Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 53(4) (2021) 503-506
DOI: 10.22060/mej.2020.17517.6609

Double hyperbolic sliding mode control based on unscented Kalman filter for three-legged mobile manipulator

S. A. Ghoreishi, A. F. Ehyaei* , M. Rahmani

Electrical Engineering Department, Imam Khomeini International University, Qazvin, Iran

ABSTRACT: In this paper, mathematical and 3D modeling of a three-legged robotic arm capable of moving objects in rough terrain is first presented. Then, considering the noise and environmental disturbances, a suitable control method is proposed. Controlling this robot because of its nonlinear dynamics and the presence of disturbances and environmental effects is a very important and complex issue. Therefore, the controller should be able to set the robot in the right position as quickly as possible and eliminate the effect of environmental disturbances and noise on the system response. Accordingly, in this paper, a double hyperbolic sliding mode control based on an unscented Kalman filter is developed for a three-legged mobile manipulator and system stability is proved by Lyapunov theory. In the proposed controller design, while considering the disturbance term in the dynamic model of the system, an unscented Kalman filter is used to reduce the noise effect, which improves the robustness of the system under severe conditions. Finally, the performance of the proposed controller is compared with the inverse dynamic controller and the integral sliding mode control on the robotic system. The results show faster operation speed and accuracy in the system response.

Review History:

Received: Dec. 12, 2019
Revised: Feb. 15, 2020
Accepted: Mar. 10, 2020
Available Online: Mar. 31, 2020

Keywords:

Mobile manipulator
Three-legged robot
Double hyperbolic sliding mode
Unscented Kalman filter

1- Introduction

Many creatures use their feet for movement, which has inspired researchers to design legged robots in recent years. These robots have many advantages over other types of moving robots, including discontinuous surface contact [1], high maneuverability, ability to move in rough terrain, ability to cross obstacles, and climb stairs. Maintaining the balance and stability of the robot in motion is one of the major challenges in designing legged robots. Since legged robots (except for biped robots) have at least two points of contact when moving, their stability and balance are guaranteed. On the other hand, as the number of legs increases, the number of actuators and joints increases. This increases the cost and complexity of robot control. Accordingly, the three-legged robot structure is proposed as a compromise between balance and complexity. This structure is well-balanced due to having two ground contact points when moving. On the other hand, the analysis of the robot is less complex because the number of legs of the robot is less than other robots [2]. Other important issues in controlling these robots are balanced movement in the presence of uncertainties and disturbances, which have been proposed several solutions to answer. In the study of Lum et al. [3], feedback linearization control is used for the stable movement of the biped robot. Tzafestas [4] used robust sliding mode control for a five-link robot in the presence of uncertainties. Jeong et al.[5] introduce a robust controller for moving a legged robot by optimizing step position and step time. In the study of Raibert and Sutherland [6], three methods, including PD control, sliding mode control, and feedback linearization control on the biped robot, are studied, the results of which confirm that the sliding mode control method is better. One disadvantage of sliding mode control is the presence of chattering on the control signal, which damages the actuators. Other sliding mode control methods have been proposed for eliminating chattering and faster convergence towards the sliding surface, most recent examples of which include exponential functions [7] or double hyperbolic functions [8]. Greater convergence speed and better chattering elimination are the advantages of double hyperbolic compared to other methods. Another issue in the design of control systems is the inaccessibility of the states or the noise over the measured values, an unscented Kalman filter can be used to solve it. This estimator directly uses nonlinear dynamics, so it is not required to calculate the Jacobian such as the extended Kalman filter [9, 10].

In this paper, we propose a method of double hyperbolic sliding mode control based on an unscented Kalman filter for controlling a three-legged mobile manipulator in the presence of disturbances and noises. In this regard, in Section 2, the robot model and unscented Kalman filter are introduced, then the control method is proposed. The results of the simulation in Section 3 and the conclusions in Section 4 are presented.

*Corresponding author's email: f.ehyaei@eng.ikiu.ac.ir

2- Methodology

2.1. Robot model

The three-legged robot model presented in this paper is illustrated in Fig. 1. In this robot, each leg has 3 DOF, which is attached to the base of the robot with 6 DOF, and a 3 DOF arm is placed on the base of the robot. The robot is also point feet because of its simplicity and less computation. In Fig. 1, $[x_b, y_b, z_b]$ are the Cartesian coordinates of the base in the reference frame and $[\theta_b, \varphi_b, \psi_b]$ are the spatial orientations of the base in the reference frame. Based on the kinematic model of the robot and the numbering of each leg according to Table 1:

The generalized coordinates of the robot include the body, legs, and the arm variables as follows:

$$q_b = \begin{pmatrix} x_b \\ y_b \\ z_b \\ \theta_b \\ \varphi_b \\ \Psi_b \end{pmatrix} \qquad q_L^1 = \begin{pmatrix} \theta_1^1 \\ \theta_2^1 \\ \theta_3^1 \end{pmatrix} \qquad q_L^2 = \begin{pmatrix} \theta_1^2 \\ \theta_2^2 \\ \theta_3^2 \end{pmatrix}$$

$$q_L^3 = \begin{pmatrix} \theta_1^3 \\ \theta_2^3 \\ \theta_3^3 \end{pmatrix} \qquad q_{ARM} = \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \end{pmatrix}$$

where q_b is the base coordinate, q_L^i the generalized coordinates of the leg with the number "i", and q_{ARM} are the generalized coordinates of the arm. The generalized coordinates of the robot are obtained as follows:

$$q = \begin{pmatrix} q_b \\ q_L^1 \\ q_L^2 \\ q_L^3 \\ q_{ARM} \end{pmatrix}$$

Using the extended Lagrangian method, the closed-form of the three-legged robot model is finally obtained as follows [11, 12]:

$$M(q)\ddot{q} + C(\dot{q}, q)\dot{q} + G(q) = \tau + d \tag{1}$$

where M is the inertia matrix, C is the Coriolis matrix, G is the gravity matrix, τ is the torque vector and d is the disturbance vector in the system.

In this paper, controller design is performed in the support phase. In the support phase, all three legs are on the ground. On the other hand, the balance of the robot is checked using the center of gravity image method. According to this method, the system is balanced if the horizontal image of the center of gravity is inside a support polygon.

2.2. Unscented Kalman filter

The unscented Kalman filter method is fully listed in references [9, 10].

2.3. Double hyperbolic sliding mode control

In the double hyperbolic sliding mode control the reaching law is given by [8]:

$$\dot{s} = -k_1 \tanh(as) - k_2 |s| .\mathrm{asinh}(bs^q) \tag{2}$$

where s is the sliding surface, k_1, k_2, a and b are the positive parameters and q are the positive and the odd power, respectively. Now select the sliding surface as follows:

$$S = \dot{e} + \lambda e \tag{3}$$

where $e = q - q_d$ is the error, and we can write:

$$S = \dot{q} - \dot{q}_r \tag{4}$$

and $\dot{q}_r = (\dot{q}_d - \lambda e)$. Now, choose the Lyapunov function as follows:

$$V = \frac{1}{2} S S^T \tag{5}$$

By differentiating the Lyapunov function and substituting Eq. (1) and Eq. (4) into it, we will have:

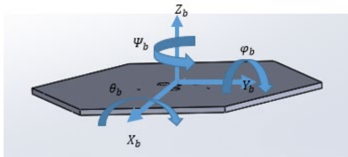
$$\dot{V} = S^T \left(-M^{-1}(C\dot{q} + g - \tau - d) - \ddot{q}_r\right) \tag{6}$$

Now, by choosing the torque as follows:

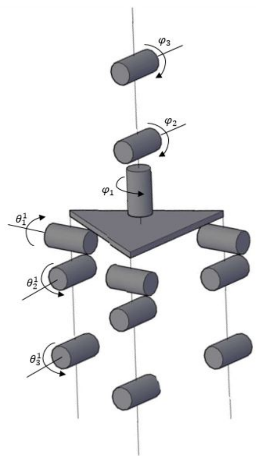
$$\begin{aligned} \tau = &C\dot{q} + g + M\ddot{q}_r - MK_1 \tanh(aS) \\ &-MK_2 |S| \mathrm{asinh}(bS^q) \end{aligned} \tag{7}$$

Table1 . Numbering of each leg

Leg location	Front	Back left	Back right
Leg number	1	2	3



a)robot base and degree of freedom



b)joints of three-legged robot

Fig. 1. Three-legged robot model

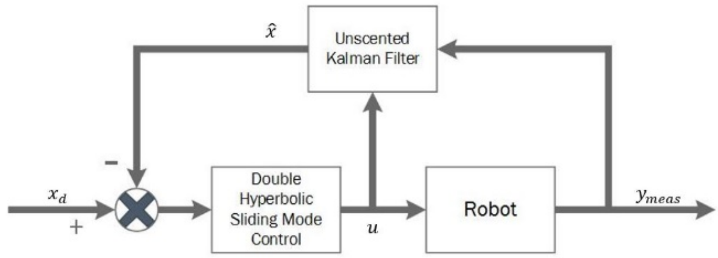
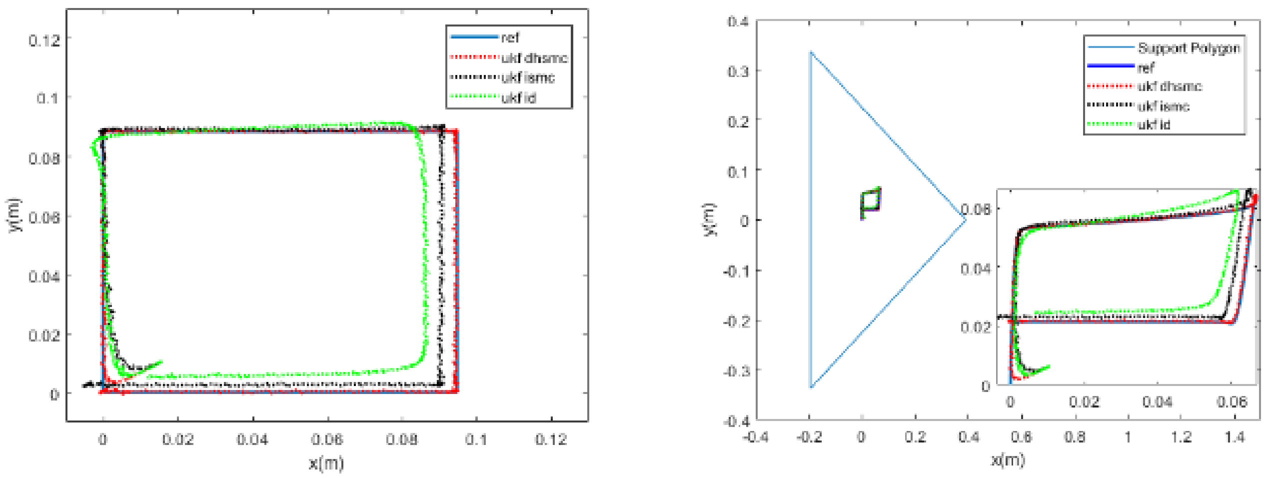


Fig. 2. Proposed control scheme



(a) **(b)**

Fig. 3. a) path pass by the robot base, b) changes in the image of the center of mass.

and substituting in Eq. (6), and considering $\left|M^{-1}d\right| \leq \varepsilon$ we will have:

$$\dot{V} = -\left|S^{T}\right|\left(K_1 \tanh\left(a\left|S\right|\right) - \varepsilon\right) - S^{T} K_2 \left|S\right| \operatorname{asinh}\left(bS^{q}\right) \quad (8)$$

So, if $\left|S\right| \geq \frac{1}{a}\tanh^{-1}\left(\frac{\varepsilon}{K_1}\right)$ the system is stable. The overall structure of the proposed control scheme is shown in Fig. 2.

3- Simulation Results

The simulation results of the three-legged robot using a double hyperbolic sliding mode control based on an unscented Kalman filter are presented in this section. The performance of this controller is also compared with the inverse dynamic controller and the integral sliding mode controller. The simulation is performed in the presence of disturbance as a shock at t = 1s to t = 1.25s and disturbance as the applied force from t = 1.5s to the end, which is applied to the first joint of the front leg. The goal is to move the base of the robot on a 9cm square on the x-y plane as well as the angle of the first and third joints of the arm varying from 0 to 90 degrees. From Fig. 3, it can be seen that the double hyperbolic sliding mode controller not only has a faster response than other methods, but it has also well robustness to disturbance. Fig. 3(a) shows the path passed by the robot base in each of the control methods, Fig. 3(b) also shows the changes in the image of the center of mass as the robot base and arm move. Since the image of the center of mass is inside the support polygon, the robot is balanced.

4- Conclusions

In this paper, after obtaining a three-legged mobile manipulator model, a double hyperbolic sliding mode controller based on an unscented Kalman filter was proposed to estimate the nonlinear states of the robot and control it in the presence of external disturbances. The stability of the closed-loop system for the proposed controller was also proved by using Lyapunov theory. Based on the results of the simulation and compared to sliding mode control and inverse dynamic control, the proposed method is more robust than the other two methods in addition to the convergence speed under the same conditions. Future work is to extend the proposed control method using neural networks and force control.

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HOW TO CITE THIS ARTICLE

S.A. Ghoreishi, A.F. Ehyaei, M. Rahmani, Double hyperbolic sliding mode control based on unscented Kalman filter for three-legged mobile manipulator, Amirkabir J. Mech. Eng., 53(4) (2021) 503-506.

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