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Configuration Control of Planar Underactuated Robotic Manipulator using Terminal Sliding Mode

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Abstract: Robotic manipulators find their applications in various fields. Some applications need cheap and light weight robotic manipulators. This need is fulfilled by using underactuated robotic manipulators, where few joints are unactuated, either by design or actuator failure. Further, it may be desired for the end effector of the robotic manipulator to reach a particular position in Cartesian space so that all its joints whether active or passive achieve their desired angular positions from any arbitrary initial positions. It is a challenging task to control such an underactuated robotic manipulator. In the present work, a finite time convergent and robust controller is presented for joint configuration control of three link planar articulated underactuated robotic manipulator using a combination of terminal sliding mode control and higher order sliding mode. Dynamic coupling between the joints has been put to use for controlling movement of passive joint. Simulation results show that all the joints obtain their desired angular positions. The control design is aimed at getting a chatter free and robust control.

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1. INTRODUCTION

Robotic manipulators are positioning devices which have utility in terrestrial and space applications. For space applications, there is always a limit on the weight to be carried. The actuators have motors which are quite heavy. If a few joints are unactuated, then the weight can be reduced considerably. A robotic manipulator in which all the joints or degrees of freedom of the system are not equipped with actuators is known as underactuated robotic manipulator. A joint which is not equipped with actuator is passive. A robotic manipulator may become underactuated if one or more actuators fail or it is deliberately designed so to reduce cost and weight. It may also be possible that certain joints are used exclusively for braking and others are used for actuation. In spite of being underactuated, the robotic manipulator in certain space applications may have to finish a given task before it can be repaired. Thus, fault tolerance in the control of such systems is very important. All the joints whether active or passive have to achieve their desired angular positions, so that the tool required for the job reaches its desired position. Controlling such manipulators is a challenging job.

Researchers have shown keen interest in studying underactuated robotic manipulator. This paper deals with the problem of joint configuration control of underactuated robotic manipulator. Various techniques have been used to control the problem undertaken. A controller using dynamic coupling between the joints has been proposed in Arai & Tachi (1991). An integral control of an underactuated robotic system has been suggested in Y.R. Teo & A. Donaire & T. Perez (2013). A sliding mode controller for a robotic manipulator with passive joints has been designed in Bergerman, M. (1994); Won Kim & Jin-Ho Shin & Ju-Jang Lee. (2002); Zhuang Lin & Qidan Zhu & Chengtao Cai (2006); Akira Inoue Tomohino Henmi & Mingcang Deng (2011), which suffers from the problem of chattering. Neural network technique has been used for position control of underactuated robotic manipulator in Hasan, A.T. (2012). In this it is observed that the desired trajectory was not tracked faithfully. An adaptive fuzzy sliding mode control technique has been used to control the position of three link robotic manipulator in Subashini Elangovan & Peng-Yung Woo (2004). However, it is observed that the error does not become zero in finite time and the problem of discontinuous control persists. The problem of chattering can be removed by using higher order sliding mode control technique. Also, the control becomes continuous by choosing appropriate order of sliding mode. A controller using higher order sliding mode technique for achieving proper positioning of end effector in Cartesian space has been proposed in Manjusha Bhave, S. Janardhanan & Lillie Dewan (2013).

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However, as the order of sliding mode increases, the control becomes complex. Terminal sliding mode control technique is another technique known for fast convergence to origin once the sliding surface is reached.

In the present work, combination of higher order sliding mode control and terminal sliding mode control is used for the joint configuration control of three link planar articulated underactuated robotic manipulator. The aim of control design is to get a robust, continuous control which will remove chattering in states. Also, the system states converge to origin in finite time, once the sliding surface is reached.

The paper is organized in the following sections. In Section 2, the dynamics of a planar articulated three link underactuated robotic manipulator are discussed. In Section 3, the robust controlling techniques called higher order sliding mode control and terminal sliding mode control are explained, control philosophy is discussed and finite time convergence of system to origin is shown. In Section 4, simulation results for three link underactuated robotic manipulator using higher order SMC and terminal SMC are discussed. Finally, the conclusion is drawn in Section 5.

2. THE MODEL

Using Lagrangian approach, the dynamic equations of an $n - link$ planar articulated equipotential robotic manipulator can be described in joint space by Craig, J.J. (1989):

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} = \tau$$

In underactuated robotic manipulator, few joints are not equipped with actuators. Here, a three link planar articulated underactuated robotic manipulator is considered where first and third joints are equipped with actuators and second joint is passive. Due to dynamic coupling between the joints, the passive joint will disturb the movements of the active joints too. It is assumed here that the passive joint has holding brake instead of actuator and hence is lockable. The dynamic equations for such a manipulator can be expressed as:

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{12} & m_{22} & m_{23} \\ m_{13} & m_{23} & m_{33} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_3 \end{bmatrix} + \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix} = \begin{bmatrix} \tau_1 \\ 0 \\ \tau_3 \end{bmatrix} \quad (1)$$

$$c_1 = c_{11}\dot{\theta}_1 + c_{12}\dot{\theta}_2 + c_{13}\dot{\theta}_3$$
$$c_2 = c_{21}\dot{\theta}_1 + c_{22}\dot{\theta}_2 + c_{23}\dot{\theta}_3$$
$$c_3 = c_{31}\dot{\theta}_1 + c_{32}\dot{\theta}_2 + c_{33}\dot{\theta}_3$$

The torque for the passive joint is zero. The system dynamics can be rewritten as

$$\ddot{\theta} = f(\theta,\dot{\theta}) + g(\theta)\tau \quad (2)$$

System functions $f(\theta,\dot{\theta})$ and $g(\theta)$ are

$$f(\theta,\dot{\theta}) = -M^{-1}(\theta)C(\theta,\dot{\theta})\dot{\theta} \quad (3)$$
$$g(\theta) = M^{-1}(\theta)$$

As a robotic manipulator is highly uncertain, its dynamics are not exactly known. Hence, differential inclusion is used to specify ranges for following system functions, $f(\theta,\dot{\theta})$ and $g(\theta)$ as $[-F, F]$ and $[G_1, G_2]$ respectively.

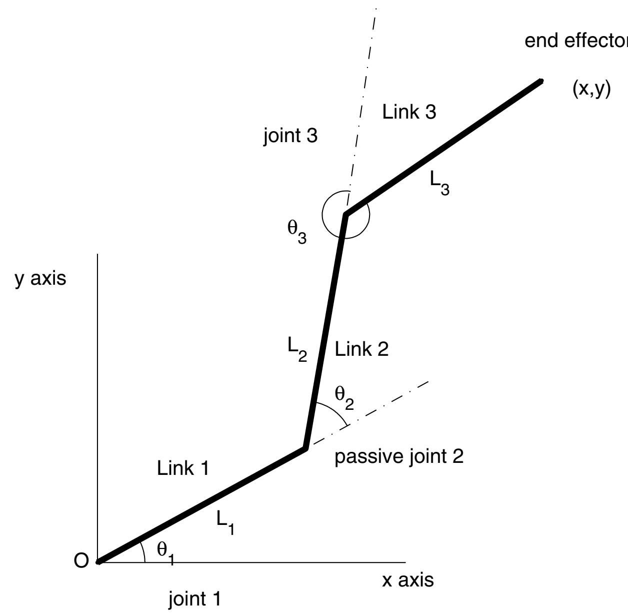

Fig. 1. Pictorial representation of three link manipulator with passive second joint

$$-M^{-1}(\theta)C(\theta,\dot{\theta})\dot{\theta} \in [-F, F]$$
$$M^{-1}(\theta) \in [G_1, G_2]$$

3. ROBUST CONTROL OF THREE LINK PLANAR ARTICULATED EQUIPOTENTIAL UNDERACTUATED ROBOTIC MANIPULATOR

Consider a three link planar robotic manipulator shown in fig. 1, with link lengths denoted by L_1, L_2 and L_3 respectively.

3.1 Problem Statement

For a planar three link robotic manipulator with second joint being passive, the dimension of vector τ is less than that of vector θ.

$$dim(\tau) < dim(\theta) \quad (4)$$

With the limitation of robotic manipulator having passive joint, the control objective is to design a continuous and robust control τ for the system using a combination of terminal sliding mode control and HOSM so that all the joints attain the certain desired positions from any arbitrary initial positions. If initial values of joint angles for three link robotic manipulator are $(\theta_1, \theta_2, \theta_3)$ and the final desired values are $(\theta_{1desired}, \theta_{2desired}, \theta_{3desired})$, then all the joints should attain their desired angular positions.

$$(\theta_1, \theta_2, \theta_3) = (\theta_{1desired}, \theta_{2desired}, \theta_{3desired}) \quad (5)$$

3.2 Control Philosophy

In underactuated three link robotic manipulator, only active joints 1 and 3 can be directly controlled, as joint 2 is passive. To control such a manipulator, dynamic coupling between the joints is put to use. The control works as follows:

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