CONTROL OF TWO-WHEELED WELDING MOBILE ROBOT USING ADAPTIVE CONTROLLER

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Abstract

This paper introduces a nonlinear adaptive controller for tracking the welding path of a two-wheeled Welding Mobile Robot (WMR) with unknown system parameters. A touch sensor that measures the errors between the WMR and the welding path is introduced. The controller is designed to drive the tracking errors to zero as fast as desired. The WMR can track any smooth curved welding path at a constant welding velocity. The effectiveness of the proposed controller is proved through simulation and experimental results.

Keywords: Smooth curved, Two-wheeled Welding Mobile Robot (WMR)

Introduction

Welding automation has lot of benefit in terms of weld-quality, increased weld consistency increased productivity, reduced weld-cost, and improved working conditions. In the field of shipbuilding industry, some robotic welding systems have been developed. Santos et al. [1] developed the ROWER system, a complex, four-legged, mobile platform welding machine, for application in naval construction process. Kim et al. [2] proposed a system of visual sensing and welding environment recognition, for intelligent ship welding robots.

The applications of the two-wheeled mobile robot for welding automation have been studied by Jeon et al. [3] and Kam et al.[4] . Jeon et al. [3] proposed a seam tracking and motion control of the WMR for lattice type welding in which were three controllers for motion controls: straight locomotion, turning locomotion and torch slider. Kam et al. [4] proposed a control algorithm for straight welding based on "trial and error" for each step time. Both controllers proposed by Jeon and Kam are used only for tracking straight path, cannot extend for tracking smooth curved path. As in most previous researches, the uncertainty of system parameters which always exists in the mobile robot control problem was not considered. It was assumed that, the system parameters of the mobile robot models were known exactly, but this cannot be achieved in fact.

In this paper, the problem of trajectory tracking for kinematic model of a WMR with unknown parameters is considered. A nonlinear controller based on the Lyapunov function to enhance the tracking properties of the WMR is proposed. Here, it is assumed that the radius of the driving wheel is not known exactly because of wear and air leakage. Moreover, the distance from the symmetric axis of the WMR to the driving wheel is also considered to be unknown parameter. These unknown parameters are estimated using update laws of adaptive control scheme. To design the tracking performance, a simple method for measuring the errors using two potentiometers is proposed. Good results from simulations and experiments have demonstrated the effectiveness of the proposed controller.

Kinematic Model of a WMR

The model of a WMR is presented in Figure 1. There are three controlled motions of this model: independent motions of the two driving wheels, and motion of the torch slider. The relation of the WMR coordinates with the reference welding path is shown in Figure 2.

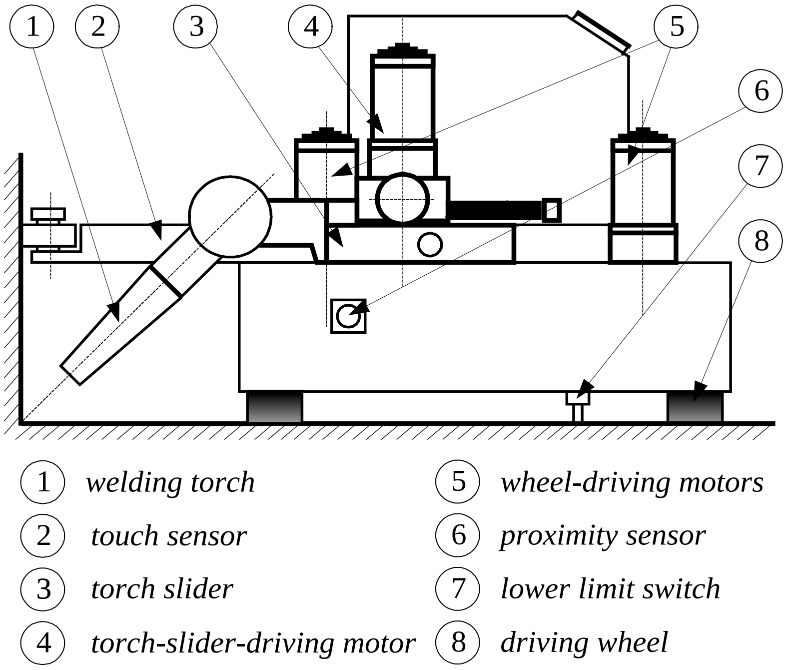


Figure 1. Configuration of the WMR

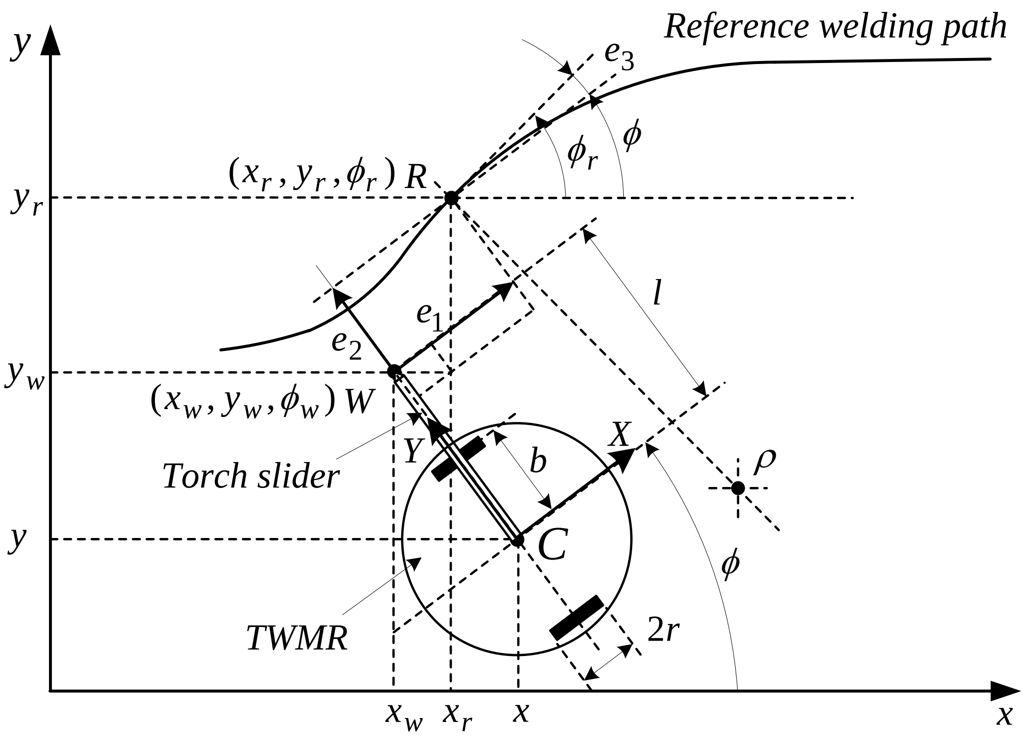


Figure 2. Coordinate of the WMR

The ordinary form of a mobile robot with two actuated wheels can be derived as follows

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} \cos\phi & 0 \\ \sin\phi & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \tag{1}$$

where v and ω are the straight and angular velocities of the WMR center, respectively.
The relationship between v, ω and the angular velocities of the right and left wheels, ω_{rw}, ω_{lw}, is

$$\begin{bmatrix} \omega_{rw} \\ \omega_{lw} \end{bmatrix} = \begin{bmatrix} \frac{1}{r} & \frac{b}{r} \\ \frac{1}{r} & -\frac{b}{r} \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \tag{2}$$

The coordinates and the heading angle of welding point, W, can be calculated by

$$\begin{cases} x_w = x - l\sin\phi \\ y_w = y + l\cos\phi \\ \phi_w = \phi \end{cases} \tag{3}$$

where l is torch length of the torch slider.
A reference point, R, moving with the constant velocity, v_r, on the reference path has the coordinates (x_r, y_r), and the heading angle, ϕ_r, satisfies the following equation

$$\begin{cases} \dot{x}_r = v_r \cos\phi_r \\ \dot{y}_r = v_r \sin\phi_r \\ \dot{\phi}_r = \omega_r \end{cases} \tag{4}$$

where ϕ_r is defined as the angle between $\vec{v}_r$ and x axis, and ω_r is the rate of change of $\vec{v}_r$ direction.
The tracking errors can be calculated from Figure 2 as follows

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_r - x_w \\ y_r - y_w \\ \phi_r - \phi_w \end{bmatrix} \tag{5}$$

Controller Design

(i) r, b - Known Parameters

The purpose is designed a controller so that the welding point tracks to the reference point at a constant velocity, v_r. That is, the tracking errors $e_i \to 0$, $(i = 1, 2, 3)$ as $t \to \infty$. The torch slider is adjusted during welding process; that is, the torch length, l, is changeable.

The dynamics of the tracking errors can be expressed as follows

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} v_r \cos e_3 \\ v_r \sin e_3 - \dot{l} \\ \omega_r \end{bmatrix} + \begin{bmatrix} -1 & e_2 + l \\ 0 & -e_1 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \tag{6}$$

The chosen Lyapunov function and its derivative are given as

$$V_0 = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 + \frac{1}{2}e_3^2 \geq 0 \tag{7}$$

$$\dot{V}_0 = e_1(-v + l\omega + v_r \cos e_3) + e_2(v_r \sin e_3 - \dot{l}\,) + e_3(-\omega + \omega_r) \tag{8}$$

To achieve the negativity of $\dot{V}_0$, choosing $(v,\ \omega)$ as

$$\begin{cases} v = l\,(\omega_r + k_3 e_3) + v_r \cos e_3 + k_1 e_1 \\ \omega = \omega_r + k_3 e_3 \\ \dot{l} = v_r \sin e_3 + k_2 e_2 \end{cases} \tag{9}$$

where k_1, k_2, k_3 are positive values.

(ii) r, b ***- Unknown Parameters (Adaptive Control)***

When r, b are unknown, the estimated values of r, b are used in design an adaptive tracking controller[7]. From Equation (9) and Equation (3), obtain

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} v_r \cos e_3 \\ v_r \sin e_3 - \dot{l} \\ \omega_r \end{bmatrix} + \begin{bmatrix} -1 & e_2 + l \\ 0 & -e_1 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{2b} & -\frac{r}{2b} \end{bmatrix} \begin{bmatrix} \omega_{rw} \\ \omega_{lw} \end{bmatrix} \tag{10}$$

Letting,

$$a_1 = \frac{1}{r}, \quad a_2 = \frac{b}{r} \tag{11}$$

Equation (10) becomes

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} v_r \cos e_3 \\ v_r \sin e_3 - \dot{l} \\ \omega_r \end{bmatrix} + \frac{1}{2} \begin{bmatrix} -1 & e_2 + l \\ 0 & -e_1 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} \frac{1}{a_1} & \frac{1}{a_1} \\ \frac{1}{a_2} & -\frac{1}{a_2} \end{bmatrix} \begin{bmatrix} \omega_{rw} \\ \omega_{lw} \end{bmatrix} \tag{12}$$

Because r, b are unknown, so

$$\begin{bmatrix} \omega_{rw} \\ \omega_{lw} \end{bmatrix} = \begin{bmatrix} \hat{a}_1 & \hat{a}_2 \\ \hat{a}_1 & -\hat{a}_2 \end{bmatrix} \begin{bmatrix} v_d \\ \omega_d \end{bmatrix} \tag{13}$$

where, $v_d = v$, $\omega_d = \omega$, $\hat{a}_1, \hat{a}_2$ are estimated values of a_1, a_2, respectively. Equation (12) becomes

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} v_r \cos e_3 \\ v_r \sin e_3 - \dot{l} \\ \omega_r \end{bmatrix} + \begin{bmatrix} -1 & e_2 + l \\ 0 & -e_1 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} \frac{\hat{a}_1}{a_1} & 0 \\ 0 & \frac{\hat{a}_2}{a_2} \end{bmatrix} \begin{bmatrix} v_d \\ \omega_d \end{bmatrix} \tag{14}$$

Define estimation errors

$$\begin{cases} \tilde{a}_1 \equiv a_1 - \hat{a}_1 \\ \tilde{a}_2 \equiv a_2 - \hat{a}_2 \end{cases} \tag{15}$$

Equation (14) becomes

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} v_r \cos e_3 \\ v_r \sin e_3 - \dot{l} \\ \omega_r \end{bmatrix} + \begin{bmatrix} -1 & e_2 + l \\ 0 & -e_1 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 1 - \frac{\tilde{a}_1}{a_1} & 0 \\ 0 & 1 - \frac{\tilde{a}_2}{a_2} \end{bmatrix} \begin{bmatrix} v_d \\ \omega_d \end{bmatrix} \tag{16}$$

The Lyapunov function is chosen as

$$V_1 = \frac{1}{2} e_1^2 + \frac{1}{2} e_2^2 + \frac{1}{2} e_3^2 + \frac{1}{2\gamma_1 a_1} \tilde{a}_1^2 + \frac{1}{2\gamma_2 a_2} \tilde{a}_2^2 \tag{17}$$

and its derivative yields

$$\dot{V}_1 = \dot{V}_0 - \frac{\tilde{a}_1}{\gamma_1 a_1} (\dot{\hat{a}}_1 - \gamma_1 e_1 v_d) - \frac{\tilde{a}_2}{\gamma_2 a_2} [\dot{\hat{a}}_2 - \gamma_2 (e_3 - e_1 l) \omega_d] \tag{18}$$

The controller is still the same (9), but there are two update laws for unknown parameters

$$\begin{cases} v_d = l\,(\omega_r + k_3 e_3) + v_r \cos e_3 + k_1 e_1 \\ \omega_d = \omega_r + k_3 e_3 \\ \dot{l} = v_r \sin e_3 + k_2 e_2 \\ \dot{\hat{a}}_1 = \gamma_1 e_1 v_d \\ \dot{\hat{a}}_2 = \gamma_2 (e_3 - e_1 l\,)\,\omega_d \end{cases} \tag{19}$$

where $\gamma_1, \gamma_2 > 0$ are adaptation gains.

Simulation and Experimental Results

To verify the effectiveness of the proposed controller in the case unknown parameters, simulation and experiment have been done for WMR tracking the smooth curved welding paths.

Table 1. Numerical and Initial Values of WMR

Parameter	Value	Unit
x_r	0.270	m
y_r	0.500	m
x_w	0.265	m
y_w	0.495	m
v	0	mm/s
ω	0	rad/s
ω_r	0	rad/s
ϕ_r	0	deg
ϕ	15	deg
l	0.15	m

The welding velocity is $v_r = 7.5 \times 10^{-3} m/s$ and $k_1 = 14.2$, $k_2 = 7.5$, $k_3 = 3.5$, $\gamma_1 = 1.2$, $\gamma_2 = 500$.

The touch sensor using potentiometers is shown in Figure 6. Figure 7 - 14 show the performances of the WMR for tracking the smooth curved path. At beginning, the convergence of tracking errors is very fast as shown in Figure 7 – 9.

The tracking errors go to nearly zero after 1.5 seconds. From straight to curved path, there is a sudden change of ω_r (from zero to a constant), the errors appear as shown in Figure 10.

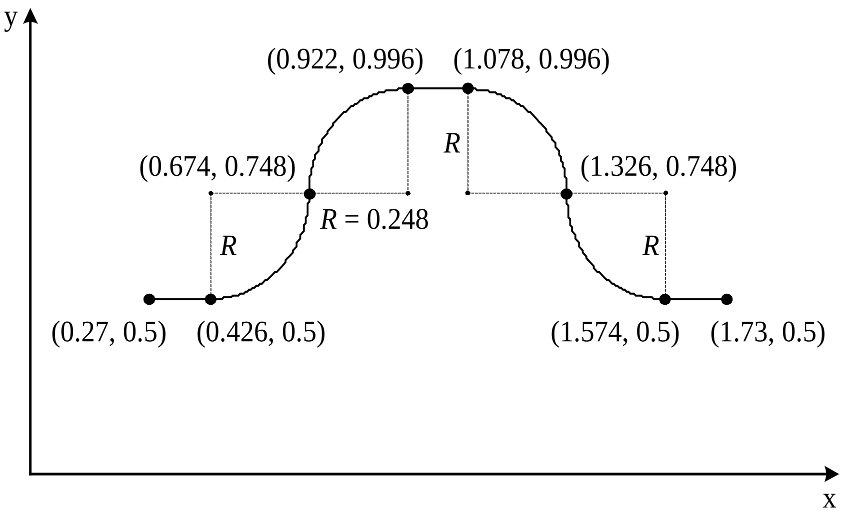


Figure 3. Smooth curved welding path

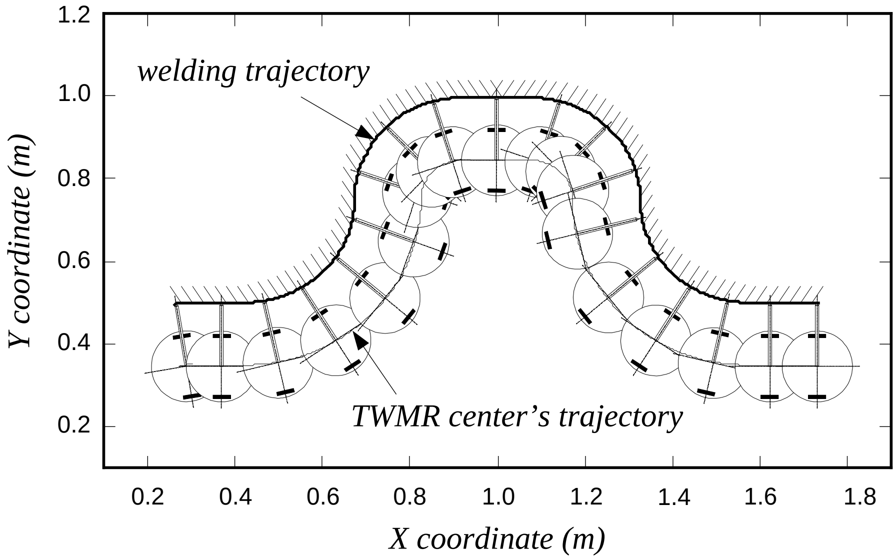


Figure 4. Movement of the WMR

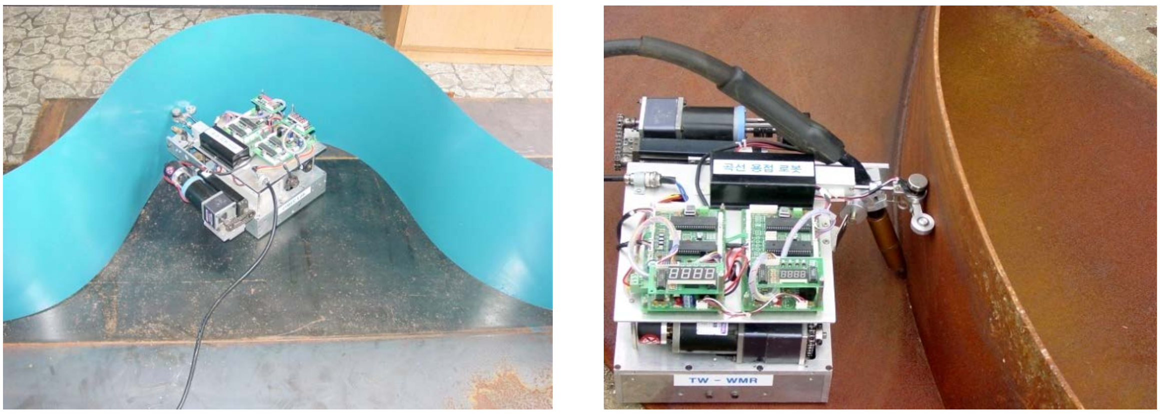


Figure 5. Experimental WMR model

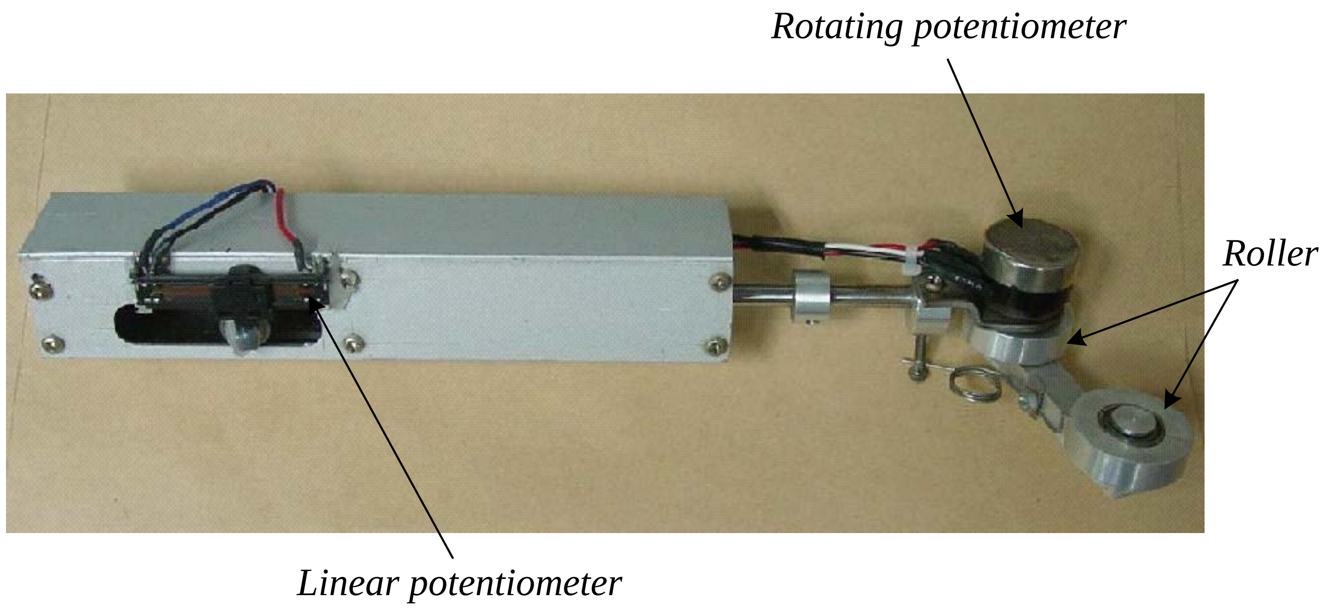


Figure 6. Touch sensor

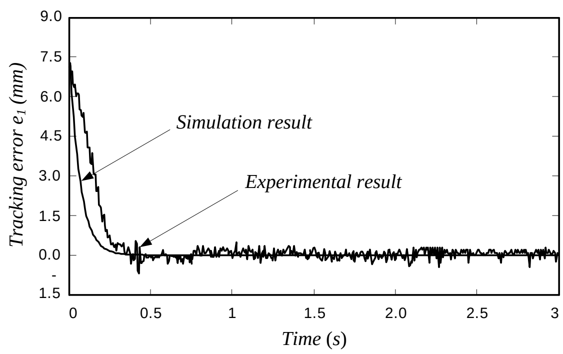


Figure 7. Tracking error e_1 at beginning

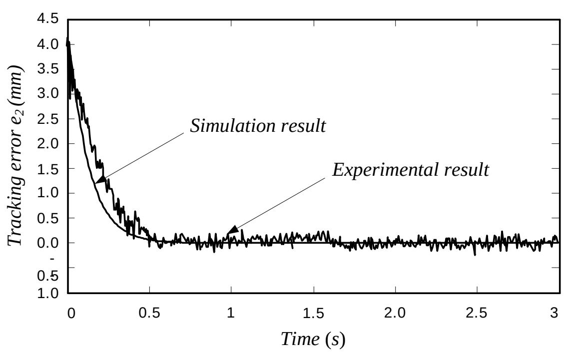


Figure 8. Tracking error e_2 at beginning

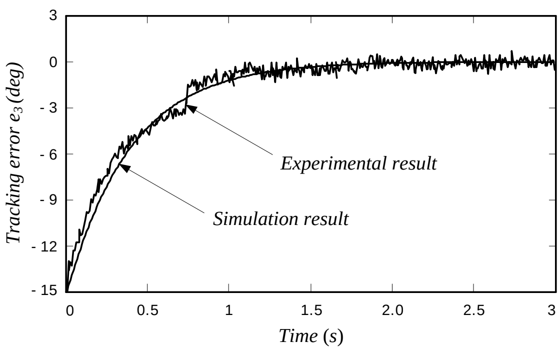


Figure 9. Tracking error e_3 at beginning

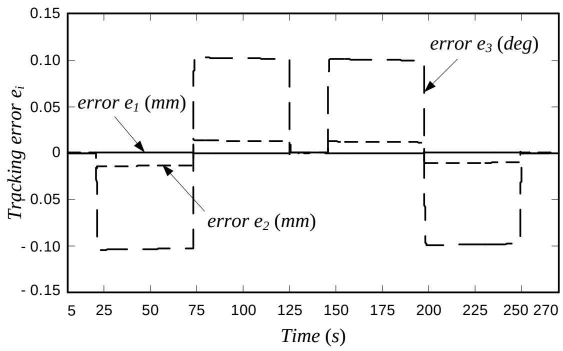
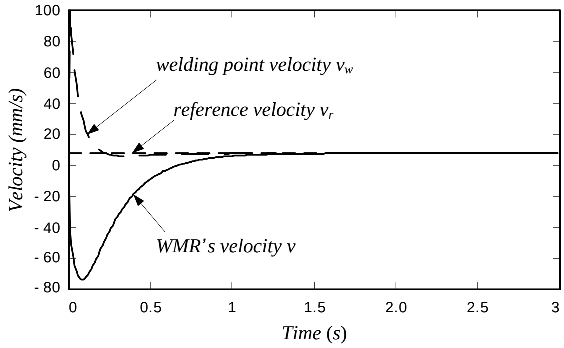


Figure 10. Tracking errors



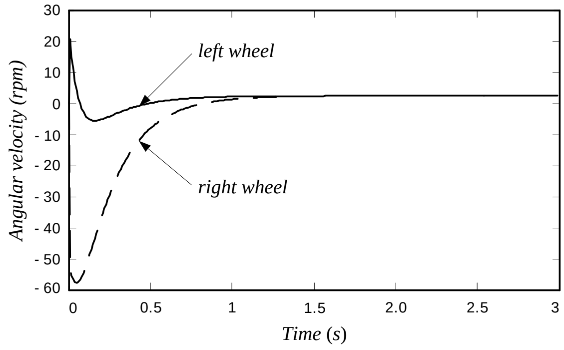


Figure 11. Velocities of the welding point and the WMR at beginning

Figure 12. Angular velocities of two driving wheels at beginning

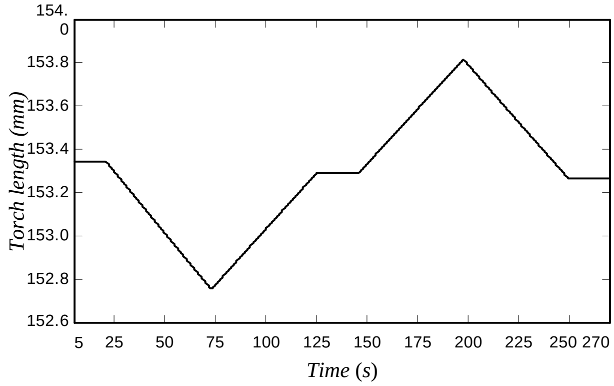


Figure 13. Torch length

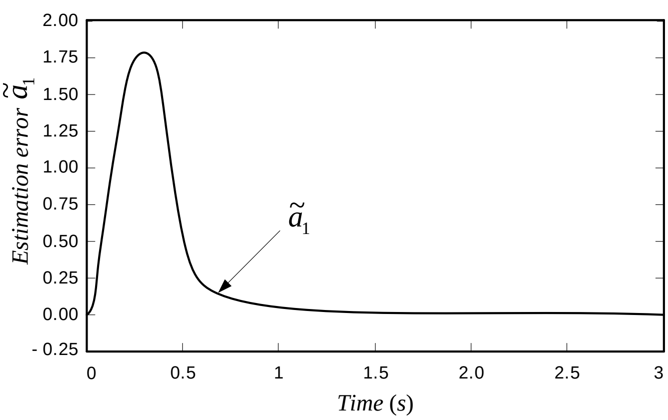


Figure 14. Estimation error $\tilde{a}_1$

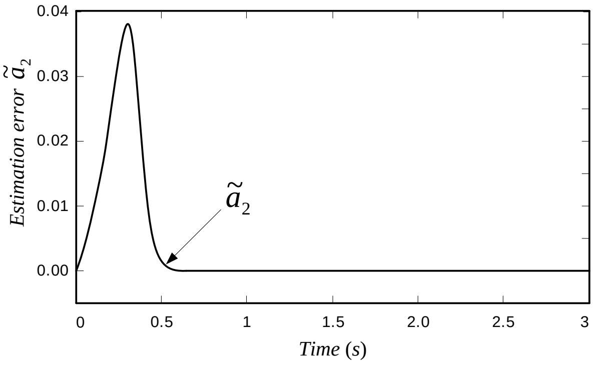


Figure 15. Estimation error $\tilde{a}_2$

The velocities of the welding point and the angular velocities of two driving are given in Figure 11 and Figure 12, respectively. The torch length is small changed as shown in Figure 13. Figure 14 and Figure 15 show the estimation errors $\tilde{a}_1$ and $\tilde{a}_2$. Figure 16 shows the experimental welding bead.

Figure 16. Experimental welding bead

Conclusions

In this paper, a nonlinear adaptive controller has been introduced to enhance the WMR's tracking performances. The simulation and experimental results show that the tracking errors have minimal oscillation, and the velocity of the welding point can track to the reference velocity. Control law is obtained from the Lyapunov control function to ensure the asymptotical stability of the system. So, the proposed controller can be used in practical welding processes to control the WMR tracking any smooth curved welding path with the radius of curved path is larger than 200mm.

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