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Tracking Control of a Scara Gas Metal Arc Welding Robot in Circular Path via Adaptive Neural Network Method

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ABSTRACT

This study is concerned with the control of Gas Metal Arc Welding robot. The control area is divided into two different categories which should be performed simultaneously. The First category is an arc length control of Gas Metal Arc Welding (GMAW) process via Multi Input Multi Output (MIMO) feedback linearization scheme. The other one is the control of a Scara robot for tracking a circular path base on adaptive neural network method. The two above-mentioned control methodologies should be performed simultaneously, due to the nature and duty of the welding robots. This goal will be achieved by introducing an interface block which plays a pivotal role to interconnect those control parts. The main task of this block is to transform knowledge of the detached droplet mass, weld path geometry and weld the density of droplet of the GMAW Process into desired joint velocities of the robot for the purpose of tracking. Finally, simulation results based on a 3-DOF Scara robot show the effectiveness of the adaptive neural network controller.

Key words: Gas metal arc welding robot, scara robot, tracking control, adaptive neural network method

INTRODUCTION

Welding is one of the mostsalientissues currently under consideration by scientists. Welding automation has been developing in the recent years. There exists a wide variety of the welding processes with specific applications which can be selected, for a particular type of operation. A majorclassof welding is the GMAW process. Because of itsabundantnaturein productivity andcostfields, the GMAW process is the most wide-spread methodology (Balasubramanian and Lakshminarayanan, 2008; Quinn *et al.*, 2005). This type of welding was used manually in the past century but did not have sufficient accuracy; also, it was extremely time-consuming. Nowadays, due to the necessities for the sake of accuracy, automation of this type of welding is inevitable. One of the best options that can prove to be usefulin automation is using robots to perform welding operations.

The main reasons which put the robotic automation in the center of attention in the presentera, include adjusting various parameters for achieving a satisfactory quality and more accuracy purpose, as well as welder's inability to produce a weld with the desired level of accuracy within a short period of time. One of the major components of thearc welding robots is the mechanical unit and the controller. The part which indicates what makes the robot move is them echanical unit. The design of these systems can be divided into several common types including an SCARA robot and Cartesian coordinate robot that use different coordinate systems to regulate the arms of the machine.

The control area itself can be directed into the different categories (Linden *et al.*, 1980; Smartt and Einerson, 1993; Nishar *et al.*, 1994; Einerson *et al.*, 1992; Aendenroomer, 1996; Henderson *et al.*, 1993; Hale and Hardt, 1992; Phillips, 1995; Johnson *et al.*, 1991; Barnett *et al.*, 1995; Chen and Chin, 1990; Fujimura *et al.*, 1987; Tomizuka, 1988; Naidu *et al.*, 1998). This study concentrates on the control of a welding robot which is determined to perform the GMAW process in a designated trajectory. In fact, controlling strategy consists of two distinct problems:

- Controlling the arc length for a GMAW process (Zhang *et al.*, 2002; Thomsen, 2005; Abdelrahman, 1998; Naidu *et al.*, 1999; Moore *et al.*, 2003; Jalili-Kharaajoo *et al.*, 2003; Lima *et al.*, 2005)
- Controlling the robot to track a desired path (Steele *et al.*, 2005; Xu *et al.*, 2008; Kim *et al.*, 1996, 1998)

The first problem has been controlled in (Bazargan-Lari, *et al.*, 2008a) for a single drop detachment without any automotive system. Since the welding process via a robotic system has a continuous trend, the arc length and robot control should be done simultaneously considering all drop detachments.

To overcome this problem, the key point is a cascade structure which involves two subsystems for modeling either of the above problems. Aninter connect computer is the best candidate tolinkthese two parts. In the following, the rulewill be explainedin more details.

MATHEMATICAL MODEL OF GMAW PROCESS

The main definition of the Gas Metal Arc Welding (GMAW) and its advantagesare explainedin (Naidu *et al.*, 1999). Detailed analysisfor deriving the state-space equationsof the GMAW processprior todropdetachmentis givenin (Abdelrahman, 1998) and the result is adoptedhere. The GMAW process can be approximately modeled as follows:

$$\begin{cases} x_1 = x \\ x_2 = \dot{x} \\ \dot{x}_3 = \dot{m}_d \\ \dot{x}_4 = \dot{l}_s \\ \dot{x}_5 = \dot{I} \end{cases} \Rightarrow \begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \ddot{x} = \dfrac{F_{tot} - Bx_2 - Kx_1}{x_3} \\ \dot{x}_3 = \dot{m}_d = \rho_w M_r + M_{ve} \\ \dot{x}_4 = \dot{l}_s = u_1 - \dfrac{M_r}{\pi r_w^2} \\ \dot{x}_5 = \dot{I} = \dfrac{u_2 - R_L x_5 - V_{arc} - R_s x_5}{L_s} \end{cases} \tag{1}$$

- $x_1 = x$: Droplet displacement (m)
- $x_2 = \dot{x}$: Droplet velocity (m sec^{-1})
- $x_3 = m_d$: Droplet mass (kg)

- $x_4 = l_5$: Stick out (m)
- $x_5 = I$: Current (A)

and:

$$M_R = C_2\rho_w x^2_5 + C_1 x_5$$

M_{ve} = A constant mass rate of vaporizing electrode

$$R_L = \rho\left[x_4 + 0.5\left(\left(\frac{3x_3}{4\pi\rho_w}\right)^{\frac{3}{2}} + x_1\right)\right] \text{: Electrode resistance}$$

The output variables are:

$$\begin{cases} y_1 = V_{arc} \\ y_2 = I \end{cases} \Rightarrow \begin{cases} y_1 = V_o + R_a x_5 + E_a(CT - x_4) \\ y_2 = x_5 \end{cases} \tag{2}$$

and the control input variables are:

- $u_1 = S$: Wire feed speed m sec^{-1}
- $u_2 = V_{oc}$: Open-circuit voltage-V

The above model of the GMAW process can be written in the following affine form:

$$\dot{x} = f(x) + g(x)u \tag{3}$$

$$y = h(x) \tag{4}$$

WELDING ROBOT

MIMO input-output feedback linearization control of the GMAW process in a period of detachment is presented in (Bazargan-Lari *et al.*, 2008a; Eghtesad *et al.*, 2008). It is evident that the action of welding should be done with a robot manipulator and its end effectors. Tracking control of a desired path for welding robots can be performed in the different control methods such as model-based control and intelligent control. As a model-based control two methods of feedback linearization and adaptive feedback linearization control has been employed to control welding robots (Bazargan-Lari *et al.*, 2011; Zakeri *et al.*, 2012). In this study tracking control will be implemented by adaptive neural network controller which is based to second method. Figure 1 depicts the suggested algorithm and Fig. 2 shows how computer inter connection structureis used. Based on the figures, the whole control of a Scara Gas Metal Arc Weldingis developed. It was found that one of the most note worthy points which require more attention in GMAW process is a cyclic form of it. There fore it is repeated during tracking the desired path.

Figure1 shows the simple suggested strategy for controlling the entire system with satisfactory results. So in the present work the strategy was selected for controlling the system. The computer block plays the role of an interconnection for this cascade structure which is explained in the next section.

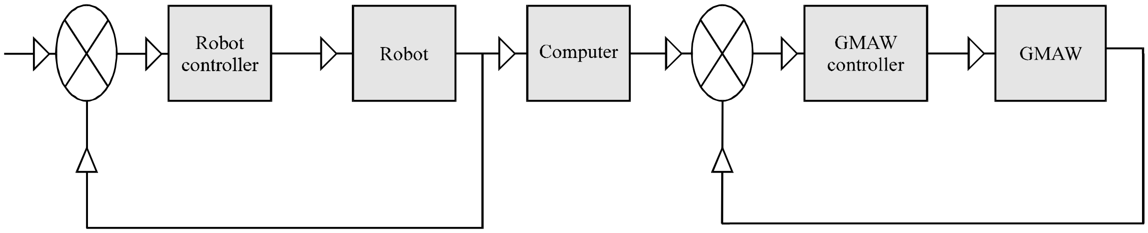

Fig. 1: Simple suggested strategy for control of the whole of the system

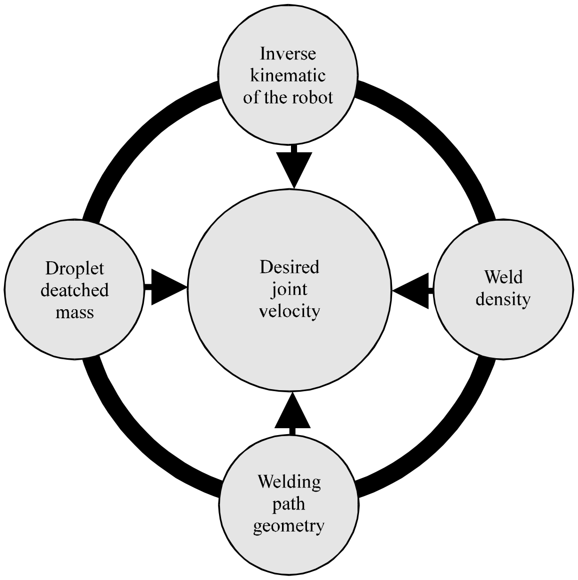

Fig. 2: Computer interconnection structur

COMPUTER INTERCONNECTION BLOCK

It isobviousthat for tracking thedesiredpathby robot manipulator, desired joint velocities are inevitable. Computer is the responsible unit for this task. One of the common paths whichare usedin the weldingprocessforindustrialactivity, is the circular one. Among the usual robots in charge of welding process, a Scara robot is an appropriatechoiceand bench mark for welding planar trajectories. So a Scara Robotis selectedfor this purpose. Theprocessthatis donein the computeris representedin Fig. 2.

WELDING ROBOT CONTROL

By choosing the control strategy in Fig. 1 and calculating the necessary inputs for the robotic system, it is time to design the controllers for both of the subsystems. According to (Bazargan-Lari *et al*., 2008b) the control inputs for the GMAW process are as follows:

$$u_1 = \frac{R_a(-V_0 - E_a(CT - x_4) + (-R_a - R_s - \rho x_4)x_5)}{L_s E_a} \\ - \frac{E_a(-C_1 x_5 - \rho C_2 x_4 x_5{}^2) + \upsilon_1}{\pi r_w{}^2 E_a} + R_a\left(\frac{-V_0 - E_a(CT - x_4) + (-R_a - R_s - \rho x_4)x_5}{L_s E_a} + \frac{\upsilon_2}{E_a}\right) \qquad (5)$$

$$u_2 = L_s\left(\frac{-V_0 - E_a(CT - x_4) + (-R_a - R_s - \rho x_4)x_5}{L_s} + \upsilon_2\right) \tag{6}$$

To control the scara robot, its' the dynamic equations should be derived. These mentioned equations have been derived by lagrangian method in (schilling, 1990). These equations are shown below:

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = r \tag{7}$$

Where, the matrices D, C and G are:

$$D(q) = \begin{bmatrix} (\frac{m_1}{3} + m_2 + m_3)a_1^2 + (m_1 + 2m_3)a_1a_2\cos(\theta_2) + (\frac{m_2}{3} + m_3)a_2^2 & (\frac{m_2}{2} + m_3)a_1a_2\cos(\theta_2) + (\frac{m_2}{3} + m_3)a_2^2 & 0 \\ (\frac{m_2}{2} + m_3)a_1a_2\cos(\theta_2) + (\frac{m_2}{3} + m_3)a_2^2 & (\frac{m_2}{3} + m_3)a_2^2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \tag{8}$$

$$C(q,\dot{q}) = \begin{bmatrix} -\frac{a_1a_2}{2}\sin(\theta_2)[(m_2 + 2m_3)]\dot{\theta}_2 & -\frac{a_1a_2}{2}\sin(\theta_2)[(m_2 + 2m_3)]\dot{\theta}_1 + \left(\frac{m_2}{2} + m_3\right)\dot{\theta}_2 & 0 \\ \left(\frac{m_2}{2} + m_3\right)a_1a_2\sin(\theta_2)\dot{\theta}_1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{9}$$

$$G(q) = \begin{bmatrix} 0 \\ 0 \\ m_3 g_0 \end{bmatrix} \tag{10}$$

There are many different methods to control the robot manipulators; one of the model-based controllers which widely used is adaptive neural network (Wei *et al*., 2005). The adaptive neural network controlmethodallows the control of a MIMO highly coupled nonlinear system. This method is suitable for systems which are in the form of equation (7), by considering that $\dot{D}(q) - 2C(q,\dot{q})$ must be a skew-symmetric matrix. In this method, D, C matrices and G whichare introducedin equation (8), equation (9) and equation (10), will be rewrittenin theformof synaptic weights for neural networkpurposeas equations below (Wei *et al*., 2005):

$$d_{jk}(q) = \sum_l \theta_{kjl}\xi_{kjl}(q) + \varepsilon_{dkj}(q) = \theta_{kj}^T\xi_{kj}(q) + \varepsilon_{dkj}(q) \tag{11}$$

$$c_{kj}(q,\dot{q}) = \sum_l \alpha_{kjl}\zeta_{kjl}(z) + \varepsilon_{ckj}(z) = \alpha_{kj}^T\zeta_{kj}(z) + \varepsilon_{ckj}(z) \tag{12}$$

$$g_k(q) = \sum_l \beta_{kl}\eta_{kl}(q) + \varepsilon_{gk}(q) = \beta_k^T\eta_k(q) + \varepsilon_{gk}(q) \tag{13}$$

where, $z = [q^T \; \dot{q}^T] \epsilon R^{2n}$ and θ_{kjl}, α_{kjl}, $\beta_{kl} \epsilon R$ are the weights of the neural networks, $\xi_{kjl}(q)$, $\zeta_{kjl}(q)$, $\eta_{kl}(q) \epsilon R$ are the corresponding Gaussian basis functions with input vector q, z and $\varepsilon_{dkj}(q)$, $\varepsilon_{ckj}(z)$, $\varepsilon_{gk}(q) \epsilon R$ are the modeling errors of the $d_{kj}(q)$, $c_{kj}(q, \dot{q})$ and $g_k(q)$, respectively and are assumed to be bounded.

Using the Gl matrix and its product operator introduced in (Wei *et al.*, 2005), the above equations are formulated in a specific matrix form in the following (Wei *et al.*, 2005):

$$D(q) = [\{\Theta\}^T \bullet \{\Xi(q)\}] + E_D(q) \tag{14}$$

$$C(q, \dot{q}) = \lfloor \{A\}^T \bullet \{Z(z)\} \rfloor + E_c(z) \tag{15}$$

$$G(q) = \lfloor \{B\}^T \bullet \{H(q)\} \rfloor + E_G(q) \tag{16}$$

where, {A}, {Z(z)}, {B} and {H(q)} are the GLs' matrices and vectors, in which their elements are α_{kj}, $\zeta_{kj}(z)$, β_k and $\eta_k(q)$, respectively.

$E_D(q)$, $E_c(z) \epsilon R^{n \times n}$ is the matrix and $E_G(q) \epsilon R^n$ is the vector with elements $\varepsilon_{dkj}(q)$, $\varepsilon_{ckj}(z)$ and $\varepsilon_{gk}(q)$, respectively which denote the modeling errors (Wei *et al.*, 2005). The control law for this type of controller is (Wei *et al.*, 2005):

$$\tau = \left[\hat{\Theta}^T \bullet \{\Xi(q)\}\right]\ddot{q}_r + \left[\left\{\hat{A}\right\}^T \bullet \{Z\{z\}\}\right]\dot{q}_r + \left[\left\{\hat{B}\right\}^T \bullet \{H(q)\}\right] + Kr + k_S \operatorname{sgn}(r) \tag{17}$$

where, $K \epsilon R^{n \times n} > 0$ and $k_s > \|E\|$ and:

$$\begin{aligned} \dot{q}_r(t) &= q_d(t) + \Lambda e(t) \\ r(t) &= \dot{q}_r(t) - \dot{q}(t) = \dot{e}(t) + \Lambda e(t) \\ e(t) &= q_d(t) - q(t) \end{aligned} \tag{18}$$

Λ is a positive definite matrix. With $E = E_D(q)\ddot{q}_r + E_C(Z)\dot{q}_r + E_G(q)$.

The first three terms of the above control law are the model-based control terms, whereas the term Kr, confers the Proportional Derivative (PD) type of control. The last term in the control law had been added with the intention of suppressing the modeling errors caused by the neural networks (Wei *et al.*, 2005).

Synaptic weights are updated via the following equations:

$$\dot{\hat{\theta}}_k = \Gamma_k \bullet \{\xi_k(q)\}\ddot{q}_r r_k \tag{19}$$

$$\dot{\hat{\alpha}}_k = Q_k \bullet \{\zeta_k(z)\}\dot{q}_r r_k \tag{20}$$

$$\dot{\hat{\beta}} = N_k \eta_k(q) r_k \tag{21}$$

where, $\Gamma_k = \Gamma^t{}_k > 0$, $Q_k = Q^T{}_k > 0$ and $N_k = N^T{}_k > 0$ and $\hat{\theta}_k$ and α_k are the column vectors containing $\hat{\theta}_{kj}$ and $\hat{\alpha}_{kj}$ as their elements, respectively.

The control law equation (17) with the adaption algorithm let the robot to track the desires. The control law is shown graphically by Fig. 3.

SIMULATION

According to the control algorithm which introduced in Fig. 1 and the control law equations (5), (6) and (11) also considering the computer interconnection, the tracking circular path of the Scara welding robot had been simulated. The parameters of the robot are presented in Table 1 and the parameters of the GMAW process were shown in (Bazargan-Lari *et al.*, 2008a, b; Eghtesad *et al.*, 2008).

The result of the stimulations are represented in the following sections:

- Controlling the are length in GMAN process
- Tracking a circular path with robot manipulator

Table 1: Parameters of the robot

Parameters of the GMAW process	Values
a_1 (m)	0.5
a_2 (m)	0.4
$m_1 = m_2$ (kg)	1
$\ddot{\theta}_{1d} = \ddot{\theta}_{2d} = \ddot{d}_{3d}$	0
$x^2+(y-0.7)^2 = 0.1^2$. Circular Welding path	
Welding path width (m)	0.01
Welding path thickness (m)	0.05

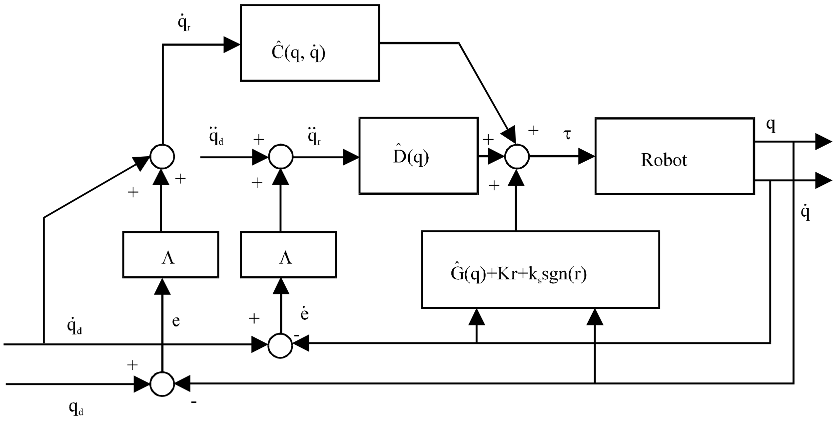

Fig. 3: Adaptive neural network algorithm

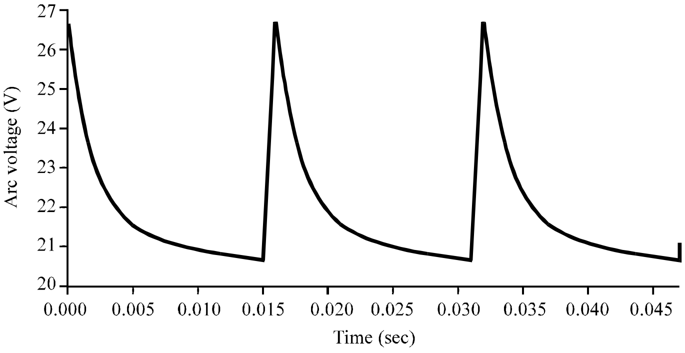

Fig. 4: Arc voltage

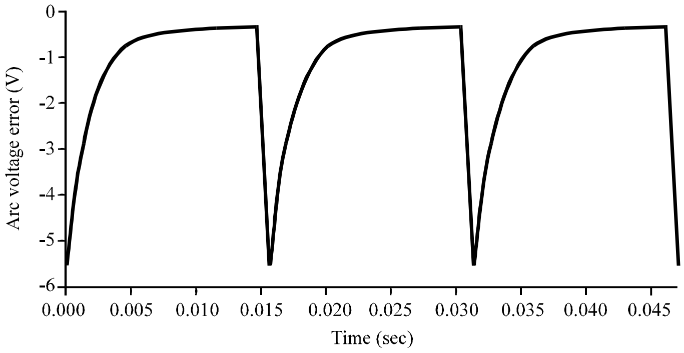

Fig. 5: Arc voltage error

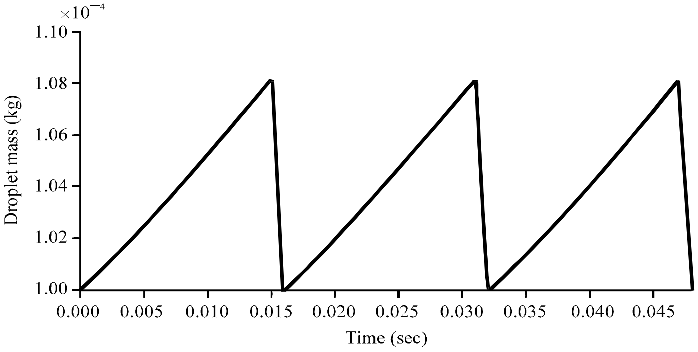

Fig. 6: Droplet mass

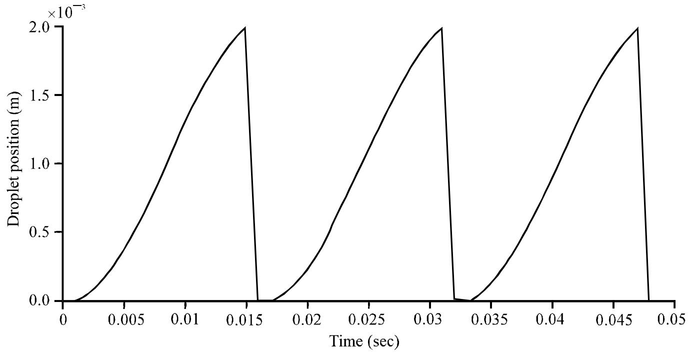

Fig. 7: Droplet position

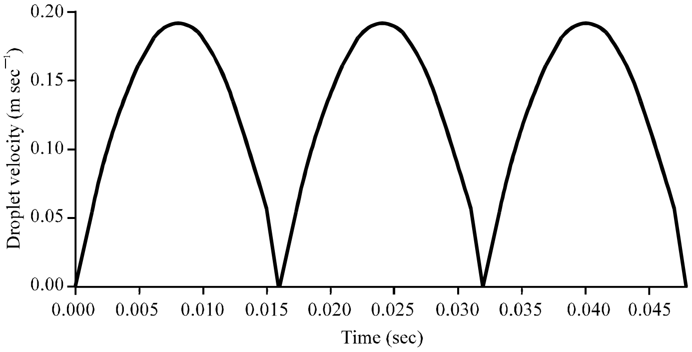

Fig. 8: Droplet velocity

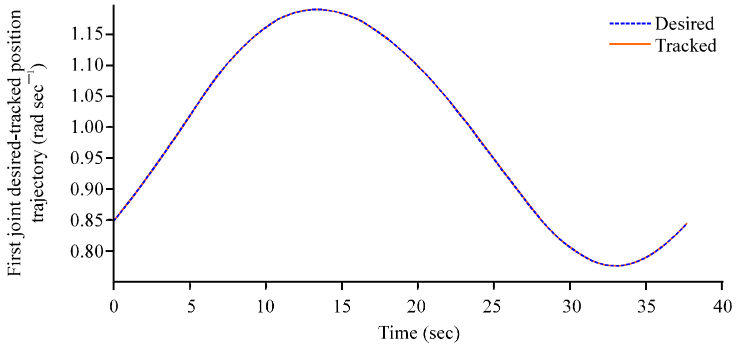

Fig. 9: First joint desired tracked position

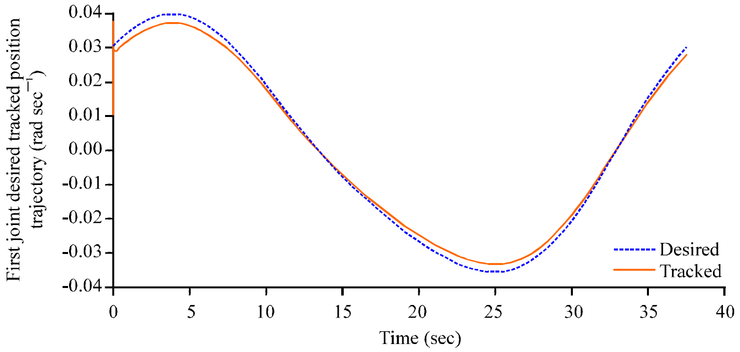

Fig. 10: First joint desired tracked velocity

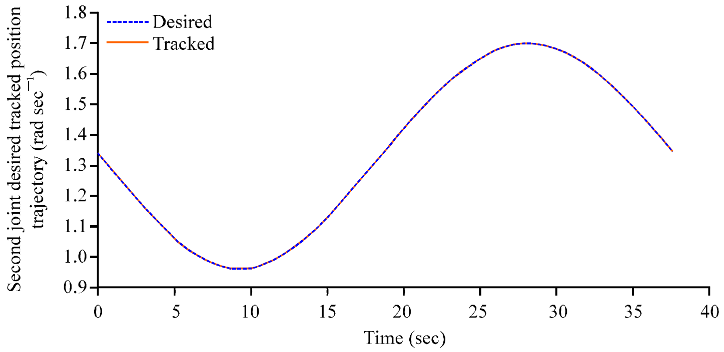

Fig. 11: Second joint desire tracked position trajectory

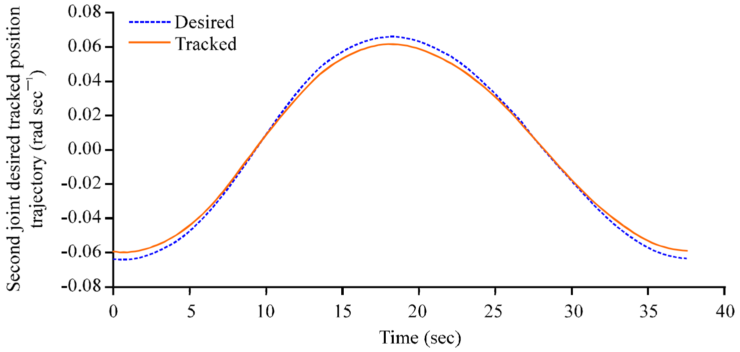

Fig. 12: Second joint desired tracked velocity trajectory

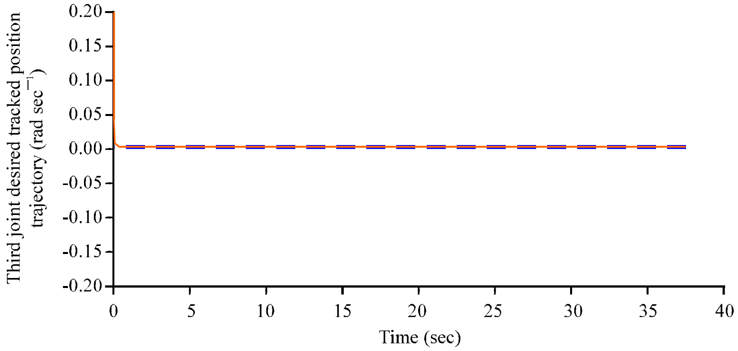

Fig. 13: Third joint desire tracked position trajectory

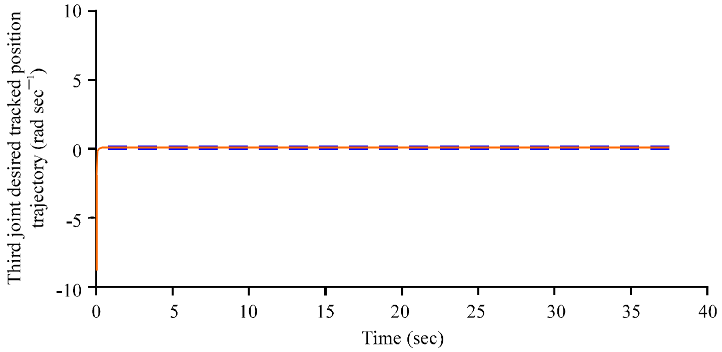

Fig. 14: Third joint desired-tracked velocity trajectory

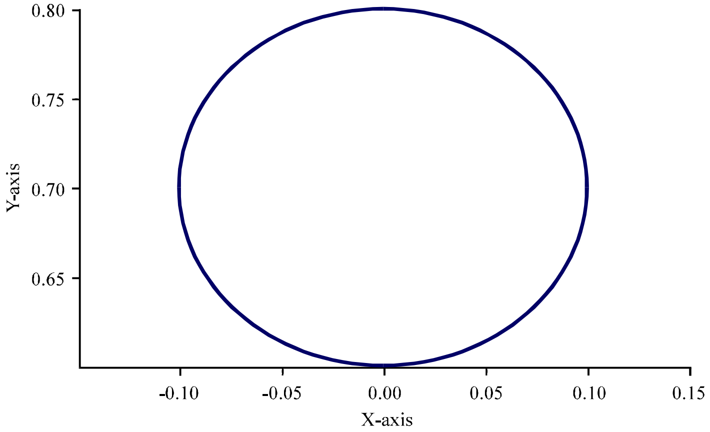

Fig. 15: Tracked circular path

CONCLUSION

In this brief, controlling the Scara gas metal arc welding is studied. To do the research, an arc length control is performed via MIMO feedback linearization method and adaptive neural network is used to control the Scara robot for tracking a circular path. The importance of cooperating GMAW system and Scara robot make the knowledge of the desired posture of the robotic system inevitable. A computer interconnection block is applied to control the whole system.

Simulations are presented to show the performance of the designed cascade structure and the controllers. The results illustrate that the robot follows the circular path and the arc length of the GMAW are controlled.

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