Robust Control of a Spherical Mobile Robot

Majid Taheri Andani[1], Zahra Ramezani[2]

[1]F Phillip M. Drayer Electrical Engineering Department of Lamar University, Beaumont, TX, USA.
[2] Electrical Engineering Department, Iran University of Science and Technology, Tehran, Iran.

Abstract - *Due to their under- actuated system, spherical robots cannot be efficiently controlled by conventional control techniques, such as PID controllers. The path tracking and the position control of spherical robots have been the main class of control issues. To address this challenge, a controller is introduced to provide the effective path following of a 2-DOF (Degrees of Freedom) spherical robot. A sliding mode controller is designed. The stability of the controllers is examined using the Lyapunov stability theorem. Comparing with conventional controllers, the presented controller provides relatively smaller tracking errors. The simulation results indicate that the spherical robot controlled by the proposed methods is capable of moving to a desired point from any given initial point with minimum tracking error.*

***Key Words*: spherical mobile robot; sliding mode control, Robust Control, Mobile Robot, Nonlinear-Control**

1.INTRODUCTION

Spherical robot is a kind of mobile robots. Todays, spherical robots have become more attractive because of the manoeuvrability and high capability to move in unknown area such as other planets and ruins of earthquakes. The main difference between the robot and other robots is in the spherical shape. A spherical robot consists of a ball-shaped outer shell that encapsulates the mechanical components, energy source(s), and control devices. The spherical shell protects the internal structure against external shocks and dust, as well as surrounding medium (liquid or gas) [1].

Due to their under-actuated system, spherical robots are difficult to control. Although there have been many attempts to control spherical robots, an effective control method for this type of robots is not available yet. In 1990, Li and Canny [2] verified the controllability of spherical robots, and provided a path planning approach for these systems. Liu et al. [3] proposed a driving ahead motion control by feedback linearization. Zhe Wang et al. [4] presented a neural network PID controller, which enables the online processing for an amphibious spherical robot. They integrated the neural network with PID controller to achieve the target tracking. Kayacan et al. [5] Proposed control of a spherical robot by utilizing an adaptive neuro-fuzzy controller. The structure of this controller includes of a neuro-fuzzy network and a traditional controller which is used for the stability of the robot. Mukherjee et al. [6] utilized two methods for position tracking. The first method uses spherical triangles to reach the robot to an appropriated goal with a desired orientation. The second method uses a kinematic model and produces a trajectory include of linear lines and circular arc parts. Joshi and Banavar [7,8] Proposed a dynamic model for the system and discussed its path tracking on a surface with barrier. They suggested the kinematics model of a spherical mobile robot utilizing Euler parameters and acquired the path tracking problems. Kamaldar et al. [9] presented a controller for improving the performance of the Robot in straight direction. Lateral vibration creates during the movement of spherical robot due to the physical nature and dynamics of spherical robots. They designed a controller whose task is to reduce the vibration. Roozegar et al. [10,11] Proposed the dynamic programming for path planning of spherical robot. With completing the dynamic programming table, the robot can find the optimal admissible path, and it can move toward the final position. Bicchi et al. [12,13] established a simple dynamic model for a spherical mobile robot and proposed its path planning on surface with barrier. With considering some subjects, a feedback controller for a kinematic based on the back-stepping method is discussed in [14].

To the best of the authors' knowledge, there are rarely useful controllers into account to follow a general path instead of only forward lines and circular arc parts. The equation of a spherical robot cannot be converted to the classical form, which presents many normal established algorithms and control algorithms. So, it becomes a difficult issue while designing controllers for finding an appropriate path for a spherical mobile robot. In this manuscript, focuses on the path tracking and control of a spherical robot system. The kinematic equation is provided for a two-DOF pendulum-driven spherical mobile robot. Besides, to address the uncertainties in equations, a sliding mode controller is provided to realize the path following of the robot. This paper is organized as follows: Section 2 describes the kinematic model of a spherical robot. In Section 3, a brief description of sliding mode for the spherical robot is presented. Simulation results are presented and discussed in Section 4. In the last section, the results are summarized.

2. MODEL OF THE SPHERICAL ROBOT

In this section, the kinematics of a pendulum-based spherical robot is addressed. By changing the pendulum to desired position, the spherical robot can move. Fig. 1 displays a schematic of the robot. Two motors are used to move the robot: the first motor is connected to the horizontal axis that goes across the sphere. The pendulum that can move is in the center. If the motor is turned on, the sphere will move since the weight of the pendulum has adequate inertia that it is simple for the pendulum to go around. The second motor provides the side-to-side motion for the pendulum. Therefore, this robot has a pendulum with two degrees of freedom [1]. Regard the motion of the robot on a flat plane. The contact point can be indicated as bellows in the coordinate system connected to the sphere midpoint.

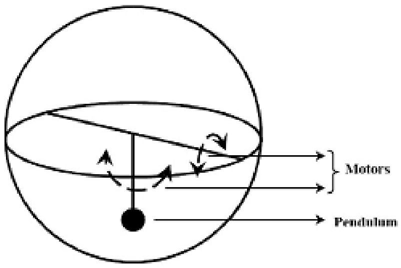

Fig -1: schematic of 2-DOFs spherical robot design

In spherical coordinates, ρ, β, α are position coordinates. The contact path on the plane is determined by c=(x,y) in the xyz-coordinates connected to the plane. The connection path on the sphere is represented by $c' = (\alpha, \beta)$ in the coordinates connected to the sphere. With consideration the plane in Cartesian coordinates, the rotation angle of the robot will be the angle among two coordinate systems at the connection point (see Fig. 2). ζ represents the "holonomy angle". The forward kinematic equation is solved in which we try to obtain c with knowing of c' is obtained as below [9,15].

$$f(\alpha,\beta) = \begin{pmatrix} \rho\cos\beta cos\alpha \\ \rho cos\beta sin\alpha \\ \rho sin\beta \end{pmatrix} \quad (0)$$

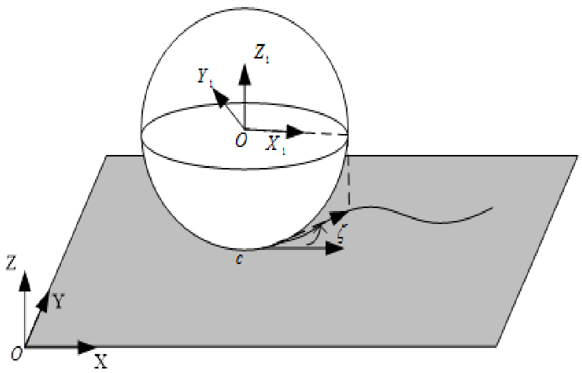

Fig -2: The holonomy angle in the spherical robot

$$\begin{cases} \dot{X} = \rho\left(-\dot{\alpha}\cos\beta\sin\zeta + \dot{\beta}\cos\zeta\right) \\ \dot{Y} = \rho\left(\dot{\alpha}\cos\beta\cos\zeta + \dot{\beta}\sin\zeta\right) \\ \dot{\psi} = -\dot{\alpha}\sin\beta \end{cases} \quad (2)$$

Where α and β are the input variables. These variables specify a path on the sphere. Since these inputs are needed in order to control the spherical robot, forward kinematics of the system are governed by (2). In this case, the spherical robot velocity is low to ignore the dynamics equation, so the sphere-plate connection points remain below the mass hanging down the pendulum. Position of the motors and the pendulum are inside the sphere to diverse the mass center for a favorable motion. The pass can find by diversity θ and φ which indicates the connection point path on the sphere. Then, using (2) we can find X and Y that demonstrate the connection point path on the plane. Control inputs are angles, so ignoring the dynamics equation of system which is a true hypothesis [16].

3. Sliding Mode Control

One approach of controlling a non-linear system is sliding mode control. This method is utilized to deal with uncertainty in the system. The model should be able to obtain the input and output the system and must be reliable, and the design of the actual physical system must function properly. Sliding mode controller is a kind of robust controller. A robust controller typically includes a nominal part is similar to that of the additional linearization of a nonlinear system in order to express the uncertainties in the model are considered. The goal of this controller is to put all of the paths of the system state on a stable surface until the paths of state systems slip on that surface and reach to the balance work. The selection of this surface is caused to reduce the order of the system from higher-order system to lower order system, so the controlling and stabling of the system would be simple.

In this section, we want to control the position of the robot by controlling the inputs. Two outputs of the robot can be controlled because this system has two inputs. X, Y that will be considered outputs in order to control the position of spherical robot. Besides, the angular velocities are considered as inputs. Kinematic equations are rewritten as follows.

$$\dot{P} = JU \quad (3)$$

$$P = \begin{bmatrix} X \\ Y \end{bmatrix}, \quad J = \begin{bmatrix} -\rho\cos\beta\sin\zeta & \rho\cos\zeta \\ \rho\cos\beta cos\zeta & \rho\sin\zeta \end{bmatrix}, U = \begin{bmatrix} \dot{\alpha} \\ \dot{\beta} \end{bmatrix} \quad (4)$$

In this section will be to design a control sliding surface, first, a sliding surface vector will be defined as follows.

$$s = P - P_d, \qquad P_d = \begin{bmatrix} X_d \\ Y_d \end{bmatrix} \tag{5}$$

In (5), X_d and Y_d are the centre of the robot in desirable position. Also, Lyapunov stability theorem is defined as follows.

$$V = \frac{1}{2} S^T MS, \qquad M = \begin{bmatrix} 1 & 1/2 \\ 1/2 & 1 \end{bmatrix} \tag{6}$$

Since the matrix M is positive definite, therefore Lyapunov function will be positive definite. Then Lyapunov function should be derivative, and the control input in such a way to be determined that the derivative of Lyapunov function is negative semidefinite. So, for the specific input the stability of the system can be proved.

$$\dot{V} = \frac{1}{2} \dot{S}^T MS + \frac{1}{2} S^T M\dot{S} = S^T M\dot{S} \tag{7}$$

So,

$$\dot{V} = S^T M \left(\dot{P}_d - \dot{P}\right) = S^T M \left(\dot{P}_d - JU\right) \tag{8}$$

The control input is considered as follows.

$$U = J^{-1}\left(\dot{P}_d + \gamma S + \eta M^{-1} sign(S)\right) \tag{9}$$

By replacing the control law that derived from Lyapunov function, the following equation is obtained [17].

$$\dot{V} = -\gamma S^T MS - \eta |S| 0 \leq 0 \tag{10}$$

It is obvious that the derivative of Lyapunov is negative semi-definite, based on the Lyapunov stability theorem the system is stable In order to evaluate the performance of this controller, in the next section the result of simulation will be presented.

4. Simulation Results

This section provides the simulation results through MATLAB, to verify the efficiency of sliding mode controllers proposed in Section 2. Considering the robot rolls without slipping on a plane. Initial conditions for simulation are presented as follows.

$$\mathbf{P_d} = \begin{bmatrix} X_d \\ Y_d \end{bmatrix} = \begin{bmatrix} 2\sin(2t) \\ \sin(t) \end{bmatrix}, \tag{11}$$

$$\mathbf{P}(t_0) = \begin{bmatrix} X \\ Y \\ \psi \end{bmatrix}_{t_0} = \begin{bmatrix} 3/4 \\ -3/4 \\ 0 \end{bmatrix}, \tag{12}$$

Radius of the robot is assumed to be ρ=0.2. The simulated of sliding mode control and fuzzy sliding mode control are as follows. Desired trajectory and robot motion path are given in Fig. 4.

Control inputs for desired path from initial point to final state will be as follows:

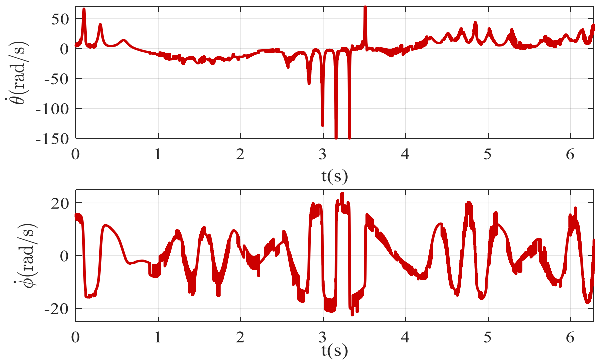

Fig -3: Control inputs

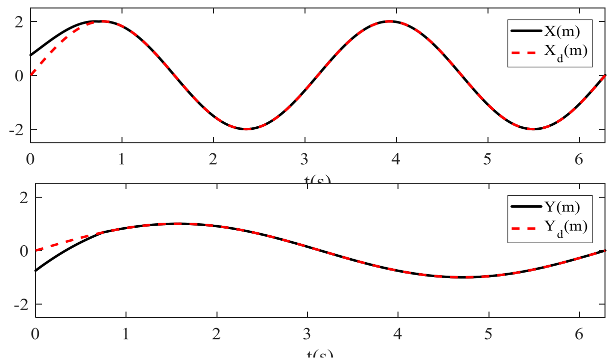

Fig -4: Robot trajectory

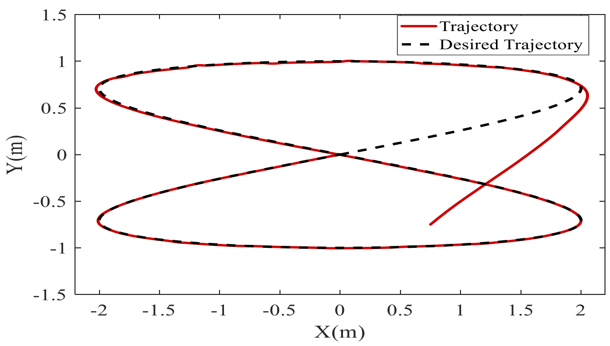

Fig -5: Robot trajectory along x-y plane

Figures show the tracking performance of the sliding mode controller. template sample paragraph. It is seen that the tracking error is bounded and the designed sliding mode control can effectively reach the trajectory tracking of the plant and controller inputs are suitably smoothed.

5. CONCLUSIONS

This paper proposed the design of a controller for controlling a two-DOF pendulum-driven spherical robot using the sliding mode algorithm. Sliding mode control is a method of robust controls. The goal of this controller is to maintain all of the paths of the system state on a stable surface until the paths of state systems slip on that surface and reach to the balanced work. The selection of this surface decreases the order of the system from higher-order system to lower order system, so the controlling and stabling of the system would be simple and the robot is capable of moving to a desired point from any given initial point with minimum tracking error. Simulation results are presented to evaluate the performance of the proposed controller. The forward kinematic model of robot is used for finding its new position. It is confirmed that this controller provides nice tracking performance, and the proposed control is not complicated. Furthermore, the performance of the sliding mode control in the existence of uncertainty is satisfactory.

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