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Robust Control of Welding Robot for Tracking a Curved and Straight Welding Line combined 3D

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***Abstract:* -** This paper highlights a welding robot (WR) for its end effector to track a curved and straight welding line combined (CSWLC). The WR includes five actuators which use a DC motor as a power source. Two controllers are proposed to control the WR's end effector: a main controller and a servo controller. Firstly, based on WR's kinematic equations and its feedback errors using backstepping method the main controller is proposed to design the reference-inputs for the WR's actuators in order that the WR's end effector tracks the CSWLC. Secondly, based on the dynamic equation of WR's actuator, the servo controller is designed using an active disturbance rejection control method. Finally, a control system incorporated with the main controller and the servo controllers make the WR's end effector robustly track a CSWLC in the presence of the modeling uncertainty and disturbances during the welding process. The effectiveness of the proposed control system is proven through the simulation results.

I. INTRODUCTION

Nowadays, the robotic systems become widely used in welding applications which are harmful and dangerous for the welders. Furthermore, a robotic welding is very practical and useful in the industrial applications in the views of increasing the welding quality, productivity and reducing the welding cost. For example, Jeon, Park and Kim (2002) proposed a welding mobile robot for Lattice Type of Welding; Bui, Chung, Nguyen and Kim (2003) proposed an Adaptive Tracking Control of Two-Wheeled Welding Mobile Robot with Smooth Curved Welding Path; Santos, Armada and Jimenez (2000) developed a four-legged welding robot for welding a straight and smooth curved welding line which is applied in naval construction process; Ngo Manh Dung, Vo Hoang Duy, Nguyen Thanh Phuong and Sang Bong Kim (2006) proposed a welding robot for its end effector to track a rectangular welding line. The problem of these proposed welding systems is that they cannot perform their ability in a Curved and Straight type of welding line combined.

II. SYSTEM MODELING

This paper deals with the WR to weld a CSWLC which is shown in Figure 1-2. The WR's end effector is controlled by five mechanism actuators which use a DC motor as a power source. The movement of the WR's end effector can divide into three motions. One is a motion that makes the WR's end effector precisely track a vertical and horizontal welding line. Another changes the welding torch's direction as a value 90^0 at the corners for the welding torch to be perpendicular to the welding line. For improving the welding quality, the last one regularly and slightly shakes the welding torch for making the WR's end effector weave around a welding line with small amplitude. Moreover, during changing torch's direction at the corners, the welding signal, the first motion and the third motion are interrupted. Furthermore, before practical welding process, two welded base material parts are prewelded. So the opened straight welding line that is not a fillet type is usually distorted. The welding path is discontinuous with two edge corners. In spite of a straight line type in each continuous section, the total shape is a three dimensional one. When the practical welding is processed, the problem for measuring of the welding line is very complicated. To overcome this problem, a type of sensor detecting the tracking errors should be considered. In this paper, a control system for precisely tracking a reference three dimensional CSWLC even in the presence of the system's modeling uncertainty and the unknown disturbance is proposed. The control system consists of a main controller and a servo controller. The main controller is based on backstepping method and the servo controller is based on Proportional Integral Derivative (PID) or Sliding Mode Control (SMC) method. The effectiveness of the proposed control system which is incorporated with the main and servo controllers is shown by simulation results.

■ Angle of torch's direction:

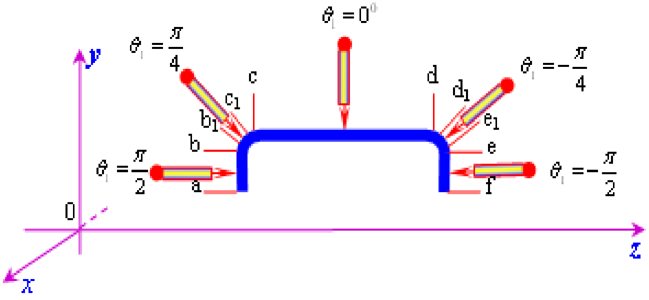

Fig 1. Welding line 2D and angle θ_1

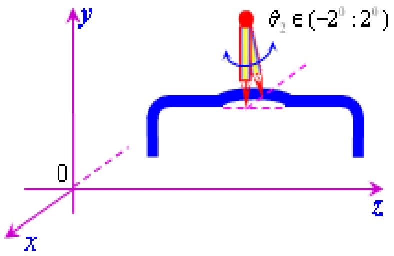

Fig 2. Welding line 3D and angle θ_2

The direction of the welding torch is assumed to be perpendicular to the welding line. The rotational angle of the torch holder's motor is assumed to be changed only at the corners. So while the WR's end effector is tracking a vertical and a horizontal welding lines the values of θ_1 are:

- $\theta_{1[a,b]} = \frac{\pi}{2}$ • $\theta_{1[b_1,c_1]} = \frac{\pi}{4}$; • $\theta_{1[c,d]} = 0^0$;
- $\theta_{1\_i+1[b,b_1]} = \theta_{1\_i[b,b_1]} - \frac{\pi/4}{b_1 - b}$;

where $i = 0,1,2,\ldots,n$ and $\theta_{1\_0[b,b_1]} = \theta_{1[a,b]}$

- $\theta_{1\_i+1[c_1,c]} = \theta_{1\_i\,[c_1,c]} - \frac{\pi/4}{c - c_1}$;

where $i = 0,1,2,\ldots,n$ and $\theta_{1\_0[c_1,c]} = \theta_{1[b_1,c_1]}$

- $\theta_{1[d,d_1]} = -\theta_{1[c,c_1]}$; $\theta_{1[d_1,e_1]} = -\frac{\pi}{4}$;
- $\theta_{1[e_1,e]} = -\theta_{1[b_1,b]}$ and $\theta_{1[e,f]} = -\frac{\pi}{2}$

■ The x axis tracking motor is designed to control the WR's end effector to track the welding line precisely. So the bound of θ_2 is assumed to be as follows $\theta_2 = \left(-2^0 \quad 2^0\right)$.

2.1 Configuration of the developed welding robot

The developed WR has five mechanism actuators which use a DC motor as a power source. The system's actuators are a vertical slider, a horizontal slider, a mechanism for x axis tracking motion which is shown in Fig 3, a mechanism of torch holder and a mechanism of weaving torch. Theses actuators above are operated by a vertical slider motor, a horizontal slider motor, a x axis tracking motor, a torch holder motor and a weaving motor, respectively. The function of each actuator is as follows: To weld vertical welding lines, the vertical slider is used to lip up and down the WR's end effector. To weld a horizontal welding line, the horizontal slider is used to shift the WR's end effector horizontally. To move the WR's end effector toward the directions perpendicular to the two sliders for tracking a distorted RWL precisely, the mechanism for x axis tracking motion is used. To keep the direction of the welding torch to be perpendicular to the welding line, the mechanism of the torch holder is used. The mechanism of the torch holder is a torch holder fixed on the axis of the gear box of the torch holder's motor. To improve the welding quality, the mechanism of the weaving torch is used as shown in Figure 3-4.

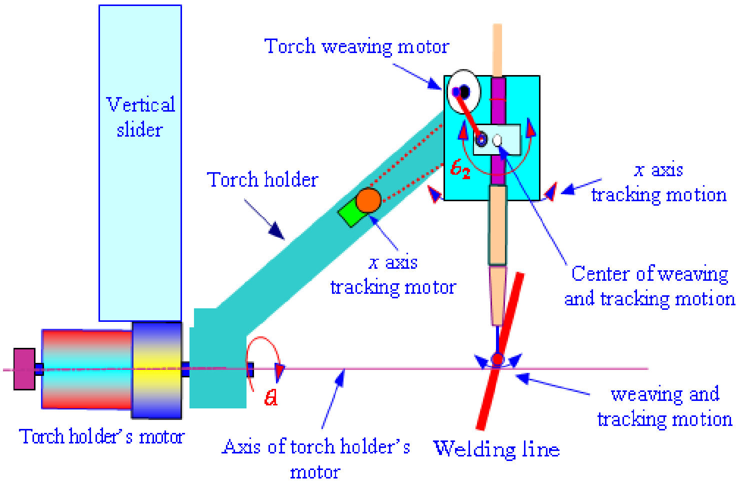

Fig 3. Mechanism of the torch holder and mechanism of the weaving torch

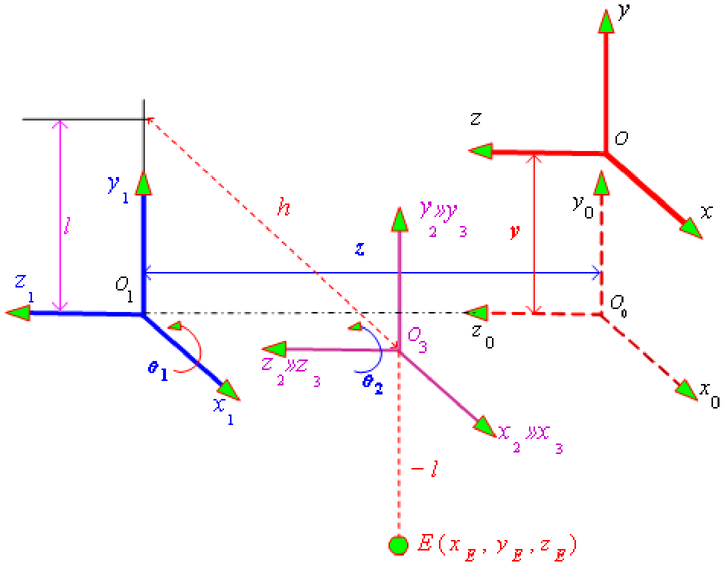

Fig. 4. Coordinate frames of the welding robot

2.2 Controllers Design.

2.2.1 Main controller

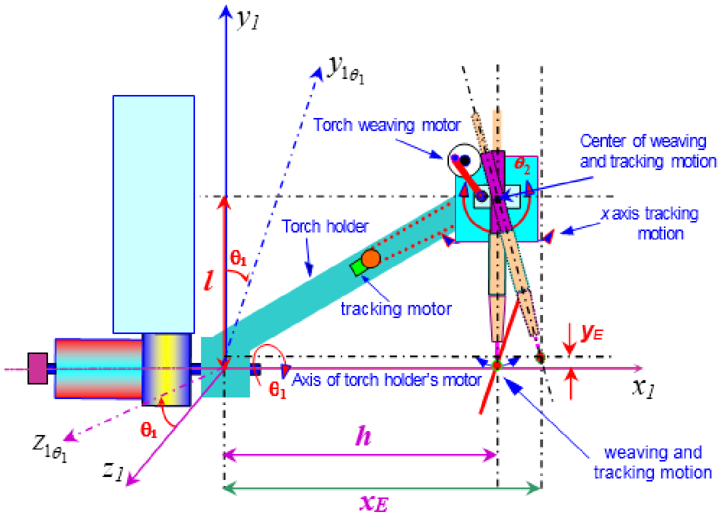

Fig 5. Mechanism of the torch holder and mechanism of the weaving torch

$$\begin{bmatrix} x_E \\ y_E \\ z_E \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_1 & -\sin\theta_1 \\ 0 & \sin\theta_1 & \cos\theta_1 \end{bmatrix} \begin{bmatrix} l\sin\theta_2 + h \\ l\cos\theta_1(1-\cos\theta_2) + y \\ l\sin\theta_1(1-\cos\theta_2) + z \end{bmatrix} \quad (1)$$

The tracking errors e_i $(i = 1,2,3)$ are defined as follows:

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_1 & \sin\theta_1 \\ 0 & -\sin\theta_1 & \cos\theta_1 \end{bmatrix} \begin{bmatrix} x_R - x_E \\ y_R - y_E \\ z_R - z_E \end{bmatrix} \quad (2)$$

$(x_R$, y_R, $z_R)$ are the position coordinates of a reference point R moving along the CSWLC at a constant velocity $\mathbf{v}_r$ as shown in Figure 6. The projections of $\mathbf{v}_r$ on the x, y and z axes are v_{xr} , v_{yr} and v_{zr} , respectively.

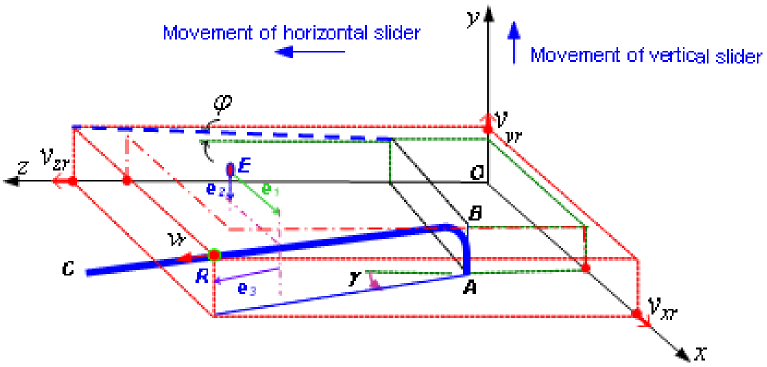

Fig 6. Reference point and tracking errors

$$\begin{cases} v_{xr} = v_r \cos\varphi \sin\gamma \\ v_{yr} = v_r \sin\varphi \cos\gamma \\ v_{zr} = v_r \cos\varphi \cos\gamma \end{cases} \quad (3)$$

γ Angle between projection of $\mathbf{v}_r$ on the plan (x, z) and the z axis , φ Angle between projection of $\mathbf{v}_r$ on the plan (y, z) and the z axis.

Based on the WR's kinematic equations, the first derivative of the tracking errors is obtained as follows:

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} v_{rx} - \omega_2 l\cos\theta_2 \\ \cos\theta_1(v_{ry} - \dot{y}) + \sin\theta_1(v_{rz} - \dot{z}) + \omega_2 l\sin\theta_2 \\ -\sin\theta_1(v_{ry} - \dot{y}) + \cos\theta_1(v_{rz} - \dot{z}) \end{bmatrix} \quad (4)$$

where $\omega_1 = \dot{\theta}_1$ is zero during welding the vertical and horizontal welding line.

The Lyapunov function is chosen as follows:

$$V = \frac{1}{2}e_1{}^2 + \frac{1}{2}e_2{}^2 + \frac{1}{2}e_3{}^2 \geq 0 \quad (5)$$

The derivative of V yields:

$$\dot{V} = e_1\dot{e}_1 + e_2\dot{e}_2 + e_3\dot{e}_3$$

$$\begin{aligned} \dot{V} = {} & e_1(v_r\cos\varphi\sin\gamma - \omega_2 l\cos\theta_2) + \\ & + e_2[\cos\theta_1(v_r\sin\varphi\cos\gamma - \dot{y}) + \sin\theta_1(v_r\cos\varphi\cos\gamma - \dot{z}) + \omega_2 l\sin\theta_2] \\ & + e_3[-\sin\theta_1(v_r\sin\varphi\cos\gamma - \dot{y}) + \cos\theta_1(v_r\cos\varphi\cos\gamma - \dot{z})] \end{aligned} \quad (6)$$

As we know, the velocities of the vertical and horizontal sliders are controlled by angular velocities of DC motor. The relationship between them is as the following:

$$\begin{cases} \dot{y} = k_y\omega_y \\ \dot{z} = k_z\omega_z \end{cases} \quad (7)$$

An obvious way to take the control outputs of the main controller, ω_2, ω_y, ω_z, θ_1, ω_w are chosen as follows

$$\begin{cases} \omega_2 = (v_r \cos\varphi \sin\gamma + k_1 e_1)/(l \cos\theta_2) \\ \omega_y = \dfrac{1}{k_y}\left[v_r \sin\varphi \cos\gamma + \cos\theta_1 (l\omega_2 \sin\theta_2 + k_2 e_2) - k_3 e_3 \sin\theta_1\right] \\ \omega_z = \dfrac{1}{k_z}\left[v_r \cos\varphi \cos\gamma + \sin\theta_1 (l\omega_2 \sin\theta_2 + k_2 e_2) + k_3 e_3 \cos\theta_1\right] \\ \theta_1 = \left\{-\dfrac{\pi}{2} \quad 0 \quad \dfrac{\pi}{2}\right\} \end{cases} \quad (8)$$

From Eq. (6) and Eq. (8), the following equation is obtained.

$$\dot{V} = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 \quad (9)$$

Clearly if $k_i > 0$ $(i = 1,2,3)$ and Eq. (8) are chosen,

$V \geq 0$ and $\dot{V} \leq 0$. It means that $e_i \rightarrow 0$ $(i = 1,2,3)$ as $t \rightarrow \infty$ by Lasalle's invariance theorem and Lasalle-Yoshizawa theorem *(Utkin, Guldner, and Shi, 1999).* That is, the system is stable in the sense of the Lyapunov under the conditions of $k_i > 0$ $(i = 1,2,3)$ in Eq. (9).

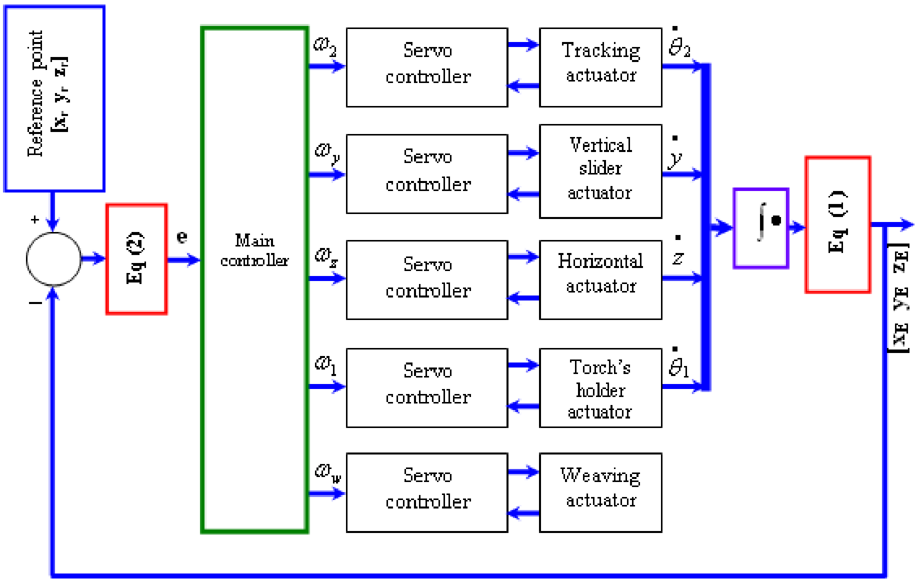

Fig 7. Block diagram incorporated with the main and servo controllers

2.2.2 Servo controller design

PID controllers have a simple control structure, inexpensive cost, many proposed systematic tuning methods, and have been used for more than half a century. However, when the system is nonlinear but known or where there are bounded uncertainties in the system, PID controllers are not perfectly able to stabilise the system, particularly, when the nonlinearity is very high or the bound of uncertainty is large.

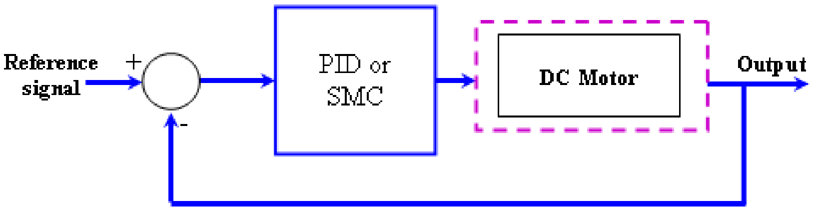

Fig 8: The block diagram a DC motor with PID or SMC system

The PID algorithm is:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \qquad (10)$$

Proportional gain, K_p, Integral gain, K_i *and* Derivative gain, K_d

Sliding mode control, or SMC, is a form of variable structure control (VSC). It is a nonlinear control method that alters the dynamics of a nonlinear system by application of a high-frequency switching control. The state-feedback control law is not a continuous function of time. Instead, it switches from one continuous structure to another based on the current position in the state space.

A state space representation of The dynamics of a DC motor may be expressed as:

$$\begin{bmatrix} \dot{\omega} \\ \dot{I}_a \end{bmatrix} = \begin{bmatrix} -\frac{B_m}{J_m} & \frac{K_i}{J_m} \\ -\frac{K_b}{L_a} & -\frac{R_a}{L_a} \end{bmatrix} \begin{bmatrix} \omega \\ I_a \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L_a} \end{bmatrix} E_a \qquad (11)$$

Let

$$x_1 = \omega,\ x_2 = I_a,\ a_1 = -\frac{B_m}{J_m},\ a_2 = \frac{K_i}{J_m},$$

$$a_3 = -\frac{K_b}{L_a},\ a_4 = -\frac{R_a}{L_a},\ b = \frac{1}{L_a},\ u = E_a$$

Then the system (11) can be written as:

$$\begin{cases} \dot{x}_1 = a_1 x_1 + a_2 x_2 \\ \dot{x}_2 = a_3 x_1 + a_4 x_2 + bu \\ y = x_1 \end{cases} \qquad (12)$$

Select the sliding surface:

$$s = c(r - x_1) + a_1 x_1 + a_2 x_2 \quad \text{where } c < 0 \qquad (13)$$

The sliding mode control is:

$$u = -Ksign(s) \quad \text{where K > 0} \qquad (14)$$

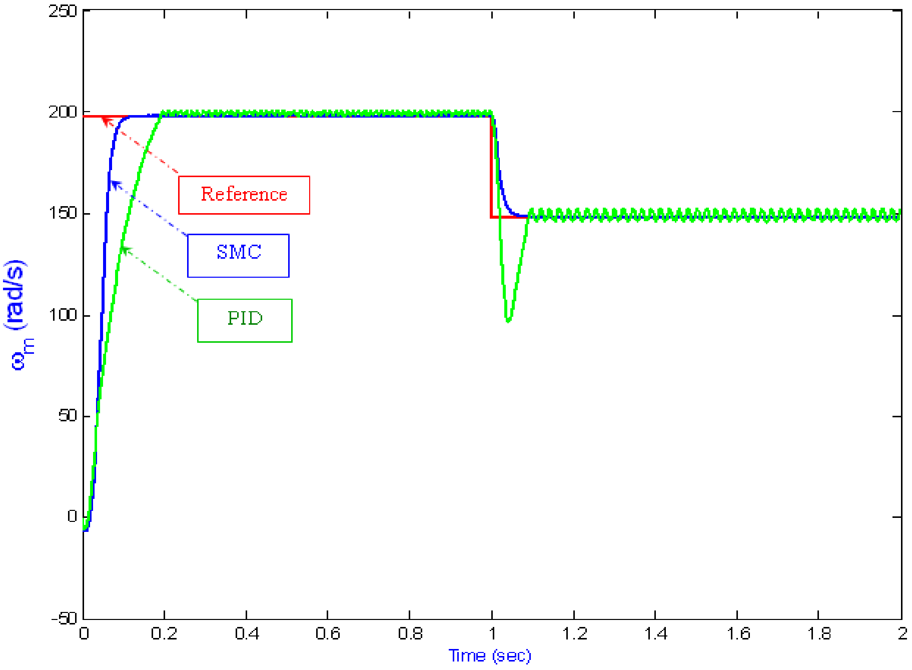

Fig 9. Simulation results of angular velocities of the actuator's DC motor

III. SIMULATION RESULTS

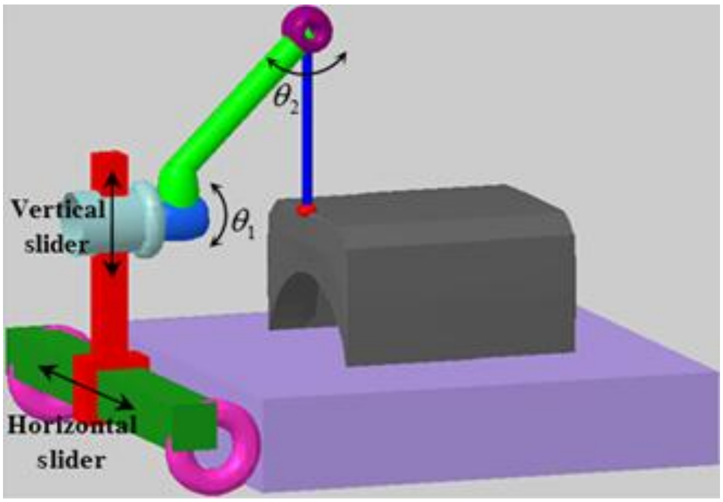

Fig 10. Welding robot

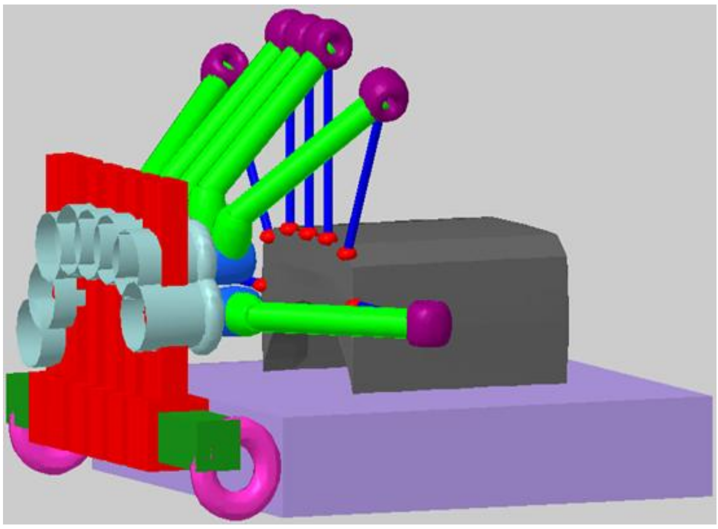

Fig 11. The WR is tracking along the welding path

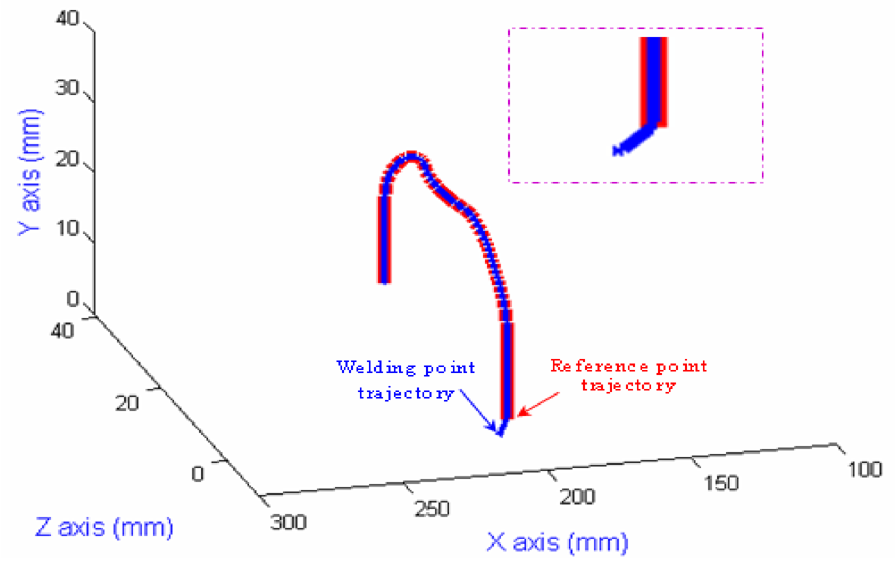

Fig 12. Results of trajectories of the end effector and its reference

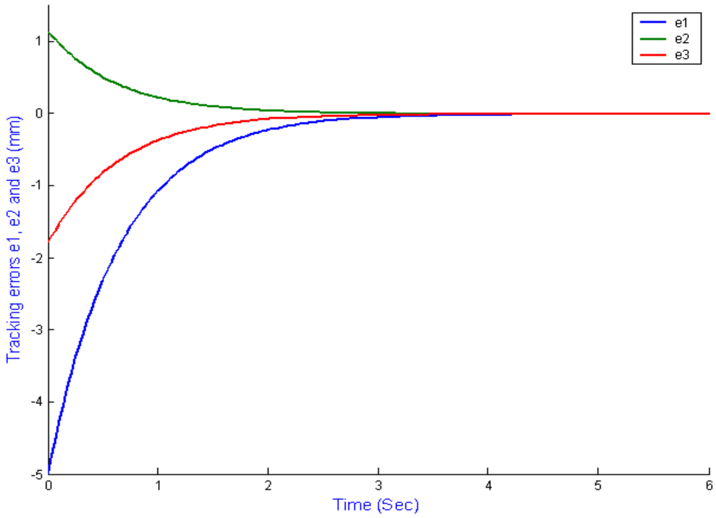

Fig 13. Results of the tracking errors at the beginning

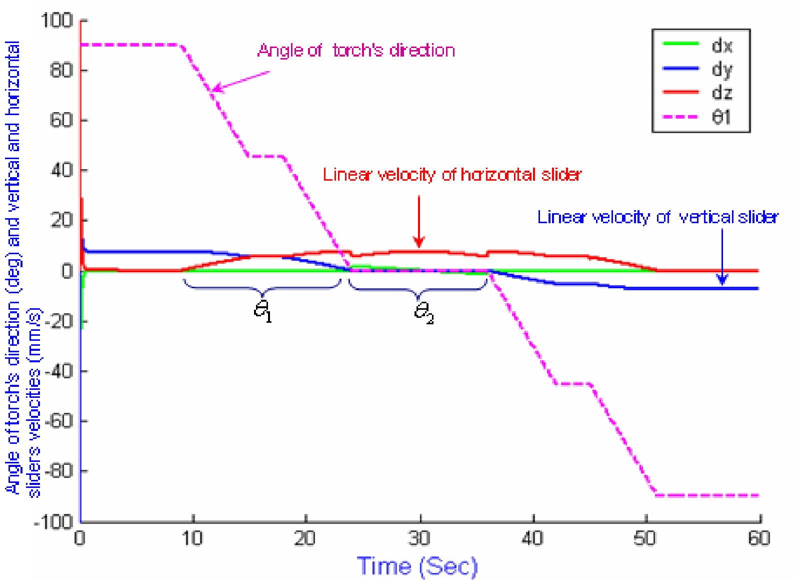

Fig 14. Linear velocities of sliders and rotational angle of the torch holder motor

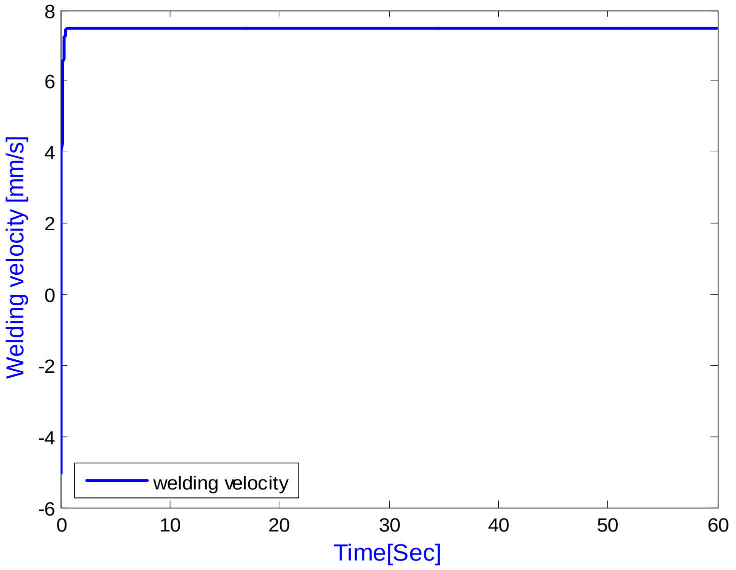

Fig 15. The velocities of the welding point

In Figure 10, Configuration of the developed welding robot. Figure 11-12, the trajectory of WR's end effector tracking the RWL with the initial values of errors $e_1 = -5mm$, $e_2 = 1.1mm$ and $e_3 = -1.8mm$ is shown. Figure 13, the simulation results of tracking errors of e_1, e_2, e_3 at beginning is shown. All the tracking errors converge to zero after three seconds. So it is shown that this result can apply to welding process. Figure 14 shows the whole movement process of vertical slider and horizontal slider and the rotational angle of the torch's holder. Figure 15 shows the end effector track along a welding trajectory with a constant velocity 7.5mm/s in the whole welding process.

IV. CONCLUSION

In this paper, a robot for welding a CSWLC is developed. A control system incorporated with the main and servo controllers is proposed to control the WR's end effector for tracking a CSWLC. The main controller is designed based on backstepping control method using Lyapunov function. The servo controller is designed for using SMC control method. The incorporation of two controllers makes the WR's end effector track CSWLC robustly. The system is stable in the sense of Lyapunov. The simulation results show that proposed control system has good performance.

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