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Adaptive Tracking Control of Two-Wheeled Welding Mobile Robot with Smooth Curved Welding Path

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This paper proposes an adaptive controller for partially known system and applies to a two-wheeled Welding Mobile Robot (WMR) to track a reference welding path at a constant velocity of the welding point. To design the tracking controller, the errors from WMR to steel wall is defined, and the controller is designed to drive the errors to zero as fast as desired. Additionally, a scheme of error measurement is implemented on the WMR to meet the need of the controller. In this paper, the system moments of inertia are considered to be partially unknown parameters which are estimated using update laws in adaptive control scheme. The simulations and experiments on a welding mobile robot show the effectiveness of the proposed controller.

Key Words: Welding Mobile Robot (WMR), Tracking Control, Reference Welding Path

1. Introduction

Welding automation has been increasingly used since they are of much benefit to welding applications in terms of weld quality, increased productivity, reduced welding costs, and increased weld consistency. Arc welding is among potential applications for the robot which places high demands on the technology. Specifically, the commercial arc welding system relies on workers to fix the parts to be welded accurately, and then the robot goes through a programmed welding sequence; in the other field, of the shipbuilding industry, an arc weld has to be made along a joint between two large work pieces of metal to make modules of ship. In this case, the welding accuracy turns to be important, and the problem can be solved with the robot which delete can detect the deviation between the welding torch and the joint using sensors in general.

A mobile robot is one of the well-known systems with non-holonomic constrains that are not integral. There are many works on the tracking control method for the mobile robot in literatures (Jeon et al., 2001 ; Lefeber et al., 2001 ; Gonzalez et al., 2000; Fukao et al., 2000; Tsuchia et al., 1999 ; Taybei and Rachid, 1997 ; Mukherjee et al., 1996 ; Yun and Sarkar, 1996 ; Zheng and Moore, 1995; Fierro and Lewis, 1995; Sarkar et al., 1994; Yun and Yamamoto, 1993). These works are mostly on kinematic models and the other works are on dynamic models. Sarkar et al. (1994) proposed a nonlinear feedback that guaranteed input-output stability and Lagrange stability for the overall system with reference paths of the straight and circular line; Fierro et al. (1995) developed a combined kinematic/torque control law using the back-stepping approach. However, these papers did not consider the uncertainties of system parameters which always exist in mobile robot control problem ; addition-

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ally, Fukao et al. (2000) dealt with adaptive tracking control of the two-wheeled mobile robot considering the model with unknown parameters in its kinematic part of overall system, and an adaptive law was proposed for updating the error of unknown parameters.

The applications of the two-wheeled mobile robot for welding automation have been studied by Jeon (2001) and Kam (2001). Jeon proposed a seam tracking and motion control of WMR for lattice type welding in which there were three controllers for motion control, such as the straight locomotion, turning locomotion, and torch slider. Kam proposed a control algorithm for straight welding based on, "trial and error" for each step time; that is if there is "error" detected by the seam tracking sensor on the torch slider, the controller will adjust the WMR's motion for seam tracking based on a programmed schedule. The two controllers are used only for straight line tracking, not for smooth curved line tracking. They have been successfully applied to the real systems.

This paper proposes an adaptive control of the partially known system and its application to design a tracking controller for two-wheeled welding mobile robot on smooth curved welding path. The controller is stable in the sense of *Lyapunov stability*. To design such a tracking controller, a configuration of errors is defined and the controller is designed to drive the error to zero as fast as desired. Moments of inertia of the system are considered to be unknown parameters which are estimated using update laws in the adaptive control scheme. The simulations and experiments of a WMR with a smooth curved reference welding path are given to show the effectiveness of the proposed controller.

2. Model of Two-Wheeled Welding Mobile Robot

There are three controlled motions in this model: two driving wheels and one torch slider. By including the motion of welding torch into system dynamics, the robot can reach faster to the reference welding path and track on it.

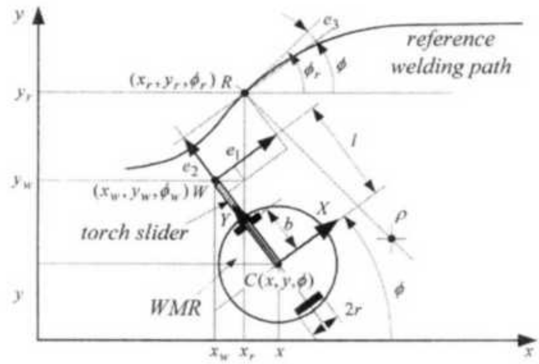

Fig. 1 Welding mobile robot coordinate

It is assumed that the wheels roll and do not slip, which implies that the center point velocity C of WMR in Fig. 1 must be in the direction of the axis of symmetry and the wheels must not slip. These constraints are presented as

$$\begin{aligned} \dot{y}\cos\phi - \dot{x}\sin\phi &= 0 \\ \dot{x}\cos\phi + \dot{y}\sin\phi + b\dot{\phi} &= r\omega_{rw} \\ \dot{x}\cos\phi + \dot{y}\sin\phi - b\dot{\phi} &= r\omega_{lw} \end{aligned} \tag{1}$$

where,

$C(x, y)$: Cartesian coordinate of WMR's center
ϕ : the heading angle of the WMR
ω_{rw}, ω_{lw} : the angular velocities of the right and the left wheels
b : the distance from WMR's center to driving wheel
r : driving wheel radius

The nonholonomic mobile robot platform with above constraints can be expressed as (Fukao et al., 2000)

$$\dot{q} = S(q)\nu \tag{2}$$

$$\bar{M}(q)\dot{\nu} + \bar{V}(q, \dot{q})\nu = \bar{B}(q)\tau \tag{3}$$

where,

$$q = \begin{bmatrix} x \\ y \\ \phi \end{bmatrix}, \; S(q) = \begin{bmatrix} \frac{r}{2}\cos\phi & \frac{r}{2}\cos\phi \\ \frac{r}{2}\sin\phi & \frac{r}{2}\sin\phi \\ \frac{r}{2b} & -\frac{r}{2b} \end{bmatrix}, \; \nu = \begin{bmatrix} \omega_{rw} \\ \omega_{lw} \end{bmatrix},$$

$$\bar{M} = \begin{bmatrix} \frac{r^2}{4b^2}(mb^2+I) + I_w & \frac{r^2}{4b^2}(mb^2-I) \\ \frac{r^2}{4b^2}(mb^2-I) & \frac{r^2}{4b^2}(mb^2+I) + I_w \end{bmatrix},$$

$$\bar{V}=\begin{bmatrix} 0 & \frac{r^2}{2b}m_c d\dot{\phi} \\ -\frac{r^2}{2b}m_c d\dot{\phi} & 0 \end{bmatrix},\ \bar{B}=\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},\ \tau=\begin{bmatrix} \tau_{rw} \\ \tau_{lw} \end{bmatrix},$$

$m \equiv m_c + 2m_w$, $I \equiv m_c d^2 + 2m_w b^2 + I_c + 2I_m$

τ_{rw}, τ_{lw} : torques of the motors which act on the right and the left wheels

m_c, m_w: the mass of body and wheel with a motor

d : the distance between the geometric center and mass center of WMR

I_c : the moment of inertia of the body about the vertical axis through WMR's mass center

I_w : the moment of inertia of the wheel with the motor about the wheel axis

I_m : the moment of inertia of the wheel with the motor about the wheel diameter

The welding point coordinates $W(x_w, y_w)$ and the heading angle ϕ_w can be calculated from the center point $C(x, y)$:

$$\begin{aligned} x_w &= x - l\sin\phi \\ y_w &= y + l\cos\phi \\ \phi_w &= \phi \end{aligned} \tag{4}$$

From Eqs. (2) and (4), the welding point dynamics can be expressed as

$$\begin{bmatrix} \dot{x}_w \\ \dot{y}_w \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} \cos\phi & -l\cos\phi \\ \sin\phi & -l\sin\phi \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \nu \\ \omega \end{bmatrix} + \begin{bmatrix} -\dot{l}\sin\phi \\ \dot{l}\cos\phi \\ 0 \end{bmatrix} \tag{5}$$

A point $R(x_r, y_r)$ moving with the constant velocity of ν_r on the reference welding path has the coordinates and the heading angle ϕ_r satisfies the following equations

$$\begin{aligned} \dot{x}_r &= \nu_r\cos\phi_r \\ \dot{y}_r &= \nu_r\sin\phi_r \\ \dot{\phi}_r &= \omega_r \end{aligned} \tag{6}$$

where ϕ_r is the angle between $\vec{\nu}_r$ and coordinate and ω_r is the rate of $\vec{\nu}_r$ change of direction.

The objective is to design a controller so that the welding point W tracks the reference point R at a constant velocity ν_r. We define the tracking errors $e=[e_1, e_2, e_3]^T$ as shown in Fig. 1.

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} x_r - x_w \\ y_r - y_w \\ \phi_r - \phi_w \end{bmatrix} \tag{7}$$

A controller is designed to achieve $e_i \to 0$ as $t \to \infty$; as the result, the welding point tracks the reference welding path. From Eq. (7), the dynamics of errors can be expressed as

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} \nu_r\cos e_3 \\ \nu_r\sin e_3 - \dot{l} \\ \omega_r \end{bmatrix} + \begin{bmatrix} -1 & e_2 + l \\ 0 & -e_1 \\ 0 & -1 \end{bmatrix}\begin{bmatrix} \nu \\ \omega \end{bmatrix} \tag{8}$$

where ν and ω are the straight and angular velocities of the WMR's center. The relationship between ν, ω and ω_{rw}, ω_{lw} can be arranged as

$$\nu = \begin{bmatrix} \omega_{rw} \\ \omega_{lw} \end{bmatrix} = \begin{bmatrix} 1/r & b/r \\ 1/r & -b/r \end{bmatrix}\begin{bmatrix} \nu \\ \omega \end{bmatrix} \tag{9}$$

Using Eq. (9), Eq. (3) can be rewritten as

$$\begin{bmatrix} \frac{r}{2}m + \frac{1}{r}I_w & \frac{r}{2b}I + \frac{b}{r}I_w \\ \frac{r}{2}m + \frac{1}{r}I_w & -\frac{r}{2b}I - \frac{b}{r}I_w \end{bmatrix}\begin{bmatrix} \dot{\nu} \\ \dot{\omega} \end{bmatrix} + \frac{r}{2b}m_c d\omega\begin{bmatrix} 1 & -b \\ -1 & -b \end{bmatrix}\begin{bmatrix} \nu \\ \omega \end{bmatrix} = \begin{bmatrix} \tau_{rw} \\ \tau_{lw} \end{bmatrix} \tag{10}$$

To derive an adaptive controller for the dynamic model of the welding mobile robot, the error dynamics, Eq. (8), and the real dynamics, Eq. (10), are used in the next section.

3. Adaptive Control Algorithm of the Welding Mobile Robot

3.1 Adaptive control algorithm of partially known system

The class of nonlinear systems with two subsystems are described as

$$\dot{\xi} = f(\xi) + g(\xi)\eta \tag{11}$$

$$\Delta_1\dot{\eta} = \Delta_2 h(\eta)\eta + k(\eta)u \tag{12}$$

where $\xi \in R^n$, η, $u \in R^m$, $f \in R^n$, $g \in R^{n\times m}$, Δ_1, $\Delta_2 (\in R^{m\times m})$ are diagonal matrices containing unknown parameters θ_{1i}, θ_{2i}, respectively; h, $k \in R^{m\times m}$; $k(\eta)$ is invertible and $\theta_{1i}>0$. The ξ-subsystem represents the known part of the system and the η-subsystem is the unknown part of the system.

Theorem:
The systems (11)-(12) are stabilized by the following adaptive tracking controller

$$u=k^{-1}(\eta)[-K_2(\eta-\alpha)-g^T(\xi)\xi+\hat{\Delta}_1\dot{\alpha}-\hat{\Delta}_2 h(\eta)\eta] \quad (13)$$

with the update laws

$$\dot{\hat{\theta}}_{1i}=\gamma_{1i}(\eta_i-\alpha_i)\dot{\alpha}_i \quad (14)$$

$$\dot{\hat{\theta}}_{2i}=-\gamma_{2i}(\eta_i-\alpha_i)\sum_{j=1}^{m}h_{ij}(\eta)\eta_j \quad (15)$$

that is, $\xi\to 0$ as $t\to\infty$

where

$K_2\in R^{m\times m}$: positive definite diagonal matrix
γ_{1i}, $\gamma_{2i}(i=1, 2, \cdots, m)$: adaptive gains and positive
$\hat{\Delta}_1$, $\hat{\Delta}_2$: the estimation values of unknown parameters Δ_1 and Δ_2
α : the stabilizing function which satisfies the following equation

$$g(\xi)\alpha=-K_1\xi-f(\xi) \quad (16)$$

where

$K_1\in R^{n\times n}$: positive definite diagonal matrix.

Proof:
Let g^+ be the pseudo-inverse matrix of g. Choose the stabilizing function as

$$\alpha=g^+(\xi)[-K_1\xi-f(\xi)] \quad (17)$$

If the virtual control law is given $\eta=\alpha$, the subsystem (11) is stable with $\dot{\xi}=-K_1\xi$.

Let z be the error between the virtual control and the stabilizing function, $z=\eta-\alpha$, then

$$\begin{aligned}&\dot{\xi}=f(\xi)+g(\xi)(z+\alpha)\\&\Delta_1\dot{z}=\Delta_2 h(\eta)(z+\alpha)-\Delta_1\dot{\alpha}+k(\eta)u\end{aligned} \quad (18)$$

The Lyapunov function is chosen as

$$V_0=\frac{1}{2}\xi^2+\frac{1}{2}\Delta_1 z^2\geq 0 \quad (19)$$

and from Eq. (18) and (19), the derivative of V_0 is

$$\begin{aligned}\dot{V}_0&=\xi^T\dot{\xi}+z^T\Delta_1\dot{z}\\&=-K_1\xi^2+z^T[g^T(\xi)\xi+\Delta_2 h(\eta)(z+\alpha)\\&\qquad-\Delta_1\dot{\alpha}+k(\eta)u]\end{aligned} \quad (20)$$

If the control law is chosen as

$$\begin{aligned}u=k^{-1}(\eta)[&-K_2 z-g^T(\xi)\xi\\&+\Delta_1\dot{\alpha}-\Delta_2 h(\eta)(z+\alpha)]\end{aligned} \quad (21)$$

then $\dot{V}_0=-K_1\xi^2-K_2 z^2\leq 0$. By Barbalat's lemma it is shown that $z\to 0$ as $l\to\infty$; therefore, $\eta\to\alpha$ and $\xi\to 0$ by the definition of $z=\eta-\alpha$. Since Δ_1, Δ_2 are unknown parameters, they are substituted by their estimation values $\hat{\Delta}_1$, $\hat{\Delta}_2$; and the above control law becomes as

$$\begin{aligned}u=k^{-1}(\eta)[&-K_2 z-g^T(\xi)\xi\\&+\hat{\Delta}_1\dot{\alpha}-\hat{\Delta}_2 h(\eta)(z+\alpha)]\end{aligned} \quad (22)$$

Now the Lyapunov function is chosen as

$$V_1=\frac{1}{2}\xi^2+\frac{1}{2}\Delta_1 z^2+\frac{1}{2}(\tilde{\Delta}_1\Gamma_1)^2+\frac{1}{2}(\tilde{\Delta}_2\Gamma_2)^2\geq 0 \quad (23)$$

where $\tilde{\Delta}_i=\Delta_i-\hat{\Delta}_i$; $\Gamma_i=[\gamma_{i1}^{-1/2}, \gamma_{i2}^{-1/2}, \cdots, \gamma_{im}^{-1/2}]^T$, $(i=1, 2)$

Its derivative yields

$$\begin{aligned}\dot{V}_1&=\xi^T\dot{\xi}+z^T\Delta_1\dot{z}-\Gamma_1^T\tilde{\Delta}_1\dot{\hat{\Delta}}_1\Gamma_1-\Gamma_2^T\tilde{\Delta}_2\dot{\hat{\Delta}}_2\Gamma_2\\&=\dot{V}_0+z^T[\tilde{\Delta}_1\dot{\alpha}-\tilde{\Delta}_2 h(\eta)(z+\alpha)]\\&\quad-\Gamma_1^T\tilde{\Delta}_1\dot{\hat{\Delta}}_1\Gamma_1-\Gamma_2^T\tilde{\Delta}\dot{\hat{\Delta}}_2\Gamma_2\\&=\dot{V}_0+\sum_{i=1}^{m}\tilde{\theta}_{1i}z_i\dot{\alpha}_i-\sum_{i=1}^{m}\tilde{\theta}_{2i}z_i\sum_{j=1}^{m}h_{ij}(\eta)(z_j+\alpha_j)\\&\quad-\sum_{i=1}^{m}\gamma_{1i}^{-1}\tilde{\theta}_{1i}\dot{\hat{\theta}}_{1i}-\sum_{i=1}^{m}\gamma_{2i}^{-1}\tilde{\theta}_{2i}\dot{\hat{\theta}}_{2i}\\&=\dot{V}_0-\sum_{i=1}^{m}\gamma_{1i}^{-1}\tilde{\theta}_{1i}(\dot{\hat{\theta}}_{1i}-\gamma_{1i}z_i\dot{\alpha}_i)\\&\quad-\sum_{i=1}^{m}\gamma_{2i}^{-1}\tilde{\theta}_{2i}\Big(\dot{\hat{\theta}}_{2i}+\gamma_{2i}z_i\sum_{j=1}^{m}h_{ij}(\eta)(z_j+\alpha_j)\Big)\leq 0\end{aligned} \quad (24)$$

To eliminate the effects of the unknown parameters $\tilde{\theta}_{ij}$, the update laws are chosen as

$$\begin{aligned}&\dot{\hat{\theta}}_{1i}=\gamma_{1i}z_i\dot{\alpha}_i\\&\dot{\hat{\theta}}_{2i}=-\gamma_{2i}z_i\sum_{j=1}^{m}h_{ij}(\eta)(z_j+\alpha_j)\end{aligned}$$

or in the form

$$\dot{\hat{\theta}}_{1i}=\gamma_{1i}(\eta_i-\alpha_i)\dot{\alpha}_i \quad (25)$$

$$\dot{\hat{\theta}}_{2i}=-\gamma_{2i}(\eta_i-\alpha_i)\sum_{j=1}^{m}h_{ij}(\eta)\eta_j \quad (26)$$

then as $\dot{V}_1\to\dot{V}_0$ as $t\to\infty$

Remark :
When $\Delta_i(i=1, 2)$ is a scalar such as $\Delta_i \rightarrow \theta_i$, the update laws given by Eqs. (14) and (15) become

$$\dot{\hat{\theta}}_{1i}=\gamma_1\sum_{i=1}^{m}(\eta_i-\alpha_i)\dot{\alpha}_i \quad (27)$$

$$\dot{\hat{\theta}}_2=-\gamma_2\sum_{i=1}^{m}(\eta_i-\alpha_i)\sum_{j=1}^{m}h_{ij}(\eta)\eta_j \quad (28)$$

3.2 Application of the proposed adaptive control algorithm to WMR

In this subsection, we will apply an adaptive control algorithm proposed in the previous subsection to the two-wheeled WMR.

3.2.1 Control input for kinematic model

The kinematic model considers velocities ν, ω as control inputs. With $\alpha=[\alpha_1\ \alpha_2]^T$, and

$$\xi=\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix},\ \eta=\begin{bmatrix} \nu \\ \omega \end{bmatrix},\ f(\xi)=\begin{bmatrix} \nu_r \cos e_3 \\ \nu_r \sin e_3-l \\ \omega_r \end{bmatrix},$$
$$g(\xi)=\begin{bmatrix} -1 & e_2+l \\ 0 & -e_1 \\ 0 & -1 \end{bmatrix}$$

then Eq. (16) becomes

$$\begin{bmatrix} -1 & e_2+l \\ 0 & -e_1 \\ 0 & -1 \end{bmatrix}\begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix}=-\begin{bmatrix} k_{11} & 0 & 0 \\ 0 & k_{12} & 0 \\ 0 & 0 & k_{13} \end{bmatrix}\begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \end{bmatrix} -\begin{bmatrix} \nu_r \cos e_3 \\ \nu_r \sin e_3-l \\ \omega_r \end{bmatrix} \quad (29)$$

From the solution of kinematic model, we get

$$\eta=\begin{bmatrix} \nu \\ \omega \end{bmatrix}=\begin{bmatrix} l(\omega_r+k_{13}e_3)+\nu_r \cos e_3+k_{11}e_1 \\ \omega_r+k_{13}e_3 \end{bmatrix} \quad (30)$$

with the control law for the torch

$$\dot{l}=\nu_r \sin e_3+k_{12}e_2 \quad (31)$$

Hence the stabilizing function α is

$$\alpha=\begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix}=\begin{bmatrix} l(\omega_r+k_{13}e_3)+\nu_r \cos e_3+k_{11}e_1 \\ \omega_r+k_{13}e_3 \end{bmatrix} \quad (32)$$

3.2.2 Adaptive control

The torques, τ_{rw} and τ_{lw}, acting on the driving wheels are considered as control inputs. Both Eqs. (8) and (10) are used. Multiplying $[1\ 1\ ;\ 1\ -1]$ and both sides of Eq. (10), and let θ_{ij} be

$$\theta_{11}=rm+\frac{2}{r}I_w,\ \theta_{12}=\frac{r}{b}I+\frac{2b}{r}I_w,$$
$$\theta_2=\frac{r}{b}m_c d \quad (33)$$

which yields

$$\begin{bmatrix} \theta_{11} & 0 \\ 0 & \theta_{12} \end{bmatrix}\begin{bmatrix} \dot{\nu} \\ \dot{\omega} \end{bmatrix}=\theta_2\begin{bmatrix} 0 & b\omega \\ -\omega & 0 \end{bmatrix}\begin{bmatrix} \nu \\ \omega \end{bmatrix} +\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} \tau_{rw} \\ \tau_{lw} \end{bmatrix} \quad (34)$$

In the WMR, the wheels are driven using gear-motors and the torch length is changed. It is difficult to measure or estimate exactly the moments of inertia and the distance between the geometric center and mass center, d. Hence in this paper, θ_{ij} are considered to be unknown system parameters. Applying the above theorem with

$$\Delta_1=\begin{bmatrix} \theta_{11} & 0 \\ 0 & \theta_{12} \end{bmatrix},\ \Delta_2=\theta_2,\ u=\begin{bmatrix} \tau_{rw} \\ \tau_{lw} \end{bmatrix},$$
$$h=\begin{bmatrix} 0 & b\omega \\ -\omega & 0 \end{bmatrix},\ k=\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

to design control law of mobile robot, the control inputs can be calculated from Eq. (22) as follows

$$\tau_{rw}=\frac{1}{2}[-k_{21}(\nu-\alpha_1)-k_{22}(\omega-\alpha_2)-(1+l)e_1 +e_3+\hat{\theta}_{11}\dot{\alpha}_1+\hat{\theta}_{12}\dot{\alpha}_2-\theta_2\omega(b\omega-\nu)]$$
$$\tau_{lw}=\frac{1}{2}[-k_{21}(\nu-\alpha_1)+k_{22}(\omega-\alpha_2)-(1-l)e_1 -e_3+\hat{\theta}_{11}\dot{\alpha}_1+\hat{\theta}_{12}\dot{\alpha}_2-\theta_2\omega(b\omega+\nu)] \quad (35)$$

where α is from Eq. (32) and

$$\dot{\alpha}_1=-k_{11}\nu+[k_{11}(e_2+l)+k_{13}l+\nu_r \sin e_3]\omega +l\dot{\omega}_r+k_{12}\omega_r e_2+k_{11}\nu_r \cos e_3+\nu_r k_{13}e_3 \sin_3 \quad (36)$$
$$\dot{\alpha}_2=\dot{\omega}_r+k_{13}(\omega_r-\omega)$$

The update laws can be obtained from Eqs. (25) and (28)

$$\dot{\hat{\theta}}_{11}=\gamma_{11}(\nu-\alpha_1)\dot{\alpha}_1$$
$$\dot{\hat{\theta}}_{12}=\gamma_{12}(\omega-\alpha_2)\dot{\alpha}_2 \quad (37)$$
$$\dot{\hat{\theta}}_2=-\gamma_2\omega[(\nu-\alpha_1)b\omega-(\omega-\alpha_2)\nu]$$

3.3 Measurement of the errors

In the mobile robot control problem, the environment information for robot operation is very important. There are two types of environments such as unknown and known environments. The former is the case of this application ; such that, WMR follows an unknown smooth curved steel wall for welding. For WMR's operation, first, it is necessary to determine the free space around the WMR for its operation ; next, the WMR must itself be located at its position relative to the working path. In this paper, the controller is derived from measurement of the tracking errors. Fig. 2 describes the measurement scheme for the errors e_1, e_2, e_3 in Eqs. (30), (31) and (35). The two rollers are placed at O_1 and O_2. 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 $\vec{v}_r // \overrightarrow{O_1O_2}$. The roller diameters are small enough to overcome the friction force.

The errors as shown in Fig. 2(a) can be expressed by

$$
\begin{aligned}
e_1 &= -r_s \sin e_3 \\
e_2 &= (l_s - l) - r_s(1 - \cos e_3) \\
e_3 &= \angle(O_1C,\ O_1O_2) - \pi/2
\end{aligned}
$$

where r_s is the radius of roller and l_s is the length of sensor. Hence we need two sensors for measuring the errors ; one linear sensor for measuring $(l_s - l)$ and one angular sensor for measuring the angular between WMR's X coordinate and $\vec{v}_r$. Implementation of tracking error measurement is shown in Fig. 2(b).

4. Simulation and Experimental Results

To verify the effectiveness of the proposed modeling and controller, simulations and experiments have been conducted for a WMR shown in Fig. 3 with a defined reference welding path.

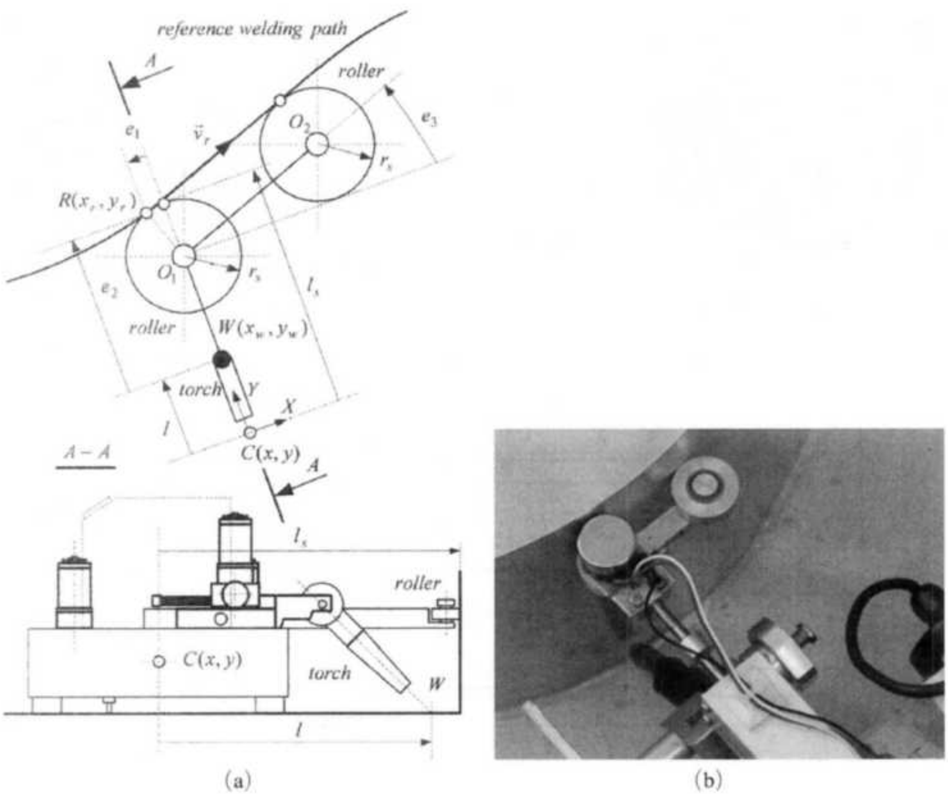

Fig. 2 Error measurement scheme (a), and its implementation (b)

4.1 Hardware of the whole system

Fig. 4 shows the schematic configuration of the WMR control system based on Microchip PIC16F877. The PIC based controller is specially designed for mobile robot with a complicated control law. The controller board integrates four PIC16F877's which comprise two servo DC motor controllers, one torch slider controller and main CPU. They are linked via I2C communication in which three controllers act as slave and the main CPU as master. To retrieve the tracking control scheme, two kinds of control are implemented on I2C communication with sampling time of 10 ms: one is velocity control for the kinematic model in which the controllers of two wheels receive the reference velocity from the master CPU and pulses from encoders; the other is the torque control for the dynamic model in which the controllers receive the reference torque from the master CPU and torque feedback signal from the DC motor driver composed of LMD 18200. Two A/D ports on the master are used to receive signals from the two sensors of the linear potentiometer and angular potentiometer. The errors are calculated with the sensor gain, and the control laws are rendered respectively.

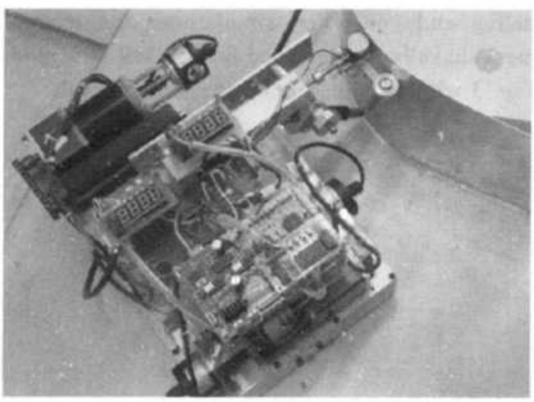

Fig. 3 The WMR for experiment

4.2 Simulation and experimental results

The numerical values used in this simulation are given as Table 1 and Table 2. The reference

Table 1 The numerical values for simulation

Parameter	Value	Unit	Parameter	Value	Unit
b	0.105	m	d	0.01	m
r	0.025	m	m_c	16.9	kg
m_w	0.3	kg	I_c	0.2081	kgm^2
I_w	3.75×10^{-4}	kgm^2	I_m	4.96×10^{-4}	kgm^2

Table 2 The initial values for simulation

Parameter	Value	Unit	Parameter	Value	Unit
x_r	0.280	m	y_r	0.400	m
x_w	0.270	m	y_w	0.390	m
v	0	mm/s	ω	0	rad/s
ϕ_r	0	deg	ϕ	15	deg
l	0.15	m	ω_r	0	rad/s

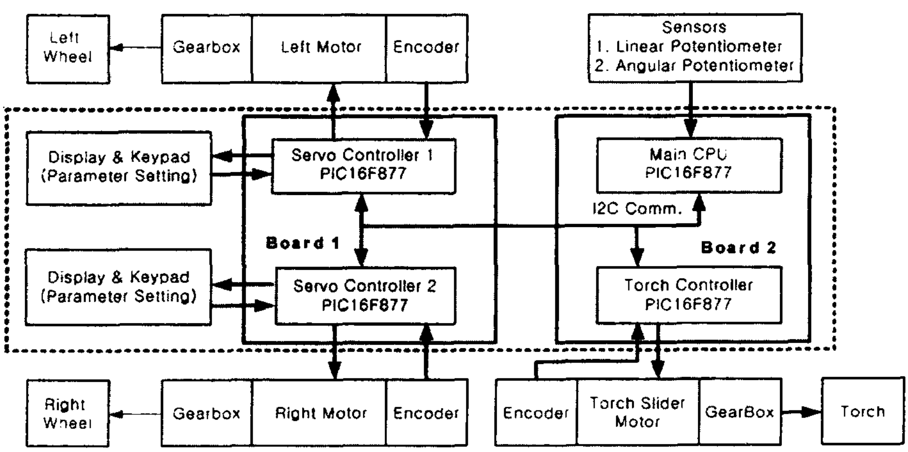

Fig. 4 The configuration of the control system

path is chosen as shown in Fig. 5. The welding speed is 7.5 mm/s. The positive constants in the controller are chosen as $k_{11}=4.2$, $k_{12}=8$, $k_{13}=3.4$ and $k_{21}=k_{22}=10$. The adaptation gains are $\gamma_{11}=\gamma_{12}=\gamma_2=1$.

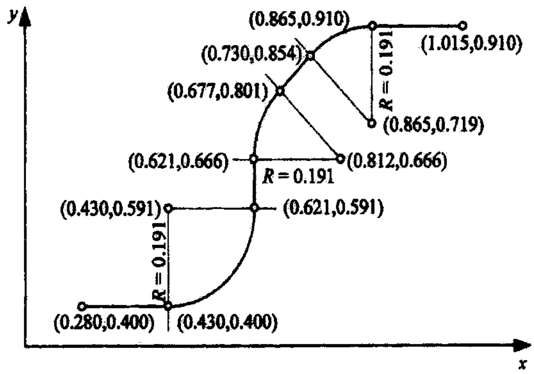

Fig. 5 Reference welding path

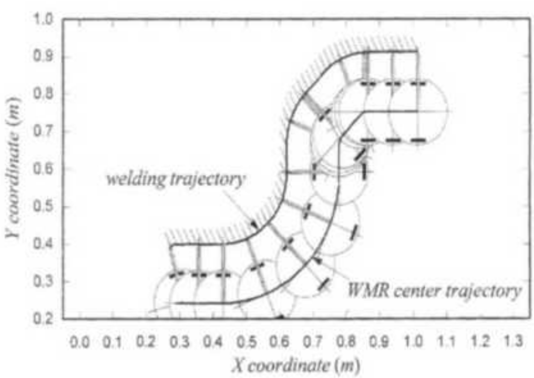

Fig. 6 WMR's movement when tracking reference welding path

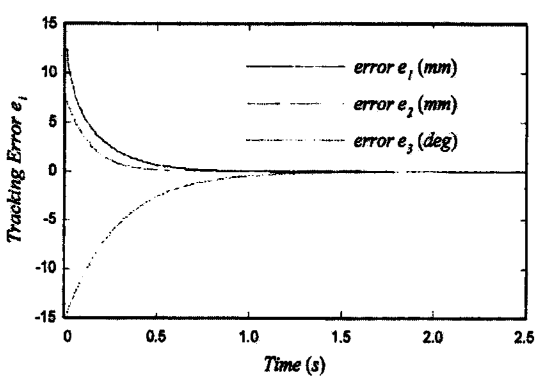

Fig. 7 Tracking errors at beginning

The simulation results are given in Figs. 7-18. The movement of the WMR when it tracks its reference welding path is illustrated in Fig. 6. At the beginning, the WMR adjusts its position very fast to reduce the initial error. These tracking errors can be seen in Fig. 7 and experimental

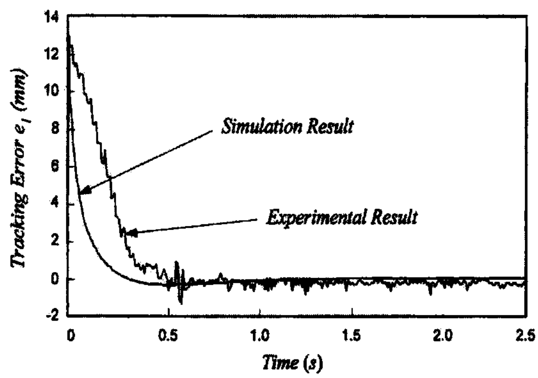

Fig. 8 Tracking error e_1 at beginning

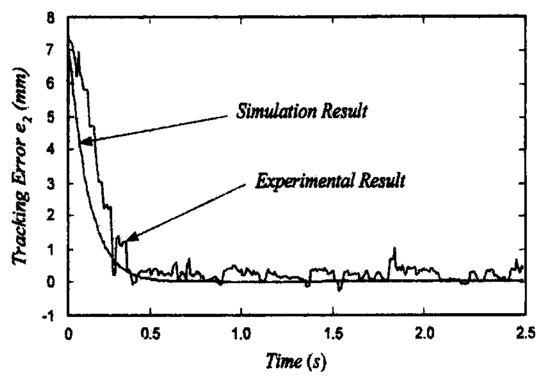

Fig. 9 Tracking error e_2 at beginning

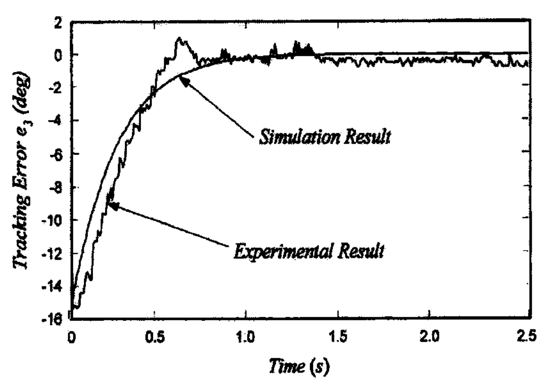

Fig. 10 Tracking error e_3 at beginning

errors are shown in Fig. 8-10. After about 1.5 seconds, the welding torch attains desired velocity as shown in Fig. 11. From straight line to curved line, there is a sudden change of ω_r (from zero to a constant); therefore, there are errors as shown in Fig. 12 and the corresponding welding velocity is shown in Fig. 13. The parameter estimation errors are given in Figs. 14-16. Torch slider must be controlled so as to follow Eq. (31) to get the desired tracking performance. Torch slider speed is given in Fig. 17 and torch length is given in

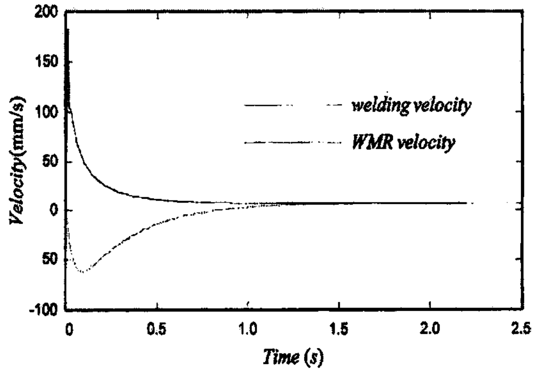

Fig. 11 Velocities of welding point and WMR

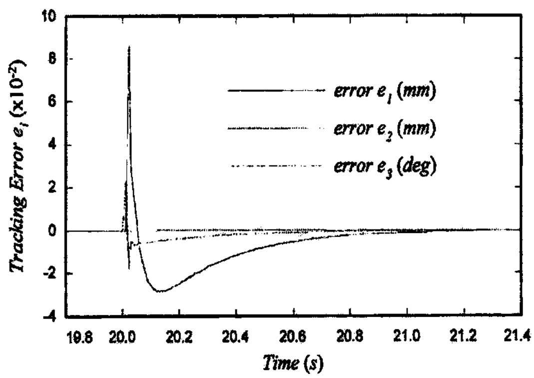

Fig. 12 Tracking errors at corner

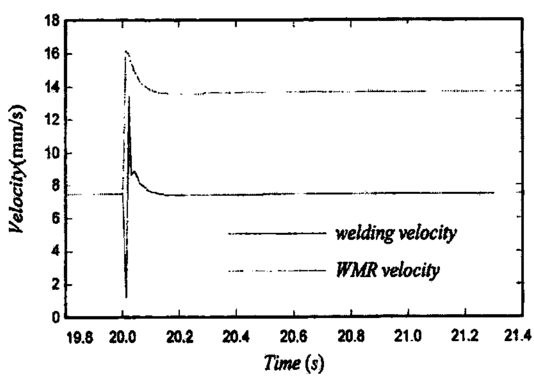

Fig. 13 Velocities of welding point and WMR at corner

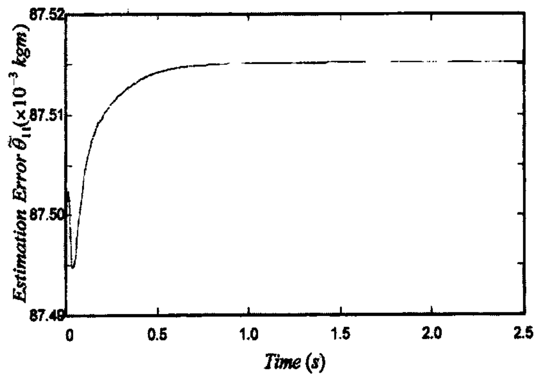

Fig. 14 Estimation error $\tilde{\theta}_{11}$

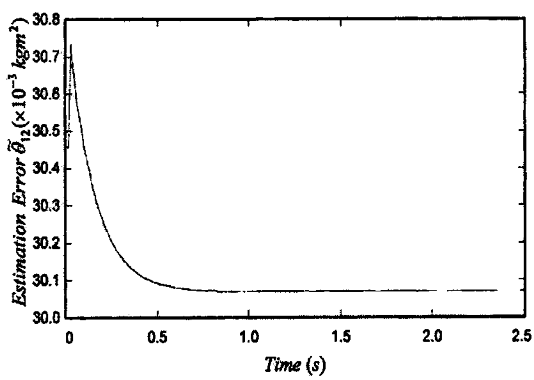

Fig. 15 Estimation error $\tilde{\theta}_{12}$

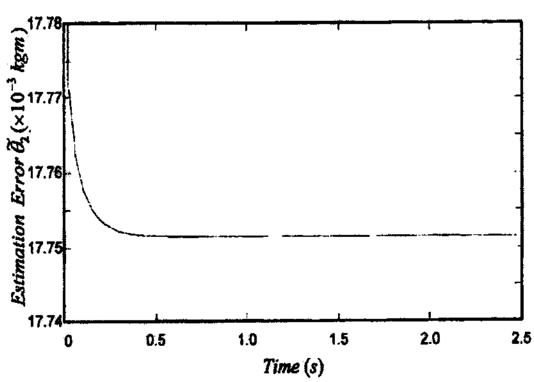

Fig. 16 Estimation error $\tilde{\theta}_2$

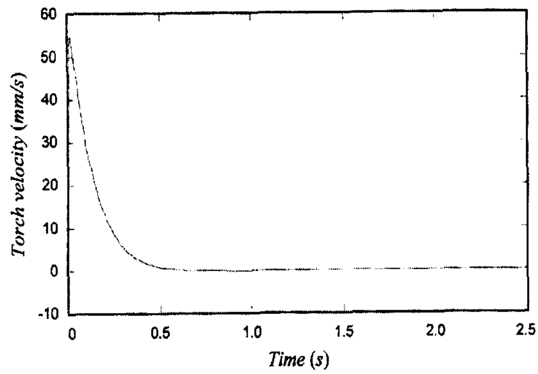

Fig. 17 Torch velocity

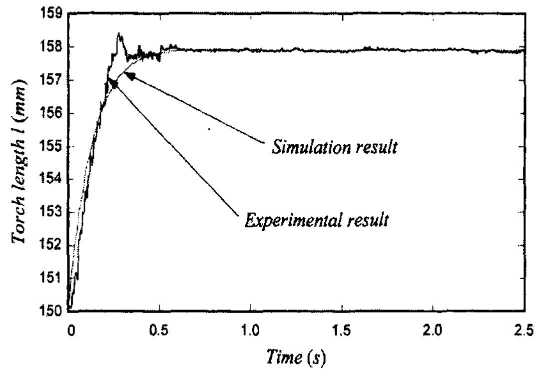

Fig. 18 Torch length

Fig. 18. From the simulation and experimental results, the proposed controller attains good tracking performance.

5. Conclusions

In this paper, we proposed a design method of an adaptive motion tracking controller of partially known system for the two-wheeled welding mobile robot. Moments of inertia of the system are considered to be unknown system parameters, and the controlled system is stable in the sense of Lyapunov stability. In addition, the proposed control algorithm is examined by computer simulation and experiment on the WMR with a smooth curved reference welding path to show the effectiveness of the proposed controller. It is shown that the controller can be used for the WMR with good performances.

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