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Adaptive Control of Mobile Manipulator to Track Horizontal Smooth Curved Apply for Welding Process

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Abstract:- In this paper, an adaptive control of mobile manipulator to track horizontal smooth curved applying for welding process is presented. The requirements of welding task are that the end effector must track along a welding trajectory with a constant velocity and must be inclined to the welding trajectory with a constant angle in the whole welding process. The mobile manipulator is divided into two subsystems such as the tree linked manipulator and the wheeled mobile platform. Two controllers are designed based on the decentralized motion method. However, there exists the relation among the controllers such as the velocities of subsystems at the previous sampling time. In order to avoid the singularity of configuration of the manipulator, a control algorithm is proposed to maintain that the initial configuration of manipulator throughout welding process. The mobile platform has to move to guarantee the unchanged configuration of the manipulator. This problem is solved using a set of tracking errors of the mobile platform so that the initial configuration of manipulator is unchanged when these errors go to zero. The interaction between the manipulator and the mobile platform is determined based on the D'Alembert principle, and an adaptive tracking motion controller for the mobile platform is designed using the "computed torque" method. The effectiveness of the proposed control system is proven through the simulation results.

Keywords:- *mobile platform (MP), welding mobile manipulator (WMM), manipulator, trajectory tracking, Lyapunov function.*

I. INTRODUCTION

Nowadays, the working condition in the industrial fields has been improved greatly. In the hazardous and harmful environments, the workers are substituted by the welding robots to perform the operations. Especially in welding field, the welders are substituted by the welding manipulators to perform the welding tasks.

Traditionally, the manipulators are fixed on the floor. Their workspaces are limited by the reachable abilities of their structures. In order to overcome this disadvantage, the manipulators that are movable are used for enlarging their workspaces. These manipulators are called the mobile manipulators. In this study, the structure of the mobile manipulator includes a three-linked manipulator plus a two-wheeled mobile platform.

In recent years, there has been a great deal of interest in mobile robots and manipulators. The study about mobile robots is mostly concentrated on a question: how to move from here to there in a structured/unstructured environment. It includes three algorithms that are the point to point, tracking and path following algorithm. The manipulator is a subject of a holonomic system. The study on manipulators is mostly concentrated on a question: how to move the end effector from here to there and it also has three algorithms like the case of the mobile robot. Although there has been a vast amount of research effort on mobile robots and manipulators in the literature, the study on the mobile manipulators is very limited. It is hopeful that this paper will make a little contribution for the mobile manipulator research.

The previous works are concentrated on the following topics

● ***Motion control of a wheeled mobile robot***

The mobile platform is a subject of non-holonomic system. Assume that the wheels roll purely on a horizontal plane without slippage. The mobile platform robot used in this study has two independent driving wheels and one passive caster for balancing. Several researchers studied the wheeled mobile robot as a non-holonomic system. Kanayama et al.[8] (1991) proposed a stable tracking control method for a non-holonomic mobile robot. The stability is guaranteed by Lyapunov function. Fierro and Lewis[3] (1995) used the backstepping kinematic into dynamic method to control a non-holonomic mobile robot. Lee et al.[4] (1999) proposed an adaptive control for a non-holonomic mobile robots using the computed torque method. Fukao et al.[5] (2000) developed an adaptive tracking control method with the unknown parameters for the mobile robot. Bui et al.[6] (2003) proposed a tracking control method with the tracking point outside the mobile robot.

● ***Motion control of a manipulator***

The control of a manipulator is an interesting area for research. In previous works, Craig et al.[1] (1986) proposed an algorithm for estimating parameters on-line using an adaptive control law with the computed torque method for the control of manipulators. Lloyd et al.[2] (1993) proposed a singularity control method for the manipulator using closed-form kinematic solutions. Tang et al.[9] (1998) proposed a decentralized robust control of a robot manipulator.

● ***Motion control of a mobile manipulator***

A manipulator mounted on a mobile platform will get a large workspace, but it also has many challenges. With regard to the kinematic aspect, the movement of the end effector is a compound movement of several coordinate frames at the same time. With regard to the dynamic aspect, the interaction between the manipulator and the mobile platform must be considered. With regard to the control aspect, whether the mobile manipulator is considered as two subsystems is also a problem that must be studied.

In previous works, Dong, Xu, and Wang[7] (2000) studied a tracking control of a mobile manipulator with the effect of the interaction between two subsystems. Tung et al [10] (2004) proposed a control method for mobile manipulator using kinematic model.

Dung et al [11] (2007) proposed a "Two-Wheeled Welding Mobile Robot for Tracking a Smooth Curved Welding Path Using Adaptive Sliding-Mode Control Technique"

2. System modeling

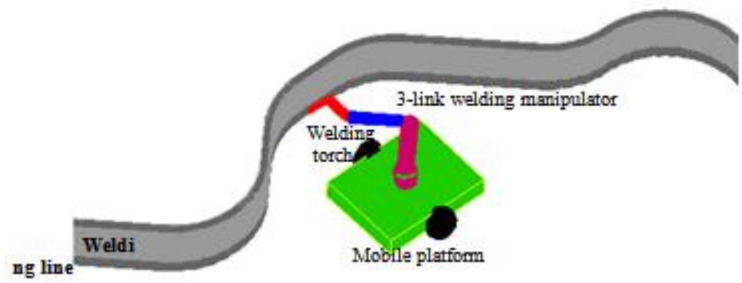

Fig 1. Three-link welding manipulator mounted on mobile platform

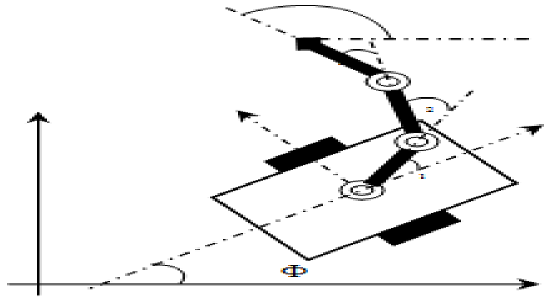

Fig 2. Schematic diagram of mobile platform-manipulator

Fig 1 The mobile manipulator is compose of a wheeled mobile platform and a manipulator. The manipulator has two independent driving wheels which are at the center of each side and two passive castor wheels which are at the center of the front anh the rear of the platform.

Fig 2 shows the schematic of the mobile manipulator considered in this paper. The following notations will be used in the derivation of the dynamic equations and kinematic equations of motion.

2.1 Kinematic equations

Consider a three-linked manipulator as shown in Fig 2. The velocity vector of the end-effector with respect to the moving frame is given by (1).

$$^{1}V_{E} = J\dot{\theta} \qquad (1)$$

Where ${}^{1}V_E = \left[\dot{x}_E\ \dot{y}_E\ \dot{\phi}_E\right]^T$ is the velocity vector of the end-effector with respect to the moving frame, $\dot{\theta} = \left[\dot{\theta}_1\ \dot{\theta}_2\ \dot{\theta}_3\right]^T$ is the angular velocity vector of the revolution joints of the three-linked manipulator, and **J** is the Jacobian matrix.

$$J = \begin{bmatrix} -L_3S_{123} - L_2S_{12} - L_1S_1 & -L_3S_{123} - L_2S_{12} & -L_3S_{123} \\ L_3C_{123} + L_2C_{12} + L_1C_1 & L_3C_{123} + L_2C_{12} & L_3C_{123} \\ 1 & 1 & 1 \end{bmatrix} \qquad (2)$$

where L_1, L_2, L_3 are the length of links of the manipulator, and

$C_1 = \cos(\theta_1)$; $S_1 = \sin(\theta_1)$; $C_{12} = \cos(\theta_1 + \theta_2)$

$C_{123} = \cos(\theta_1 + \theta_2 + \theta_3)$; $S_{12} = \sin(\theta_1 + \theta_2)$;

$S_{123} = \sin(\theta_1 + \theta_2 + \theta_3)$;

The dynamic equation of the end-effector of the manipulator with respect to the world frame is obtained as follows:

$$V_E = V_P + W_P \times {}^{0}Rot_1\, {}^{1}p_E + {}^{0}Rot_1\, {}^{1}v_E \qquad (3)$$

Where

$$v_E = \begin{bmatrix} \dot{X}_E \\ \dot{Y}_E \\ \dot{\Phi}_E \end{bmatrix};\ v_P = \begin{bmatrix} \dot{X}_P \\ \dot{Y}_P \\ \dot{\Phi}_P \end{bmatrix};\ W_P = \begin{bmatrix} 0 \\ 0 \\ \dot{\Phi}_P \end{bmatrix};\ {}^{1}p_E = \begin{bmatrix} x_E \\ y_E \\ \phi_E \end{bmatrix};\ {}^{1}p_E = \begin{bmatrix} L_1C_1 + L_2C_{12} + L_3C_{123} \\ L_1S_1 + L_2S_{12} + L_3S_{123} \\ \phi_E \end{bmatrix}\ {}^{0}Rot_1 = \begin{bmatrix} \cos\Phi_P & -\sin\Phi_P & 0 \\ \sin\Phi_P & \cos\Phi_P & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\Phi_E = \theta_1 + \theta_2 + \theta_3 + \Phi_P - \frac{\pi}{2};\ \dot{\Phi}_E = \dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3 + \dot{\Phi}_P$$

The relationship between v, ω and the angular velocities of two driving wheels is given by

$$\begin{bmatrix} \omega_R \\ \omega_L \end{bmatrix} = \begin{bmatrix} 1/r & b/r \\ 1/r & -b/r \end{bmatrix} \begin{bmatrix} v_p \\ \omega_p \end{bmatrix} \qquad (4)$$

Where b is the distance between the driving wheels and the axis of symmetry, r is the radius of each driving wheel.

The linear velocity and the angular velocity of the end-effector in the world coordinate (frame X-Y)

$$v_E = \dot{X}_E \cos\Phi_E + \dot{Y}_E \sin\Phi_E;\ \omega_E = \dot{\Phi}_E \qquad (5)$$

2.2 Dynamic equations

In this application, the welding speed is very slow so that the manipulator motion during the transient time is assumed as a disturbance for MP. For this reason, the dynamic equation of the MP under nonholonomic constraints in $A(q_v)\dot{q}_v = 0$ is described by Euler-Lagrange formulation as follows:

$$M_v(q_v)\ddot{q}_v + C_v(q_v, \dot{q}_v)\dot{q}_v = E(q_v)\tau_v - A^T(q_v)\lambda \qquad (6)$$

where

$$A(q_v) = \left[-\sin\Phi_p\ \cos\Phi_p\ 0\right];\ q_v = \left[X_p\ Y_p\ \Phi_p\right]^T$$

$$M_v(q_v) = \begin{bmatrix} m + \frac{2I_w}{r^2} & 0 & -m_c d \sin\Phi_p \\ 0 & m + \frac{2I_w}{r^2} & m_c d \cos\Phi_p \\ -m_c d \sin\Phi_p & m_c d \cos\Phi_p & I + \frac{I_w}{2c^2} \end{bmatrix}$$

$$C_v(q_v, \dot{q}_v) = \begin{bmatrix} 0 & 0 & -m_c d\dot{\Phi}_p \cos\Phi_p \\ 0 & 0 & -m_c d\dot{\Phi}_p \sin\Phi_p \\ 0 & 0 & 0 \end{bmatrix}$$

$$E(q_v) = \frac{1}{r}\begin{bmatrix} \cos\Phi_p & \cos\Phi_p \\ \sin\Phi_p & \sin\Phi_p \\ b & -b \end{bmatrix};\ \tau_v = \begin{bmatrix} \tau_R \\ \tau_L \end{bmatrix}$$

$$\lambda = \left(m + \frac{2I_w}{r^2} \right)\left(\dot{X}_P \cos\Phi_p + \dot{Y}_P \sin\Phi_p \right)\dot{\Phi}_p + m_c d\ddot{\Phi}_p$$

Consider a WMM as shown in Fig 2. It is model under
the following assumptions:

• The MP has two driving wheels for body motion, and those are positioned on an axis passed through its geometric center.
• The three-linked manipulator is mounted on the geometric center of the MP.
• The distance between the mass center and the rotation center of the MP is d . Fig. 2 doesn't show this distance. This value will be presented in the dynamic equation of MP.
• A magnet is set up at the bottom of the WMM to avoid slipping.

In Fig. 2, (X_P, Y_P) is a center coordinate of the MP, Φ_p is heading angle of the MP, ω_R, ω_L is angular velocities of the right and the left wheels, $\tau_v = [\tau_R \quad \tau_L]^T$ is torques vector of the motors acting on the right and the left wheels, $2b$ is distance between driving wheel, r is radius of driving wheel, m_c is mass of the WMM without the driving wheels, m is mass of each driving wheel with its motor, Iw is moment of inertia of wheel and its motor about the wheel axis, I is moment of inertia of wheel and its motor about the wheel diameter axis and Ic is moment of inertia of the body about the vertical axis through the mass center.

$$m = m_c + 2m_w; \quad I = I_c + 2m_w b^2 + 2I_m$$

3. Controllers Design

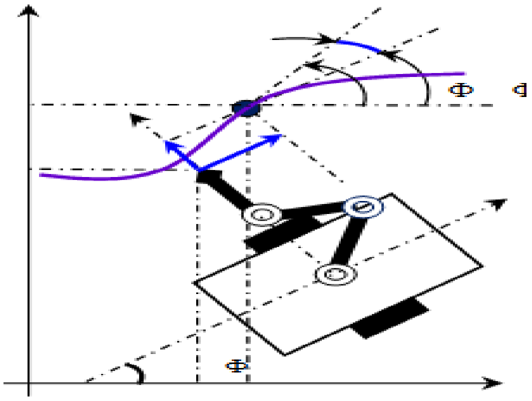

Fig 3. Scheme for deriving the tracking error vector $\mathbf{E_E}$ of manipulator

As the view point of control, this paper addressed to an adaptive dynamic control algorithm. All of them are based on the Lyapunov function to guarantee the asymptotically stability of the system and based on the decentralized motion control method to establish the kinematic and dynamic models of system.

3.1 Defined the errors

From Fig. 3, the tracking error vector $\mathbf{E_E}$ is defined as follows:

$$E_E = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \cos\Phi_E & \sin\Phi_E & 0 \\ -\sin\Phi_E & \cos\Phi_E & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_R - X_E \\ Y_R - Y_E \\ \Phi_R - \Phi_E \end{bmatrix} \qquad (7)$$

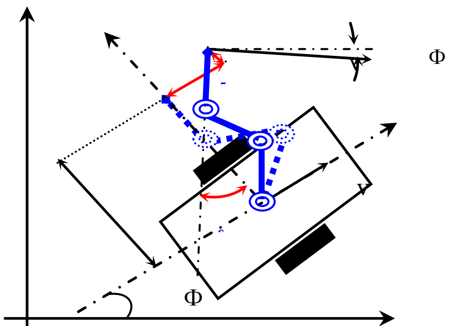

Fig 4. Scheme for deriving the MP tracking error vector

From Fig. 4, A new tracking error vector $\mathbf{E_M}$ for MP is defined as follows:

$$E_M = \begin{bmatrix} e_4 \\ e_5 \\ e_6 \end{bmatrix} = \begin{bmatrix} \cos\Phi_M & \sin\Phi_M & 0 \\ -\sin\Phi_M & \cos\Phi_M & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_E - X_M \\ Y_E - Y_M \\ \Phi_E - \Phi_M \end{bmatrix} \qquad (8)$$

3.2 Kinematic controller design for manipulator

To obtain the kinematic controller a back stepping method is used. The Lyapunove function is proposed as follows:

$$V_0 = \frac{1}{2} E_E^T E_E \qquad (9)$$

The first derivative of V_0 yields

$$\dot{V}_0 = \dot{E}_E E_E^T \qquad (10)$$

To achieve the negativeness of $\dot{V}_0$, the following equation must be satisfied

$$\dot{E}_E = -KE_E \qquad (11)$$

where $\mathbf{K}$=diag(k_1 k_2 k_3) with k_1, k_2 and k_3 are the positive constants. Substituting (1), (3) and (7) into (11) yields

$$\dot{\theta} = J^{-1}\, {}^0Rot_1^{-1}\left[A^{-1}\left(\dot{A}A^{-1} + K\right)E_E + V_R - V_P - W_P \times {}^0Rot_1^1 p_E\right] \qquad (12)$$

3.3 Kinematic controller design for mobile platform

The Lyapunove function is proposed as follows:

$$V_1 = \frac{1}{2} E_M^T E_M \qquad (13)$$

The first derivative of V_1 yields

$$\dot{V}_1 = \dot{E}_M E_M^T \qquad (14)$$

To achieve the negativeness of $\dot{V}_0$, the following equation must be satisfied

$$v_p = v_E \cos e_6 + D\omega_P + k_4 e_4 \qquad (15)$$

$$\omega_p = \omega_E + v_E \sin e_6 + k_5 e_5 + k_6 e_6$$

with k_4, k_5 and k_6 are the positive constants.

3.4 Sliding mode controller design

To design a sliding mode controller, the sliding surfaces are defined as follows:

$$s = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \begin{bmatrix} \dot{e}_4 + k_4 e_4 \\ \dot{e}_6 + k_6 e_6 + k_5 \psi(e_6) e_5 \end{bmatrix} \qquad (16)$$

where k_4 , k_5 and k_6 are positive constant values. $\psi(e_6)$ is a bounding function and is defined as follows:

$$\psi(e_6) = \begin{cases} 0 \to 1 & if\ |e_6| \le \varepsilon \\ 1 \to 0 & if\ |e_6| \ge 2\varepsilon \\ no\,change & \varepsilon < |e_6| < 2\varepsilon \end{cases} \qquad (17)$$

Where ε is a positive constant value.

The Lyapunov's function is chosen as follows:

$$V = \frac{1}{2} s^T s \qquad (18)$$

To satisfy the Lyapunov's stability condition $\dot{V} \le 0$, the following proposed controller $\mathbf{u}_{mb}$ can be calculated as follows:

$$u_{mb} = \begin{bmatrix} \dot{e}_5 \omega_r + (e_5 + D)\dot{\omega}_r - v_E \dot{e}_6 \sin e_6 \\ \dot{e}_3 \end{bmatrix} + \qquad (19)$$

$$\begin{bmatrix} k_4 \dot{e}_4 \\ k_6 \dot{e}_6 + k_5 \psi(e_6) \dot{e}_5 \end{bmatrix} + Q\,\mathrm{sgn}(s) + \gamma\,\mathrm{sgn}(s)$$

Where $\gamma = [\gamma_1 \quad \gamma_2]^T$; $Q = [Q_1 \quad Q_2]^T$

A new smooth switching controller than previous switching controller can be obtained by substituting *sgn*(•) function to *sat*(•) function:

$$Q\,\mathrm{sgn}(s) = \begin{bmatrix} Q_1 & 0 \\ 0 & Q_2 \end{bmatrix} \begin{bmatrix} Sat(\xi_1) \\ Sat(\xi_2) \end{bmatrix}; \quad \gamma\,\mathrm{sgn}(s) = \begin{bmatrix} \gamma_1 & 0 \\ 0 & \gamma_2 \end{bmatrix} \begin{bmatrix} Sat(\xi_1) \\ Sat(\xi_2) \end{bmatrix}$$ where the saturation function is defined as

$$\begin{cases} Sat(\xi_i) = Sat\left(\dfrac{s_i}{\delta}\right) = \xi_i \quad if \ |\xi_i| \le 1 \\ Sat(\xi_i) = \mathrm{sgn}(\xi_i) \qquad otherwise \end{cases} \tag{20}$$

In this case, the welding velocity is rather slow, 7.5mm/s. Therefore, a thin boundary layer δ=0.1 is chosen.

3.5 Hardware design

3.5.1 Measurement of the errors

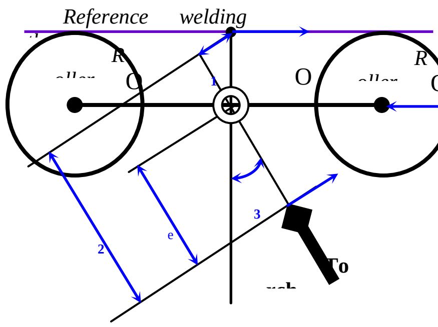

Fig 5. The scheme of measuring errors $e_{1,2,3}$

From Fig. 5, the tracking errors relations are given as

$$\begin{aligned} e_1 &= -r_s \sin e_3 \\ e_2 &= d_e + r_s \cos e_3 \\ e_3 &= \angle(O_1E, O_1O_3) - \frac{\pi}{2} \end{aligned} \tag{21}$$

From Fig. 4, the tracking errors e_4, e_5, e_6 with respect to moving frame can be calculated as follows:

$$\begin{aligned} e_4 &= x_M - x_E = -L_1\cos\theta_1 - L_2\cos(\theta_1+\theta_2) - L_3\cos(\theta_1+\theta_2+\theta_3) \\ e_5 &= y_M - y_E = D - L_1\sin\theta_1 - L_2\sin(\theta_1+\theta_2) - L_3\sin(\theta_1+\theta_2+\theta_3) \\ e_6 &= \theta_1+\theta_2+\theta_3 - \frac{\pi}{2} \\ \Phi_E &= \Phi_P + \theta_1+\theta_2+\theta_3 - \frac{\pi}{2} \end{aligned} \tag{22}$$

3.5.2 Measurement of the angle rotate of MP

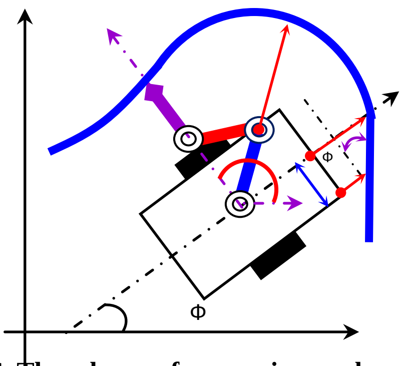

Fig 6. The scheme of measuring angle rotate of MP

$$\begin{aligned} \Phi_{PF} &= \tan^{-1}\left(\frac{l_{s2} - l_{s1}}{l_{ds}}\right) + \frac{\pi}{2} \\ \omega_p &= \dot{\Phi}_{PF} \end{aligned} \tag{23}$$

3.6 Control algorithms

The schematic diagram for a decentralized control method is shown in Fig 7. In this diagram, a relationship between controllers is illustrated by means of the output of this controller is one of the input of another controller and vice versa. The control task demands a real-time algorithm to guide the mobile manipulator in a given trajectory. Laser sensor, rotary potentiometer and linear potentiometer were adopted in the simulation to obtain the position and orientation of the mobile platform relative to the walls.

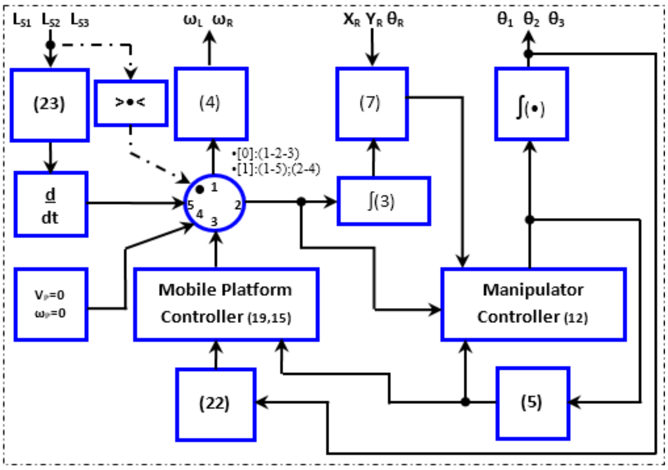

Fig 7. Block diagram of control system

IV. SIMULATION RESULTS

In this section, some simulation resuls are presented to demonstrate the effectiveness o the control algorithm developed for horizontal smooth curved welding.

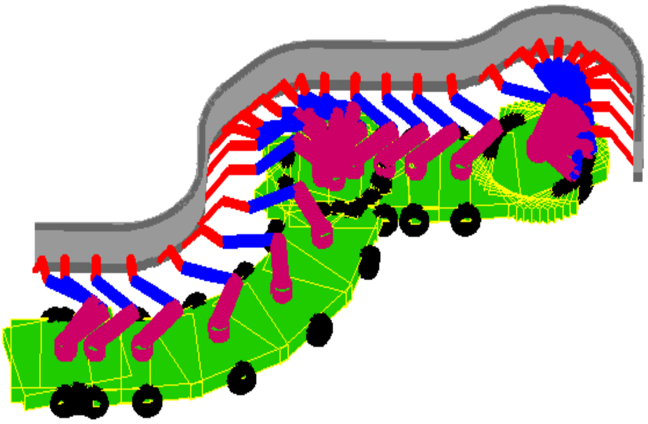

Fig 8a. The WMM is tracking along the welding path

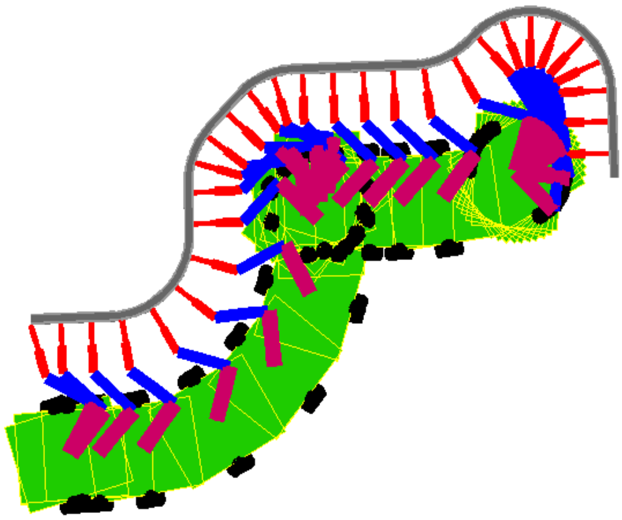

Fig 8b. Different perspective about WMM.

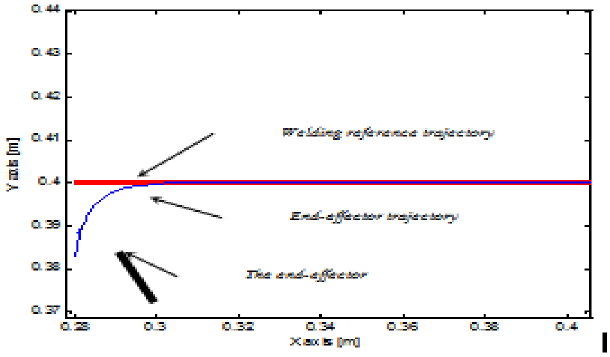

Fig 9. Trajectory of the end-effector and its reference at beginning

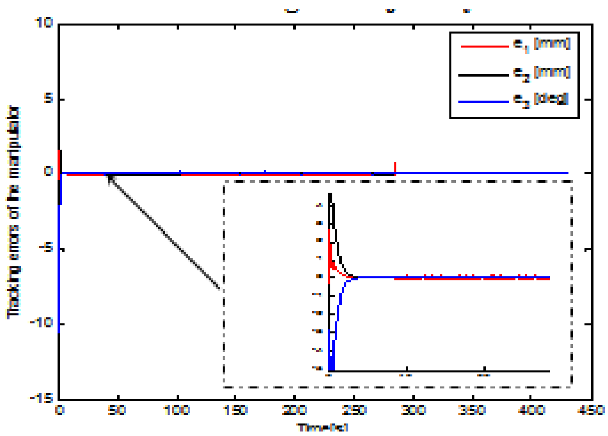

Fig 10. Tracking errors e_1 e_2 e_3 at beginning

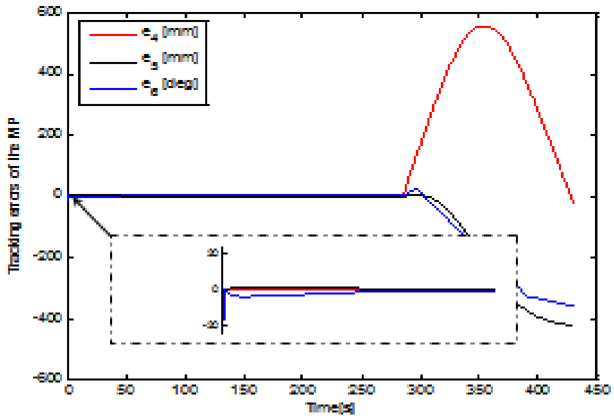

Fig 11. Tracking errors e_4 e_5 e_6 at beginning

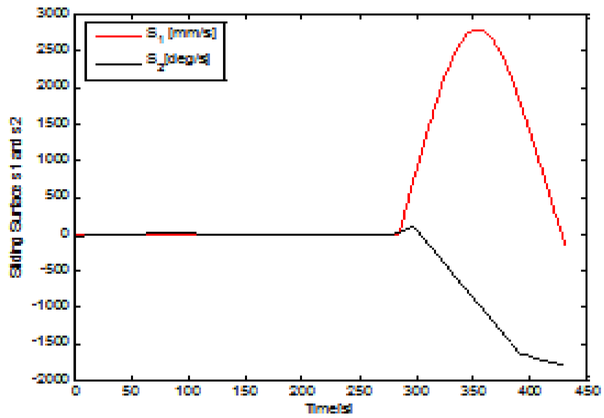

Fig 12. Sliding surfaces

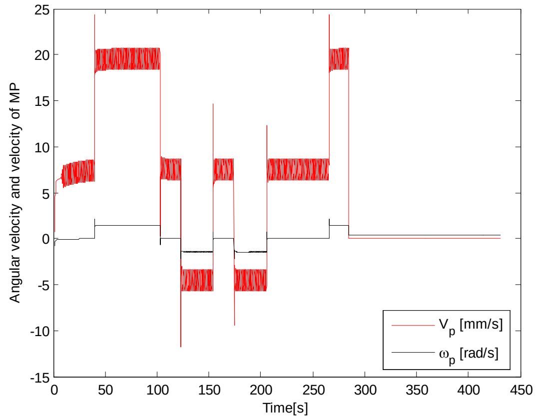

Fig 13. Angular velocity and velocity of the center point of platform

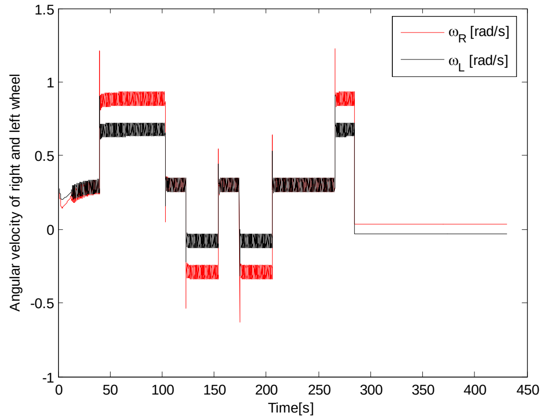

Fig 14. Angular velocities of the right and the left wheels

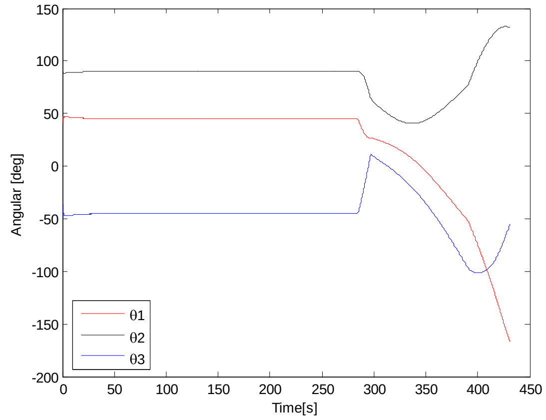

Fig 15. Angular of revolution joints

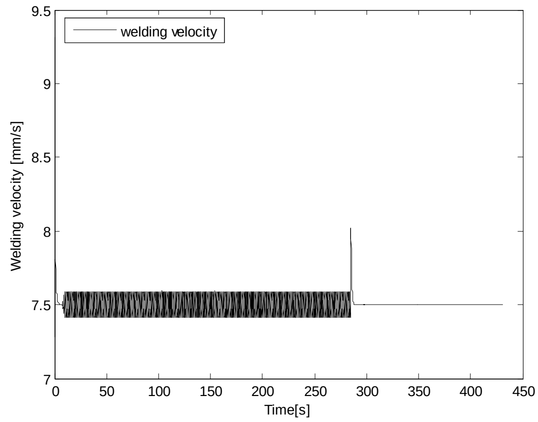

Fig 16. Linear and angular velocities of welding point

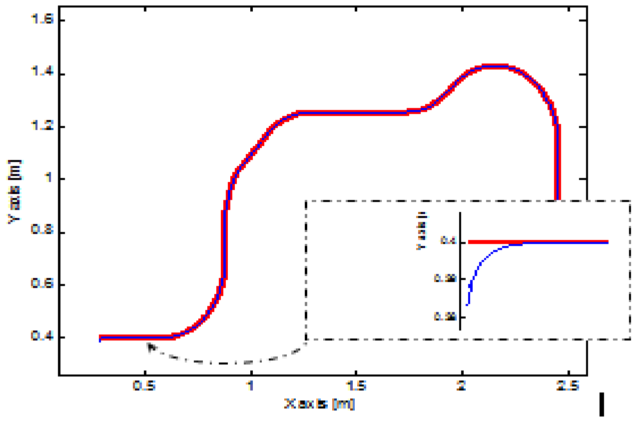

Fig 16. Results of trajectories of the end effector and its reference

V. CONCLUSION

In this study, developed a WMM which can co-work between mobile platform and manipulator for tracking a long horizontal smooth curved welding path. The main task of the control system is to control the end-effector or welding point of the WMM for tracking a welding point which is moved on the welding path with constant velocity. The angle of welding torch must be kept constant with respect to the welding curve. The WMM is divided into two subsystems and is controlled by decentralized controllers. The kinematic controller and sliding mode controller are designed to control the manipulator and the mobile-platform, respectively. These controllers are obtained based on the Lyapunov's function and its stability condition to ensure the error vectors to be asymptotically stable. From the simulation results are presented to illustrate the effectiveness of the proposed algorithm.

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