# Built-in Cable Type Welding Robot "ARCMAN™-GS"

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*This paper describes the features of the "ARCMAN™-GS", a welding robot with built-in cables. The robot was launched in the market in September 2011. To reach deep inside hollow workpieces, the robot has a sufficient working area especially designed for an overhead-suspended system and has a torch-integrated arm that is suitable for teaching. These features make the "ARCMAN™-GS" a more versatile robot, enabling the welding of various workpieces and improving the customers' production. The robot is expected to see worldwide sales.*

## Introduction

Kobe Steel's arc welding robots target the fields of medium- and heavy-thick plates, (e.g., construction machinery, buildings steel structures, bridges and rolling stock), and have been widely adopted by domestic and overseas users. The user's needs in these fields include; ① productivity improvement (increased automation rate), ② the improvement of welding quality, ③ space saving and ④ the reduction of production costs.

A specific example of need ① is as follows. In the field of construction machinery, there are many cases where a welding torch enters deep inside a workpiece, increasing the possibility of the welding torch and torch cables interfering with the workpiece. In such a case, welding cannot be done by a robot and must be done by hand. To improve productivity in such a work environment, there has been a need for a "built-in cable type welding robot" with its torch cable running through the upper arm of the robot to avoid interference with the workpiece.

On the other hand, there is a strong need for downsizing and space saving in welding systems, while the workpieces are becoming larger. As a result, there is an increasing demand for overhead-suspended systems that can easily approach large workpieces and save space.

Kobe Steel has therefore developed a built-in cable type robot, the ARCMAN™ note) -GS (**Fig. 1**), having the advantages of ① built-in cables, in which the torch cable is much less likely to interfere with the workpiece, and ② a large working area suitable for overhead-suspended systems.[1)]

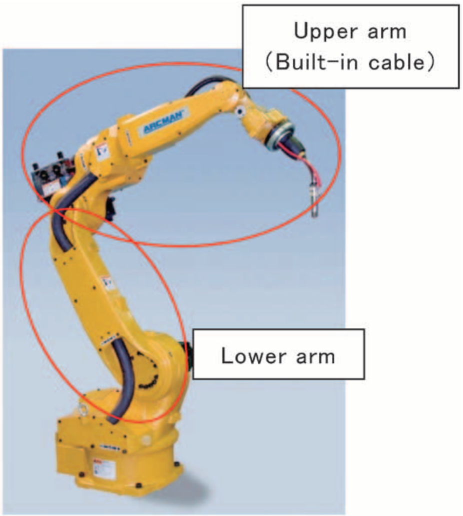

**Fig. 1** Appearance of ARCMAN-GS [1)]

The ARCMAN-GS has a structure newly developed for built-in cables and has mechanical advantages that are different from those of the conventional ARCMAN series. A new control technology was also developed to achieve high position-tracking precision (e.g., weaving precision and sensing precision). The new structure and control technology have realized the development of this new robot with high functioning and high performance.

The name, "ARCMAN-GS", is derived from "Global Standards / Global Strategy" and reflects Kobe Steel's intention to build robots that serve for many users over the world.

## 1. The advantages of ARCMAN-GS

### 1.1 Upper arm types that can be selected to suit the system

The ARCMAN-GS has the following two options for upper arm types:

①A type having a welding torch passing through the wrist and torch cables passing through the upper arm (**Fig. 2**).

②A type having a torch passing through the wrist and torch cables not passing through the upper arm (**Fig. 3**).

Type ①, with the welding torch passing through the wrist and the torch cables passing through the upper arm, significantly decreases the interference

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[note)] ARCMAN (**ARCMAN™**) is a trademark of Kobe Steel, Ltd.

of the cable with the workpiece, compared with conventional robots. Type ② is effective in decreasing interference around the wrist when exchanging the welding torch and torch cable with others, such as in the case of the automatic exchange of single and tandem torches.

**Fig. 4** shows a conventional robot, ARCMAN-SR, approaching the workpiece of a construction machine. The problem with a torch approaching a narrow and deep part of the workpiece is that the torch may interfere with the object and the torch cable may become entangled with it. In the example shown, the torch cable, extending from a feeding apparatus, is about to come in contact with the inner surface of the workpiece. By adopting type ① with the built-in torch cable, interference of the torch cable with the workpiece can be avoided. This facilitates the robot teaching operation and is suitable for off-line teaching using a PC.

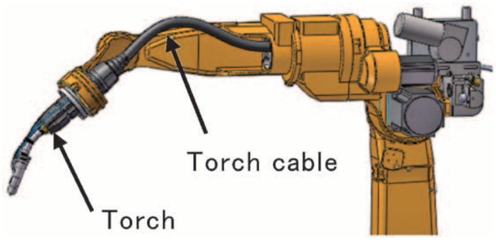

Fig. 2 Upper arm with built-in torch cable

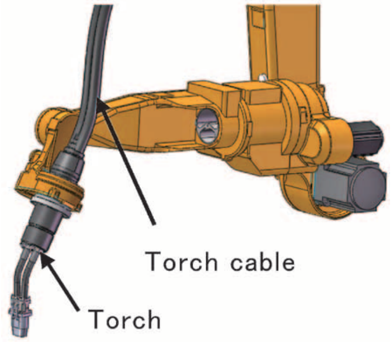

Fig. 3 Torch-integrated wrist axis

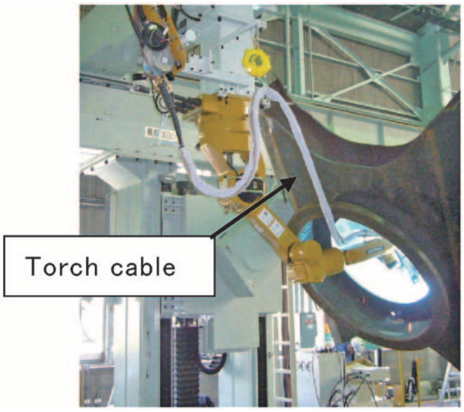

Fig. 4 ARCMAN-SR approaching a construction machine

Type ②, with the torch cable not passing through the upper arm, is adopted when the torch cable cannot be built into the upper arm, such as in the case of the automatic exchange of single and tandem torches described later. Even in this case, the welding torch passes along the center of the S6 axis in the robot axis configuration (**Fig. 5**) without protruding out of the robot. Thus interference with the workpiece is decreased even when the welding is performed in a narrow and deep part of it.

In order to realize the built-in torch cables described above, a new wrist structure, different from the ones for conventional robots, has been developed.

### 1.2 Newly developed wrist structure

The wrist structure of the ARCMAN-GS comprises an upper arm and a torch cable built into it. The structure has an asymmetric configuration (cantilever) around the S4 axis of the upper arm (**Fig. 6**) to allow for the automatic exchange of single and tandem torches. It should be noted that a conventional robot (e.g., the ARCMAN-MP) does not have a built-in torch cable and has a symmetric structure around its S4 axis (**Fig. 7**).

In order to have a built-in torch cable while slimming down the wrist structure, an arrangement that is totally different from the conventional ones

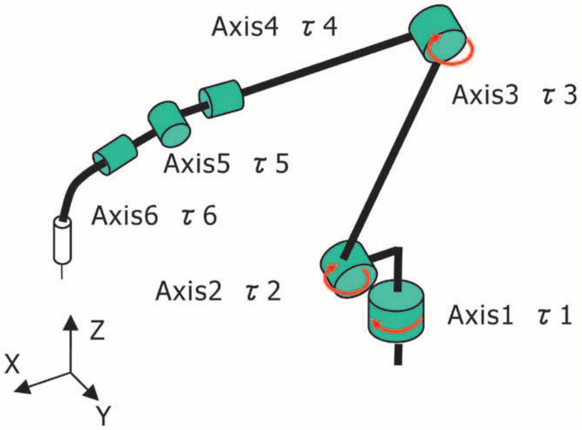

Fig. 5 Torque of each axis

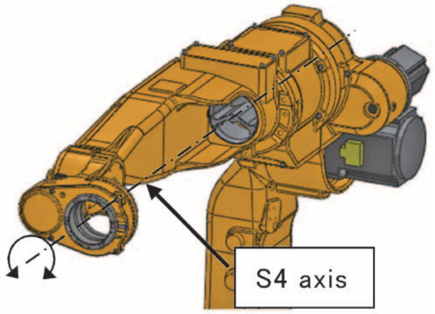

Fig. 6 Asymmetrical wrist of ARCMAN-GS

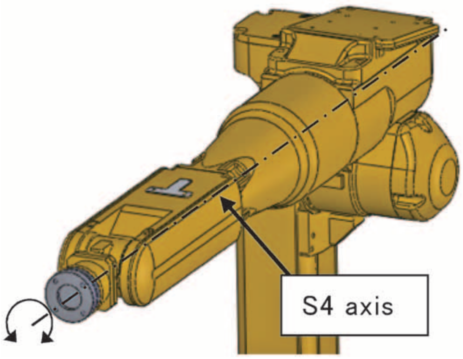

Fig. 7 Symmetrical wrist of conventional robot (ARCMAN-MP)

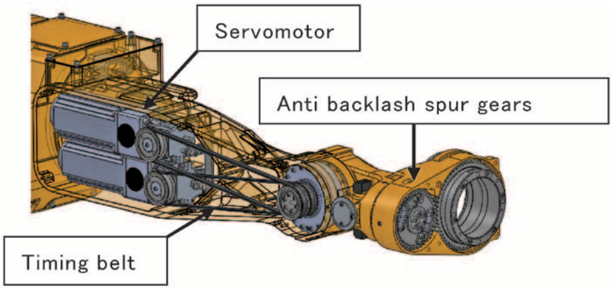

Fig. 8 Wrist structure

has been employed. The new arrangement includes the S5 and S6 axes with their timing belts crossing each other and a new structure with zero backlash spur gears. (**Fig. 8**)

With the welding torch and torch cable built-in, there is no protrusion at the tip of the wrist, which has realized a structure causing less entanglement of the torch cable and less interference with the workpiece.

### 1.3 Automatic exchange of single and tandem welding torches (tool exchange)

One of the advantages of the ARCMAN series exists in tandem welding (two-electrode welding) that increases the welding efficiency for medium- and heavy- thick plates. The ARCMAN-GS can build-in the tandem torches centered on its S6 axis. The advantage of the robot with a built-in torch cable has improved the application ratio of tandem welding in narrow and deep parts, which has conventionally been impossible. Its combination with the tool exchange exclusively designed for the ARCMAN-GS enables the automatic exchange of single and tandem torches during the welding process, allowing the use of welding torches based on the shapes of the workpieces and joints (**Fig. 9**).

**Fig.10** shows the operation of automatically dismounting a single torch, preparatory as the first step in the automatic exchange. A single torch is fixed on a holder. The mounting and dismounting of the welding torches is done along the S6 axis of the robot from the tip of the torch. By thus automatically exchanging a welding torch for a more suitable one, the application ratio can be maximized.

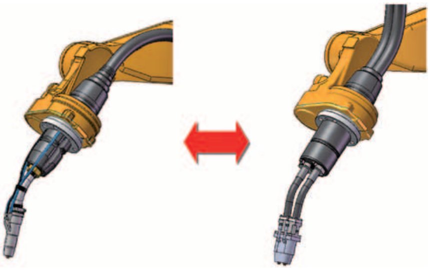

Fig. 9 Single torch (left) and tandem torch (right)

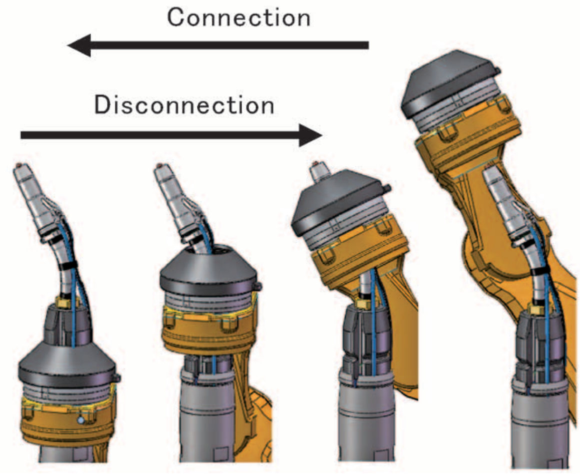

Fig.10 Automatic exchange operation of single torch

### 1.4 Reverse-elbow of S3 axis

A posture in which a robot arm is bent such that its upper arm extends to the rear of the robot is called a "reverse-elbow position." In an overhead-suspended system, which is suitable for welding large objects consisting of medium- and heavy-thick plates, this reverse-elbow position is advantageous, providing a larger working area than a conventional robot does when the robot approaches the object from the top.

**Fig.11** compares the working areas in overhead-suspended postures of the ARCMAN-GS with those of a conventional robot (ARCMAN-MP). The weldable area (depicted in pink) in the rear of the robot is 40% larger than that of the conventional robot. Thanks to its ability to take the reverse elbow position, the ARCMAN-GS, overhead-suspended, has an enlarged working area despite its arm size being in the same class as the ARCMAN-MP.

**Fig.12** shows examples of approaches to a workpiece when using an overhead-suspended system. This comparison shows how, of the two approaches to the same welding location, the

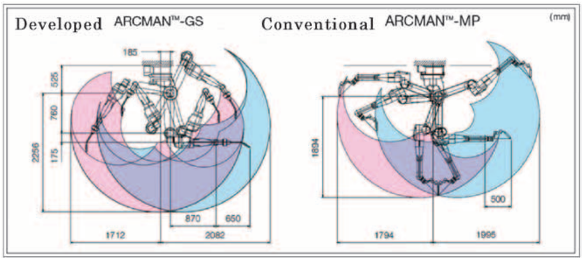

Fig.11 Comparison of working area

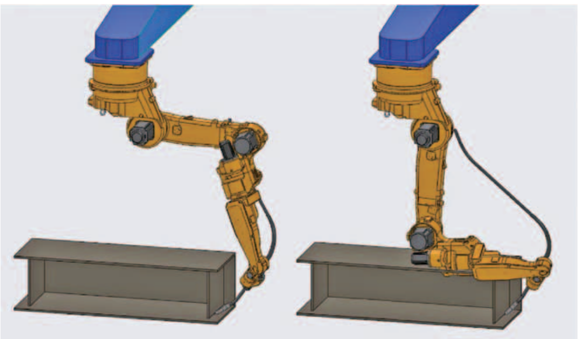

Fig.12 Reverse posture (left) and conventional posture (right)

reverse-elbow capability allows a posture that can take the shape of the workpiece into account and avoid interference. The conventional way of avoiding interference involves once moving the robot away from the workpiece on a moving apparatus (e.g., a cradle for moving the robot itself). The ARCMAN-GS, on the other hand, can avoid interference by a simple motion of the robot without the help of any moving apparatus, which decreases the length of the stroke required for the moving apparatus. This example offers a wider range of possibilities for the space saving and weight reduction of the entire system.

## 2. Development of new control technology

Unlike the conventional ARCMAN series, the ARCMAN-GS has an "asymmetric wrist structure." Therefore, the following new control technology had to be developed to achieve equal or better performance (e.g., weaving precision and sensing precision), important for welding robots used in the field of medium- and heavy-thick plates.

①Feed-forward model for six-axis articulated robot
②Elastic deformation compensation for six-axis articulated robot
③New backlash compensation
④New coulomb friction compensation
⑤New acceleration/deceleration trajectory

This paper explains only the above ① and ②, due to space limitations.

### 2.1 Feed-forward model for six-axis articulated robot

Assuming that a robot joint is a rigid body, its motion is described by the following general equation.

$$\{J_M+J_L(\theta_M)\}\ddot{\theta}_M+(B_M+B_L)\dot{\theta}_M+C(\dot{\theta}_M,\theta_M)+F=\tau \cdots (1)$$

wherein, $\theta_M$ : motor position

$J_M$ , $J_L(\theta_M)$: motor inertia, load-side inertia
$B_M$, $B_L$: viscosity friction coefficient of the motor, viscosity friction coefficient of the load-side
$C(\dot{\theta}_M,\theta_M)$: centrifugal/Coriolis force, gravity
$F$ : external force
$\tau$ : motor torque

Equation (1) is a general equation for only one axis. Conventionally, the axes that significantly affect the position of the robot tip are considered to be only the principal axes (S1 axis to S3 axis), as indicated by equation (2). The ARCMAN-GS has an upsized wrist structure, as well as left-right asymmetry of the upper arm. As a result, it has turned out that the wrist axes (S4 axis to S6 axis) also significantly affect the positioning of the robot tip. Therefore, equation (2) was extended to develop a new model that takes account of all the axes (equation (3)).

Equation (3) is used to calculate, in advance, the torque that would be required at the time of operation so as to add the calculation result to the control system as feed forward. This has achieved a high degree of position-tracking accuracy. The originally derived model required a large quantity of computation, involving approximately twenty thousand calculations, which made it difficult to implement the model on a robot controller. Repeated verification of the equation on an actual robot has decreased the amount of computation to one-twentieth of what it was, which has enabled implementation on the controller.

(1) Conventional control law

$$\begin{bmatrix}\tau_1\\\tau_2\\\tau_3\end{bmatrix}=\begin{bmatrix}J_{11}&J_{12}&J_{13}\\J_{21}&J_{22}&J_{23}\\J_{31}&J_{32}&J_{33}\end{bmatrix}\begin{bmatrix}\ddot{\theta}_1\\\ddot{\theta}_2\\\ddot{\theta}_3\end{bmatrix}+\begin{bmatrix}B_1&0&0\\0&B_2&0\\0&0&B_3\end{bmatrix}\begin{bmatrix}\dot{\theta}_1\\\dot{\theta}_2\\\dot{\theta}_3\end{bmatrix}+C(\theta_1,\theta_2,\theta_3)+F \quad\cdots (2)$$

(2) New control law

$$\begin{bmatrix}\tau_1\\\tau_2\\\tau_3\\\tau_4\\\tau_5\\\tau_6\end{bmatrix}=\begin{bmatrix}J_{11}&J_{12}&J_{13}&J_{14}&J_{15}&J_{16}\\J_{21}&J_{22}&J_{23}&J_{24}&J_{25}&J_{26}\\J_{31}&J_{32}&J_{33}&J_{34}&J_{35}&J_{36}\\J_{41}&J_{42}&J_{43}&J_{44}&J_{45}&J_{46}\\J_{51}&J_{52}&J_{53}&J_{54}&J_{55}&J_{56}\\J_{61}&J_{62}&J_{63}&J_{64}&J_{65}&J_{66}\end{bmatrix}\begin{bmatrix}\ddot{\theta}_1\\\ddot{\theta}_2\\\ddot{\theta}_3\\\ddot{\theta}_4\\\ddot{\theta}_5\\\ddot{\theta}_6\end{bmatrix}+\begin{bmatrix}B_1&0&0&0&0&0\\0&B_2&0&0&0&0\\0&0&B_3&0&0&0\\0&0&0&B_4&0&0\\0&0&0&0&B_5&0\\0&0&0&0&0&B_6\end{bmatrix}\begin{bmatrix}\dot{\theta}_1\\\dot{\theta}_2\\\dot{\theta}_3\\\dot{\theta}_4\\\dot{\theta}_5\\\dot{\theta}_6\end{bmatrix}$$
$$+C(\theta_1,\theta_2,\theta_3,\theta_4,\theta_5,\theta_6)+F \quad\cdots\cdots\cdots\cdots (3)$$

The torque at the tip (S6 axis) during the operation of all axes was estimated, and the results are shown in **Fig.13** and **Fig.14**. The conventional control technique, adapted to the ARCMAN-GS, has caused a difference between the estimated torque value and feedback torque (Fig.13). On the

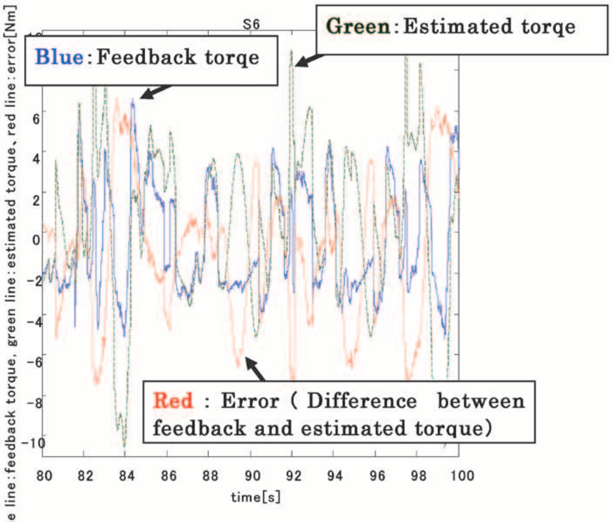

**Fig.13** Estimated torque with existing control (Axis 6)

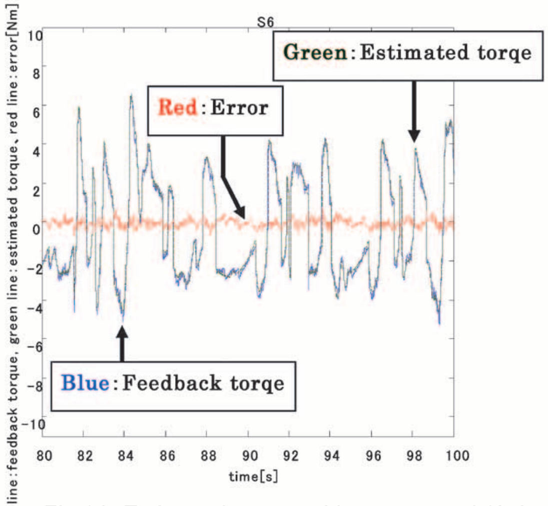

**Fig.14** Estimated torque with new control (Axis 6)

other hand, it has been verified that the new control technique accurately estimates the torque (Fig.14). This torque, accurately estimated, has been added to the control system as feed-forward to achieve high precision in position tracking.

### 2.2 Elastic deformation compensation for six-axis articulated robot

The effects of the strain placed on the wrist portion, due to its increased weight and complexity, have made it more difficult for the ARCMAN-GS to ensure the weaving precision of the robot. Therefore, the predictive control of strain was extended from the conventional 3 axes to 6 axes (equation (4)). This has made it possible to secure the weaving precision required.

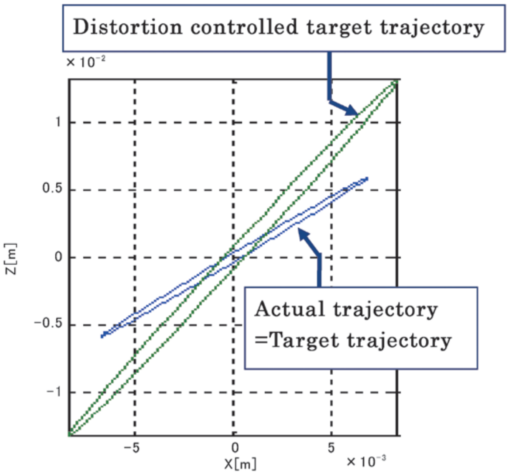

**Fig.15** Prediction result with new control

$$\begin{bmatrix}\Delta\theta_1\\ \Delta\theta_2\\ \Delta\theta_3\\ \Delta\theta_4\\ \Delta\theta_5\\ \Delta\theta_6\end{bmatrix}=\begin{bmatrix}K_1^{-1}&0&0&0&0&0\\ 0&K_2^{-1}&0&0&0&0\\ 0&0&K_3^{-1}&0&0&0\\ 0&0&0&K_4^{-1}&0&0\\ 0&0&0&0&K_5^{-1}&0\\ 0&0&0&0&0&K_6^{-1}\end{bmatrix}\begin{bmatrix}\tau_1\\ \tau_2\\ \tau_3\\ \tau_4\\ \tau_5\\ \tau_6\end{bmatrix}\quad\cdots\cdots\cdots\cdots\cdots\ (4)$$

wherein $K$ represents the spring constant.

The above model enables the prediction of strain in the robot arm, allowing the ARCMAN-GS to track the desired trajectory with its robot tip.2) **Fig.15** shows a result of the predictive control as an example. The horizontal axis is the coordinate in the X direction, while the vertical axis is the coordinate in the Z direction, of the robot tip (See Fig. 5). When the robot tip is aimed so as to move along an oblique angle of 45 degrees, the target trajectory of strain prediction falls on the solid green line. When the robot is operated with this green trajectory as a target, the actual trajectory falls on the angle of 45 degrees, indicated by the solid blue line, as targeted. This verifies the precision of the strain prediction.

## Conclusions

In the development of the ARCMAN-GS, new machine technology and new control technology were integrated to create a world-class robot. We will strive to improve the technology to develop high performance robots by exploiting the experience acquired through this study.

## References

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2) Y. Nishida et al. "Motion control of arc welding robot for medium- and heavy-thick plates" Journal of the Society of Instrument and Control Engineers (Journal of SICE). 2012, Vol.51, No.9.