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Back-Stepping and Neural Network Control of a Mobile Robot for Curved Weld Seam Tracking

Gao Yanfeng[a*,b], Zhang Hua[a],Ye Yanhui[a],a*

[a]*Key Laboratory of Robot and Welding Automation of Jiangxi, Nanchang University, Nanchang 330031, China*
[b]*NanChang HangKong University,NanChang 330063,China*

Abstract

This paper proposes a back-stepping and neural network hybrid control method for mobile platform and slider of mobile robot used in shipbuilding welding. The kinematics model of the robot is built firstly, and then a motion controller is designed based on the model and back-stepping method. Stability of the controller is proved through use of Liapunov theory. For improving the tracking precision and anti-interference performance of the controller, a neural network is designed to identify the kinematical model of the robot and to adjust the control coefficients in real time based on the tracking errors. The simulation and experiments have been done to verify the effectiveness of the proposed controllers.

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Keywords: Mobile robot; Back-stepping; Neural Network; Weld seam tracking

1. Introduction

In the shipbuilding processing, welding is often carried out at out of workshop and the welded seam always is vary long and cannot be re-programmed. Recently, differential driving wheeled mobile robot applied to welding has been attached much attention by many researchers. B.O.Kam [1] et al developed a mobile robot for lattice type welding, and proposed a PID controller for torch slider and PD controller for wheels. However, he considered two controllers to be separated. Seong Jin Ma [2] proposed an adaptive controller based on back-stepping method and applied to two-wheeled mobile robot to track a smooth curved welding path. However, he supposed that the kinematical model of the robot was constant, but in the process of tracking the slider always moving, which makes the mass center of the robot cannot fix in a constant point. Many researchers [3-5] have studied the control method of mobile robot based on back-

* Corresponding author. Tel.: +0-86-0791-3969630; fax: +0+86-0791-3969630.
E-mail address: gyf_2672@163.com.

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stepping and neural networks theories. However, they only concentrated on the mobile platform, did not consider the torch slider.

In this paper, we first use the back-stepping method to design a novel controller based on the kinematical model of the mobile platform and torch slider. Then a neural network is designed to identify the kinematical model of the robot and to adjust the control gains in real time. Last, the simulation and experiment have been done to verify the effectiveness of the proposed controllers.

2. Kinematical model of the mobile welding robot

The mobile welding robot used in this paper is composed of a wheeled mobile platform and a cross slider which carries a rotational welding torch. Fig.1 describes the configuration of the mobile welding robot. The mobile platform has two non-deformable driving wheels mounted on the same axis and two passive self-adjusted supporting wheels mounted respectively rear and front of the mobile platform. The cross slider is mounted on the mobile platform and parallel to the axis of two driving wheels, and the welding gun is attached on it. The two driving wheels are independently driven by two actuators, e.g., DC motors, and the horizontal slider is driven by an independent DC motor for driving welding gun motion in horizontal direction.

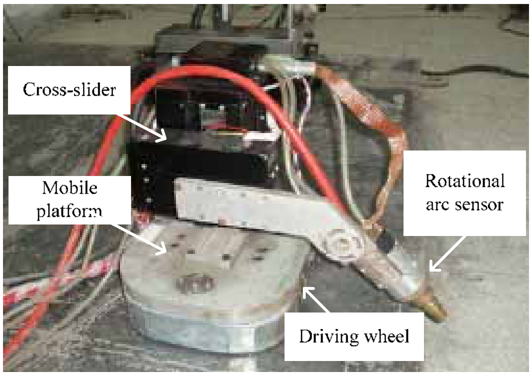


Fig.1 The mobile welding robot

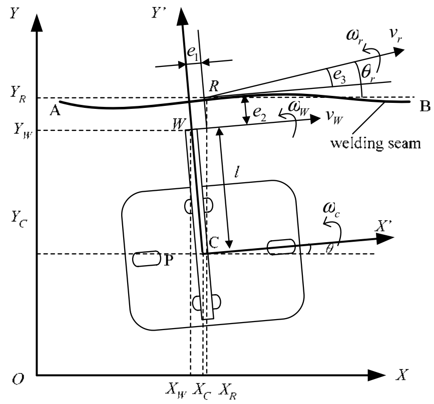


Fig.2 Mathematical model of the mobile robot

Fig.2 shows the mathematical model of the mobile welding robot. Two bases are constructed here to specify the posture of the mobile welding robot: an internal Cartesian frame $\{X \quad O \quad Y\}$ linked to the world and $\{X' \quad C \quad Y'\}$ linked to the mobile platform. Center of mass of the mobile robot is located at C, and C is the middle of the axis of the two deriving wheels. The posture of the robot in the global coordinate frame $\{X \quad O \quad Y\}$ can be described by three generalized coordinates

$$q = [x_c \quad y_c \quad \theta]^T \tag{1}$$

where, x_c , y_c are the coordinates of the point C in the global coordinate frame and θ is the orientation of the mobile robot measured from X-axis.

The non-holonomic constraint declares that driving wheels purely roll and do not slip. In other words, the mobile robot can only move in a direction which is normal to the axis of the driving wheels.

$$\dot{y}_c \cos\theta - \dot{x}_c \sin\theta = 0 \tag{2}$$

Therefore, the kinematical equation of the mass center of the mobile robot can be described as

$$\dot{q} = \begin{bmatrix} \dot{x}_c \\ \dot{y}_c \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_c \\ \omega_c \end{bmatrix} \tag{3}$$

where v_c is the linear velocity of the point C along the robot axis, and ω_c is the angular velocity.

The welding point $w(x_w, y_w)$ on torch and its orientation angle θ_w can be derived from the mobile robot mass center $c(x_c, y_c)$ as

$$x_\mathrm{w} = x_\mathrm{c} - l\sin\theta, \quad y_\mathrm{w} = y_\mathrm{c} + l\cos\theta, \quad \theta_\mathrm{w} = \theta \tag{4}$$

where l is the length of welding torch. The derivative of equation (4) is

$$\begin{bmatrix} \dot{x}_w \\ \dot{y}_w \\ \dot{\theta}_w \end{bmatrix} = \begin{bmatrix} \cos\theta & -l\cos\theta \\ \sin\theta & -l\sin\theta \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_c \\ \omega_c \end{bmatrix} + \begin{bmatrix} -\dot{l}\sin\theta \\ \dot{l}\cos\theta \\ 0 \end{bmatrix} \tag{5}$$

3. Control design

3.1. Back-stepping controller

As shown in Fig.2, AB is the welding seam, R is the reference position, where the reference welding velocity is v_r, and the angular velocity is ω_r, and the posture tracking error is defined as q_e, which is a transformation of the reference posture q_r relative to a frame fixed on the mobile platform.

$$q_e = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_r - x_W \\ y_r - y_W \\ \theta_r - \theta_W \end{bmatrix} \tag{6}$$

From equations (5), (6), we can get

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = v_c \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix} + \omega_c \begin{bmatrix} l + e_2 \\ -e_1 \\ -1 \end{bmatrix} + \begin{bmatrix} v_r \cos e_3 \\ v_r \sin e_3 - \dot{l} \\ \omega_r \end{bmatrix} \tag{7}$$

We define the control parameters of the robot including mobile platform and slider as follows

$$q_c = \begin{bmatrix} v_c \\ \omega_c \\ v_s \end{bmatrix} = \begin{bmatrix} k_1 e_1 + v_r \cos e_3 + (\omega_r + k_2 v_r e_2 + k_3 \sin e_3) l \\ \omega_r + k_2 v_r e_2 + k_3 v_r \sin e_3 \\ k_4 e_2 \end{bmatrix} \tag{8}$$

where $k_1, k_2, k_3, k_4 > 0$, and v_s is the motion velocity of horizontal slider.

3.2. Stability analysis

In above control rule, $q_e = 0$ is a stable equilibrium point if the reference velocity $v_r > 0$ .Let us propose a scalar function V as Lyapunov function candidate by using the back-stepping method

$$V = (e_1^2 + e_2^2)/2 + (1 - \cos e_3)/k_2 \tag{9}$$

Apparently, $V \geq 0$. Furthermore, we can get following results.

$$\dot{V} = e_1\dot{e}_1 + e_2\dot{e}_2 + \frac{1}{k_2}\dot{e}_3 \sin e_3 = -k_1 e_1^2 - k_4 e_2^2 - \frac{k_3}{k_2} v_r \sin^2 e_3 \tag{10}$$

Apparently, $\dot{V} \le 0$. Then, V becomes a Liapunov function.

Assume that v_r and ω_r are continuous, and v_r, ω_r, k_1, k_2, k_3 and k_4 are bounded, and $\dot{v}_r$, $\dot{\omega}_r$ are sufficiently small. We linearize the following differential equation around $q_e = 0$.

$$\dot{q}_e = \begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} -v_c + (l+e_2)\omega_c + v_r \cos e_3 \\ -e_1\omega_c + v_r \sin e_3 - \dot{l} \\ \omega_r - \omega_c \end{bmatrix} = \begin{bmatrix} -k_1 e_1 + (\omega_r + k_2 v_r e_2 + k_3 \sin e_3) e_2 \\ -(\omega_r + k_2 v_r e_2 + k_3 \sin e_3) e_1 + v_r \sin e_3 - k_4 e_2 \\ -k_2 v_r e_2 - k_3 v_r \sin e_3 \end{bmatrix}$$
$$\approx \begin{bmatrix} -k_1 e_1 + \omega_r e_2 \\ -\omega_r e_1 - k_4 e_2 + v_r e_3 \\ -k_2 v_r e_2 - k_3 v_r e_3 \end{bmatrix} = \begin{bmatrix} -k_1 & \omega_r & 0 \\ -\omega_r & -k_4 & v_r \\ 0 & -k_2 v_r & -v_r k_3 \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = A q_e \tag{11}$$

Then, A is continuously differentiable and is a bounded matrix. The characteristic equation for A is

$$a_3 s^3 + a_2 s^2 + a_1 s + a_0 = 0 \tag{12}$$

Where $a_3 = 1, a_2 = v_r k_3 + k_1 + k_4, a_1 = k_1 k_4 + v_r k_3 (k_1 + k_4) + v_r^2 k_2 + \omega_r^2, a_0 = k_1 k_4 k_3 v_r + v_r^2 k_2 k_1 + \omega_r^2 v_r k_3$.
Since all conditions $a_i > 0 (i = 1,2,3,4)$

$$a_1 a_2 - a_0 a_3 = (v_r^2 k_3^2 + k_1 k_4 + \omega_r^2)(k_1 + k_2) + v_r^3 k_2 k_4 + v_r k_3 (k_1 + k_4)^2 + v_r^2 k_2 k_4 > 0 \tag{13}$$

The real parts of all roots are negative through the Routh-Hurwitz Criterion. Under these conditions, $q_e = 0$ is uniformly asymptotically stable over $[0, \infty]$.

3.3. Control scheme and neural network self-turning

If the kinematical model of the mobile robot (5) with velocity input (8) is considered only and assume “perfect velocity tracking”, then the kinematical model is asymptotically stable with respect to the reference trajectory (i.e. $q_e \to 0$ as $t \to \infty$). However, in many practical cases, exact knowledge of the mobile robot kinematics is unattainable, and the “perfect velocity tracking” assumption may not hold well in practice. From above description we can see that our robot system has a rotational arc sensor, it can detect e_2 directly. From equation (8) we know that v_s is influenced only by e_2 and the influence coefficient k_4 is independent of v_c and ω_c. So we take e_2 and $\dot{e}_2$ as input vector to design fuzzy controller to control slider, and take the velocity V_c ($V_c = [v_c \quad \omega_c]$) as desired value to control left and right wheels.

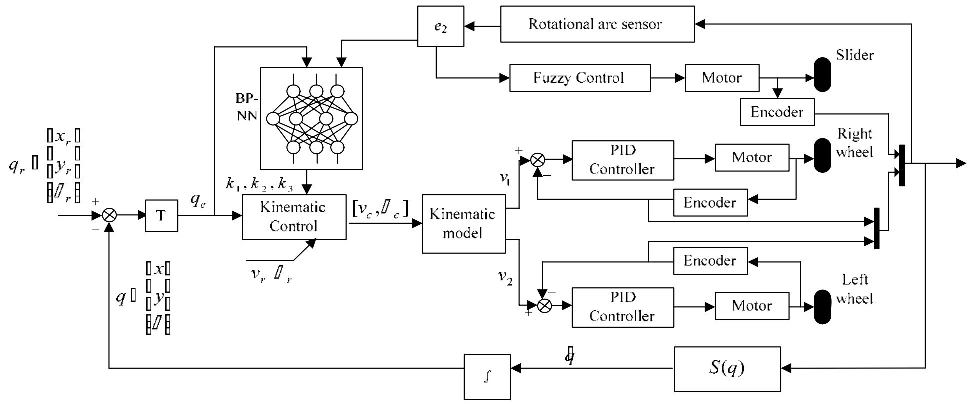


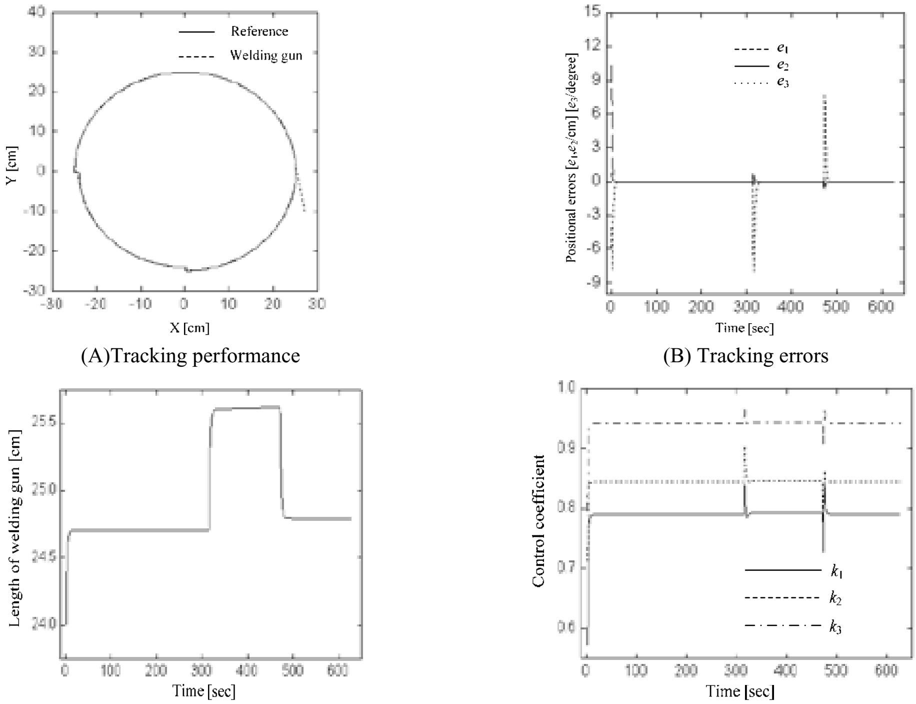
Fig.3 Block diagram of tracking control of mobile robot

The proposed tracking control scheme is shown in Fig.3. The nonlinear feedback control law (8) is applied to produce desired velocity vector V_c, and then based on V_c the desired velocities of left and right wheels are acquired. The velocity commands are applied via proportional integral derivative (PID) controllers to the motors. Each wheel (right and left) is actuated by a DC motor. The data provided by the encoders attached to the motors allow calculating the actual velocities of wheels, and taken as the inputs of the robot kinematics model, where the model is used to calculate robot posture. A back propagation neural networks is designed to adjust the values of k_1, k_2 and k_3. The neural networks has three inputs e_1, e_2 and e_3, and has five neurons in hidden layer. The neuron activation function in hidden layer and output layer is sigmoid function.

4. Simulation and experiment results

The proposed control method is first verified with computer simulation using MATLAB. For simulation purpose, two types of reference trajectories have been chosen. The first simulation is carried out with a circular reference trajectory and the other simulation is carried out with a sinusoidal reference trajectory. For the first simulation, the circular reference trajectory is given by $x_r(t) = 250\cos\omega t$, $y_r(t) = 250\sin\omega t$, $\omega = 0.1$ .The reference trajectory starts from $q_r = [250, 0, \pi/2]^{\mathrm{T}}$,and the welding gun end point initial posture is taken as $q(0) = [270, -100, \pi/1.9]^{\mathrm{T}}$.

The initial length of the welding is taken as $L(0) = 240\text{mm}$. For verify the ability of anti-jamming of the proposed control method, the circular trajectory radius is changed from 250 to 240 between π and $3\pi/2$. The simulation results are shown in Figs.4A-D.



(A)Tracking performance

(B) Tracking errors

(C) Length of welding gun

(D) Control coefficient

Fig.4 Simulation results of tracking a circular

Fig.4A shows the welding gun tracks the virtual reference, from where we can see when the tracked trajectory is changed, the welding gun can rapidly track it, and the tracking errors sharply drop to very small values as shown in Fig.4B. Fig.4C shows that the welding gun rapidly extends and draw back based on the change of the circular radius. Fig.4D shows that when the tracking errors have a sharp change, the control coefficients k_1, k_2, k_3 would change correspondingly based on the neural networks adjusting.

Simulation is also curried out with a sinusoidal reference trajectory. The reference trajectory is given by $x_r(t) = \omega t$, $y_r(t) = 500\sin(\omega t)$, $\omega = 0.01$, $t \in [0, 200\pi]$ .The robot and slider initial posture is same to the reference trajectory starts posture. The initial length of the slider is taken as $L(0) = 240\text{mm}$. The simulation results are shown in Fig.5-Fig.8.

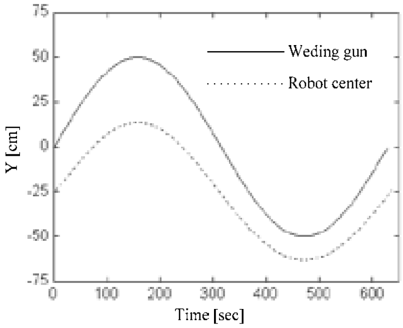


Fig.5 Trajectories of welding gun and robot center

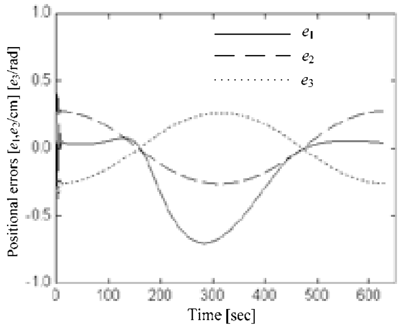


Fig.6 Tracking errors

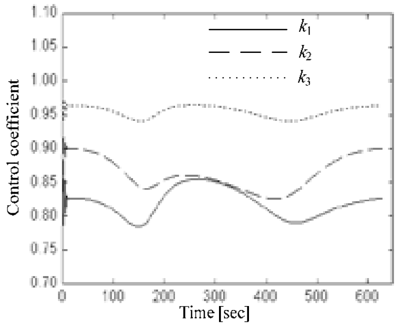


Fig.7 Control coefficients

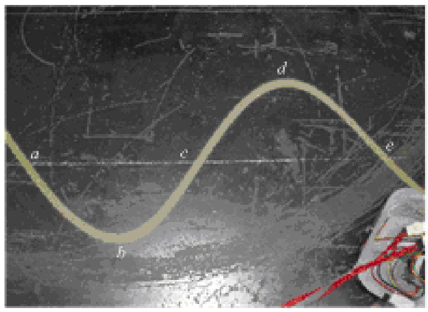


Fig.8 Experimental result

Fig.5 shows trajectories of welding gun and robot center respectively. It shows that the curvature of the robot center trajectory is small than welding gun trajectory, which enable robot moving more smoothness. Fig.6 shows that the tracking errors and Fig.7 shows the change of control coefficients k_1, k_2, k_3 respectively. To demonstrate the feasibility and effectiveness of the control method further, the control laws are applied to the experimental mobile robot. We use falling sands method to record the welding gun trajectory and to simulate the welding process. The reference trajectory is same to the trajectory in Fig.5, and the experiment result is shown as Fig.8.

5. Conclusion

In this paper a controller is proposed for solving the welding seam tracking problem of mobile robots and the stability of the controller is proved using Lyapunov stability theory. A neuronal net work is designed to tune control gains in real time based on the data detected from arc sensor. Simulation and experimental results validate the proposed controller. The characteristics of the proposed control method are summary as follows.

1) No dynamics model of the mobile robot is required for the controller design. The control parameters are tuned in real time fashion based the detected errors in the process of welding seam tracking
2) The control object is the end point of the manipulator instead of the mobile robot center. The controller controls horizontal slider and driving wheels coordinately in the tracking process and makes the manipulator end point moving with a constant velocity.
3) The mass center of the robot is not a constant point in the tracking process because of the moving of the horizontal slider.

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