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Simultaneous Control of GMAW Process and SCARA Robot in Tracking a Circular Path via a Cascade Approach

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ABSTRACT

In this study, controlling the arc length via SCARA robot for welding a circular path will be studied. This task is divided into two distinct problems; controlling the arc length for a Gas Metal Arc Welding (GMAW) process and controlling the SCARA robot to track the specified welding path. Since these two subsystems are cooperating with each other, the knowledge of the desired configuration of the robot manipulator is necessary. Considering the droplet detached mass, welding path geometry, weld density and the inverse kinematics of the robot, the desired joint velocities could be calculated. In the present work, four algorithms are suggested for interconnection of these two subsystems and the control methodology for one of them is followed. In the present study, controlling the arc length is done using the MIMO Input-Output Feedback Linearization and for controlling, the SCARA robot computed torque method is utilized and the simulation results are presented.

Key words: Feedback linearization, GMAW, cascade systems, welding robot, computed torque, MIMO systems

INTRODUCTION

There exists a wide variety of welding processes (Iranmanesh and Armin Rahmati, 2008; Manurung *et al.*, 2010; Hussein *et al.*, 2011). Each one represents some advantages and is usually best suited for a particular type of operation. The GMAW process is the widest spread because of its low initial cost and high productivity (Balasubramanian and Lakshminarayanan, 2008; Quinn *et al.*, 2005).

The process can be performed either automatically or manually. Nowadays, the industrial processes such as welding are implemented using automatic devices and robotic systems. Robot welding is a relatively new application of robotics. The use of robots in welding was not initiated until the 1980s, when the automotive industry began using robots extensively for spot welding. Since then, both the number of robots used in industry and the number of their applications have grown enormously. This growth is primarily limited by high equipment costs which has resulted in a restriction of high-production applications (Cary and Helzer, 2005).

Robot arc welding has been growing rapidly just recently, already covering about 20% of industrial robot applications. Because of the complex nature of the process which needs many parameters to be adjusted to give a superb quality weld; even an experienced welder may be slightly perplexed while producing a weld with an accurate level of desired results (Ghazvinloo and Raouf, 2010). In addition, toxic fumes and gasses produced during the welding process can be hazardous to the welder. Welding robots can play an important role in overcoming these problems and difficulties. Considering these facts and the growing demand faster, safer and more accurate production procedures, the control and automation of the GMAW process seems to be inevitable. In fact, controlling strategies consist of two distinct problems:

- Controlling the arc length for a GMAW process which can be divided into the following categories:
  - Controlling mass and heat transfer (Linden *et al.*, 1980; Smartt and Einerson, 1993)
  - Controlling weld temperature and/or cooling rate (Nishar *et al.*, 1994; Einerson *et al.*, 1992)
  - Controlling weld pool and its geometry (Aendenroomer, 1996; Henderson *et al.*, 1993; Hale and Hardt, 1992)
  - Controlling droplet transfer frequency (Phillips and Nagle, 1995; Johnson *et al.*, 1991)
  - Controlling weld penetration (Barnett *et al.*, 1995; Chen and Chin, 1990)
  - Controlling joint profile (fill rate) and trajectory (Fujimura *et al.*, 1987; Tomizuka, 1988)
  - Controlling arc length controlling (Thomsen, 2005; Jalili-Kharaajoo *et al.*, 2003; Chi *et al.*, 2006)
- Controlling the robot to track a desired path (Lima *et al.*, 2005; Steele *et al.*, 2005; Xu *et al.*, 2008; Kim *et al.*, 1996, 1998)

The first problem has been controlled for a single drop detachment without any automotive system. Since the welding process via a robotic system has a continuous trend, arc length and robot control should be performed simultaneously as far as all drop detachments are concerned.

To solve this problem, a cascade structure has been proposed which involves two subsystems for modeling either of the above problems. A computer interconnection is the best choice for linking these two parts.

This study constitutes from a brief introduction of GMAW process, followed by proposing the governing dynamical equations and explaining the significant role of welding robots in various industrial applications and the necessity to direct proper attention to an efficient control law for such systems. Afterwards, four distinct control algorithms are suggested for controlling welding robots to track particular trajectories and one of them is verified by numerical simulations.

GMAW process: Gas metal arc welding (GMAW) can be defined as an arc welding process that coalesces metals by heating them with an arc between a continuously fed metal filler electrode and the work piece (Abdelrahman, 1998). The process uses shielding from an externally supplied gas to protect the molten weld pool. The application of GMAW generally requires DC + (reverse) polarity to the electrode.

Because of its versatility and advantages, GMAW is an optimal choice for almost all industrial applications:

- The GMAW process is easily adapted for high-speed robots, hard automation and semiautomatic welding applications
- It requires lower heat input when compared to other welding processes
- Generally, it needs lower cost per length of weld metal deposited when compared to other open arc welding processes

- It is capable of joining a wide range of materials with varying thicknesses
- It can be used in every welding position
- It has excellent weld bead appearance
- It produces less welding fumes when compared to SMAW (Shielded Metal Arc Welding) and FCAW (Flux-Cored Arc Welding) processes

MATHEMATICAL MODEL FOR GMAW PROCESS

What follow are a detailed discussion about deriving the state-space equations of the GMAW process before drop detachment (Abdelrahman, 1998) and the results. The GMAW process can be approximated by the following model:

$$\begin{cases} x_1 = x \\ x_2 = \dot{x} \\ x_3 = m_d \\ x_4 = l_s \\ x_5 = I \end{cases} \Rightarrow \begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \ddot{x} = \dfrac{F_{tot} - Bx_2 - Kx_1}{x_3} \\ \dot{x}_3 = \dot{m}_d = \rho_w M_r + M_{ve} \\ \dot{x}_4 = \dot{l}_s = u_1 - \dfrac{M_r}{\pi r_w^2} \\ \dot{x}_5 = \dot{I} = \dfrac{u_2 - R_L x_5 - V_{arc} - R_s x_5}{L_s} \end{cases} \tag{1}$$

Where the state variables are:

$x_1 = x$: Droplet displacement-m

$x_2 = \dot{x}$: Droplet velocity-m sec^{-1}

$x_3 = m_d$: Droplet mass-kg

$x_4 = l_s$: Stick out-m

x_5: Current-A

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

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

Electrode resistance is given as:

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

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: In researches carried out by Bazargan-Lari *et al.* (2008a, b) and Eghtesad *et al.* (2008), an arc length of GMAW process was controlled in a period of detachment by Multi Input-Multi Output (MIMO) feedback linearization method. Clearly, the act of welding should be performed by a robot manipulator. The purpose of controlling the robot is to track a desired path for welding. The main point is how to interconnect these two subsystems (GMAW and robot) in order to construct a cascade structure. It should be mentioned that the GMAW process is a cyclic one and it is repeated during tracking the desired path obviously, controlling the arc length of GMAW and tracking the desired path should be done simultaneously to achieve a suitable cascade structure. Some control strategies are shown in Fig. 1.

The differences of the strategies appear in:

- open or close loop control
- arrangement of the subsystems

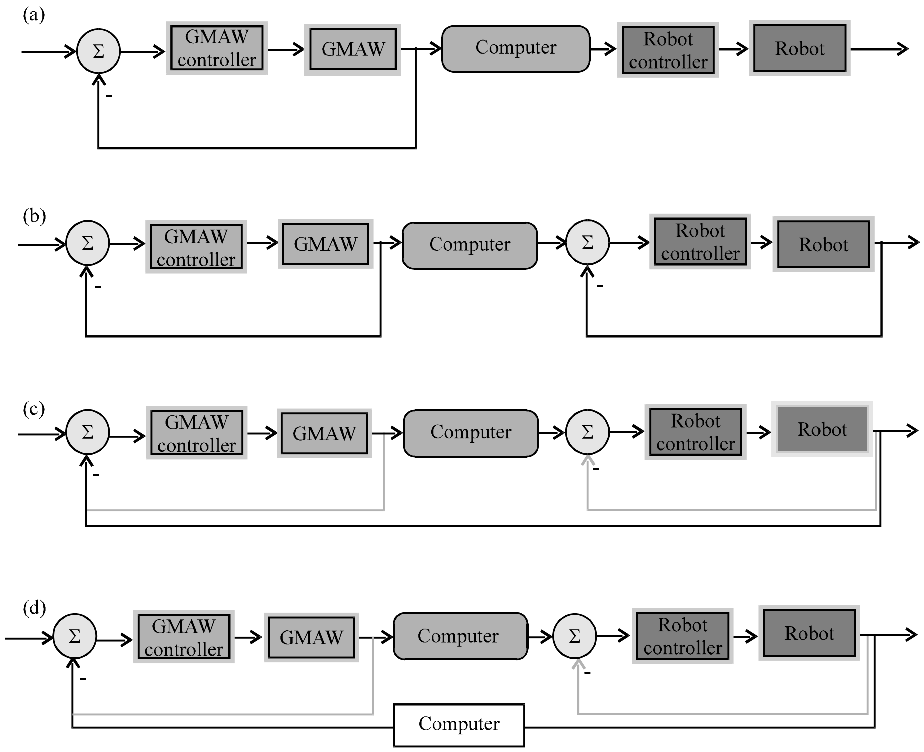

Fig. 1(a-d): Closed loop control for GMAW versus (a) Open loop control for SCARA and (b) Closed loop control for SCARA and closed loop for the whole control system consisting of (c) Fig. 1b component and (d) Fig. 1b components using an extra computer unit

Although the first strategy (Fig. 1a) is simpler than the others, the results are satisfactory. As a result, the strategy was selected for controlling the system in the present study. The computer block which is explained in the next section, plays the role of an interconnection for this cascade structure.

Computer interconnection: Clearly, desired joint velocities are an indispensable factor in tracking the desired path by the robot manipulator. A Computer is responsible for this task. One of the common paths used in the welding process is a circular one. Among the usual robots in charge of the welding process, a SCARA robot is an appropriate choice for welding planar trajectories. So SCARA robots are selected for this purpose. Figure 2 illustrates the process that takes place in the computer.

Welding robot control: By choosing the first suggested strategy in Fig. 1a and calculating the necessary inputs for the robotic system, it is time to design the different controllers for the both subsystems (Hourfar and Salahshoor, 2009; Asseu *et al.*, 2008). According to Bazargan-Lari *et al.* (2008b), the control inputs for the GMAW processes are as follows:

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

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

To control the SCARA robot, the dynamic equations of this robot should be calculated. These equations have been derived by Lagrangian method (Schilling, 1990). These equations are as follows:

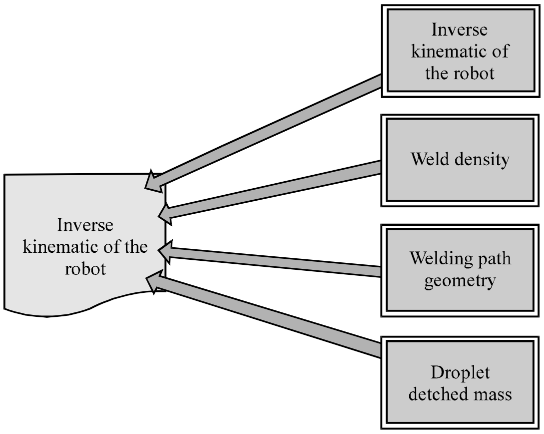

Fig. 2: Computer interconnection structure

$$M(q)\ddot{q}+C(q,q)+g(q)=\tau \tag{7}$$

where, the matrices M, C and g are:

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

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

$$g(q)=\begin{bmatrix} 0 \\ 0 \\ m_3g_0 \end{bmatrix} \tag{10}$$

The Denavit-Hartenberg parameters of the SCARA robot are illustrated in Table 1.

There are many different methods for controlling the robot manipulators (Soltanpour *et al.*, 2008). One of the widely used model-based controllers is Computed Torque (Canudas de Wit *et al.*, 1996). The control law for this controller is:

$$\tau=M(q)\lfloor\ddot{q}_d+k_v(\dot{q}_d-\dot{q})+K_p(q_d-q)\rfloor+C(q,\dot{q})\dot{q}+g(q) \tag{11}$$

Respectively leading to the error equation:

$$\ddot{\tilde{q}}+K_v\dot{\tilde{q}}+K_P\tilde{q}=0 \tag{12}$$

Which is exponentially stable by a suitable choice of the matrices K_P, K_V the control law is shown graphically by Fig. 3:

- Controlling the arc length of the GMAW process (Fig. 4-8)
- Tracking a circular path by the robot manipulator (Fig. 9-13)

Table 1: The Denavit-Hartenberg parameters

Link	θ_i	α_i	a_i	d_i
1	θ_1	0	a_1	d_1
2	θ_2	0	a_2	0
3	0	0	0	d_3

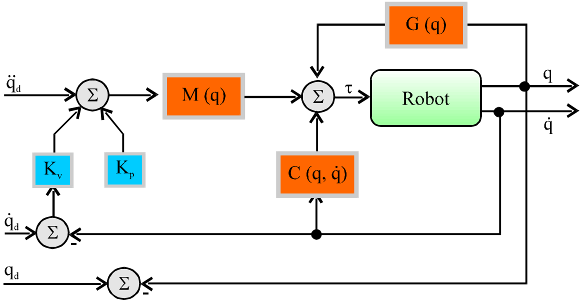

Fig. 3: Computed torque algorithm $q = [\theta_1\ \theta_2 y]^t$

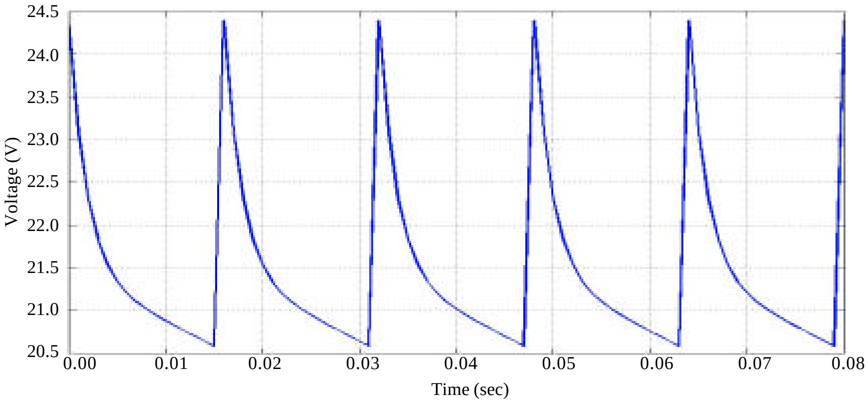

Fig. 4: Arc voltage versus time

RESULTS AND DISCUSSION

As mentioned in this article, to control the welding robot in a circular path, the control units below are required:

- Controlling the arc length in order to achieve good quality welds
- Controlling the robot to traverse the circular path

These two units are working simultaneously with the respect of the proposed algorithm and the robots velocity (speed) desires will be obtained at an intermediate computer by the use of the information given from the droplet detached mass, welding path geometry, weld density and the inverse kinematic of the robot. Hence, the results for each part are presented separately.

Results of controlling the arc length in order to achieve good quality welds. In this section, the arc length controlled indirectly, by controlling the arcs voltage. While the welding droplet is not formed yet, the welding voltage has its maximum that is 21.7 volts and when it is ready to detach, the arc voltage is 20 volts. By considering this issue, to have the proper arc length, the arc voltage should be tracked in a linear graph between 20 and 21.7 volts. Furthermore, the electric power supply must be 160 amps to remain globular welding mode. Figure 4 shows that after a period of 0.06 seconds, the arc voltage is controlled on its desired value and after the certain amount of 0.015 seconds (in which the droplet mass dropped and replaced with a new one) this process happens again.

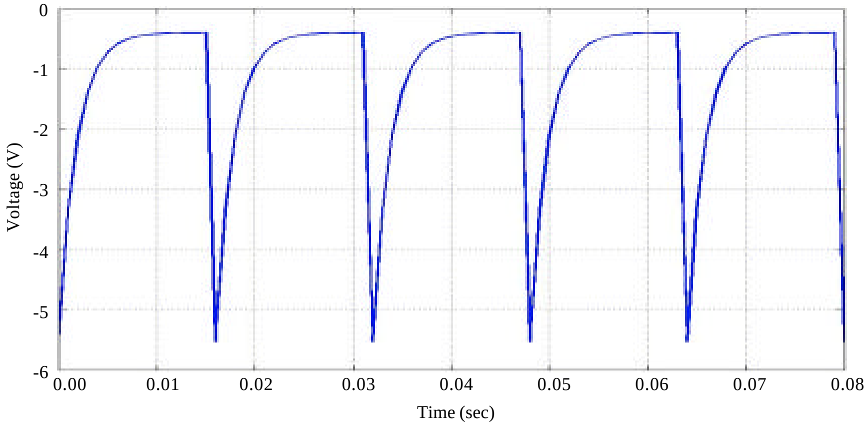

Fig. 5: Arc voltage error versus time

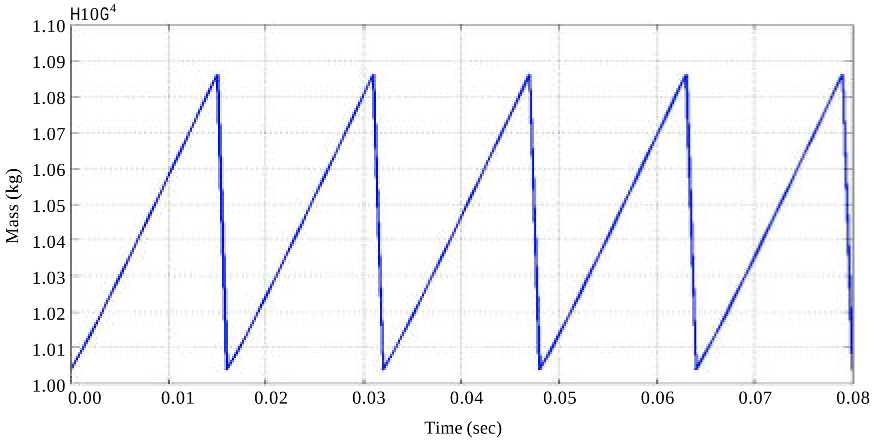

Fig. 6: Droplet mass versus time

Figure 5 shows the error of the arc voltage that as mentioned, after 0.078 sec, goes to 0 and is repeated for subsequent drops. Figure 6 shows the welding droplet mass that is zero at first, but when it grows over time; its weight increases and finally after 0.015 sec the droplet detaches and a new one is formed again. Figure 7 demonstrates the droplets position which is in the zero point a first and by a gradual growth changes and finally after 0.015 sec reaches to 2.05×10^{-3} which is the separation point. Figure 8 illustrates the droplets velocity which increases at first and then, around the separation point, is reduced to a value of 0.02.

Results of controlling the robot to traverse the circular path to traverse a circular path in the form of $x^2+(y-7)^2 = 0.1^2$ by the use of inverse kinematics, proper angles to the first and second joints are obtained. The path tracked by the robot is shown in Fig. 13 which shows a circular motion, very close to the expected circle.

Figure 9a is the diagram of the first joints desired angles, while Fig. 9b demonstrates its traveled angle and Fig. 9c shows its control. As is evident on Fig. 9d which is the controllers' error, both desired and tracked paths are almost on a same line that proves the controllers exactness. Figure 10 reflects all the above in the second joint.

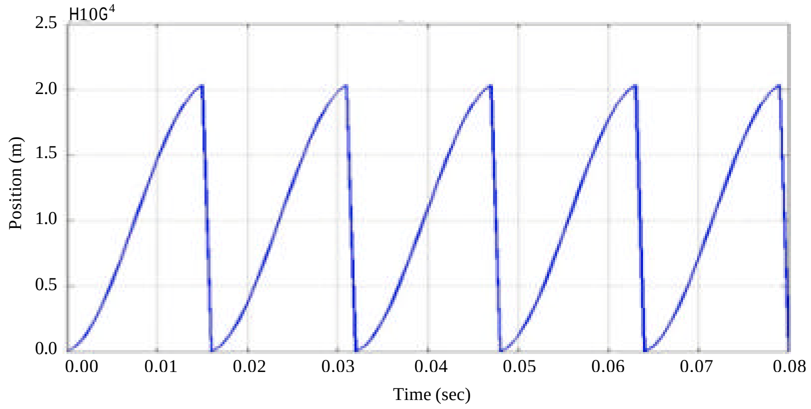

Fig. 7: Droplet position versus time

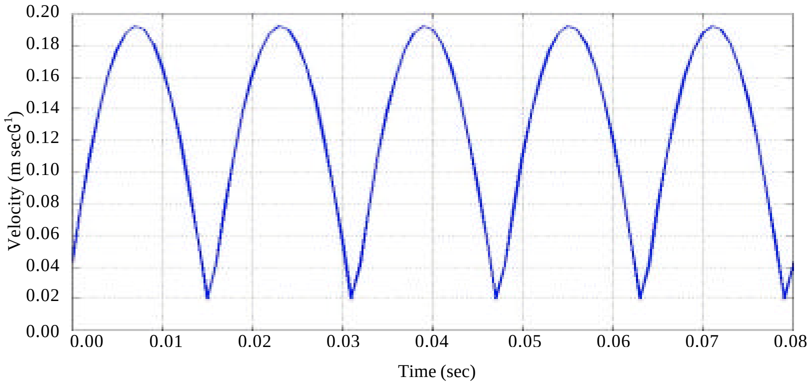

Fig. 8: Droplet velocity versus time

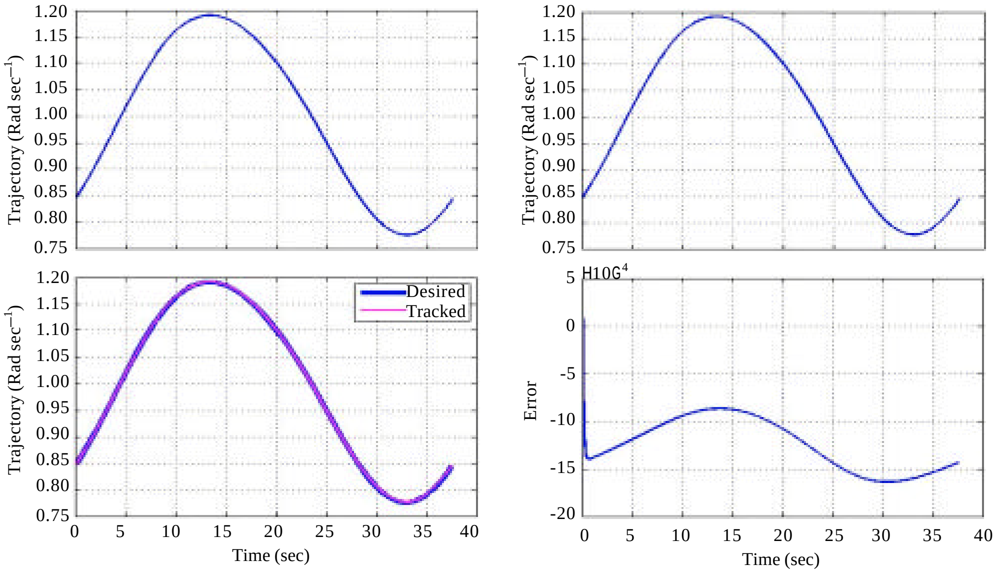

Fig. 9(a-d): (a) First joint desired position trajectory, (b) First joint tracked position trajectory, (c) First joint desired-tracked position trajectory and (d) First joint position error

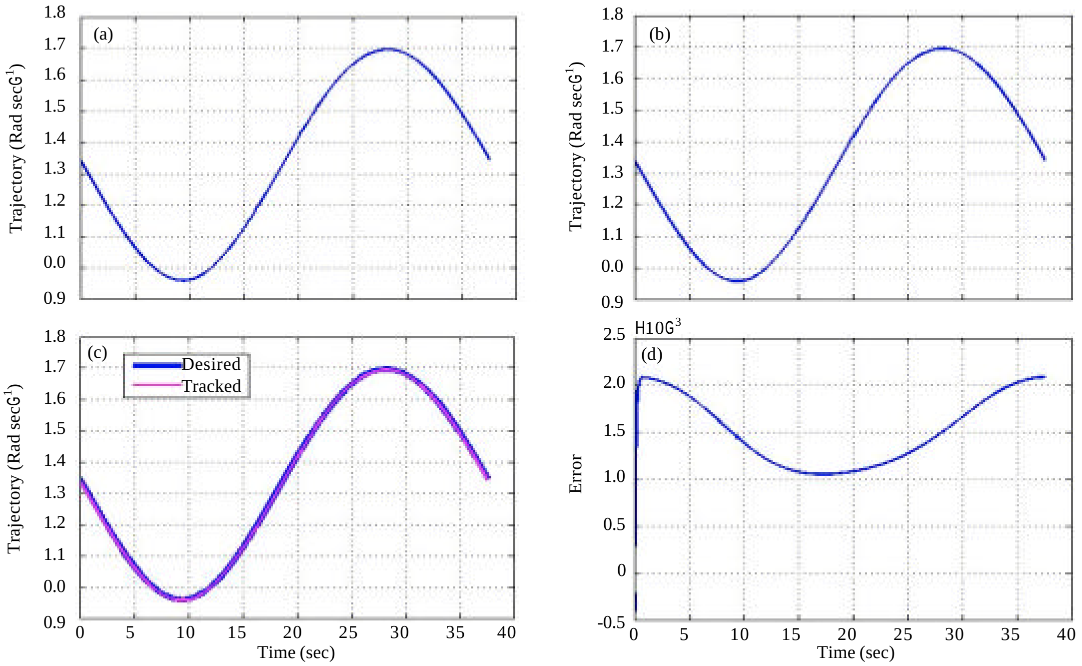

Fig. 10(a-d): Third joint position of (a) Desired trajectory, (b) Tracked trajectory and (c) Desired-tracked trajectory and (d) Third joint position error

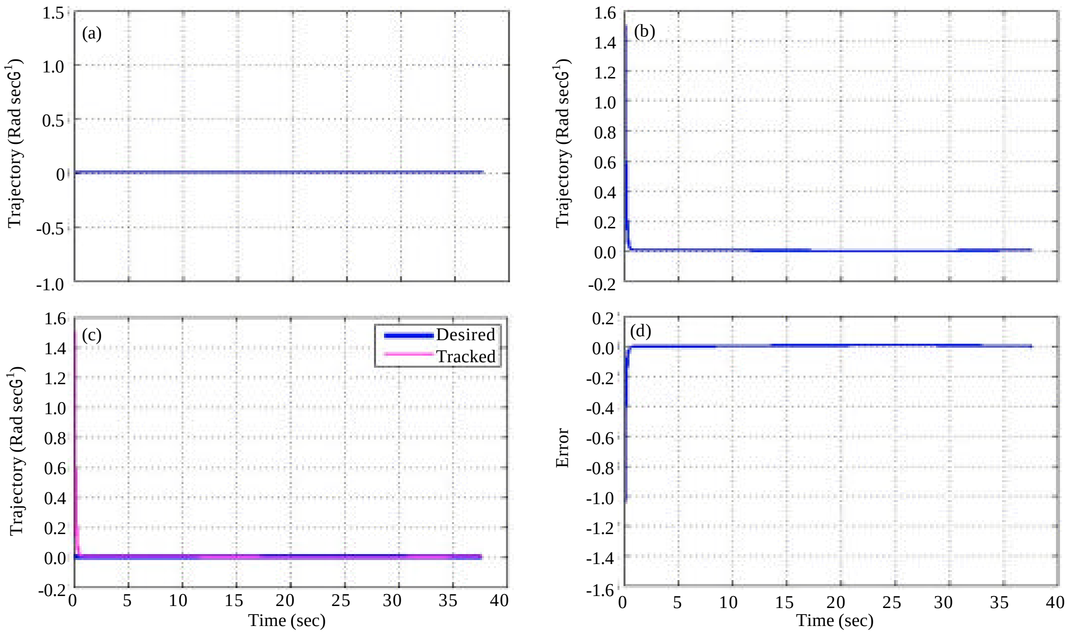

Fig. 11(a-d): Second joint position of (a) Desired trajectory, (b)Tracked trajectory and (c) Desired-tracked trajectory and (d) Second joint position error

Since the arcs length is controlled by the welding controller, some configurations are considered for the robots third joint which is a prismatic joint. These configurations are visible in Fig. 11.

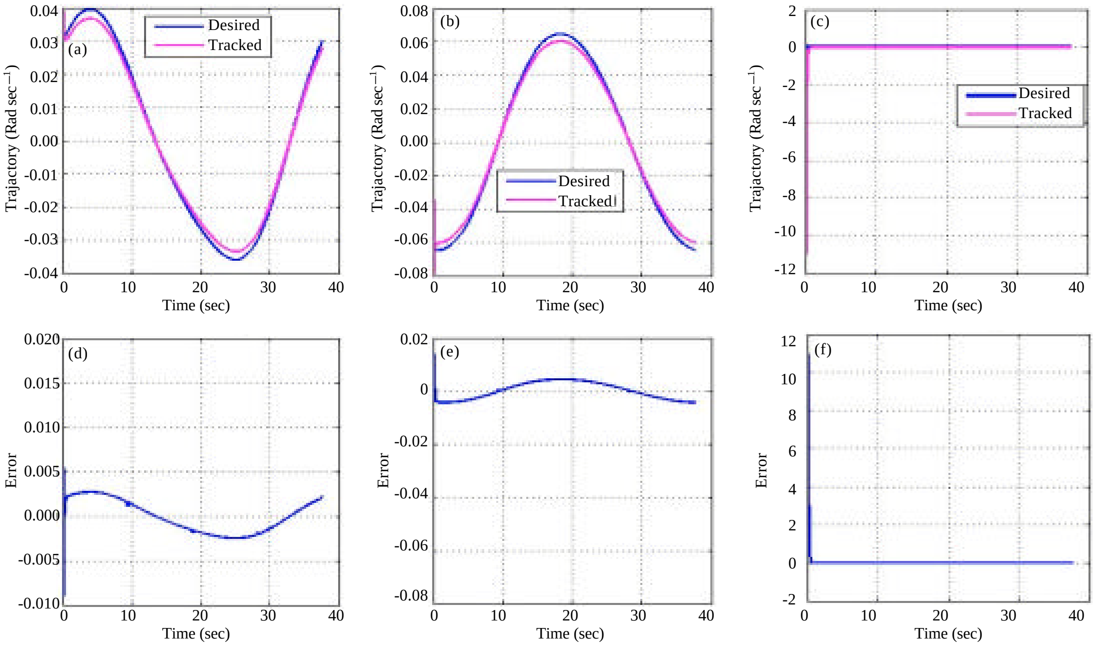

Fig. 12(a-f): Desired-Tracked velocity trajectory of (a) First, (b) Second and (c) Third joint and velocity error of (d) First (e) Second and (f) Third joint

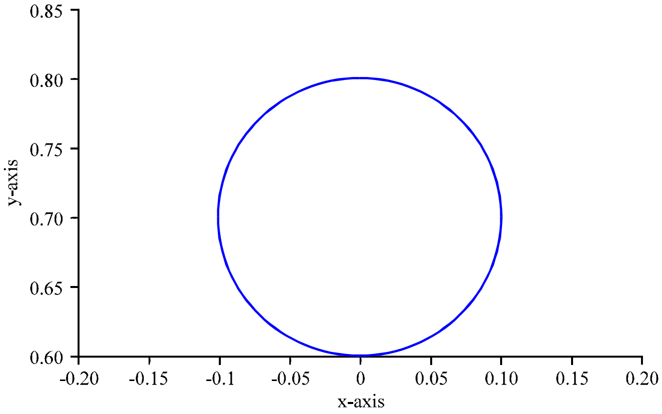

Fig. 13: Tracked circular path

Figure 12 presents the desired angular velocities of the robot's joints, their tracked angular velocities and errors between this tow.

CONCLUSION

This study was concerned with controlling the arc length via a SCARA robot for welding a circular path using a cascade structure. The first step was controlled by feedback linearization method and the second one was a process through computed Torque algorithm. The salient point is that the controlling procedure cannot be accomplished without an appropriate interconnection for these two units. The co-operation of these two subsystems is so momentous that it requires sufficient knowledge of the desired posture of the robotic system. Considering the droplet detached mass, welding path geometry, weld density and the inverse kinematics of the robot, the desired joint velocities have been calculated. As it was mentioned above, four algorithms were suggested, while the control methodology for one of them was utilized. Simulations were 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 was controlled.

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