A Nonlinear Controller of a Two-Wheeled Welding Mobile Robot Tracking Smooth-Curved Welding Path Using Sliding Mode Control

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Abstract: In this paper, a nonlinear controller based on sliding mode control is applied to a two-wheeled Welding Mobile Robot (WMR) to track a smooth-curved welding path at a constant velocity of the welding point. The mobile robot is considered in terms of dynamics model in Cartesian coordinates and its parameters are exactly known. To obtain the controller, the tracking errors are defined, and the two sliding surfaces are chosen to guarantee that the errors converge to zero asymptotically. Two cases are to be considered: fixed torch and controllable torch. In addition, a simple way of measuring the errors is introduced using two potentiometers. The simulation results are included to illustrate the performance of the control law.

Keywords: Welding Mobile Robot (WMR), tracking, sliding mode control

1. INTRODUCTION

Welding automation has been widely used in all types of manufacturing, and one of the most complex applications is welding systems based on autonomous robots. Some special welding robots can provide several benefits in certain welding applications. Among them, welding mobile robot used in line welding application can generates the perfect movements at a certain travel speed, which makes it possible to produce a consistent weld penetration and weld strength.

In practice, some various robotic welding systems have been developed recently. Kim et al., 2000, developed a three dimensional laser vision system for intelligent shipyard welding robot to detect the welding position and to recognize the 3D shape of the welding environments [9]; Jeon, 2001, presented the seam tracking and motion control for two-wheeled welding mobile robot of lattice type welding; the control is separated into three driving motions: straight locomotion, turning locomotion, and torch slider control [10]. Kam, 2001, proposed a control algorithm based on "trial and error" method for straight welding using body positioning sensors and seam tracking sensor [11]. Both of controllers proposed by Jeon and Kam have been successfully applied to the practiced field. Ibanez I. et al., 2002, developed a 3D visual system with three cameras for positioning welding mobile robots so-called UNSHADES-1 system, which is a full controlled system that computes the position of the welding point [8]. T. H. Bui et al., 2003, proposed a simple nonlinear controller for two-wheeled welding mobile robot tracking a smooth-curved welding path using Lyapunov function candidate [12].

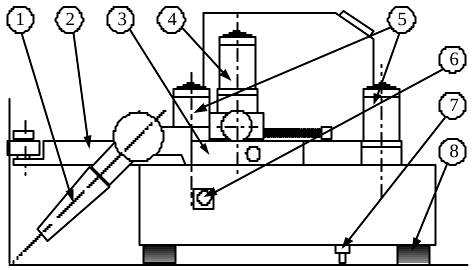
On the other hand, there are several works on adaptive and sliding mode control theory for tracking control of mobile robots in literatures, especially, the mobile robots are considered under the model uncertainties and disturbances. Fierro, 1995, developed a combined kinematic and torque control law using backstepping approach and asymptotic stability is guaranteed by Lyapunov theory which can be applied to the three basic nonholonomic navigation: tracking a reference trajectory, path following and stabilization about a desired posture [3]. Jung-Min Yang et al., 1998, proposed a new sliding mode control law which is robust against initial condition errors, measurement disturbances and noise in the sensor data to asymptotically stabilize to a desired trajectory by means of the computed-torque method [4]. T. Fukao, 2000, proposed the integration of a kinematic controller and a torque controller for the dynamic model of a nonholonomic mobile robot. In the design, a kinematics adaptive tracking controller is proposed. Then a torque adaptive controller with unknown parameters is derived using the kinematic controller [7]. Dong Kyoung Chwa et al., 2002, proposed a new sliding mode control method for trajectory tracking of nonholonomic wheeled mobile robots presented in two-dimensional polar coordinates in the presence of the external disturbances [1]; additionally, the controller shown the better effectiveness in the comparison with one in [4] in terms of the sensitivity to the parameters of sliding surface.

In this paper, a nonlinear controller using sliding mode control is applied to two-wheeled welding mobile robot to track a smooth-curved welding path. To design a tracking controller, the errors are defined between the welding point on torch and the reference point moving at a specified constant welding speed on welding path. There are two cases of controller: fixed torch controller and controllable torch controller. The two sliding surfaces are chosen to make the errors to approach zeros as reasonable as desired for practical application. The control law is extracted from the stable conditions respectively. The controllable torch controller gives much more performance in comparison with the other. In addition, a simple way for sensing the errors using potentiometers is introduced to realize the above controller. The simulation results have been done to show the effectiveness of the proposed controller.

2. DYNAMIC MODEL OF WMR

In this section, the dynamic of two-wheeled welding mobile robot is considered with the nonholonomic constraints in relation with its coordinates and the reference welding path.

It is observable that the welding point is away from the WMR's center; consequently, that property makes tracking errors slow to convergence. Therefore, the WMR used in this paper is of two-wheel mobile robot with some modifications on mechanical structure for welding application (Fig. 1), rather, there are three motions in this mobile robot: two driving wheels and one torch slider. With the motion of the torch slider, the robot can reach to the reference welding path faster. Therefore, two cases are to be considered: controllers with and without torch slider in the controller design.



1 *welding torch* 5 *wheel- driving motors*
2 *sensor* 6 *proximity sensor*
3 *torch slider* 7 *lower limit switch*
4 *torch-slider-driving motor* 8 *driving wheels*

Fig. 1 WMR configuration

The model of two-wheeled welding mobile robot is shown in Fig. 2. The posture of the mobile robot can be described by three generalized coordinates:

$$q = [x \quad y \quad f]^T$$

where, (x, y) : Cartesian coordinates of the WMR's center
f : heading angle of the WMR

Also it is chosen the internal state variables as follows

$$z = [v \quad w]^T$$

We assume that the wheels roll and do not slip, that is, the robot can only move in the direction normal to the axis of the driving wheels. Analytically, the mobile base satisfies the conditions as following [7]

$$\dot{y} \cos f - \dot{x} \sin f = 0$$

where $C(x, y)$ is the coordinates of the WMR's center.
The constraint equations can be written in matrix form:

$$A(q)\dot{q} = 0 \qquad (1)$$

As the result, the kinematic model under the nonholonomic constraints (1) can be derived as follows:

$$\dot{q} = S(q)z \qquad (2)$$

where $S(q)$ is a $nx(n-m)$ full rank matrix satisfying $S^T(q)A^T(q) = 0$.

Moreover, the dynamic equations of the mechanical system under nonholonomic constraints (1) can be described by Euler-Lagrange formulation [4]

$$M(q)\ddot{q} + V(q,\dot{q}) = E(q)t - A^T(q)l \qquad (3)$$

where,
$M(q) \in R^{nxn}$: symmetric and positive definite inertia matrix
$V(q,\dot{q}) \in R^{nxn}$: centripetal and coriolis matrix
$E(q) \in R^{nxr}$: input transformation matrix
$A(q) \in R^{mxn}$: matrix related with nonholonomic constraints
$t \in R^r$: a control input vector
$l \in R^m$: a constraint force vector

For simplicity of analysis, we assume that $r = n - m$

From (2) and (3), we have the nonholonomic mobile robot platform's system dynamics in which the constraint (1) is embedded and take into account disturbances can be derived by the result of [14]

$$\begin{cases} \dot{q} = S(q)z \\ H(q)\dot{z} + G(q,z) + t_d = t \end{cases} \qquad (4)$$

where,

$$H(q) = (S^T E)^{-1} S^T MS^T MS \in R^{(n-m)x(n-m)}$$
$$G(q,z) = (S^T E)^{-1} S^T (M\dot{S}z + V) \in R^{(n-m)xm}$$

$t \in R^{(n-m)xm}$ is the input torque vector. In this application, it is torque vector applied to driving wheels.
It is assumed that the disturbance vector can be expressed as a multiplier of matrix $H(q)$, or it satisfies the matching condition with a known boundary:

$$t_d = H(q)f$$
$$f = [f_1, f_2]^T, \quad |f_1| \le f_1^m, |f_2| \le f_2^m$$

where f_1^m and f_2^m are upper bounds of disturbances.

The model of the WMR is shown in Fig. 2. It is modeled including the motion of welding torch into system dynamics so that the welding point on torch can track the reference path at specified constant welding speed.

First, the kinematic equations of the WMR in the Cartesian space corresponding to (2) are set up as following

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{f} \end{bmatrix} = \begin{bmatrix} \cos f & 0 \\ \sin f & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} \qquad (5)$$

where $C(x, y)$ is position variables of WMR's center point, f is the orientation angle of the WMR, v and w are the linear and angular velocities of the WMR at its center point.

The relationship between v, w and the angular velocities of two driving wheels is the following

$$\begin{bmatrix} w_{rw} \\ w_{lw} \end{bmatrix} = \begin{bmatrix} 1/r & b/r \\ 1/r & -b/r \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} \qquad (6)$$

where w_{rw}, w_{lw} represent the angular velocities of right and left wheels, b is distance from WMR's center point to the driving wheel, r is the radius of wheel.

Second, the welding point $W(x_w, y_w)$ on torch and its orientation angle f_w can be derived from WMR's center $C(x, y)$ [12]

$$\begin{cases} x_w = x - l \sin f \\ y_w = y + l \cos f \\ f_w = f \end{cases} \qquad (7)$$

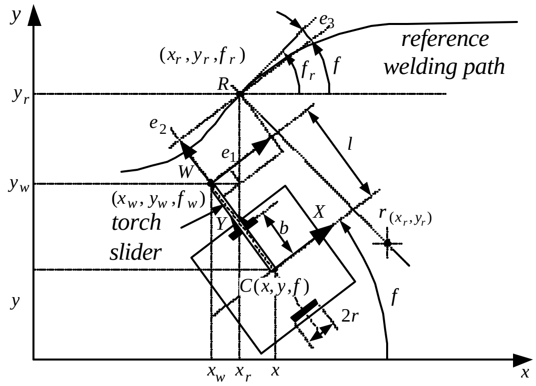


Fig. 2 Scheme for deriving WMR kinematic equations

where l is the length of torch. The derivative of (8) yields

$$\begin{bmatrix} \dot{x}_w \\ \dot{y}_w \\ \dot{z}_w \end{bmatrix} = \begin{bmatrix} \cos f & -l\cos f \\ \sin f & -l\sin f \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} v \\ w \end{bmatrix} + \begin{bmatrix} -\dot{l}\sin f \\ \dot{l}\cos f \\ 0 \end{bmatrix} \qquad (8)$$

It is assumed that a reference point $R(x_r, y_r)$ on the reference path moving at the constant velocity of v_r with the orientation angle f_r. The dynamic equation is shown below

$$\begin{cases} \dot{x}_r = v_r \cos f_r \\ \dot{y}_r = v_r \sin f_r \\ \dot{f}_r = w_r \end{cases} \qquad (9)$$

where f_r is defined as the angle between v_r and x axis, and w_r is the rate of angular change of v_r.

3. SLIDING MODE CONTROLLER DESIGN

The scheme of errors are shown in Fig. 2, and the tracking errors $e = [e_1, e_2, e_3]^T$ are defined as following [12]

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \cos f & \sin f & 0 \\ -\sin f & \cos f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_r - x_w \\ y_r - y_w \\ f_r - f_w \end{bmatrix} \qquad (10)$$

The first derivative of errors yields

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} -1 & e_2 + l \\ 0 & -e_1 \\ 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} v \\ w \end{bmatrix} + \begin{bmatrix} v_r \cos e_3 \\ v_r \sin e_3 - \dot{l} \\ w_r \end{bmatrix} \qquad (11)$$

Also, the second derivative,

$$\begin{bmatrix} \ddot{e}_1 \\ \ddot{e}_2 \\ \ddot{e}_3 \end{bmatrix} = \begin{bmatrix} 0 & \dot{e}_2 \\ 0 & -\dot{e}_1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} + \begin{bmatrix} -1 & e_2 + l \\ 0 & -e_1 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{w} \end{bmatrix} + \begin{bmatrix} -v_r \dot{e}_3 \sin e_3 \\ v_r \dot{e}_3 \cos e_3 - \ddot{l} \\ \dot{w}_r \end{bmatrix} \qquad (12)$$

We will design a controller to achieve $e_i \to 0$ when $t \to \infty$; in other words, the welding point W tracks to the reference point R at a desired velocity of welding.

3.1. The case of fixed torch

To design the controller of fixed torch, the sliding surface $S = [S_1 \quad S_2]^T$ is defined as follows

$$S = \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} \dot{e}_1 + k_1 e_1 + k_2\, sgn(e_1)|e_2| \\ \dot{e}_3 + k_3 e_3 \end{bmatrix} \qquad (13)$$

where k_1, k_2 and k_3 are positive values and $sgn(.)$ is the sign function. When reached the sliding surface, the system dynamics satisfies the differential equation obtained from $s = 0$, namely

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} -k_1 e_1 - k_2\, sgn(e_1)|e_2| \\ -k_3 e_3 \end{bmatrix} \qquad (14)$$

The first row of (14) is considered, when e_1 becomes positive, $\dot{e}_1$ becomes negative and vice versa. Thus, the equilibrium point of e_1 converges to zero, which, in turn, leads to the asymptotic convergence of $|e_2|$ to zero. Similarly, the second row, e_3 also converges to zero

As a feedback linearization of the system, the control input is defined by computed-torque method [4] as follows

$$H(q)\dot{z} + G(q, z) + H(q)u = t \qquad (15)$$

where $u = [u_1 \quad u_2]^T$ is a control law which makes error dynamics. Substitution of the proposed control law (15) into the dynamic equation (4) yields [4]

$$\begin{aligned} &\dot{z} + f = \dot{z}_r + u \\ &\Rightarrow \dot{z} - \dot{z}_r = u - f \end{aligned} \qquad (16)$$

The following procedure is to design a control law u which make the sliding mode stable. From (12) & (13), we have

$$\begin{bmatrix} \ddot{e}_1 \\ \ddot{e}_3 \end{bmatrix} = \begin{bmatrix} \dot{e}_2 w - \dot{v} + (e_2 + l)\dot{w} - v_r \dot{e}_3 \sin e_3 \\ \dot{w}_r - \dot{w} \end{bmatrix} \qquad (17)$$

In this application, the speed of the welding point is constant, or $\dot{v}_r = 0$, (17) is rewritten as follows

$$\begin{bmatrix} \ddot{e}_1 \\ \ddot{e}_3 \end{bmatrix} = -\begin{bmatrix} (\dot{v} - \dot{v}_r) \\ (\dot{w} - \dot{w}_r) \end{bmatrix} + \begin{bmatrix} \dot{e}_2 w + (e_2 + l)\dot{w} - v_r \dot{e}_3 \sin e_3 \\ 0 \end{bmatrix} \qquad (18)$$

For the simplicity, (18) is modified as below

$$\begin{aligned} &\begin{bmatrix} \ddot{e}_1 + k_1 \dot{e}_1 + k_2\, sgn(e_1)|\dot{e}_2| \\ \ddot{e}_3 + k_3 \dot{e}_3 \end{bmatrix} = -\begin{bmatrix} (\dot{v} - \dot{v}_r) \\ (\dot{w} - \dot{w}_r) \end{bmatrix} + \\ &\begin{bmatrix} \dot{e}_2 w + (e_2 + l)\dot{w} - v_r \dot{e}_3 \sin e_3 \\ 0 \end{bmatrix} + \begin{bmatrix} k_1 \dot{e}_1 + k_2\, sgn(e_1)|\dot{e}_2| \\ k_3 \dot{e}_3 \end{bmatrix} \end{aligned} \qquad (19)$$

Substituting (13) and (16) into (19), it is reduced to following

$$\begin{bmatrix}\dot S_1\\ \dot S_2\end{bmatrix} = -\begin{bmatrix}u_1\\ u_2\end{bmatrix} + \begin{bmatrix}f_1\\ f_2\end{bmatrix} + \begin{bmatrix}\dot e_2 w + (e_2+l)\dot w - v_r \dot e_3 \sin e_3\\ 0\end{bmatrix} + \begin{bmatrix}k_1\dot e_1 + k_2\, sgn(e_1)|\dot e_2|\\ k_3\dot e_3\end{bmatrix} \qquad (20)$$

Let the control law $u = [u_1 \quad u_2]^T$ be

$$\begin{bmatrix}u_1\\ u_2\end{bmatrix} = \begin{bmatrix}Q_1 & 0\\ 0 & Q_2\end{bmatrix}\begin{bmatrix}S_1\\ S_2\end{bmatrix} + \begin{bmatrix}P_1 & 0\\ 0 & P_2\end{bmatrix}\begin{bmatrix}sgn(S_1)\\ sgn(S_2)\end{bmatrix} + \begin{bmatrix}(v_r \sin e_3 - e_1 w)w + (e_2+l)\dot w - v_r\dot e_3 \sin e_3\\ 0\end{bmatrix} + \begin{bmatrix}k_1\dot e_1 + k_2\, sgn(e_1)|\dot e_2|\\ k_3\dot e_3\end{bmatrix} \qquad (21)$$

where Q_i and P_i, $i = 1,2$ are constant positive values. Equation (20) becomes

$$\dot S = -QS - P\, sgn(S) + f$$

Define $V = \frac{1}{2}S^T S$ as a Lyapunov function candidate

$$\begin{aligned}\Rightarrow \dot V &= S_1\dot S_1 + S_2\dot S_2 = S^T\dot S\\ &= S^T(-QS - P\, sgn(S) + f)\\ &= -S^T QS - PS\, sgn(S) + fS\\ &= -S^T QS - (P|S| - fS)\end{aligned} \qquad (22)$$

where,

$$S = \begin{bmatrix}S_1\\ S_2\end{bmatrix};\ Q = \begin{bmatrix}Q_1 & 0\\ 0 & Q_2\end{bmatrix};\ P = \begin{bmatrix}P_1 & 0\\ 0 & P_2\end{bmatrix};\ f = \begin{bmatrix}f_1\\ f_2\end{bmatrix}$$

If we choose $Q_i \ge 0, P_i \ge f_i^m$, $i = 1,2$, then $\dot V$ to be negative semi-definite, and the control law u stabilizes sliding surfaces (14).

3.2 The case of controllable torch

To design the controller of controllable torch, the sliding surface $S = [S_1 \quad S_2]^T$ is defined as follows

$$S = \begin{bmatrix}S_1\\ S_2\end{bmatrix} = \begin{bmatrix}\dot e_1 + k_1 e_1\\ \dot e_3 + k_3 e_3\end{bmatrix} \qquad (23)$$

Similarly, the control law u can be derived as

$$\begin{bmatrix}u_1\\ u_2\end{bmatrix} = \begin{bmatrix}Q_1 & 0\\ 0 & Q_2\end{bmatrix}\begin{bmatrix}S_1\\ S_2\end{bmatrix} + \begin{bmatrix}P_1 & 0\\ 0 & P_2\end{bmatrix}\begin{bmatrix}sgn(S_1)\\ sgn(S_2)\end{bmatrix} + \begin{bmatrix}(v_r \sin e_3 - e_1 w)w + (e_2+l)\dot w - v_r\dot e_3 \sin e_3\\ 0\end{bmatrix} + \begin{bmatrix}k_1\dot e_1\\ k_3\dot e_3\end{bmatrix} \qquad (24)$$

We have to design one more controller for torch as follows

Let the Lyapunov function candidate be

$$V = \frac{1}{2}e_2^2 \qquad (25)$$

$$\begin{aligned}\Rightarrow \dot V &= e_2\dot e_2\\ &= e_2(-e_1 w + v_r \sin e_3 - \dot l)\end{aligned} \qquad (26)$$

To achieve $\dot V \le 0$, we choose control law for the torch

$$\dot l = v_r \sin e_3 + k_{22}e_2 - e_1 w \qquad (27)$$

4. MEASUREMENT OF THE ERRORS

In this paper, the controller is derived from measurement of the tracking errors e_1, e_2, e_3 in Eq. (21). The errors measurement scheme is described in Fig. 2: the two rollers are placed at O_1 and O_2. The roller at O_1 is used to specify the two errors e_1 and e_2 and the other, error e_3. The distance between the two rollers O_1O_2 is chosen according to the curve radius of the reference welding path at the contact $R(x_r, y_r)$ such as $\vec v_r \,//\, \vec{O_1O_2}$. The rollers' diameters are chosen small enough to overcome the friction force.

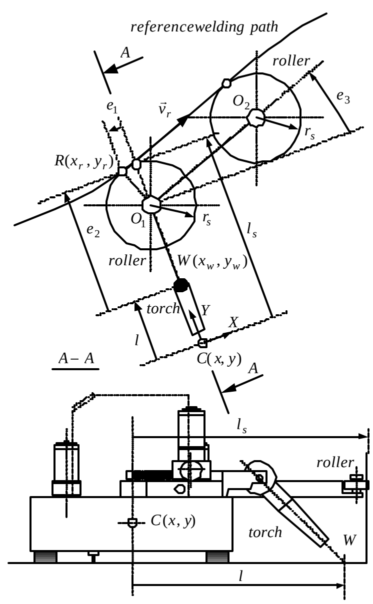


Fig. 3 Scheme for measuring the errors

From Fig. 3, we have the relationships

$$\begin{cases}e_1 = -r_s \sin e_3\\ e_2 = (l_s - l) - r_s(1 - \cos e_3)\\ e_3 = \angle(O_1C, O_1O_2) - p/2\end{cases} \qquad (28)$$

where r_s is the radius of roller, and l_s is the length of sensor. And the two potentiometers are usedfor measuring the errors: one linear potentiometer for measuring $(l_s - l)$ and one rotating potentiometer, the angular between X coordinate of WMR and $\vec v_r$.

5. SIMULATION RESULTS AND DISCUSSIONS

To verify the effectiveness of the proposed controller, simulations have been done with controller (21) with a defined reference smooth-curved welding path (Fig. 4). In the case of fixed torch, the design parameters of the sliding surfaces are $k_1 = 0.5, k_2 = 0.5, k_3 = 0.7$ and the parameters of the control law, $P_1 = 0.6$, $P_2 = 2$ and $Q_1 = 10$, $Q_2 = 0.35$, and in the case of controllable torch, $k_1 = 2$ $k_3 = 5$, $k_{22} = 2$; $P_1 = 0.6$ and $P_2 = 2$; $Q_1 = 10$ and $Q_2 = 1$. The input disturbances are chosen to be random noises of mean 0.5 and the upper bounds of disturbances are assumed as $f_{m1} = f_{m2} = 0.5N$. The WMR's parameters and the initial values are given in table 1 and table 2. The welding speed is 7.5 mm/s.

Table 1. The numerical values for simulation

Parameter	Value	Comment
b	0.105m	displacement from driving wheel to the axis of symmetry
l	0.24m	length of torch
r	0.025m	radius of wheel
m_c	8.5kg	mass of body
m_w	0.3kg	mass of wheel and motor

Table 2. The initial values for simulation

Parameter	Value	Comment
x_r	0.28m	x coordinate of reference
x_w	0.27m	x coordinate of welding point
y_r	0.4m	y coordinate of reference
y_w	0.39m	y coordinate of welding point
f_r	0deg	angle of reference
f_w	15deg	heading angle of welding point
v w	0 mm/ 0 rad/s	linear velocity of WMR angular velocity of WMR

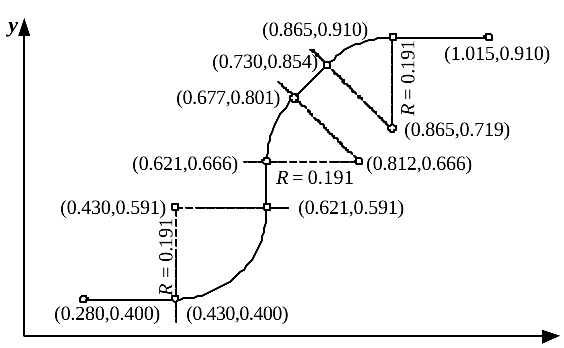


Fig. 4 The reference welding path

Simulation results are given through Figs. 5-10. In Figs. 5 and 6, it can be seen that the errors go to zeros after 20 seconds in the case of fixed torch; but, only 2 seconds in the case of controllable torch. Therefore, the simulations are only presented in the case of torch control. The errors are almost zeros as WMR passes through the curved line. The torch length is shown in Fig. 9 for the first 5 seconds. The torch length rises to the stable value of about 248mm, and there are some errors as WMR passes through the curve. The posture and the welding trajectory are shown in Figs. 10.

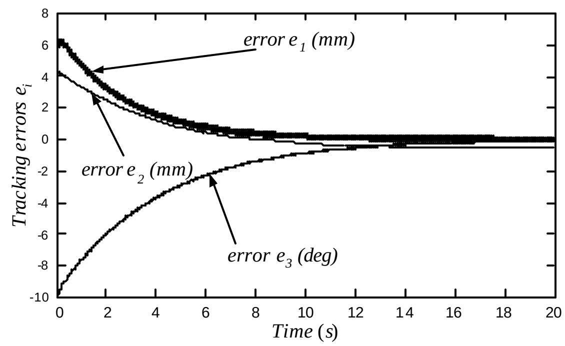


Fig. 5 Tracking errors without torch control (20s)

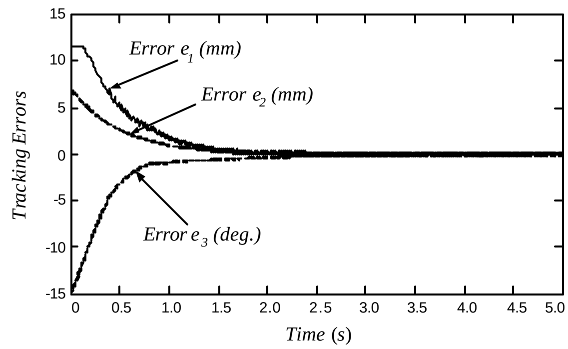


Fig. 6 Tracking errors with torch control (5s)

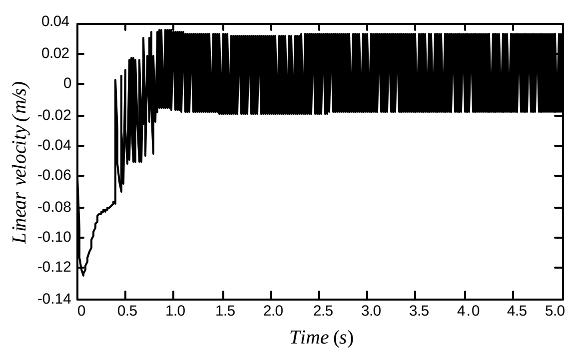


Fig. 7 Linear velocity of WMR's center (5s)

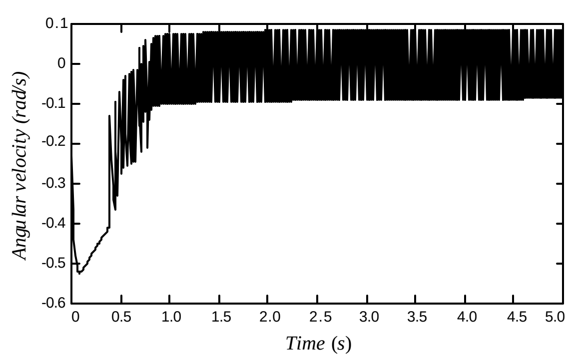


Fig. 8 Angular velocity of WMR's center (5s)

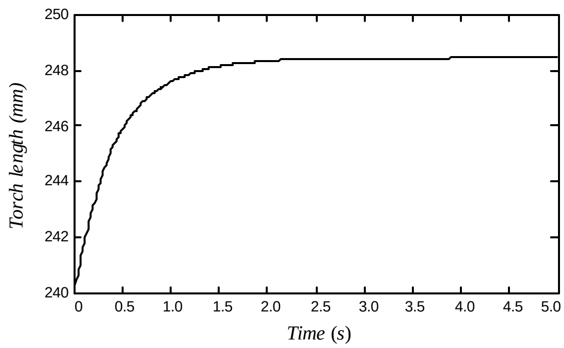


Fig. 9 Torch length

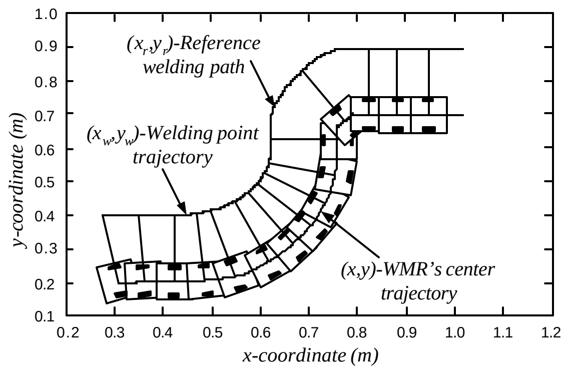


Fig. 10 WMR's movement tracking reference welding path

From the simulation results, we can conclude as follows:

- The controller of controllable torch give much more performance in comparison with the other: (1) the time convergence reduces to 2 seconds, (2) the system is less sensitive to the parameters; particularly, (3) the convergence of e_2 is fast enough.
- The chattering phenomena, as nature of this control, have to be eliminated for the implementation to practiced welding mobile robot. And the controller can be used for tracking any smooth curved line with acceptable small errors. This problem would be considered in the future work.

6. CONCLUSIONS

A simple nonlinear controller based on sliding mode control has been introduced to enhance the tracking performances of WMR. The controllers were designed in two cases: fixed torch controller and controllable torch. To design the tracking controllers, an error configuration is defined and the two sliding surfaces are chosen to drive the errors to zeros as reasonable as desired. Also, a simple way of measuring the errors for derivingthe control law is proposed. The simulation results show that the controller is possible and implemented in the practiced field in the future. It can be concluded that the controller with torch control gives the much more performance than the other.

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