** contains the test conditions and test results. Welding was performed under the condition where a state in which the electrode position is shifted is simulated by providing deviation of distance from the weld test piece in the advancing direction of the welding device and a state in which the vertical and horizontal position of the welding wire are shifted is simulated by bending the wire. In addition, the heat input condition was widely changed. As a result of the test, it was confirmed that welding can be performed without intervention by a welding operator even once. **Figure 8** shows the appearance photograph of the weld and the microstructure observation photograph of the weld cross section. Weld defects were not observed in the microstructure observation results of the cross section and the radiation transmission test after welding, and it was confirmed that the test piece was welded without any problems in quality.

Table 2 Test condition and result of welding test simulating actual equipment

Item			Specification
Test material			Austenitic stainless steel
Welding condition	Welding method		TIG welding
	Welding position		Downward
	Weaving		No weaving
	Change of heat input and wire conditions	1st layer	Current: Low → High
		2nd layer	Current: High → Low
		3rd layer	Welding speed: Low → High
		4th layer	Welding speed: High → Low
		5th layer	Wire feeding amount: Small → Large
		6th layer	Wire feeding amount: High → Low
		7th layer	Current and welding speed: Low → High Wire feeding amount: High → Low
		8th layer	Current and welding speed: High → Low Wire feeding amount: Small → Large
Disturbance factor	Misalignment between welding equipment and test piece		Misaligned
	Bending of weld wire		Bent
Test result	Number of automatic controls	Electrode position	153 times
		Wire position	678 times
	Number of interventions by welding operator		No intervention
	Radiation penetration test		No indication

Figure 8 Appearance photograph of weld and microstructure photograph of weld cross section

5. Conclusion

We are working on the development of automatic welding technology that does not depend on the skill of a welding operator. This paper presented our developed image processing technology that can perform automatic one-pass straight narrow groove welding and technology that utilizes machine learning to enable automatic welding without a welding operator's intervention. We plan to apply these technologies to actual equipment and further improve them toward application to the welding of complicated shape parts while working on the development of welding that does not depend on a welding operator's skill.

This development was implemented as a project covered by "Development of Advanced Technology for Safety Measures for Nuclear Power Reactors, etc., in fiscal 2015 and 2016" of the Ministry of Economy, Trade and Industry.

References

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