Trajectory Tracking of a 2-Link Mobile Manipulator Using Sliding Mode Control Method

Abolfazl Mohammadijoo

Abstract**—**In this paper, we are investigating sliding mode control approach for trajectory tracking of a two-link-manipulator with wheeled mobile robot in its base. The main challenge of this work is dynamic interaction between mobile base and manipulator which makes trajectory tracking more difficult than n-link manipulators with fixed base. Another challenging part of this work is to avoid chattering phenomenon of sliding mode control that makes lots of damages for actuators in real industrial cases. The results show the effectiveness of sliding mode control approach for desired trajectory.

Keywords**—**Mobile manipulator, sliding mode control, dynamic interaction, mobile robotics

I. Introduction

In recent decades, robots made a great share of industrial processes. The robotic manipulators can perform a lot of repetitive daily jobs with high precision. The use of constant manipulator could be seen in many factories like car industry. However, many researchers have worked in field of dynamic modelling of mobile manipulators and different control methods for robotic manipulators to reach better performances, as much as possible. Non-holonomic constraint of mobile robots has been studied in some papers [2]-[4]. Some papers considered flexibilities of manipulators and its joints to have better kinematic and dynamic model of robot for precise path planning and positioning [5]-[7].

Due to limitation of working area for fixed robotic manipulators, mobile manipulators had emerged which have more working environment and, in some cases, can be portable. In this case, due to dynamic interaction between mobile base and manipulators, dynamic modelling of mobile robot is more complicated. Some researchers studied dynamic modelling of mobile manipulators [8]-[13].

One of important characteristics of fixed or mobile robotic manipulators is dynamic load carrying capacity of manipulator. To determine the dynamic load carrying capacity or maximum allowable carrying capacity for a manipulator, we should consider some constraints like maximum allowable torques for actuators and joints and bound of accuracy of end effector for a given trajectory. This was subject of many studies in robotic manipulators [14]-[18].

Different control methods are implemented to control fixed manipulators, mobile robots and mobile manipulators, for path planning or dynamic load carrying capacity purposes. Nonlinear control approaches like feedback linearization, back stepping, adaptive control, sliding mode control etc. have been studied in many papers [19]-[23]. Artificial intelligence approaches like neural network, fuzzy control, genetic algorithms were subject of many other researches in field of control of mobile manipulators [24]-[30].

In this paper, we used sliding mode control as control method for trajectory tracking purpose. Our wheeled mobile base is assumed to be holonomic and we assumed that all of manipulators and joints are solid and flexibility terms are negligible.

We simulated our control design system for a desired path, when wheeled mobile robot in base is following a straight line, and end effector of manipulator follows a circular path. The result shows the effectiveness of sliding mode control for trajectory tracking of mobile manipulators. We showed in simulation results, how we can tune sliding parameters and get different results.

Abolfazl Mohammadijoo is Control/Robotic/ML/AI Engineer, Programmer and Software Developer with Iran University of Science and Technology, Iran (e-mail: a.mohamadijoo@gmail.com).

II. Dynamic Modeling of Mobile Manipulator

Dynamic modeling of N-link manipulators, in general form, and with fixed base, was the topic of robotics researches in past decades and many researchers improved [5]-[7] the governing equations by considering flexibility in joints and manipulators etc. In recent decades, study of governing equation of manipulators with mobile base is one of trending topics for robotic researchers. Considering holonomic and non-holonomic constraint of mobile base, type of mobile base and dynamic interaction between mobile base and manipulators makes this topic challenging for researchers. In Fig. 1, schematic of the mobile manipulator which will be studied in this paper is shown.

In this section, we present the dynamic equations of mobile manipulator in general form and with n-link. These equations are based on PhD thesis of Yamamoto [1]. The general form of motion equations of N-link manipulator with fixed base, is as (1):

$$\sum_{j=1}^{n} M_{ij}\ddot{q}_j + \sum_{j=1}^{n}\sum_{k=1}^{n} C_{ijk}\dot{q}_j\dot{q}_k + G_i = Q_i \qquad i = 1,\ldots,n \qquad (1)$$

The general form of motion equations of a wheeled mobile manipulator is as (2):

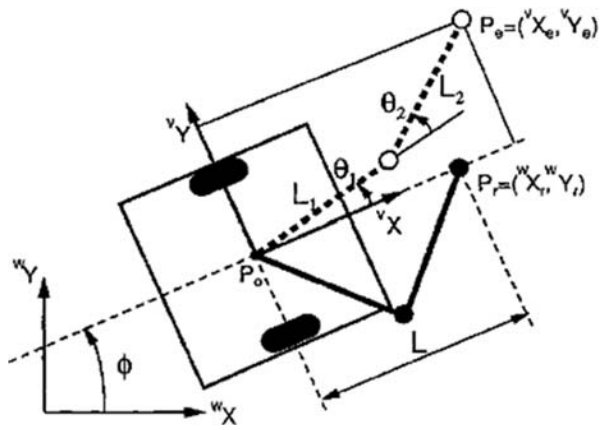

Fig. 1 Schematic of a two-link mobile manipulator

$$M_r(q_r)\ddot{q}_r + C_{r1}(q_r,\dot{q}_r) + C_{r2}(q_r,\dot{q}_r,\dot{q}_v) = \tau_r - R_r(q_r,q_v)\ddot{q}_v \quad (2)$$

where q_r represents the n-dimensional coordinates of the n-link manipulator mounted on wheeled mobile robot. M_r is the inertia matrix, which its elements are given in (3):

$$M_{ij} = \sum_{k=\max(i,j)}^{n} trace\left[\frac{\partial T_k}{\partial q_i} J_k \frac{\partial T_k^T}{\partial q_j}\right] \quad (3)$$

C_{r1} denotes the Coriolis and centrifugal terms of manipulator and its elements are given in (4):

$$C_{ijk} = \sum_{h=\max(i,j,k)}^{n} trace\left[\frac{\partial T_h}{\partial q_i} J_h \frac{\partial^2 T_h^T}{\partial q_j \partial q_k}\right] \quad (4)$$

C_{r2} denotes the Coriolis and centrifugal terms caused by angular motion of mobile base, τ_r is the input torque/force affecting on joints and mobile base actuator, and R_r is the inertia matrix which represent effect of dynamic interaction between N-link manipulator and mobile base. Actually, by comparing (1) and (2), we can find that terms $C_{r2}(q_r,\dot{q}_r,\dot{q}_v)$ and $R_r(q_r,q_v)\ddot{q}_v$ are caused by dynamic interaction between mobile base and N-link manipulator. The expressions for C_{r2} and R_r are given as (5) and (6):

$$C_{r2}^{(i)} = 2\sum_{j=1}^{m}\sum_{k=1}^{n}\sum_{h=\max(i,k)}^{n} trace\left[\frac{\partial \tau_h}{\partial q_i} J_h \frac{\partial \tau_h^T}{\partial q_{v,j}\partial q_k}\right]\dot{q}_{v,j}.\dot{q}_k + \sum_{j=1}^{m}\sum_{k=1}^{m}\sum_{h=i}^{n} trace\left[\frac{\partial \tau_h}{\partial q_i} J_h \frac{\partial \tau_h^T}{\partial q_{v,j}\partial q_{v,k}}\right]\dot{q}_{v,j}.\dot{q}_{v,k} \quad (5)$$

$$R_r^{(ij)} = \sum_{k=i}^{n} trace\left[\frac{\partial \tau_k}{\partial q_i} J_k \frac{\partial \tau_k^T}{\partial q_{v,j}}\right] \quad (6)$$

$$1 \le i \le n \quad , \quad 1 \le j \le m$$

By collecting the velocity terms of C_{r1} and C_{r2} into C_r, (2) could be simplified as:

$$M_r(q_r)\ddot{q}_r + C_r(q_r,\dot{q}_r,\dot{q}_v) = \tau_r - R_r(q_r,q_v)\ddot{q}_v \quad (7)$$

Dynamic equation of motion for wheeled mobile base in general form [1], is as (8):

$$M_{v1}(q_v)\ddot{q}_v + C_{v1}(q_v,\dot{q}_v) + C_{v2}(q_r,q_v,\dot{q}_r,\dot{q}_v) = E_v\tau_v - A^T\lambda - M_{v2}(q_r,q_v)\ddot{q}_v - R_v(q_r,q_v)\ddot{q}_r \quad (8)$$

M_{v1} and C_{v1} are the mass inertia matrix and the velocity dependent terms of the mobile base. Respectively, M_{v2} and C_{v2} represents the Coriolis and centrifugal term due to the presence of the manipulator. τ_v denotes input torque to the mobile base, E_v is a constant matrix, λ represents the vector of Lagrange multipliers corresponding to the kinematic constraints, and R_v is the inertia matrix which reflects the dynamic effect of manipulator's motion on mobile base. The complete expression for each term of (8) could be find in [1].

Finally, to obtain state space form of equations, we set the state variable as:

$$x = \left[q_v^T \quad q_r^T \quad \eta^T \quad \dot{q}_r^T\right]^T \quad (9)$$

in which q_r represents the coordinates of the n-link manipulator and q_v is the coordinates of mobile base. The $\dot{q}_r$ is the velocity of coordinates of n-link manipulator and η is the velocity of coordinates of mobile base and in another notation η is equal to $\dot{q}_v$. We can also consider $\eta = \dot{\theta} = [\dot{\theta}_r \quad \dot{\theta}_l]$ in which $\dot{\theta}_r$ and $\dot{\theta}_l$ are the velocity of right and left wheels of mobile base, respectively. Then, using x from (9), we have:

$$\dot{x} = \begin{bmatrix} S\eta \\ \dot{q}_r \\ P^{-1}\xi \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ P^{-1}Q \end{bmatrix}\tau \quad (10)$$

where,

$$P = \begin{bmatrix} S^T M_v S & S^T R_v \\ R_r S & M_r \end{bmatrix} \qquad Q = \begin{bmatrix} S^T E_v & 0 \\ 0 & I \end{bmatrix}$$
$$\xi = \begin{bmatrix} -S^T M_v \dot{S}\eta - S^T C_v \\ -C_r - R_r \dot{S}\eta \end{bmatrix} \qquad \tau = \begin{bmatrix} \tau_v \\ \tau_r \end{bmatrix} \quad (11)$$

Applying the following feedback,

$$\tau = Q^{-1}\left(Pu - \xi\right) \tag{12}$$

We simplify the state equation as:

$$\dot{x} = \begin{bmatrix} S\eta \\ \dot{q}_r \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ I \end{bmatrix} u \tag{13}$$

More detail about deriving dynamic equation of motion of mobile manipulator could be find in [1].

III. Sliding Mode Control Design

For controlling a mobile manipulator, with natural nonlinear dynamic and considering uncertainties in parameters and external disturbances, we need a robust nonlinear control method. Linear control methods, such as PID[1], make a lot of error and are almost impossible to use as control method separately. The nonlinear control approach we chose in this paper is sliding mode control method.

The idea behind sliding mode control is that, we design a sliding surface for those states of our dynamic we want to control and when the states reach to that surface, by sliding mode control law, we keep the states near the sliding surface. Therefore, we have two steps in sliding mode control design. First, we should design a sliding surface for our desired states and second, we should design a control law to make states attracted to sliding surface. The sliding mode controller design should also satisfy Lyapunov stability theorem.

For mobile manipulators, our desired states which we want to design sliding surface for, are the manipulator's joint and also mobile base velocity. The reason is, when we design a desired trajectory for end effector, by inverse kinematic, we have the desired required rotation for joints and base and these states are our favorable states for designing sliding surface. In this paper, we considered omni-direction for mobile base and circular path for two link manipulators mounted on mobile base, so we need to design three sliding surfaces. The control input or control law that we need to design in next step, are the torque of motors for two joints and torque of motor of mobile base. However, when we derive desired rotation for each joint, the error function would be like this: $e = \theta - \theta_d$

For a dynamic system with general governing equation like (14), the sliding surface design should be like (15):

$$x^{(n)} = f(x) + g(x)u \qquad e = y - y_d \\ y = x \tag{14}$$

$$s = \left(\frac{d}{dt} + k\right)^{n-1} e \tag{15}$$

[1] Proportional-Integral-Derivative

In our equations of motion, the y should be rotation of joints and velocity of mobile base and also order of derivatives is two, thus, the sliding surface is like (16):

$$s = \dot{e} + ke \tag{16}$$

By solving (16), we know this equation is asymptotically globally stable. However, the first step of sliding mode control which is sliding surface design, is done and in next step, we should design control law. We should note that we have three separate sliding surfaces and three separate control inputs. For achieving control law, we should use Lyapunov stability theorem to make our surfaces stable. The recommended Lyapunov function is as (17):

$$V(s) = \frac{1}{2}s^2 \tag{17}$$

Accordingly, we can find the derivative of Lyapunov function as (18):

$$\dot{V}(s) = s\dot{s} = s\left(f(x) + g(x)u + kx_2\right) \tag{18}$$

By assuming control input u, as (19), we can assure that $\dot{V}(s) \le 0$ and surface is asymptotically globally stable. In (19), η is a positive constant.

$$u = -F sign(s) - \eta sign(s) \tag{19}$$

One of the important weaknesses of sliding mode control method is chattering phenomenon which is caused by term $sign(s)$ in (19). This term means that whenever working point is going out of surface, the control input will be giving it back to surface. But when this job happens a lot, we will see chattering problem which in real world will make significant harm to actuators and makes a lot of noise. One of the solutions for this problem is using another function instead of $sign(s)$ that makes same job, but smoother. The alternative functions could be sigmoid function and arctan function which is shown in Figs. 2-4. In this paper, we used arctan function for our simulations to avoid chattering.

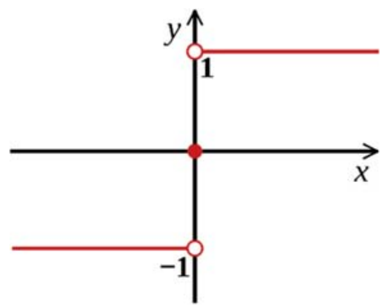

Fig. 2 Sign Function

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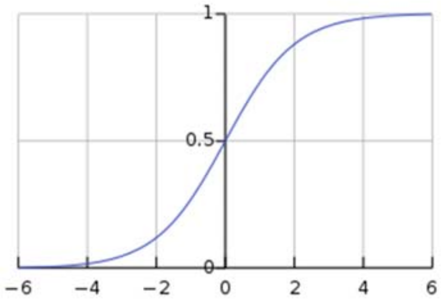

Fig. 3 Sigmoid Function

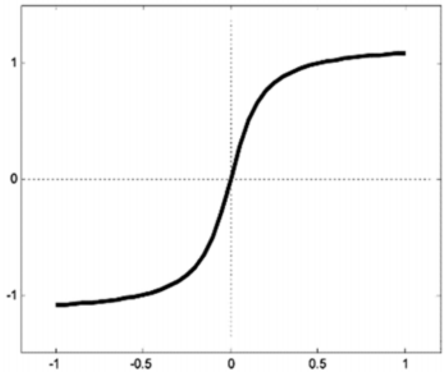

Fig. 4 Arctan Function

IV. Simulation Results

In this section, we implemented our designed control system for a two-link mobile manipulator with specifications mentioned in Table I. The goal of simulation is that the end effector follows a circular path and at the same time, the base follows a linear path (like a prismatic joint or a rack). There are some saturation limits for torques of joints of manipulators. If the mass in end effector exceeds the limitations of torque, we have to decrease its amount and with this strategy, we can investigate the maximum allowable load for a desired path for our mobile manipulator, which is not studied in this paper.

TABLE I
Mobile Manipulator Dimensions and Specifications

Variable	Quantity	Description
L_1	0.5	Length of first link of manipulator
L_2	0.5	Length of second link of manipulator
M_1	5	Weight of first link of manipulator
M_2	3	Weight of second link of manipulator
M_b	50	Weight of mobile base
M_w	1	Weight of each wheel
R	0.1	Radius of wheel
B	0.25	Distance of manipulator to center of mass of mobile bae
J_0	1	Rotational Inertia of mobile base
J_1	0.416	Rotational Inertia of first link
J_2	0.0625	Rotational Inertia of second link
J_w	0.02	Rotational Inertia of wheel
K_{11}	34.67	Saturation coefficient for actuator torques (first actuator)
K_{12}	12.21	Saturation coefficient for actuator torques (first actuator)
K_{21}	6.45	Saturation coefficient for actuator torques (second actuator)
K_{22}	2.4	Saturation coefficient for actuator torques (second actuator)

As we can see in Figs. 5-7, the end effector and base followed the path well, with no chattering in inputs which are actuator torques. Sliding parameters in this case are λ = 50 and k = 10. Other figures (Figs. 6, 9, 12 and 15) will show that sliding mode controller is depended to its parameters. Sliding parameters are shown in (20)-(23):

$$e = x(i) - xdesired(i) \tag{20}$$

$$Surface = \dot{e}(i) - \lambda e(i) \tag{21}$$

$$u = -\lambda \dot{e}(i) - k \arctan\left(\frac{surface(i)}{saturate}\right) \tag{22}$$

The saturation of torque of actuators comes from:

$$K_{11} - K_{12}\dot{\theta} \tag{23}$$

in which $\dot{\theta}$ is rotational velocity of joint.

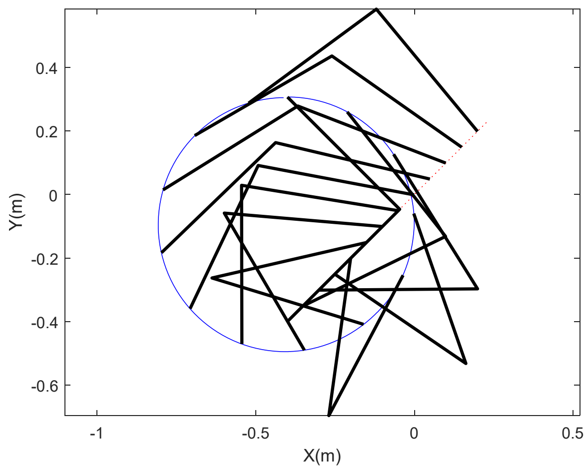

Fig. 5 Trajectory tracking for end effector and mobile base (λ = 50, k = 10)

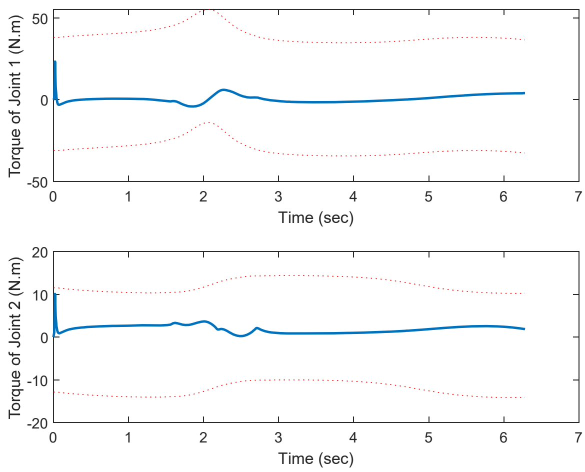

Fig. 6 Control inputs in joints which are actuator torque (λ = 50, k = 10)

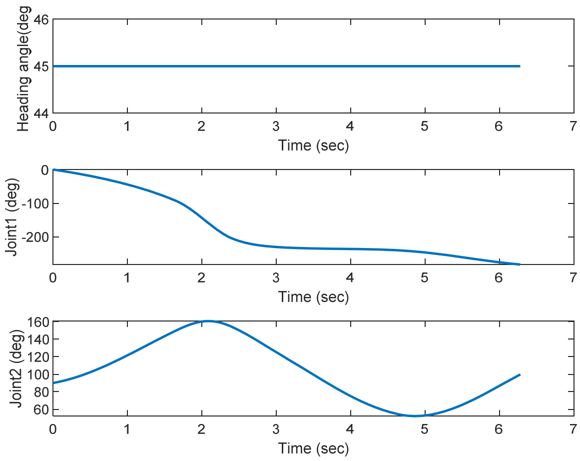

Fig. 7 Heading angle for joints and mobile base (λ = 50, k = 10)

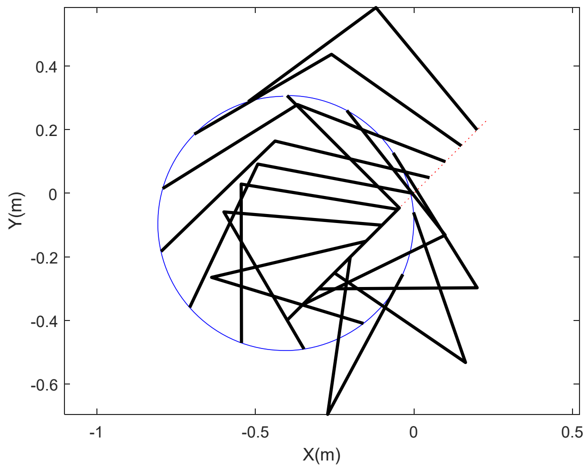

Fig. 8 Trajectory tracking for end effector and mobile base (λ = 20, k = 50)

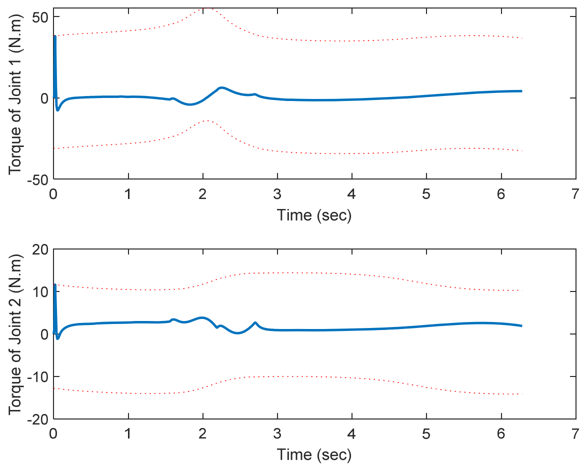

Fig. 9 Control inputs in joints which are actuator torque (λ = 20, k = 50)

For example, in Figs. 8-10, we see that there is no chattering but the torque of actuators is so close to its limits which is not preferable for us. The dotted lines show the limits of torques and as we know, the saturate for torque of an actuator depends on the velocity of the joint by some constant factors. In this case, the sliding mode parameters are k = 50 and λ = 20.

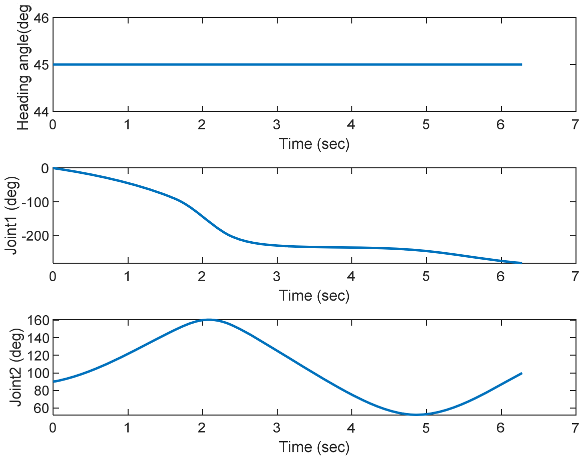

Fig. 10 Heading angle for joints and mobile base (λ = 20, k = 50)

In Figs. 11-13, we see that chattering phenomenon seems to be starting and at same time torques are so close to its limitations for these sliding parameters (k = 50, λ = 100).

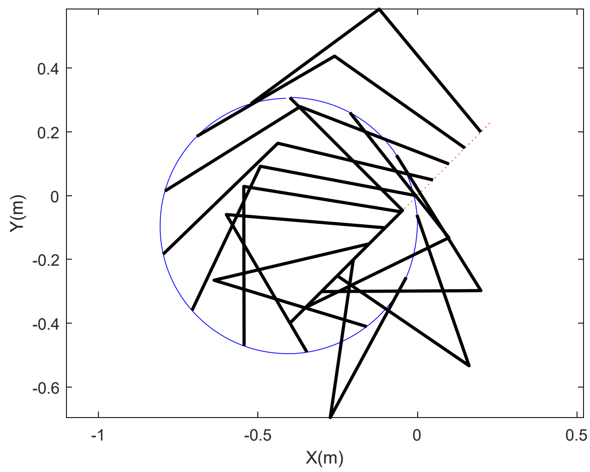

Fig. 11 Trajectory tracking for end effector and mobile base (λ = 50, k = 100)

In Figs. 14-16, we see that for the specific parameters of sliding mode controller (k = 100, λ = 100), there is absolute chattering for the torque of the joints.

All of figures (Figs. 7, 10, 13 and 16) in simulation results show that angle of joints is fairly smooth and there is no singular point for angles of manipulator during the following of the path. For all cases, with different sliding parameters (k, λ), the mobile manipulator followed the path very well (as shown in Figs. 5, 8, 11 and 14), but only those cases are acceptable which we do not have chattering on control inputs (actuator torques) and control inputs are not near its saturation limits.

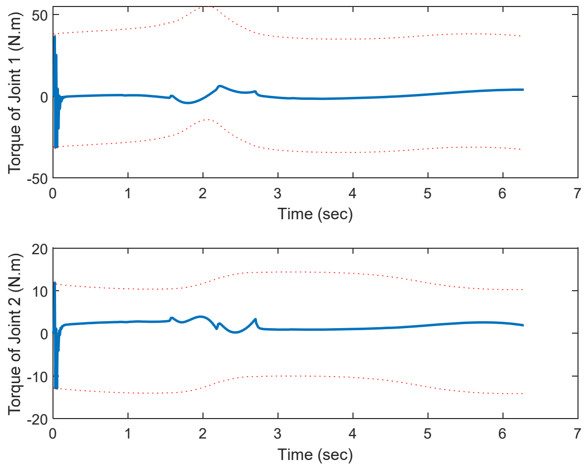

Fig. 12 Control inputs in joints which are actuator torque (λ = 50, k = 100)

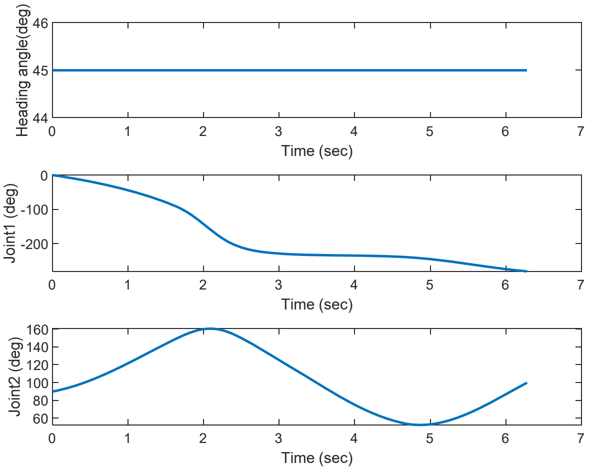

Fig. 13 Heading angle for joints and mobile base (λ = 50, k = 100)

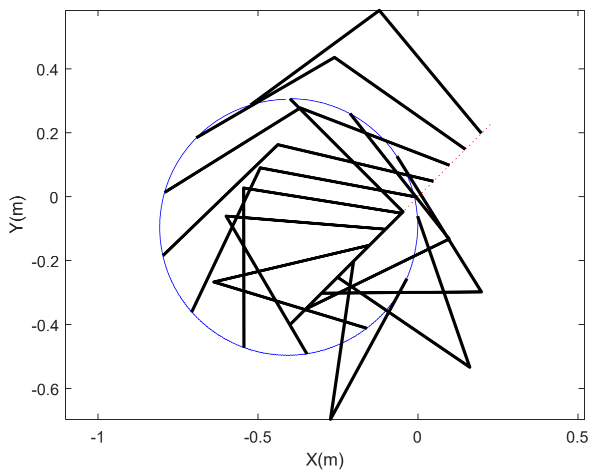

Fig. 14 Trajectory tracking for end effector and mobile base (λ = 100, k = 100)

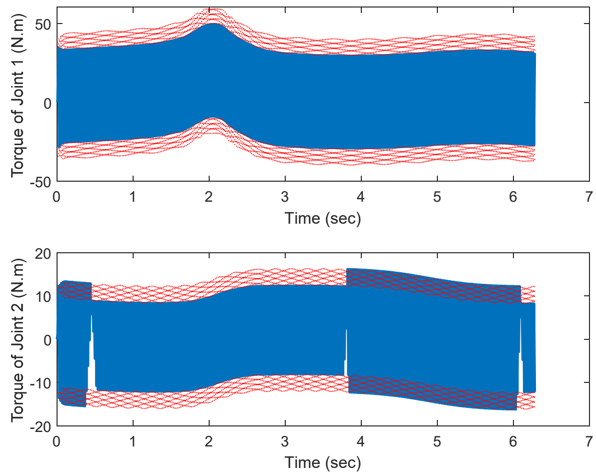

Fig. 15 Control inputs in joints which are actuator torque (λ = 100, k = 100)

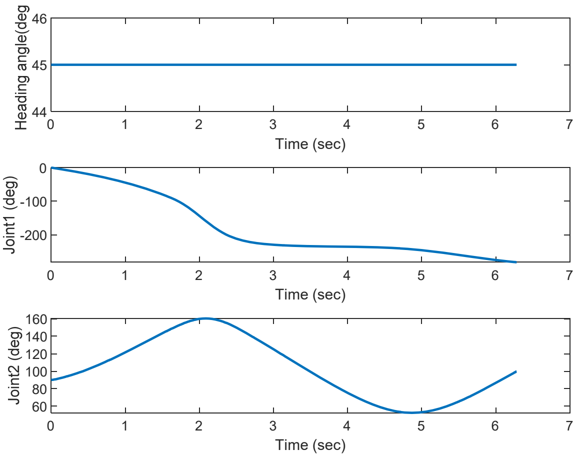

Fig. 16 Heading angle for joints and mobile base (λ = 100, k = 100)

V. Conclusion

Our paper and its simulation results show that sliding mode is a powerful nonlinear method which can control complex nonlinear dynamics, like mobile manipulator dynamic, very well. But we should consider that the chattering phenomenon is a known problem for this nonlinear controller method. For avoiding that, we can tune the sliding parameters and we can also use some smooth functions like sigmoid and arctan function instead of sign function. For future researches, we can add some uncertainty bounds to mobile manipulator dynamic equation parameters and use some other methods like adaptive fuzzy sliding method to design our robust controller. Also, we can consider non-holonomic constraints for mobile base and design some other complex paths for mobile base and end effector.

References

[1] Y. Yamamoto, Ph.D. Thesis: Control and Coordination of Locomotion and Manipulation of a Wheeled Mobile Manipulator, Philadelphia, PA, USA: Department of Computer and Information Science, School of Engineering and Applied Science, University of Pennsylvania, 1994.

[2] Abdelouahab Hassam and Miloud Hamani, "Motion Control of Non-Holonomic Mobile Manipulator Using Fuzzy Logic," in 8th Saudi Engineering Conference, Buraydah, Saudi Arabia, 2011.
[3] Zhong-Ping Jiang, Erjen Lefeber and Henk Nijmeijer, "Saturated stabilization and tracking of a nonholonomic mobile robot," Systems & Control Letters, vol. 42, no. 5, pp. 327-332, 2001.
[4] J.P. Desai, J.P. Ostrowski and V. Kumar, "Modeling and control of formations of nonholonomic mobile robots," IEEE Transactions on Robotics and Automation, vol. 17, no. 6, pp. 905-908, 2001.
[5] Santosha Kumar Dwivedy and Peter Eberhard, "Dynamic analysis of flexible manipulators, a literature review," Mechanism and Machine Theory, vol. 41, no. 7, pp. 749-777, 2006.
[6] Subudhi and A.S. Morris, "Dynamic modelling, simulation and control of a manipulator with flexible links and joints," Robotics and Autonomous Systems, vol. 41, no. 4, pp. 257-270, 2002.
[7] S. Nicosia, P. Tomei and A. Tornambe, "Dynamic modelling of flexible robot manipulators," in IEEE International Conference on Robotics and Automation, San Francisco, CA, USA, 1986.
[8] Y. Yamamoto and Xiaoping Yun, "Effect of the dynamic interaction on coordinated control of mobile manipulators," IEEE Transactions on Robotics and Automation, vol. 12, no. 5, pp. 816-824, 1996.
[9] O. Khatib, K. Yokoi, K. Chang, D. Ruspini, R. Holmberg and A. Casal, "Vehicle/arm coordination and multiple mobile manipulator decentralized cooperation," in IEEE/RSJ International Conference on Intelligent Robots and Systems, Osaka, Japan, Nov. 1996.
[10] Vivek A. Sujan and Steven Dubowsky, "An Optimal Information Method for Mobile Manipulator Dynamic Parameter Identification," IEEE/ASME Transactions on Mechatronics, vol. 2, no. 2, pp. 215-225, June 2003.
[11] Glenn D. White, Rajankumar M. Bhatt, Chin Pei Tang and Venkat N. Krovi, "Experimental Evaluation of Dynamic Redundancy Resolution in a Nonholonomic Wheeled Mobile Manipulator," IEEE/ASME Transactions on Mechatronics, vol. 14, no. 3, pp. 349-357, June 2009.
[12] V. Padois, J.-Y. Fourquet and P. Chiron, "Kinematic and dynamic model-based control of wheeled mobile manipulators: a unified framework for reactive approaches," Robotica, vol. 25, no. 2, pp. 157-173, 2007.
[13] N.A.M. Hootsmans and S. Dubowsky, "Large motion control of mobile manipulators including vehicle suspension characteristics," in IEEE International Conference on Robotics and Automation, Sacramento, CA, USA, April 1991.
[14] L. T. Wang and B. Ravani, "Dynamic Load Carrying Capacity of Mechanical Manipulators—Part I: Problem Formulation," Journal of Dynamic Systems, Measurement, and Control, vol. 110, no. 1, pp. 46-52, 1988.
[15] L. T. Wang and B. Ravani, "Dynamic Load Carrying Capacity of Mechanical Manipulators—Part II: Computational Procedure and Applications," Journal of Dynamic Systems, Measurement, and Control, vol. 110, no. 1, pp. 53-61, 1988.
[16] M.H.Korayem and A.Basu, "Dynamic load carrying capacity of robotic manipulators with joint elasticity imposing accuracy constraints," Robotics and Autonomous Systems, vol. 13, no. 3, pp. 219-229, October 1994.
[17] M. H. Korayem and M. Bamdad, "Dynamic load-carrying capacity of cable-suspended parallel manipulators," The International Journal of Advanced Manufacturing Technology, vol. 44, no. 7-8, p. 829–840, October 2009.
[18] Jun Wu, Xiaolei Chen, Liping Wang and Xinjun Liu, "Dynamic load-carrying capacity of a novel redundantly actuated parallel conveyor," Nonlinear Dynamics, vol. 78, no. 1, p. 241–250, October 2014.
[19] Zhijun Li, Shuzhi Sam Ge and Aiguo Ming, "Adaptive Robust Motion/Force Control of Holonomic-Constrained Nonholonomic Mobile Manipulators," IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics), vol. 37, no. 3, pp. 607-616, June 2007.
[20] Naijian Chen, Fangzhen Song, Guoping Li, Xuan Sun and Changsheng Ai, "An adaptive sliding mode backstepping control for the mobile manipulator with nonholonomic constraints," Communications in Nonlinear Science and Numerical Simulation, vol. 18, no. 10, pp. 2885-2899, October 2013.
[21] Zhijun Li, Shuzhi Sam Ge, Martin Adams and Wijerupage Sardha Wijesoma, "Adaptive Robust Output-Feedback Motion/Force Control of Electrically Driven Nonholonomic Mobile Manipulators," IEEE Transactions on Control Systems Technology, vol. 16, no. 6, pp. 1308-1315, Nov. 2008.
[22] Cihan Acar and Toshiyuki Murakami, "Underactuated two-wheeled mobile manipulator control using nonlinear backstepping method," in 34th Annual Conference of IEEE Industrial Electronics, Orlando, FL, USA, Nov. 2008.
[23] Z. Li, S.S. Ge, M. Adams and W.S. Wijesoma, "Robust adaptive control of uncertain force/motion constrained nonholonomic mobile manipulators," Automatica, vol. 44, no. 3, pp. 776-784, March 2008.
[24] Zhijun Li and Chun-Yi Su, "Neural-Adaptive Control of Single-Master–Multiple-Slaves Teleoperation for Coordinated Multiple Mobile Manipulators with Time-Varying Communication Delays and Input Uncertainties," IEEE Transactions on Neural Networks and Learning Systems, vol. 24, no. 9, pp. 1400-1413, Sept. 2013.
[25] Sheng Lin and A.A. Goldenberg, "Neural-network control of mobile manipulators," IEEE Transactions on Neural Networks, vol. 12, no. 5, pp. 1121-1133, Sep 2001.
[26] Dong Xu, Dongbin Zhao, Jianqiang Yi and Xiangmin Tan, "Trajectory Tracking Control of Omnidirectional Wheeled Mobile Manipulators: Robust Neural Network-Based Sliding Mode Approach," IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics), vol. 39, no. 3, pp. 788-799, June 2009.
[27] Yugang Liu and Yangmin Li, "Sliding Mode Adaptive Neural-Network Control for Nonholonomic Mobile Modular Manipulators," Journal of Intelligent and Robotic Systems, vol. 44, no. 3, p. 203–224, November 2005.
[28] Jean Bosco Mbede, Pierre Ele, Chantal-Marguerite Mveh-Abia, Youssoufi Toure, Volker Graefe and Shugen Ma, "Intelligent mobile manipulator navigation using adaptive neuro-fuzzy systems," Information Sciences, vol. 171, no. 4, pp. 447-474, May 2005.
[29] Homayoun Najjaran and Andrew Goldenberg, "Real-time motion planning of an autonomous mobile manipulator using a fuzzy adaptive Kalman filter," Robotics and Autonomous Systems, vol. 55, no. 2, pp. 96-106, February 2007.
[30] Yangmin Li and Yugang Liu, "Real-Time Tip-Over Prevention and Path Following Control for Redundant Nonholonomic Mobile Modular Manipulators via Fuzzy and Neural-Fuzzy Approaches," Journal of Dynamic Systems, Measurement, and Control, vol. 128, no. 4, pp. 753-764, Dec 2005.
[31] Y. Yamamoto and X. Yun, "Coordinating locomotion and manipulation of a mobile manipulator," in Proceedings of the 31st IEEE Conference on Decision and Control, Tucson, AZ, USA, 1992.
[32] K. Liu and F.L. Lewis, "Decentralized continuous robust controller for mobile robots," in Proceedings., IEEE International Conference on Robotics and Automation, Cincinnati, OH, USA, May 1990.