Sensors & Transducers

Study on Intelligent Control of Metal Filling System by Welding Robots in the Open Environment

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Abstract: robot model of three-arm and five-degree freedom plus large scope of traversing welding was established, and decoupling of models of "large scope of traversing", "triangle movement of two arms" and "spherical movement of one arm" was realized. The model of "triangle movement of two arms "is able to use geometrical calculation to solve the kinematics inverse problem , avoid the multiplicity, improve the calculation speed, eliminate the blind spots of the motions of welding gun of welding robot, and simplify the kinematic pair of kinematic mechanism for the arc filling strategy during welding travelling of robot. Binocular stereo vision camera was used to detect the edges of welds, and laser array sensor was used to detect the amount of metal filling of welds. In completely open conditions, feedback was fused based on sensor data to realize the welding tracking control by welding robot. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Welding robot, Kinematics inverse problem, Binocular stereo vision camera, Metal filling, Laser array sensor.

1. Introduction

Now robots with six-degree freedom structure are applied in both domestic and foreign markets, whose critical defect is that the inverse problem of kinematics must be solved by inversion of homogeneous matrix. This calculation is slow and has multiple solutions. In particular, when the homogeneous transfer matrix is singular, the inversion problem of kinematics has no solution [1], [2]. That is to say, welding robots with six-degree freedom structure used in open environment have blind spots and the solution accuracy of inversion problem of kinematics nearby the blind spots is greatly reduced. Therefore, three-arm and six-degree freedom welding robots in the current market can only work in the mode of teaching box and cannot work in completely open environment. The welding robot during the plate welding usually weld with deviation and false action due to factors like strong arc light, high temperature, fume and error of workpiece, clamp accuracy, surface conditions and thermal deformation of workpiece. This is bottleneck where current three-arm and six-degree freedom welding robots cannot be widely applied to industries [3, 4].

In open operation conditions, two basic conditions must be addressed for welding robots. Firstly, sensor which can observe the open operation condition; at the second place, the robot can be controllable in completely open operation conditions. In order to empower the robot with the functions to observe the environmental condition and coordinates of target position, perform the analysis and judgment, and finish the tasks intelligently and independently, binocular stereo vision system was adopted in this paper to be used as the guide of tracking control of arc welds. Within the small scope, laser array was used to check accurately the three-dimensional shape of the welds, track in real time the position, size, concave and convex faces of the work piece to be welded, select intelligently the filling strategy of the welding robot, plan in real time the trajectory and the metal filling amount of the welding robot. Finally during the high-temperature welding, the size of stem extension of arc sensors of electric three-arm and five-freedom plus large scope of traversing was used to control the swinging of the welding robot so that the robot could be widely applied to work in open environment. In order to be controlled in open work conditions, special mechanism of "welding robot of three-arm and five-degree freedom plus large scope of traversing whose models can be decoupled" was established in this paper. It could be decoupled into the superposition of the model of "large scope of traversing" and the model of "three-arm and five-degree freedom mechanic arm of welding robot", while the model of "three-arm and five-freedom mechanic arm of welding robot" was further decoupled into the superposition of model of "triangle movement of two arms" and the model of "spherical movement of one arm". The model of "triangle movement of two arms" could use geometrical calculation to solve the inverse problem of kinematics to avoid multiplicity, increase the calculation speed, eliminate the blind spots of motions of welding gun of the welding robot, and simplify the kinematic pair of kinematic mechanism for arc filling strategy during welding travelling of the robot. The model of "spherical movement of one arm" and the model of "large scope of traversing" were simply the translation relation.

2. Robot Structure of Three-arm and Five-degree Freedom Plus Large Scale of Traversing

As shown in Fig. 1, this kind of robot is defined in accordance with six Cartesian coordinates {k}; k is from 0 to 5. Obviously when traversing in large scope the {0} coordinate, only the direction of x0 is traversed in large scale, so it is enough to let y1 traverse the welding robot in the opposite direction in coordinate of {1}. Therefore, the direct problem of kinematics of this kind of robot only considers the mapping transformation of the three-arm and five-freedom manipulator.

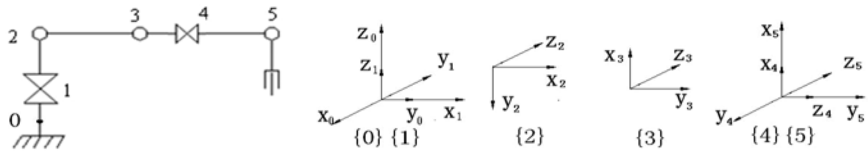

Fig. 1. Six Cartesian coordinates for welding robots of three-arm and five-degree freedom plus large scope of traversing.

The attitude at the end of the three-arm and five-degree freedom mechanic arm of the welding robot can be described with five independent variables: $[\theta_1\ \theta_2\ \theta_3\ \theta_4\ \theta_5]^T$. The direct problem of kinematics of five-degree freedom welding robot can be transformed with formula (1) for the direct problem of kinematics of mechanic arm described by Denavit-Hartenberg method.

$$ {}^0_5\boldsymbol{T} = {}^0_1\boldsymbol{T}(\theta_1)\,{}^1_2\boldsymbol{T}(\theta_2)\,{}^2_3\boldsymbol{T}(\theta_3)\,{}^3_4\boldsymbol{T}(\theta_4)\,{}^4_5\boldsymbol{T}(\theta_5)\,, \qquad (1) $$

If the formula (1) for direct problem of kinematics of five-degree freedom welding robot is solved inversely, the joint variables of $[\theta_1\ \theta_2\ \theta_3\ \theta_4\ \theta_5]^T$ corresponding to attitude at one end of the welding robot can be obtained. This kind of inverse problem of kinematics must be solved through inversion of transformation matrix of each connection rod, in which the calculation speed is slow and it has multiple solutions. In particular, when the homogenous transfer matrix is singular, the inverse problem of kinematics has no solution. That is to say, it is still not enough to obtain the joint variables by direct inversion of formula (1) for positive problem of kinematics of five-degree freedom welding robot. How to solve this difficult problem was one key issue of this paper.

As shown in Fig. 1, when the welding robot traverses in large scale the travelling mechanism in {0} coordinate, only the direction of xo is traversed in large scale. So it is enough to let y1 traverse in opposite direction the welding robot with relevant transverse length in coordinate {1}.

Assume that in Cartesian coordinate {1}, given the corresponding coordinate $\{x_p, y_p, z_p\}$ of attitude at one end of the welding robot, when it is required that the trajectory of welding robot keep not shaking during the welding and the welding gun keep perpendicular to the welding surface, the $\{x_B, y_B, z_B\}$ and the coordinate corresponding to welding point only traverse with the rod length L in the direction z1 in Cartesian coordinate. During the design of welding robot of three-arm and five-degree freedom plus large scale of traversing, the joint angle is made larger than 0 through limit mechanism, that is to say, the three-arm and five-degree freedom mechanic arm of this welding robot will not have the attitude at the welding end related to the dotted line shown in Fig. 2.

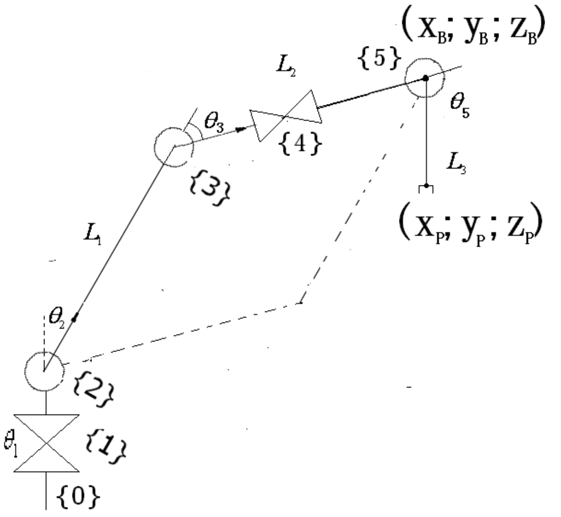

Fig. 2. Coordinate corresponding to attitude of end position of weld.

The expected attitude of three-arm welding robot corresponding to welding point P can be fixed through above three methods. By triangular geometrical calculation, we have:

$$\theta_1 = \arg\tan(y_P / x_P);$$

$$\theta_2 = \frac{\pi}{2} - \arg\tan((z_p + L_3)/\sqrt{x_p{}^2 + y_p{}^2}) - \arg\cos(\frac{x_p{}^2 + y_p{}^2 + (z_p + L_3)^2 + L_1{}^2 - L_2{}^2}{2L_1\sqrt{x_p{}^2 + y_p{}^2 + (z_p + L_3)^2}});$$

$$\theta_3 = \pi - \arg\cos(\frac{L_1{}^2 + L_2{}^2 - x_p{}^2 - y_p{}^2 - (z_p + L_3)^2}{2L_1 L_2});$$

θ_4=0;

$$\theta_5 = \pi - \theta_2 - \theta_3, \quad (2)$$

Among which: θ_1 θ_2 θ_3 θ_4 θ_5 are joint angles of free-degree freedom mechanical arm respectively; L_1= 480 mm, L_2=480 mm, L_3=280 mm are length of three arm rods respectively.

The geometrical calculation of (2) solves the difficult problem of solution of inverse kinematics of welding robot of three-arm and five-degree freedom plus large scale of traversing. Assume that one end position (x; y; z) of welding robot was given, the joint variables of $[\theta_1\ \theta_2\ \theta_3\ \theta_4\ \theta_5]^T$ related to the attitude can be quickly obtained by geometrical calculation (2) and this is one-to-one correspondence. The welding gun of the welding robot is able to reach the expected end position point only by controlling the five servo motors to these joint variables.

When the welding robot is required to work as human beings, which is to control the welding gun to make operations like up, down, left, right, stretch and extend in Euclidean three-dimensional space (x, y, z), it is just to make the welding robot in Cartesian coordinate {1}. Based on one end position of wielding robot and through the geometrical calculation of (2), joint angel variables of $[\theta_1\ \theta_2\ \theta_3\ \theta_4\ \theta_5]^T$ related to the attitude can be obtained and then the requirement can be fulfilled when the five position servo motors are controlled in to place. This kind of "linked operation" mode is line with the human welding habits.

As shown in Fig. 2, θ_4=0, although θ_5 is joint variable, rod L_3 always keeps parallel to z_1. The welding gun with this attitude keeps unchanged during welding, which is equivalent to the fact that the gun is always perpendicular to the welding surface. In real welding conditions, the welding surface is not always parallel to the surfaces of $x_1o_1y_1$. At this time, change θ_4 from -90° to 90o and aim at the welding surface. Particularly during fillet welding, the welding gun should be raised to certain angle in elevation direction, at which moment, with calculated joint variable of θ_5, θ_5 can be reduced by Δ from 0° to 90° . Obviously to keep the welding gun not shaking, it is required that the θ_4 and Δ keep unchanged during one welding.

As shown in Fig. 2 with basic conditions of θ_4=0, and θ_5 of joint variable, θ_4 from -90° to 90°; with additional θ_5 of joint variable, θ_5 is reduced by Δ from 0o to 90° and the space diagram is shown in Fig. 3, since θ_4 and Δ are within the value scope, just like arm L_3 is moving under hemisphere, so it is called "model of one arm spherical movement".

Geometrical correspondence of this model is:

$$\begin{aligned} x_B &= x - L_3 \bullet \sin\Delta \\ y_B &= y - L_3 \bullet \cos\Delta \bullet \sin\theta_4 \\ z_B &= z - L_3 \bullet \cos\Delta \bullet con\theta_4 \end{aligned} \quad (3)$$

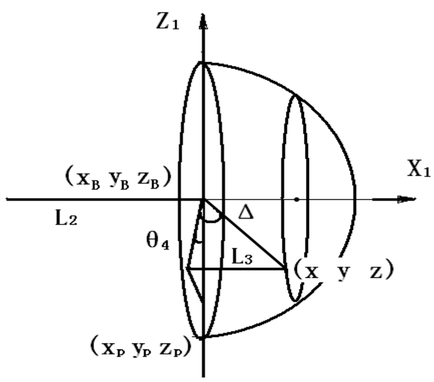

Fig. 3. Model of one arm spherical movement.

3. Weld Tracking Technology of Welding Robots Based on Multi-sensor Data Fusion in Open Conditions

Currently, sensors on welding robots which can reflect the site conditions for work pieces to be welded are one-axis high voltage contact sensor, arc sensor, laser sensor and weld tracking sensor for linear array CCD and two-dimensional area array CCD. The function of these sensors is to detect accurately the information of position and shape of welds and transform it into electric signals to be processed in real time by the control system. The control system controls the motor position servo mechanism based on the detection results, adjusts the attitude of welding gun, swinging strategy and metal filling amount, so as to realize automatic tracking of welds. However, the laser sensors, weld tracking sensors for linear array CCD and two-dimensional area array CCD picture cannot solve radically the problem of site condition feedback. Two sensing technologies for welding robots which are mostly applied and mature are: firstly, high voltage contract sensing: its function is also called initial position tracking technology It is based on principles of locating before welding and on-line compensation, but the efficiency of the welding robots is greatly reduced. Besides, during the sensing, situations like wear of spare parts and bending of welding wire are factors which affect the accuracy. What is more, the application of non-contact sensor for arc weld tracking can correct on line the trace deviation of the robot. Generally, the arc weld tracking must trace with the initial point, so in combination with the contact sensing function, the welding current will be changed when the voltage of network is changed and contact tube is worn. Therefore, the welding deviation and error actions often occur on site, which is a great barrier for further application of plate wielding [5].

As shown in Fig. 4, this purpose of this research is to make the welding robots work in open environment (namely: inaccurate positioning of workpiece, irregular weld size and rough welding face). Binocular stereo vision camera was adopted in this paper to obtain on line the weld position coordinate (x, y, z) of the work piece to be welded in open environment. Firstly in the large space scope, the left image f(*m*, *n*) collected by binocular stereo camera was used. It was assumed that left image f(*m*, *n*) was collected by binocular stereo camera and the storage format of the pixel was 360×360. Among which: m, n were the line and row coordinate of the pixel; f(*m*, *n*) was the gray value corresponding to the coordinate. The assumption was that left image f(*m*, *n*) was collected by binocular stereo camera, the line coordinate of the pixel was in line with the direction of weld extension, and first order row difference was made at this time for grey value f(*m*, *n*) corresponding to the pixel coordinate, and then average grey value of

$$DV = \frac{1}{360\times 360}\sum_{m=1}^{360}\sum_{n=1}^{360} \partial \mathrm{f}(m,n)$$

was gained for discretized points of the obtained row difference ∂f (*m*, *n*); then the gray value of discretized points of row difference ∂f (*m*, *n*) was transformed as follows:

$$T_L \partial \mathrm{f}(m,n) = \begin{cases} 0 & \partial f(m,n) \le DV \\ 255 & \partial f(m,n) > DV \end{cases},$$

Apparently the black area of image corresponding to discretized points function of $T_L\partial$f (*m*, *n*) was the left image obtained by binocular stereo vision camera. Finally, line coordinate information of pixels at edges of both weld ends was gained in turn in the direction of pixel increase of row coordinate for left image of weld $T_L\partial$f (*m*, *n*). The right and left images were matched by using the calibration of binocular stereo vision camera and formulate once again the space coordinate related to information points of edges of both weld ends (x_i^1, y_i^1, z_i^1) corresponding to upper weld curvature, (x_i^2, y_i^2, z_i^2) corresponding to lower weld curvature [6, 7].

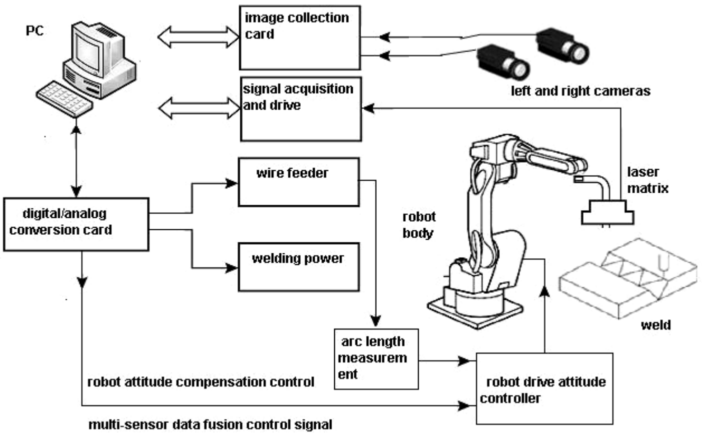

Fig. 4. Overall structure of welding robot with multi-sensor data fusion.

As shown in Fig. 4, laser array sensors are arranged in the radial direction of upper and lower weld curvatures. Six sensors in total with interval of 0.4 mm, perpendicular to the welding surface are non-contact measurement with the measurement scope of 45 mm to 90 mm. When welding robot of three-arm and five-degree freedom plus large scale of traversing is traversing in areas 45 mm above the middle line of upper and lower weld curvatures, the laser array sensor can obtain accurately the dimensions and three-dimensional shape of the welds so as to gain on-line in real time the volume of metal filing by welding robot. In particular, during the welding of plates, due to the large amount of metal filling, air holes, cracks and loose region will occur when the welding is finished in one time. Therefore, the metal filling has to be finished in several times so as to finish high-quality welding. In this condition, welding robots based on multi-sensor data fusion have more advantages. After the first welding, laser array sensors are used to detect the sizes and three-dimensional shape of the welds, and metal filling amount of next welding is planned in real time, thus avoiding the deviation due to deformation of high-temperature bath [8], [9].

4. Space Position Control System of Welding Robots with Attitude Compensation Feedforward in Open Conditions

As shown in Fig. 4, the feedforward signals of attitude compensation for space position control system of welding robots are generated by weld tracking results of data fusion of multi-sensors. Firstly, the middle line of upper weld curvature and lower weld curvature obtained by binocular stereo vision system is used as space travelling curvature of welding robot. Apparently with formula (1-2), five joint angle variables corresponding to attitude of at the end of three-arm and five-freedom mechanism arm can be obtained quickly. Soundly, weld dimensions and three-dimensional shape obtained with laser array sensors are used as the estimate of metal filling amount for welding during space travelling of welding robot. Particularly in welding of plates, in order to increase the metal filling, the welding gun has to swing and advance. During swinging and advancing, large scale traversing mechanism of welding robot of three-arm and five-degree freedom plus large scale of traversing can be used to finish the advancing, and the joint variable of can be used to make circular swinging, which simplifies the kinematic pair of the robot. The travelling time is determined by current of robot and the circular swinging is determined by weld width.

As shown in Fig. 4, during welding, the welding robot might produce slight weld deformation due to high temperature. The binocular stereo vision and laser array sensor can not take effect due to the action of strong arc light. In this circumstance, extension electric acr sensor can be used to reflect in real time the slight deformation of welds [10].

By doing this, in open work conditions, with the space position feedback control of welding robot with attitude compensation feedforward control, the operation target of working in completely open conditions can be achieved.

5. Conclusions

"Welding robot of three-arm and five-degree freedom plus large scope of traversing whose models can be decoupled" could be decoupled into the superposition of the model of "large scope of traversing" and the model of "triangle movement of two arms" and the model of "spherical movement of one arm". The model of "triangle movement of two arms" could use geometrical calculation to solve the inverse problem of kinematics to avoid multiplicity, increase the calculation speed, eliminate the blind spots of motions of welding gun of the welding robot, and simplify the kinematic pair of kinematic mechanism for arc filling strategy during welding travelling of the robot. That is to say, during the weld tracking space, the newly established welding robots of three-arm and five-degree freedom plus large scope of traversing could be controlled anywhere in real time. The experiment proves that in completely open environment, the weld tracking accuracy can reach 0.1 %, meeting the welding process requirements.

Upper weld curvature and the lower weld curvature detected by binocular stereo vision camera were used, metal filling was detected by laser array sensors, real time welding control signals based on multi-sensor dada fusion technology were formed. In completely open situations, space position control system for arc extension of welding robots with attitude compensation feedforward was realized, which apparently improves the weld success rate and welding quality.

Acknowledgements

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