USING ADAPTIVE CONTROL TO SOLVE THE TRACKING PROBLEM FOR A MOBILE MANIPULATOR

Tran Thien Phuc
University of Technology, VNU-HCM

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ABSTRACT: *In this paper, the control of a mobile manipulator for tracking smooth 3D-curved welding trajectory is discussed. This case can be found in any metal processing factories such as ship building factories and pre-fabricated metal structure factories. The mobile manipulator is made up of a multilink manipulator and a two-wheeled mobile platform. The kinematic modeling and the constraints for both the platform and the manipulator are discussed. Based on these modeling, an adaptive control algorithm for the welding mobile manipulator is proposed. A candidate Lyapunov function is also introduced for proving the stability of system upon the adaptive algorithm. For increasing the flexibility of system, the control of system with unknown parameter such as the arc length of the torch is considered, and an update control law based on the adaptive back-stepping method is proposed. In this paper, the numerical simulation results are shown to illustrate the validity of the proposed algorithm. The experiments are also performed for getting the good values of parameters and proving the feasibility that a mobile manipulator is applied to a 3D smooth curve welding task.*

Keywords: *Mobile manipulator, 3D smooth curve welding task, unknown parameter, update control law, adaptive back-stepping method.*

1. INTRODUCTION

Recently, a mobile manipulator has been widely used in various industrial fields such as ship building industry, automobile industry, electronic assembling, and pre-fabricated metal structure industry. Furthermore, it can be applied to works in the hazardous environments such as waste management and treatment, desolate exploration and even space operation. Especially, the mobile robots are extensively used in industry for resistance and arc-welding applications. The mobile manipulator can be used for performing the welding task with high quality. Furthermore, the workers with the aid of the welding robot can perform their tasks even in contaminative environment with smoke and light arc. Nowadays, the application of the mobile robot to welding task has been studied by many researchers, such as Bui et al. (2003), Fukao et al. (2000), Jeon et al. (2002), Lefeber et al. (2001), and Lee et al. (2001). These mobile robots are focused on horizontal line tracking purpose. To attain the same purpose in the narrow space, Yoo et al. (2001) used a mobile manipulator, a horizontal multi-link manipulator mounted on a platform with two independent driving wheels. Thus, this mobile manipulator was used only for the horizontal fillet welding paths.

In this paper, an adaptive controller is applied to a two-wheeled welding mobile manipulator to track a smooth 3D-curved welding trajectory. To design a tracking controller, the tracking errors are defined between the welding point on the torch and the reference point moving at a specified constant welding speed along the welding trajectory. Both kinematic modeling of the mobile platform and the manipulator are introduced. Hence, the relationship between the input variables (angular velocities of the wheels of the platform and the links of the manipulator) and the output parameter (position and velocity of the end effector) is established. In order to increase the flexibility of the system, an adaptive control algorithm based on the back-stepping concept with unknown parameter such as the arc length of torch is proposed. The simulations using MatLab V6.5 and Simulink V5.1 are also performed to show the effectiveness of the proposed controller. The paper also shows how to get the tracking errors by the potentiometer and the camera sensor. The experiments are performed for getting the practical information. A camera sensor made in Carnegie Mellon University and a potentiometer are used for gathering the feedback signals that are invoked for measure the tracking errors.

2. SYSTEM MODELING

2.1. Configuration of the Mobile Manipulator

The following constraints will be examined for choosing the configuration of the mobile manipulator. The orientation of the torch should lie on the tangent plane of the welding trajectory at the welding point. The orientation of the torch should also be inclined with 45 degrees with respect to the intersectional line between the tangent plane and the welding trajectory surface at welding point. This is considered for ensuring the good condition for the quality of the welding seam.

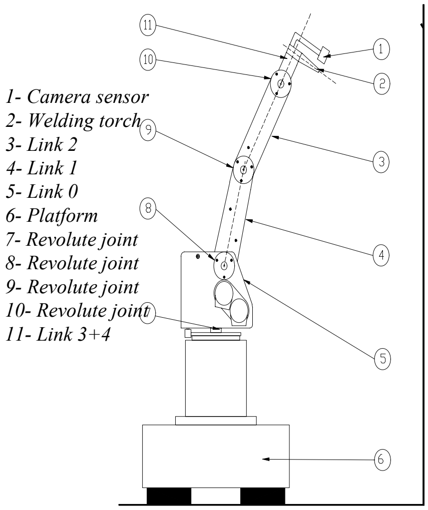


Fig 1. Mobile manipulator configuration

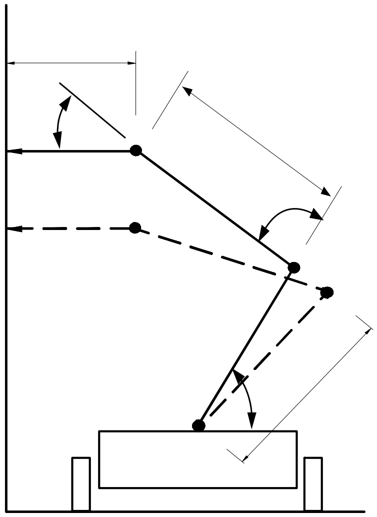


Fig 2. Manipulator motion in welding process

According to the above conditions, in the configuration of the manipulator, the torch orientation is fixed on the tilt of 45 degrees with respect to the link direction of the 4th-link. The link direction of the 4th-link always is kept in the perpendicular direction of the welding trajectory surface at the welding point (see in the Fig. 2 for more detail). With the above condition, the torch orientation always lies on the plane which is created by the tangent line and the normal line of the welding trajectory at the welding point, and is inclined with 45 degrees with respect to the tangent line of the welding trajectory at the welding point. The rotation of the last link assures that the orientation of torch has a right gesture at the certain welding point. In order to perform the welding task, an assignment for the mobile platform and the manipulator is made as: the mobile platform should track the curved surface in which the welding trajectory lies on, and the manipulator has the duty of reaching to the altitude of the welding point.

2.2 Kinematic Modeling for the Mobile Platform

The kinematic equation of the platform can be described as the following:

$$\begin{bmatrix} \dot{x}_C \\ \dot{y}_C \\ \dot{\phi}_C \\ \dot{\theta}_r \\ \dot{\theta}_l \end{bmatrix} = \begin{bmatrix} \cos\phi_C & 0 \\ \sin\phi_C & 0 \\ 0 & 1 \\ 1/r & b/r \\ 1/r & -b/r \end{bmatrix} \begin{bmatrix} v_{xy} \\ \omega_\phi \end{bmatrix}, \tag{1}$$

where $q_p = [x_C \quad y_C \quad \phi_C \quad \theta_r \quad \theta_l]^T$ is the generalized coordinate of the mobile platform, for more detail, $C(x_C, y_C, 0)$ is the coordinate of the platform's center point, and ϕ_C is the heading angle of the platform; $\dot{\theta}_r, \dot{\theta}_l$ are the angular velocities of the right and left wheels of the mobile platform; r, b are radius of the wheel and the distance from wheel to the symmetry axis, respectively ; v_{xy} and ω_ϕ are the straight and angular velocity of the platform in x-y plane, respectively and are supposed be bounded values.

It is assumed that the wheels of the mobile platform do not slip. So, the velocity of C must be kept in the direction of the axis of symmetry and the wheels must purely roll. The constraints are expressed as follows:

$$A(q_p)\dot{q}_p = 0, \tag{2}$$

or for this case:

$$\begin{bmatrix} -\sin\phi_C & \cos\phi_C & 0 & 0 & 0 \\ \cos\phi_C & \sin\phi_C & b & -r & 0 \\ \cos\phi_C & \sin\phi_C & -b & 0 & -r \end{bmatrix} \begin{bmatrix} \dot{x}_C \\ \dot{y}_C \\ \dot{\phi}_C \\ \dot{\theta}_r \\ \dot{\theta}_l \end{bmatrix} = 0. \tag{3}$$

2.3 Kinematic Modeling for the Manipulator

In practice, the manipulator is considered as a plane mechanism with three links as shown in Fig. 2. Furthermore, in welding process, to retain the correct direction of the torch with respect to the welding path, the link 3 is always fixed in the horizontal direction. The constraint can be expressed as below:

$$\begin{cases} \theta_1 + \theta_2 + \theta_3 = \pi \\ \omega_1 + \omega_2 + \omega_3 = 0 \end{cases}. \tag{4}$$

where θ_i and ω_i are the link variables and the angular velocities of the ith-link of the manipulator.

The kinematic equation of the manipulator can be described as the following:

$$\dot{q}_E = J(q_m)\dot{q}_m \,, \tag{5}$$

where $\dot{q}_E$ is position of the torch tip, J is Jacobian matrix of the manipulator, q_m is link variable of the manipulator.

In case of the planar three-link manipulator, (5) can be re-expressed as:

$$\begin{bmatrix} \dot{x}_E \\ \dot{z}_E \\ \dot{\omega}_E \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} , \tag{6}$$

where l_i is the length of ith-link, and $S_{ij} = \sin(\theta_i + \theta_j), C_{ij} = \cos(\theta_i + \theta_j)$,

$J_{11} = l_2 S_3 + l_1 S_{23}\,, J_{12} = l_2 S_3\,, J_{13} = 0$, $J_{21} = l_3 + l_2 C_1 + l_1 C_{23}\,, J_{22} = l_3 + l_2 C_3$,

$J_{23} = l_3\,,\ J_{31} = J_{32} = J_{33} = 1$,

The inverse kinematic equation is defined as:

$$\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} = \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} = \begin{bmatrix} J_{11}^{-1} & J_{12}^{-1} & J_{13}^{-1} \\ J_{21}^{-1} & J_{22}^{-1} & J_{23}^{-1} \\ J_{31}^{-1} & J_{32}^{-1} & J_{33}^{-1} \end{bmatrix} \begin{bmatrix} \dot{y}_E \\ \dot{z}_E \\ \dot{\omega}_E \end{bmatrix} , \tag{7}$$

where $J_{11}^{-1} = l_2 C_3\,, J_{12}^{-1} = -l_2 S_3 - l_1 S_{23}$, $J_{13}^{-1} = l_2 l_3 S_3\,, J_{21}^{-1} = -l_2 C_3 - l_1 C_{23}$,

$J_{22}^{-1} = l_2 S_3 + l_1 S_{23}$, $J_{23}^{-1} = -l_2 l_3 S_3 - l_1 l_3 S_{23}$, $J_{31}^{-1} = l_1 C_{23}\,, J_{32}^{-1} = -l_1 S_{23}$,

$J_{33}^{-1} = l_1 l_3 S_{23} + l_1 l_3 S_2$.

2.4 Kinematic Equation for the Welding Torch Tip

The relationship between the welding point $W(x_w, y_w, z_w, \phi_w)$ and the center of the mobile platform $C(x_C, y_C, z_C, \phi_C)$ can be expressed as following:

$$\begin{bmatrix} x_w \\ y_w \\ z_w \\ \phi_w \end{bmatrix} = \begin{bmatrix} x_C - p_m \sin\phi_C \\ y_C + p_m \cos\phi_C \\ z_C + l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) \\ \phi_C \end{bmatrix} \tag{8}$$

where p_m is the distance from the projection of the manipulator torch tip on the x-y plane to the center C of platform, ϕ_w is the heading angle in the horizontal plane of the welding torch, and ϕ_C is the heading angle of the mobile platform.

Combining the derivative of (8) and the angular velocity of the torch yields the kinematic equation for the welding torch tip as follows:

$$\begin{bmatrix} \dot{x}_w \\ \dot{y}_w \\ \dot{z}_w \\ \dot{\phi}_w \\ \dot{\psi}_w \end{bmatrix} = \begin{bmatrix} \cos\phi_C & -p_m\cos\phi_C & 0 & 0 & 0 \\ \sin\phi_C & -p_m\sin\phi_C & 0 & 0 & 0 \\ 0 & 0 & l_1\cos\theta_1 + l_2\cos(\theta_1+\theta_2) & l_2\cos(\theta_1+\theta_2) & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_{xy} \\ \omega_\phi \\ \omega_1 \\ \omega_2 \\ \omega_\psi \end{bmatrix} \quad (9)$$

where ψ_w and ω_ψ are the heading angle and the angular velocity of the welding torch in vertical plane, respectively. It is assumed that ω_ψ is bounded.

3. CONTROLLER DESIGN

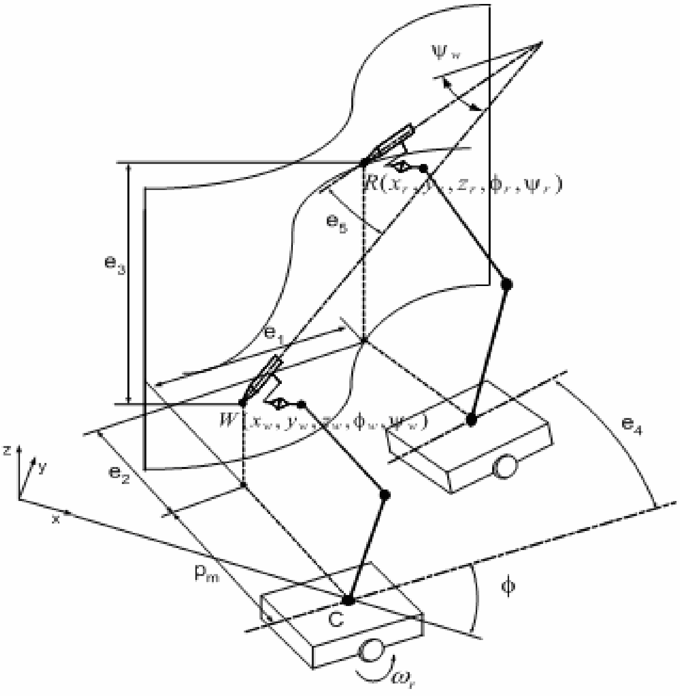


Fig 3. Tracking errors of the mobile manipulator

The vector $[e_1 \quad e_2 \quad e_3 \quad e_4 \quad e_5]^T$ is denoted as the vector of the tracking error that is the difference between the welding position $W(x_w, y_w, z_w, \phi_w, \psi_w)$ and the reference position $R(x_r, y_r, z_r, \phi_r, \psi_r)$ (see Fig. 3 for more detail). This vector is expressed as:

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \end{bmatrix} = \begin{bmatrix} \cos\phi_w & \sin\phi_w & 0 & 0 & 0 \\ -\sin\phi_w & \cos\phi_w & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_r - x_w \\ y_r - y_w \\ z_r - z_w \\ \phi_r - \phi_w \\ \psi_r - \psi_w \end{bmatrix} \tag{10}$$

where the subscript r and w imply reference and welding, respectively.

A control law should be found out to obtain $e_i \rightarrow 0$ as $t \rightarrow \infty$ for the welding point W to become to coincide with its reference point R. Easily, the derivative form of the tracking errors is as follows:

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \\ \dot{e}_4 \\ \dot{e}_5 \end{bmatrix} = \begin{bmatrix} v_r \cos\psi_r \cos e_4 \\ v_r \cos\psi_r \sin e_4 \\ v_r \sin\psi_r \\ \omega_{\phi r} \\ \omega_{\psi r} \end{bmatrix} + \begin{bmatrix} -1 & e_2 + p_m & 0 & 0 \\ 0 & -e_1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} v_{xy} \\ \omega_\phi \\ v_z \\ \omega_\psi \end{bmatrix} \tag{11}$$

where v_r is the reference velocity in the welding trajectory, and is bounded and large than zero, v_{xy} is the x-y component velocity of v_r, v_z is the z component velocity of v_r, $\omega_{\phi r}$ and $\omega_{\psi r}$ are reference rotational velocity in x-y plane and vertical plane, respectively .

The projection of manipulator in x-y plane is denoted pm. In practice, the value of parameter pm can be varied because the arc length of the torch depends on many other parameters such as the current intensity of power supplied, and the geometric quality of the surface. Thus, an adaptive controller is designed to obtain the control objective by using the estimates of the parameter pm. $\hat{p}_m$ and $\tilde{p}_m$ are denoted as the estimated values and the estimated error of p_m , respectively.

$$\hat{p}_m = p_m + \tilde{p}_m , \tag{12}$$

$$\dot{\hat{p}}_m = \dot{\tilde{p}}_m , \tag{13}$$

Equation (11) can be re-expressed as follows:

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \\ \dot{e}_4 \\ \dot{e}_5 \end{bmatrix} = \begin{bmatrix} v_r \cos\psi_r \cos e_4 \\ v_r \cos\psi_r \sin e_4 \\ v_r \sin\psi_r \\ \omega_{\phi r} \\ \omega_{\psi r} \end{bmatrix} + \begin{bmatrix} -1 & e_2 + \hat{p}_m & 0 & 0 \\ 0 & -e_1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} v_{xy} \\ \omega_\phi \\ v_z \\ \omega_\psi \end{bmatrix} \tag{14}$$

The Lyapunov candidate function is chosen as follows:

$$V = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 + \frac{1}{2}e_3^2 + \frac{1-\cos e_4}{k_2} + \frac{1}{2}e_5^2 + \frac{1}{2k_6}\hat{p}_m^2 > 0 \tag{15}$$

The derivative form of (15) is expressed as follows:

$$\dot{V} = e_1\dot{e}_1 + e_2\dot{e}_2 + e_3\dot{e}_3 + \frac{\sin e_4}{k_2}\dot{e}_4 + e_5\dot{e}_5 + \frac{\hat{p}_m}{k_6}\dot{\hat{p}}_m$$

$$= e_1(v_r \cos\psi_r \cos e_4 - v_{xy}) + e_3(v_r \sin\psi_r - v_z) + \frac{\sin e_4}{k_2}(k_2 e_2 v_r \cos\psi_r + \omega_{\phi r} - \omega_\phi)$$

$$+ e_5(\omega_{\psi r} - \omega_\psi) + \hat{p}_m(\omega_\phi e_1 + \frac{\dot{\hat{p}}_m}{k_6})$$

The control law is chosen as the following:

$$\begin{cases} v_{xy} = v_r \cos\psi_r \cos e_4 + k_1 e_1 \\ v_z = v_r \sin\psi_r + k_3 e_3 \\ \omega_\phi = \omega_{\phi r} + k_2 e_2 v_r \cos\psi_r + k_4 \sin e_4 \\ \omega_\psi = \omega_{\psi r} + k_5 e_5 \\ \dot{\hat{p}}_m = -k_6 \omega_\phi e_1 \end{cases} \tag{16}$$

where $k_1, k_2, k_3, k_4, k_5, k_6$ are positive values.

From (15) and (16), $\dot{V}$ can be re-expressed as the following:

$$\dot{V} = -k_1 e_1^2 - k_3 e_3^2 - \frac{k_4}{k_2}\sin^2 e_4 - k_5 e_5^2 \le 0 \tag{17}$$

It is assumed that all errors ei are bounded so $\ddot{V}$ is bounded too, that is to say, $\dot{V}$ is uniformly continuous. Since V does not increase and converges to certain constant value, by Barbalat's lemma, $\dot{V} \to 0$ as $t \to \infty$ (Fierro and Lewis (1995)). When $\dot{V}$ equals zero, from (17) one can implies that $\begin{bmatrix} e_1 & e_3 & e_4 & e_5 \end{bmatrix}^T \to 0$ as $t \to \infty$. From the third row of (16) it is easy to obtain $e_2 \to 0$ as $t \to \infty$.

And so, from (1), (7), and (16), the control law for mobile manipulator with update rule can be expressed as the following:

$$\begin{bmatrix} \omega_r \\ \omega_l \\ \omega_1 \\ \omega_2 \\ \omega_\psi \\ \dot{\hat{p}}_m \end{bmatrix} = \begin{bmatrix} 1/r & 0 & b/r & 0 \\ 1/r & 0 & -b/r & 0 \\ 0 & \dfrac{\sin\theta_{12}}{l\sin\theta_2} & 0 & 0 \\ 0 & \dfrac{-\sin\theta_1 - \sin\theta_{12}}{l\sin\theta_2} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -k_6 e_1 & 0 \end{bmatrix} \begin{bmatrix} v_{xy} \\ v_z \\ \omega_\phi \\ \omega_\psi \end{bmatrix} \tag{18}$$

and $\omega_3 = -(\omega_1 + \omega_2)$

4. SIMULATION AND EXPERIMENT RESULTS

Table 1. Numerical values for the simulation

Parameter	K_1	k_2	K_3	K_4	k_5	p_m	l	B	r
Value	1	5	1.5	2.5	1.2	380	222	150	30

A reference welding trajectory as shown in the Fig. 6 is chosen for simulation and experiment. Matlab software (version 6.5) and Simulink software (version 5.1) are also invoked to perform the simulation. Some parameter values of the mobile manipulator used in the simulation are given in Table 1. In Figs. 4 and 5, the model of mobile manipulator used in the experiments is shown. The simulation results are shown in the Figs. 7 - 10.

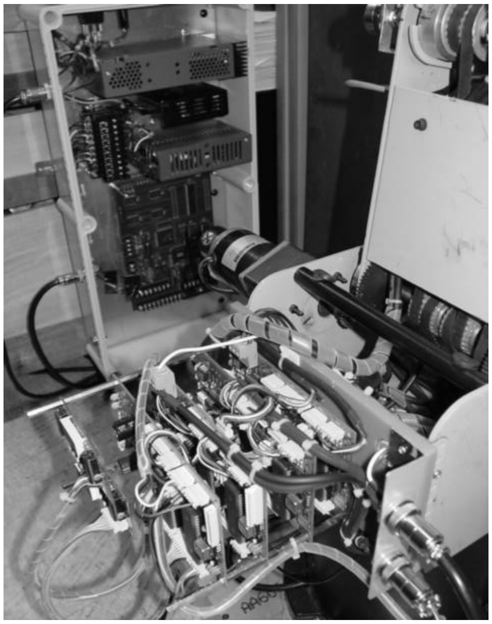


Fig 4. Implementation of the control system

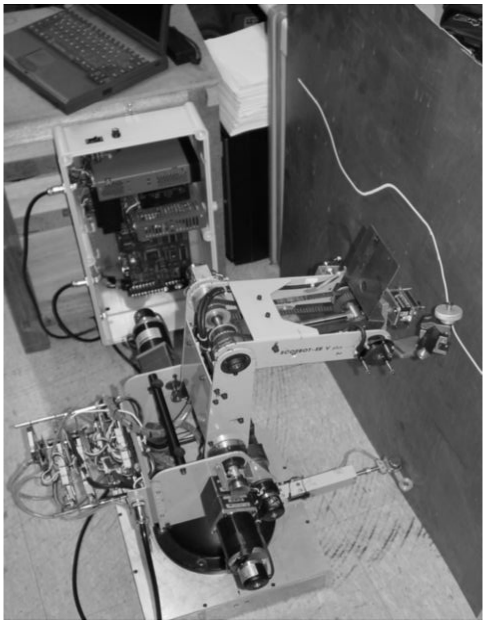
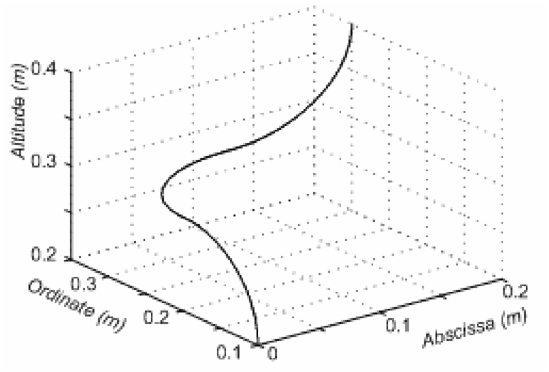


Fig 5. Mobile manipulator in welding process

In Figs. 7 and 8, all of tracking errors converge to zero after about 4.5 seconds, and they show the validity of the proposed algorithm. Fig. 9 shows the estimation value $\hat{p}_m$, and the comparison between reference and welding trajectories is shown in Fig. 10.

The experiments are also performed, and the results are shown in Figs. 11 - 15. For an easy comparison, both the simulation value and the experiment value of the same tracking error are put on the same graph.

The experiment results with the errors not exceed 1mm or 1.5 degree from the simulation values show the feasibility of proposed algorithm for applied on welding process after the system is stable.



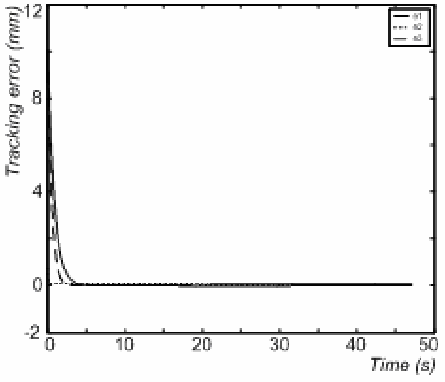
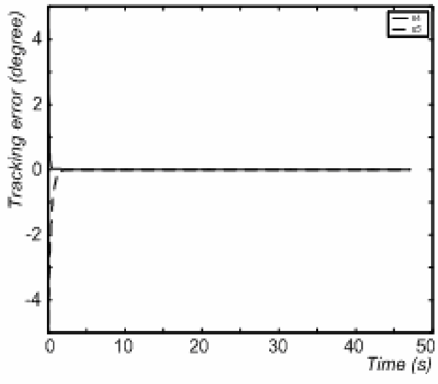


Fig 6. Reference 3D curved trajectory

Fig 7. Tracking errors e1, e2, e3



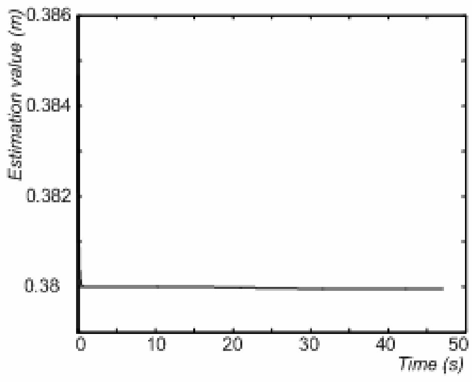
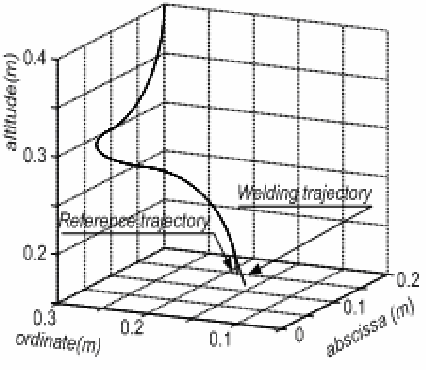


Fig 8. Tracking errors e4, e5

Fig 9. Estimate value of pm



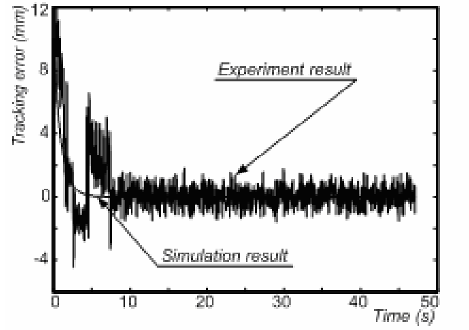


Fig 10. Reference and welding trajectories

Fig 11. Tracking error e1

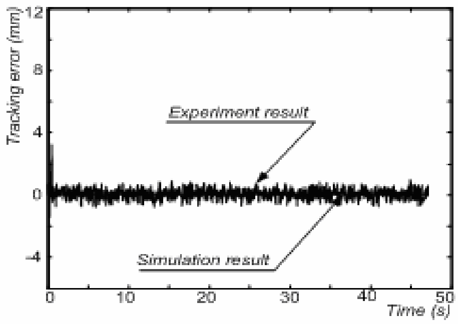


Fig 12. Tracking error e2

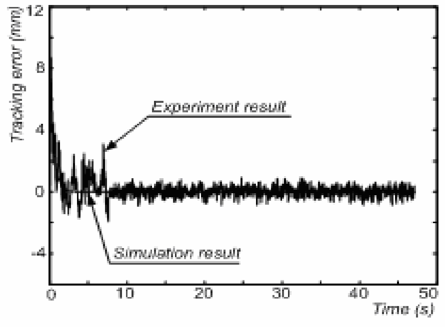


Fig 13. Tracking error e3

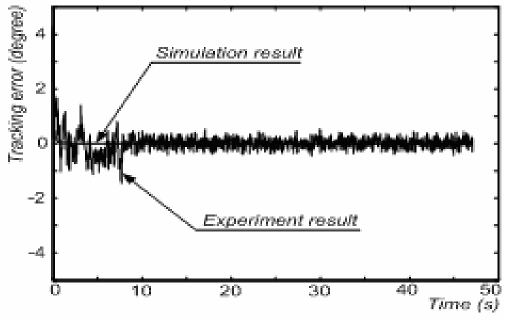


Fig14. Tracking error e4

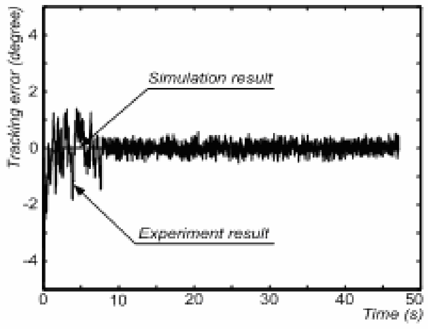


Fig 15. Tracking error e5

5. CONCLUSIONS

The proposed algorithm is really simple and very easy for use but it has shown the feasibility of an application performing a smooth 3D curved welding trajectory. The controller of the mobile manipulator is designed based on the Lyapunov stability and the kinematic modeling. The algorithm also solves a common problem that occurs in welding process: the arc length cannot be precisely measured. An unknown parameter adaptive control update law was used for solving this problem. The simulation results show the quick convergence to zero of the tracking errors and the good system response of model in the welding process. The experiment results also show the validity of the proposed control algorithm.

ÁP DỤNG ĐIỀU KHIỂN THÍCH NGHI VÀO BÀI TOÁN THEO VẾT ĐƯỜNG HÀN CHO TAY MÁY DI ĐỘNG

Trần Thiên Phúc
Trường Đại học Bách khoa, ĐHQG-HCM

TÓM TẮT: *Chủ đề của bài báo này là điều khiển một tay máy di động theo vết một đường cong hàn không gian. Đây là vấn đề thường gặp trong các nhà máy gia công kim loại cỡ lớn như đóng tàu hay kết cấu thép tiền chế. Tay máy di động ở đây bao gồm một tay máy nhiều bậc tự do và một xe robot dạng hai bánh. Bài báo trình bày các vấn đề về mô hình động học của cả hai phần tử này. Bộ điều khiển thích nghi cho tay máy di động được xây dựng dựa trên mô hình này. Tiêu chuẩn ổn định Lyapunov được sử dụng để chứng minh sự hội tụ ổn định của sai số hệ thống. Nhằm tăng tính thực dụng của hệ thống, thông số dự đoán là chiều dài hồ quang hàn được tính đến trong bài toán. Các thí nghiệm mô phỏng và thực nghiệm trên mô hình cũng được tiến hành để chứng minh tính khả thi của bộ điều khiển.*

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