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Adaptive Sliding Mode Control of Mobile Manipulator Welding System for Horizontal Fillet Joints

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Abstract : *In this paper, an adaptive sliding mode control of mobile manipulator welding system for horizontal fillet joints 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. 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 thesis 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

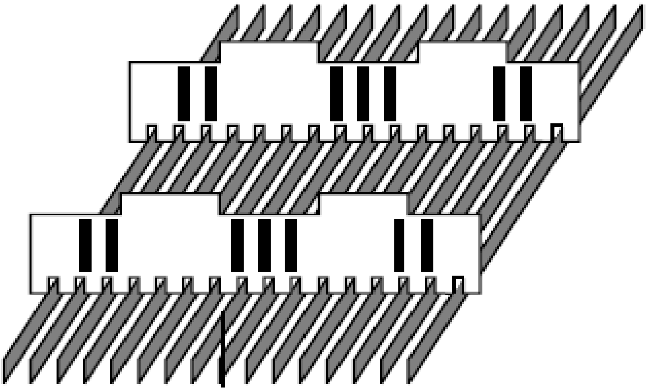

Fig 1. Grillage assembling method for flat hull block

The task is to track the horizontal fillet seam in the grillage assembling method, which is one of the conventional procedures for assembling the flat hull blocks in shipbuilding and consists of only the horizontal fillet seam.

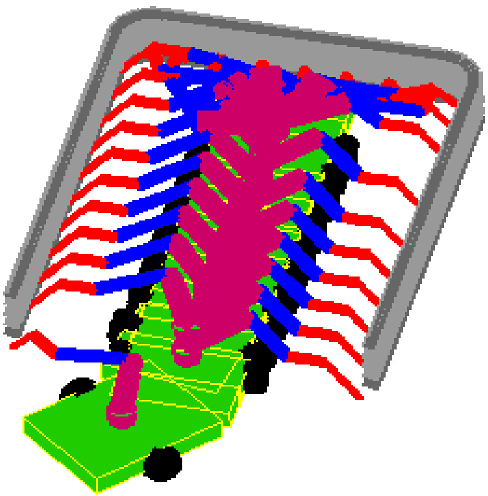

Fig 2. Three-link welding manipulator mounted on mobile platform

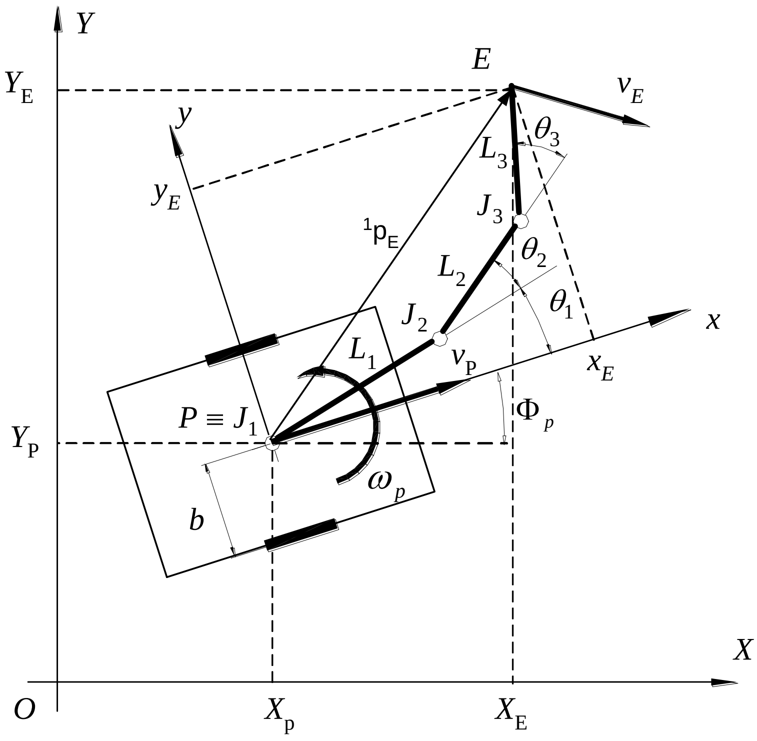

Fig 3. Schematic diagram of mobile platform-manipulator

Fig 2 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 3 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 3. The velocity vector of the end-effector with respect to the moving frame is given by (1).

$$^1V_E = J\dot{\theta} \tag{1}$$

Where $^1V_E = \left[\dot{x}_E \; \dot{y}_E \; \dot{\phi}_E\right]^T$ 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.

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

where $L1, L2, L3$ 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:

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

Where

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

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

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

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

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)

$$v_E = \dot{X}_E \cos\Phi_E + \dot{Y}_E \sin\Phi_E\,;\ \omega_E = \dot{\Phi}_E \tag{5}$$

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:

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

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 3. 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 3 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 3, (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, $\tau_v = \left[\tau_R \quad \tau_L\right]^T$ 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, I_w 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 I_c is moment of inertia of the body about the vertical axis through the mass center.

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

III. CONTROLLERS DESIGN

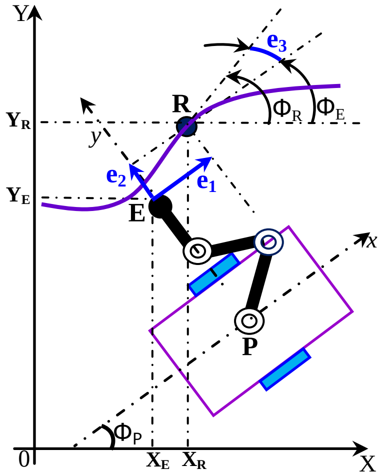

Fig 4. Scheme for deriving the tracking error vector $\mathbf{E_E}$ of manipulator

As the view point of control, this thesis 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 4, the tracking error vector $\mathbf{E_E}$ is defined as follows:

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

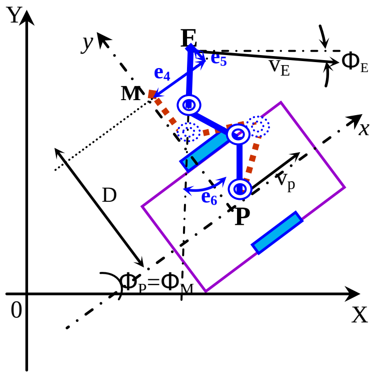

Fig 5. Scheme for deriving the MP tracking error vector

From Fig. 5, A new tracking error vector $\mathbf{E_M}$ for MP is defined as follows:

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

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:

$$V_0 = \frac{1}{2} E_E^T E_E \tag{9}$$

The first derivative of V_0 yields

$$\dot{V}_0 = \dot{E}_E E_E^T \tag{10}$$

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

$$\dot{E}_E = -KE_E \tag{11}$$

where 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

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

3.3 Kinematic controller design for mobile platform

The Lyapunove function is proposed as follows:

$$V_1 = \frac{1}{2}E_M^T E_M \tag{13}$$

The first derivative of V_1 yields

$$\dot{V}_1 = \dot{E}_M E_M^T \tag{14}$$

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

$$v_p = v_E \cos e_6 + D\omega_P + k_4 e_4 \tag{15}$$
$$\omega_p = \omega_E + v_E \sin e_6 + k_5 e_5 + k_6 e_6$$

with k_4, k_5 and k_6 are the positive constants.

3.4 Adaptive sliding mode controller design

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

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

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

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

Where ε is a positive constant value.

The following procedure will design an adaptation law $\dot{\hat{p}}$ and a control law u which stabilize and converge the sliding surface $s \to 0$ as $t \to \infty$

Firstly, the adaptation law is proposed as the following:

$$\dot{\hat{p}} = -\xi^{-1} s^T(t) \tag{18}$$

Where $\hat{p} = [\hat{p}_1 \quad \hat{p}_2]^T$ is an estimate value of $f = [f_1 \quad f_2]^T$; $\xi^{-1} = [\xi_1^{-1} \quad \xi_2^{-1}]^T$ is positive definite vector which denotes as an adaptation gain and.

The estimation error is defined as follows:

$$\tilde{p} = f - \hat{p} \Rightarrow \hat{p} = f - \tilde{p} \tag{19}$$

Secondly, the control law u is chosen as follows:

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

$$\mathbf{u}_{mb} = \begin{bmatrix} \dot{e}_5 \omega_r + (e_5 + D)\dot{\omega}_r - v_E \dot{e}_6 \sin e_6 \\ \dot{e}_3 \end{bmatrix} + \begin{bmatrix} k_4 \dot{e}_4 \\ k_6 \dot{e}_6 + k_5\, \psi(e_6)\, \dot{e}_5 \end{bmatrix} + \mathbf{Q}s^T + \hat{P} \tag{20}$$

where $Q = \begin{bmatrix} q_{11} & 0 \\ 0 & q_{22} \end{bmatrix}$; $\hat{P} = \begin{bmatrix} \hat{p}_1 & 0 \\ 0 & \hat{p}_2 \end{bmatrix}$

The above control laws u and adaptation law $\dot{\hat{p}}$ with the assumption (8) make the sliding surfaces in Eq. (16) be stabilized and converge to zero as $t \to \infty$.

3.5 Hardware design

Measurement of the errors

From Fig. 6, the tracking errors relations are given as

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

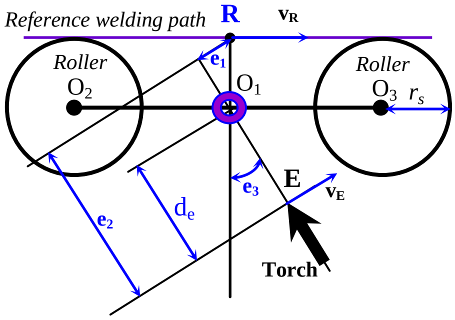

Fig 6. The scheme of measuring errors $e_{1,2,3}$

From Fig. 5, the tracking errors e_4, e_5, e_6 with respect to moving frame can be calculated as follows:

$$e_4 = x_E - x_M = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) + L_3 \cos(\theta_1 + \theta_2 + \theta_3)$$
$$e_5 = y_E - y_M = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2) + L_3 \sin(\theta_1 + \theta_2 + \theta_3) - D \qquad (22)$$
$$e_6 = \phi_E - \frac{\pi}{2} = (\theta_1 + \theta_2 + \theta_3) - \frac{\pi}{2}$$

3.6 Control algorithms

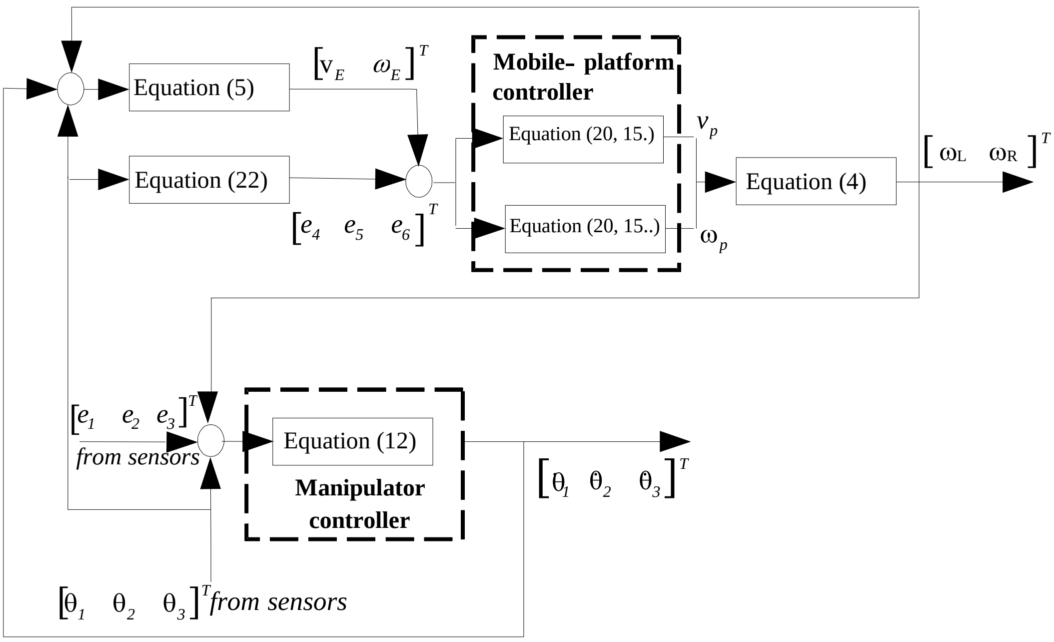

Fig 7. Block diagram of control system

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.

IV. SIMULATION RESULTS

In this section, some simulation resuls are presented to demonstrate the effectiveness o the control algorithm developed for Horizontal Fillet Joints welding.

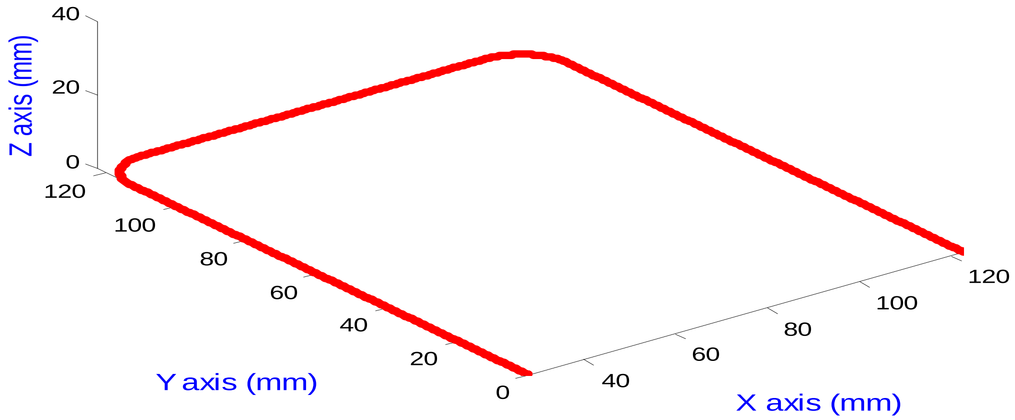

Fig 8. Welding reference trajectory

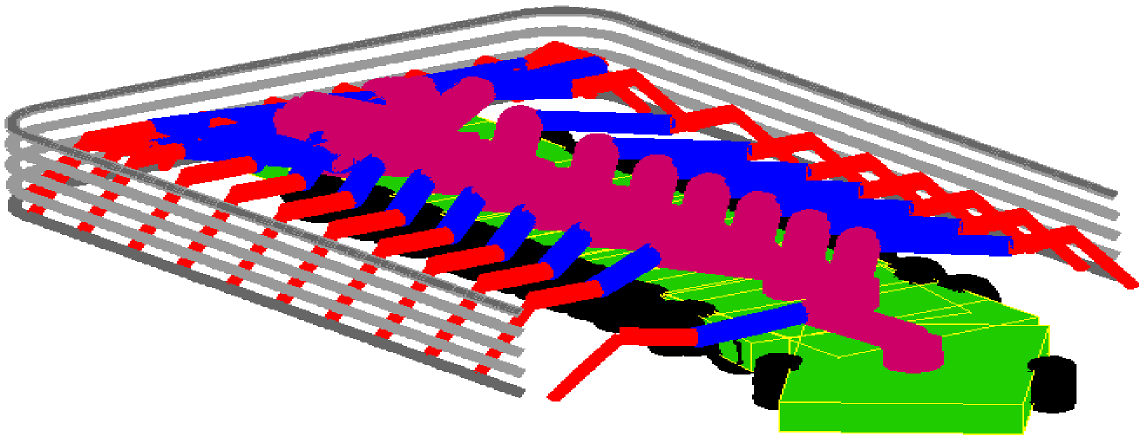

Fig 9. 3D model of the welding mobile manipulator

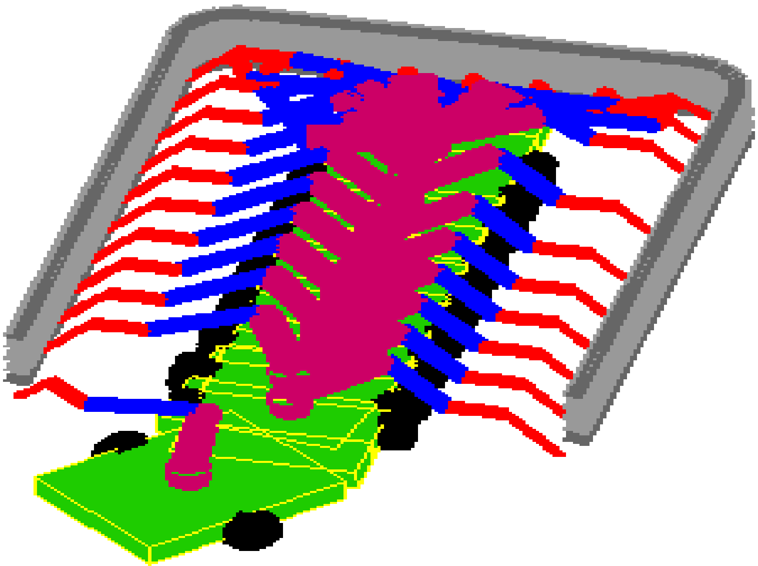

Fig 10. The WMM is tracking along the welding path

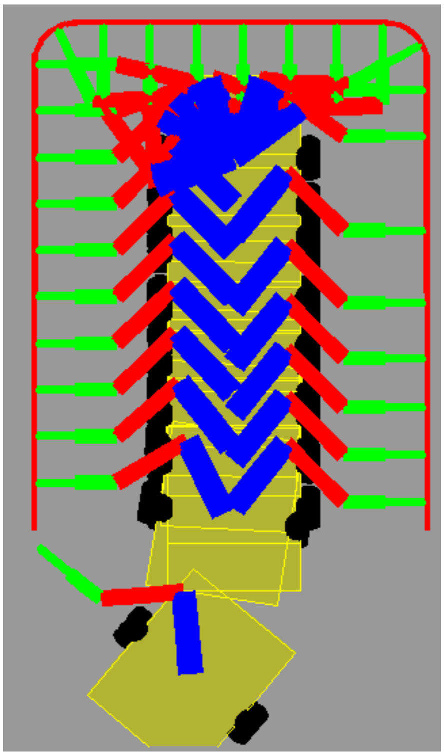

Fig 11. Different perspective about WMM.

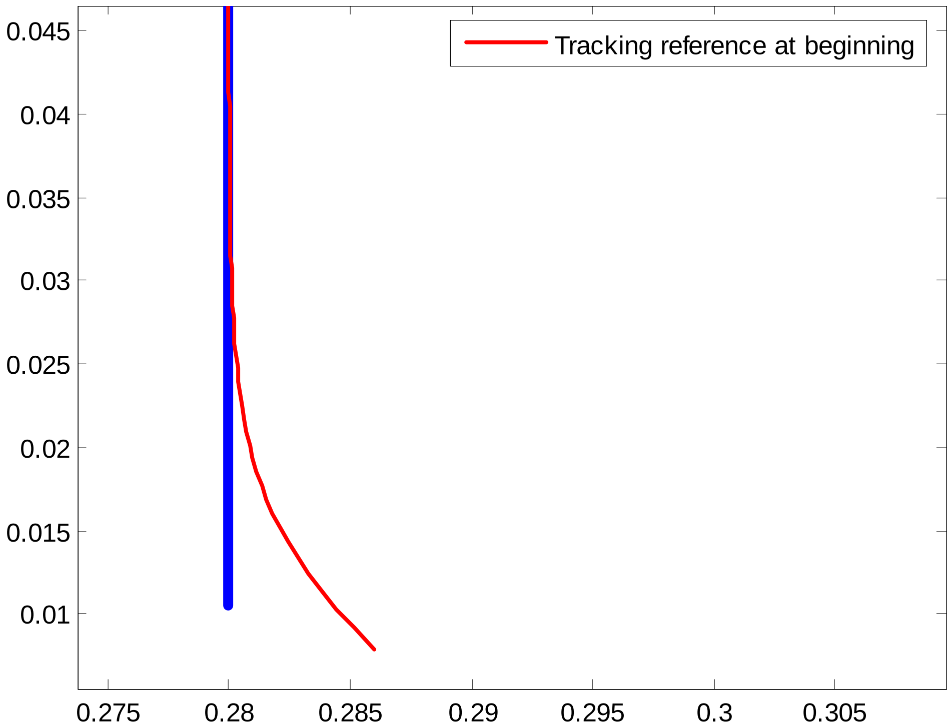

Fig 12. Trajectory of the end-effector and its reference at beginning

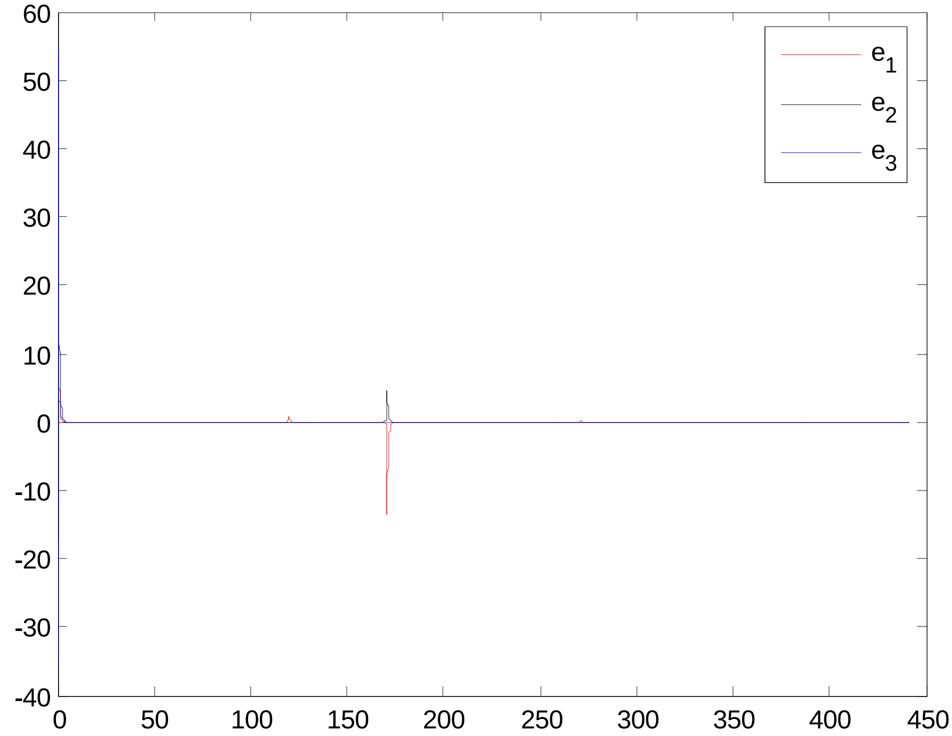

Fig 13. Tracking errors e_1 e_2 e_3 at beginning

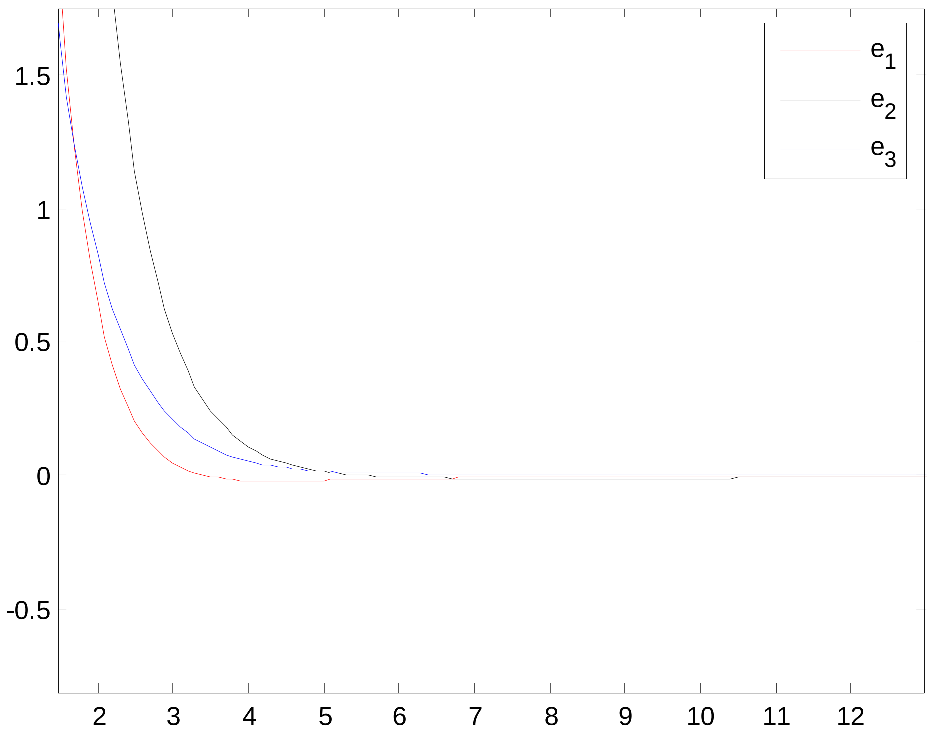

Fig 14. Tracking errors e_1 e_2 e_3 at beginning (zoom in)

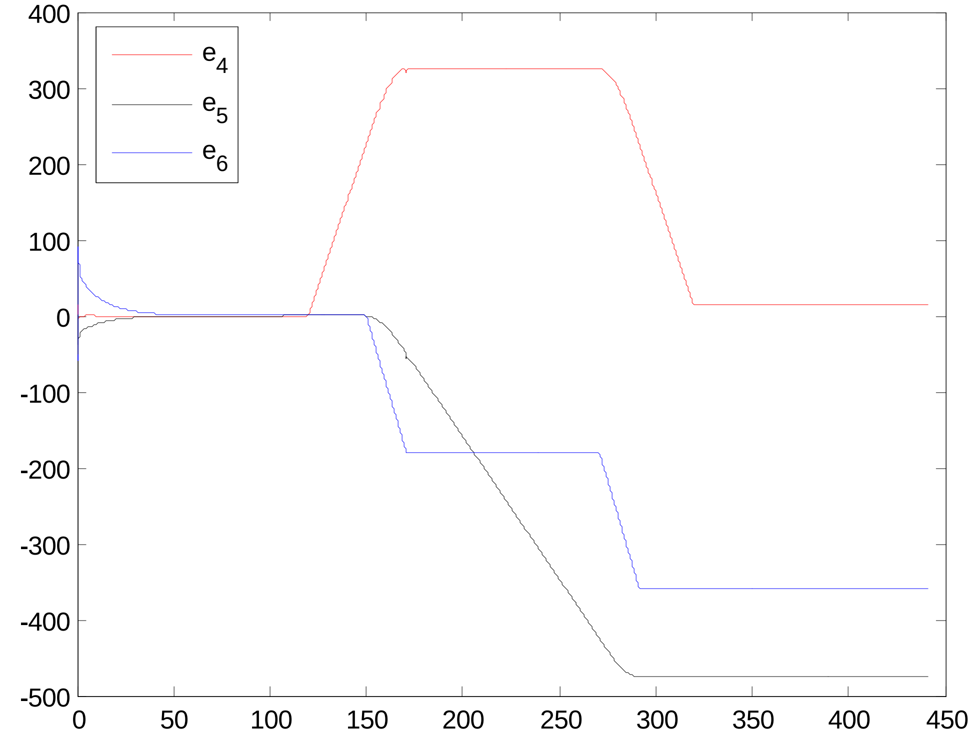

Fig 15. Tracking errors e_4 e_5 e_6 at beginning

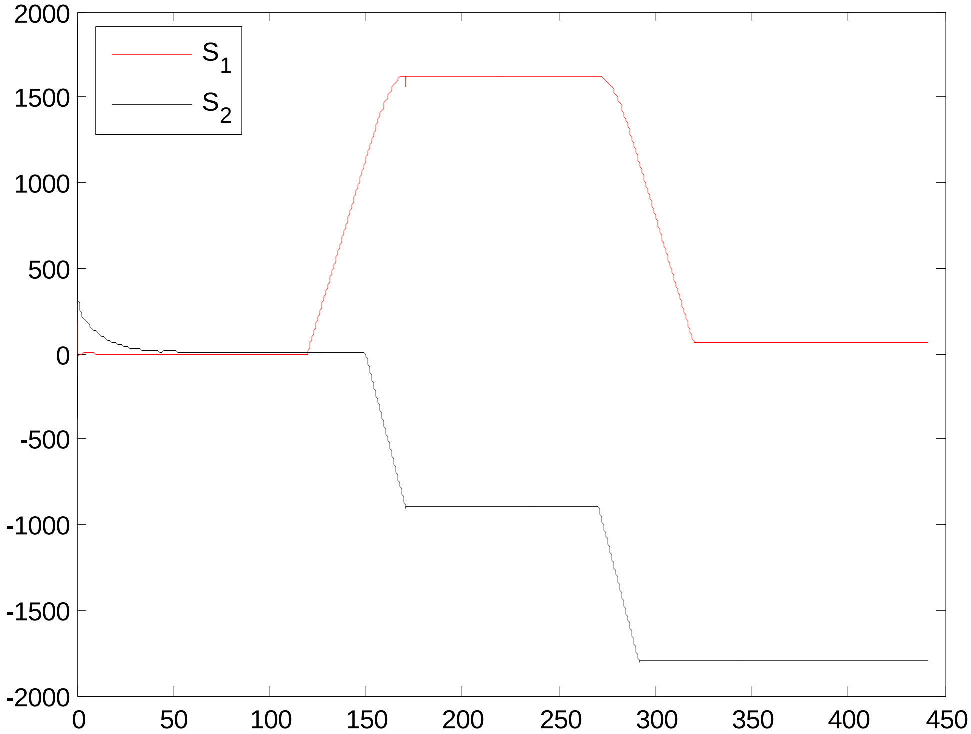

Fig 16. Sliding surfaces

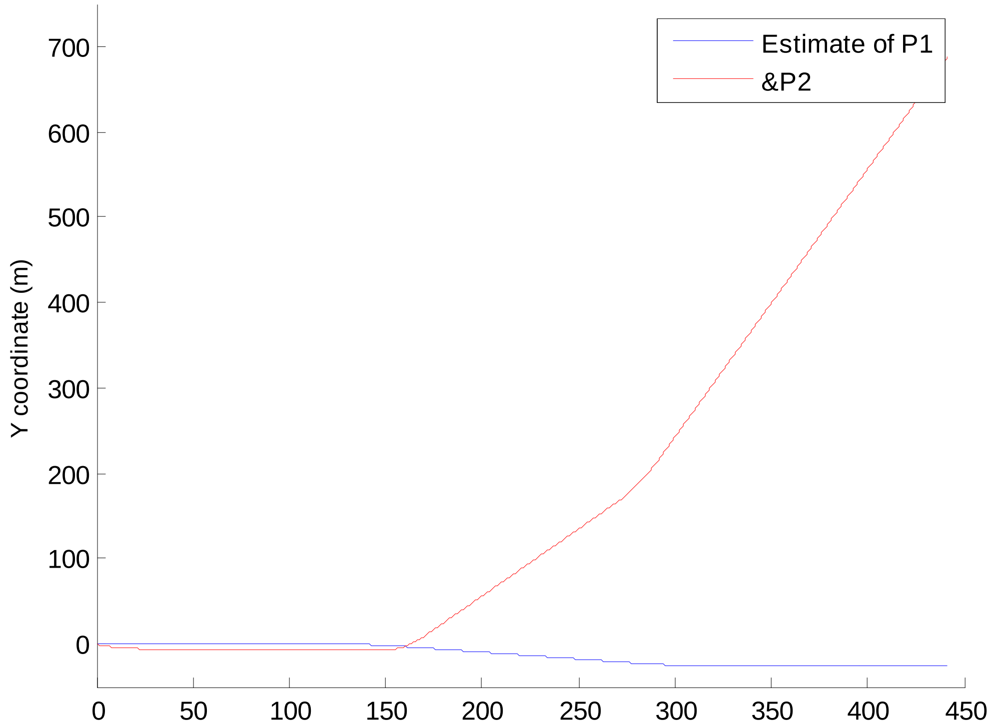

Fig 17. Estimated value of the P1 & P2

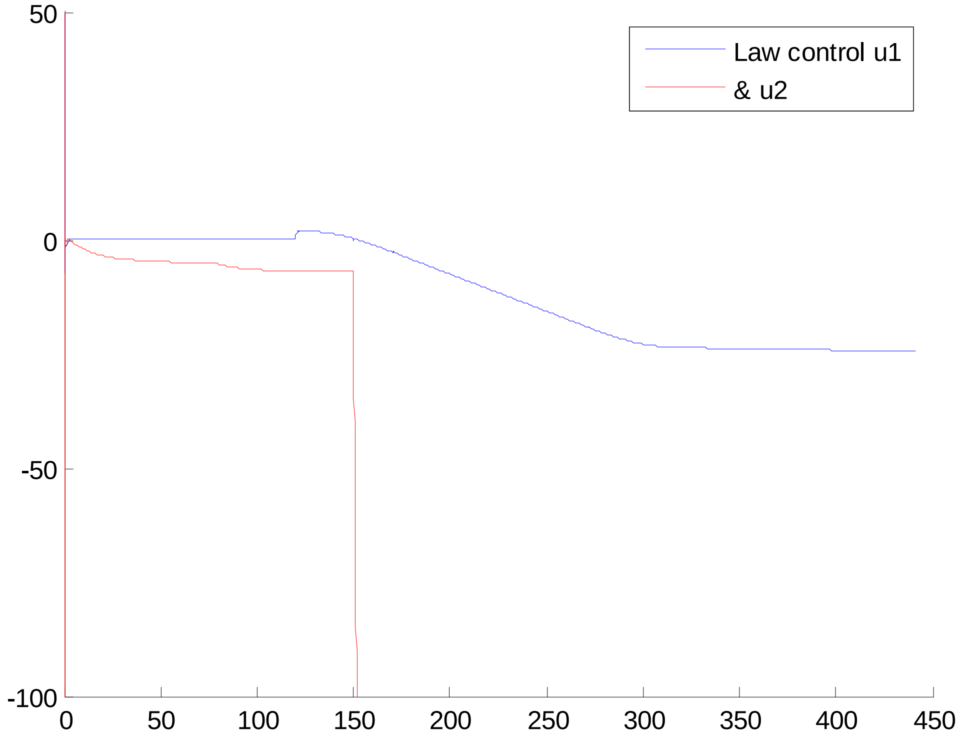

Fig 18. Law control

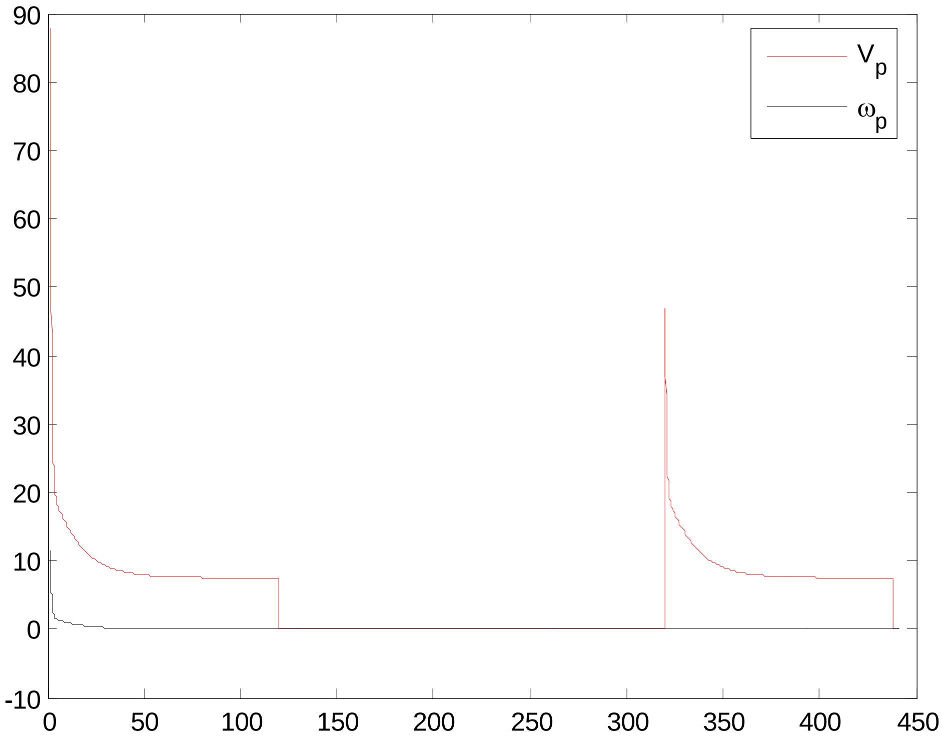

Fig 19. Angular velocity and velocity of the center point of platform

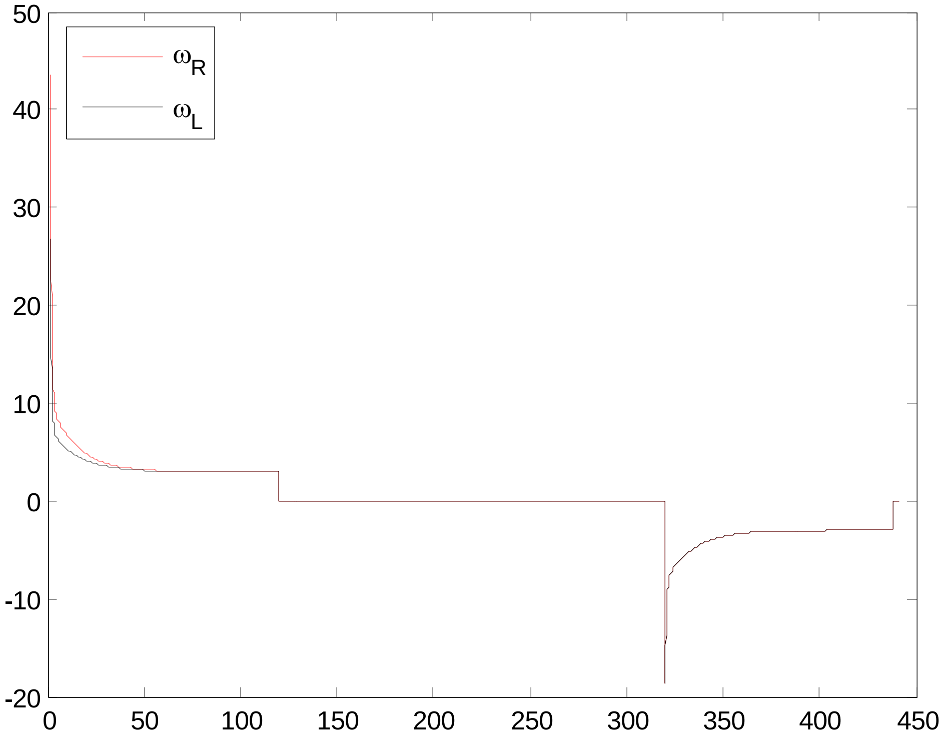

Fig 20. Angular velocities of the right and the left wheels

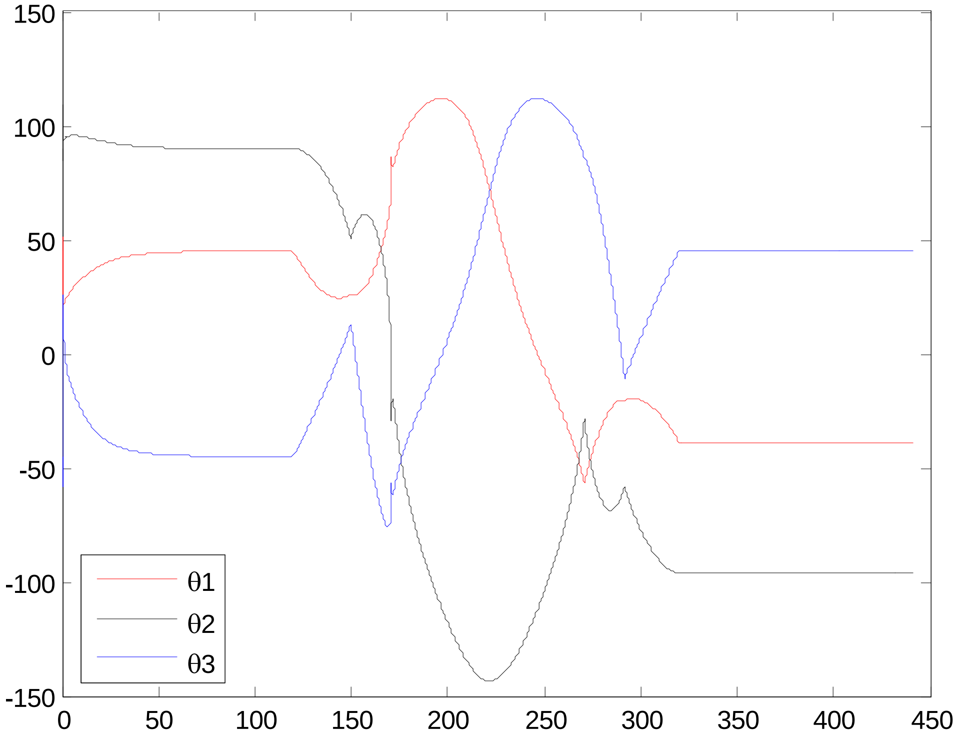

Fig 21. Angular of revolution joints

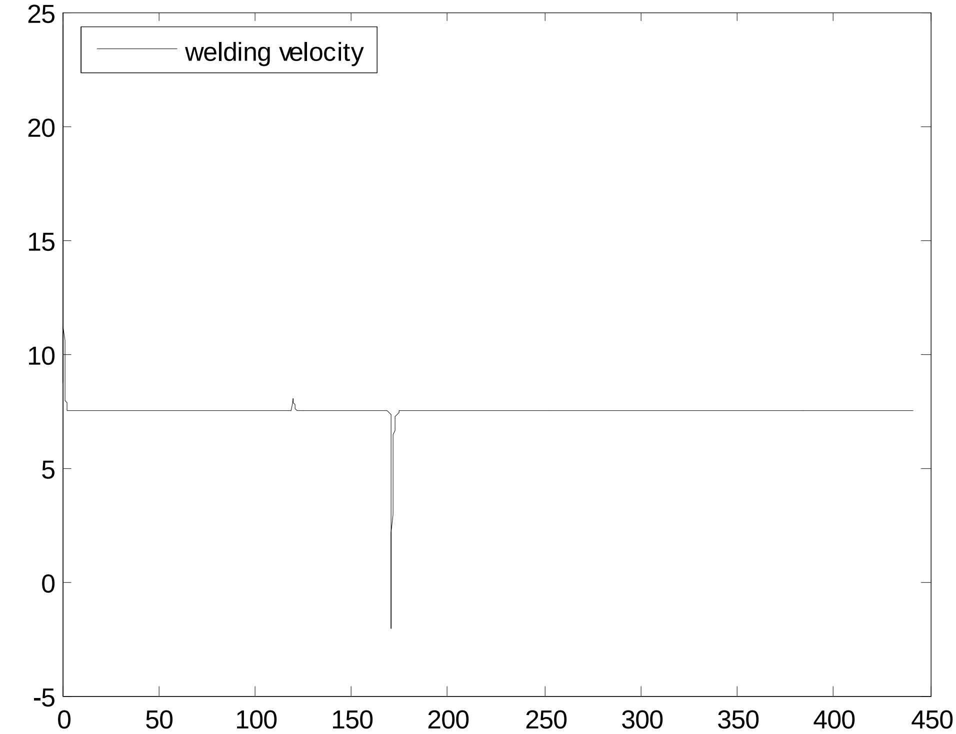

Fig 22. Linear and angular velocities of welding point

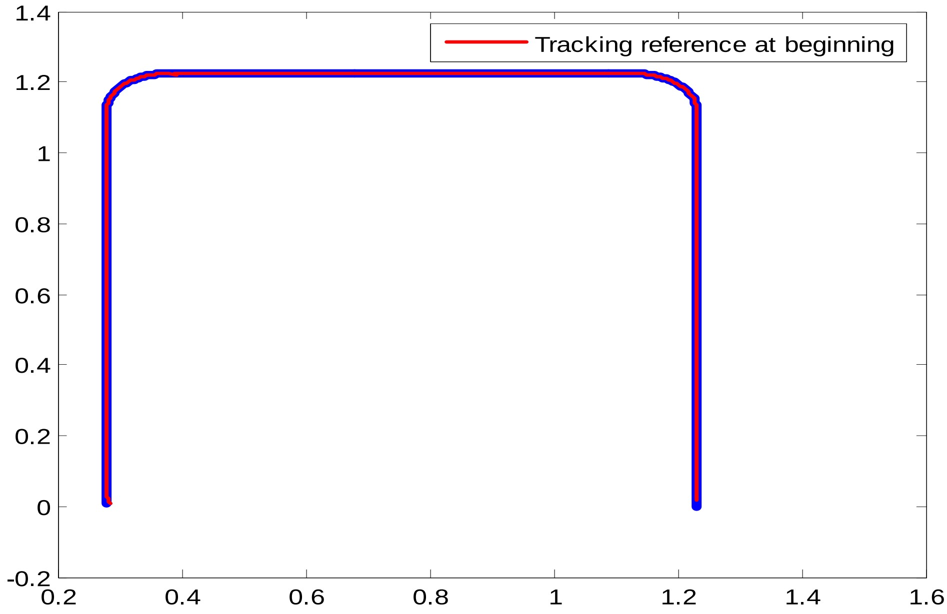

Fig 23. Results of trajectories of the end effector and its reference

V. CONCLUSION

In this study, developed a WMM which can co-work between mobile platform and manipulator for tracking a long Horizontal Fillet Joints 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 adaptive 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.

REFERENCES

[1] J. J. Craig, P. Hsu, and S. S. Sastry, "Adaptive Control of Mechanical Manipulators", *Proceedings of the IEEE International Conference on Robotics and Automation*, Vol. 2, pp. 190-195, 1986.

[2] J. Lloyd, and V. Hayward, "Singularity Control of Robot Manipulator Using Closed Form Kinematic Solutions", *Proceedings of the Conference on Electrical and Computer Engineering*, Vol.2, pp. 1065-1068, 1993.

[3] R. Fierro, and F. L. Lewis, "Control of a Nonholonomic Mobile Robot: Backstepping Kinematics into Dynamics", *Proceedings of the IEEE Conference on Decision and Control*, Vol. 4, pp. 3805-3810, 1995.

[4] T. C. Lee, C. H. Lee, and C. C. Teng, "Adaptive Tracking Control of Nonholonomic Mobile Robots by Computed Torque", *Proceedings of the Conference on Decision and Control*, Vol. 2, pp. 1254-1259, 1999.

[5] T. Fukao, H. Nakagawa, and N. Adachi, "Adaptive Tracking Control of a Nonholonomic Mobile Robot", *Transactions on Robotics and Automation*, Vol. 16, No. 5, pp. 609-615, 2000.

[6] Tr. H. Bui, T. L. Chung, J. H. Suh, and S. B. Kim, "Adaptive Control for Tracking Trajectory of a Two Wheeled Welding Mobile Robot with Unknown Parameters", *Proceedings of the International Conference on Control, Automation and Systems*, pp. 191-196, 2003.

[7] W. Dong, Y. Xu, and Q. Wang, "On Tracking Control of Mobile Manipulators", *Proceedings of the IEEE International Conference on Robotics and Automation,* Vol. 4, pp. 3455-3460, 2000.

[8] Y. Kanayama, Y. Kimura, F. Miyazaki, and T. Noguchi, "A Stable Tracking Control Method for a Nonholonomic Mobile Robot", *Proceedings of the IEEE/RSJ International Workshop on Intelligent Robots and Systems*, Japan, Vol. 3, pp. 1236-1241, 1991.

[9] Y. Tang, and G. Guerrero, "Decentralized Robust Control of Robot Manipulator", *Proceedings of the American Control Conference*, Pennsylvania, USA, pp. 922-926, June 1998.

[10] Tan Tung Phan, Thien Phuc Tran, Trong Hieu Bui, and Sang Bong Kim, "Decentralized Control Method for Welding Mobile Manipulator", Proceedings of the International Conference on Dynamics, Instrumentation, and Control, Nanjin, China, pp. 171-180, August 18-20, 2004.

[11] Ngo Manh Dung, Vo Hoang Duy, Nguyen Thanh Phuong, Sang Bong Kim*, and Myung Suck Oh, "Two-Wheeled Welding Mobile Robot for Tracking a Smooth Curved Welding Path Using Adaptive Sliding-Mode Control Technique" Proceedings of the International Journal of Control, Automation, and Systems, vol. 5, no. 3, pp. 283-294, June 2007.

[12] W.-S. Yoo, J.-D. Kim, S.-J. Na, "A study on a mobile platform-manipulator welding system for horizontal fillet joints" Mechatronics 11 (2001) 853-868