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Sliding mode controller design for trajectory tracking of a non-holonomic mobile robot with disturbance☆

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ABSTRACT

This paper develops sliding mode controller for the trajectory tracking of a non-holonomic differentially driven wheeled mobile robot (DDWMR) with measurement noise, frictional disturbances and model uncertainties. The proposed controller is designed with the help of an existing Proportional-Integral (PI) sliding surface for trajectory tracking followed by a new Proportional-Integral-Derivative (PID) sliding surface for velocity tracking. The PI and PID sliding surfaces are based on the kinematic model and dynamic model of the robot, respectively. An adjustable gain switching controller is incorporated for minimizing the effect of disturbances and uncertainties. The closed loop stability of the system is proved using Lyapunov stability criteria. The proposed controller is validated with the help of numerical examples and real-time experiments on DDWMR.

1. Introduction

Mobile robot has become an important area of research among engineers and scholars in recent years because of its wide area of application such as, automation industry, services and planetry exploration. A differentially driven wheeled mobile robot (DDWMR) is a type of non-holonomic underactuated system having degree of freedom higher than the number of actuators. This gives advantages in terms of lesser number of control inputs, drives and energy efficiency but poses challenges like, non-linearity and constrained motion in trajectory tracking. Researchers have come up with control algorithms based on linearization of the system as well as direct application of non-linear control algorithm. An output feedback controller design has been developed for unicycle-type mobile robot [1]. Shaojei and Shahari in [2] proposed a dynamic surface control approach for the uncertain non-holonomic wheeled mobile robot. An integral sliding mode controller design [3] for an under-actuated two-wheeled mobile robot has been developed. For under-actuated systems without uncertainties, control algorithms are developed based on Lyapunov stability criteria, passivity and feedback linearization [4]. For a class of non-linear system a controller design method using hierarchal fuzzy sliding mode(HFSM) [5] was proposed to achieve stability and decoupling performance. A new fuzzy adaptive motion control system is proposed for wheeled under-actuated cars with non-holonomic constraints including on-line extended Kalman's filter (EKF) [6]. For stabilization and tracking control of a non-linear two-axis inverted-pendulum servomechanism, a cascade adaptive fuzzy sliding-mode control scheme with inner and outer control loops is given in [7]. An integral sliding manifold design for a linear system with matched disturbance [8] is proposed by applying singular value decomposition to cope with singularities of the system matrix. For full-scale trajectory tracking via input-output linearization and asymptotically stable inter-dynamics [9] of a two-wheeled driven cart is

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proposed. Additionally, real-time control of two- wheeled mobile robots (2 WMRs) and similar under-actuated systems is achieved in [10,11].

In the absence of uncertainties in the system, the controller design and stability analysis completely rely on the accurate knowledge of the mathematical model of the system. However, the presence of external disturbances, system model inaccuracies and measurement noise degrade the tracking performance and even devastate system's stability. This motivated researchers to look towards developing robust controller design for the under-actuated system [12,13]. Owing to the unexpected nature of uncertainties, designing the controller becomes difficult problem. In this paper, two known bounded functions [14,15] are taken as uncertainties in the system model for the development of robust controller design. Having the underactuated nature of the system, two sliding surfaces are proposed. The performance and stability of these sliding surfaces depend on each other. Finally, to obtain the desired control law for the system, the closed-loop stability and performance of these sliding surfaces are examined e.g., [5] and [16,17]. The key concepts for the development of these control laws are discussed as follows. An adaptive fuzzy hierarchal sliding-mode controller has been proposed for a class of MIMO nonlinear time-delay systems [18] with input saturation. To avoid potential singularity problem and to solve the problem of input saturation, the adaptive law is used. An adaptive fuzzy sliding-mode controller is designed for trajectory tracking of a movable cart with an inverted pendulum system [19]. However, approximations were taken to develop the equivalent non-linear under-actuated system function and for the upper bound of time-varying external disturbances functions. Finally, a hierarchal sliding -mode under-actuated control [20] is proposed for the trajectory tracking of a nonholonomic wheeled mobile robot in the presence of frictional disturbances and uncertainties.

Considering the aforementioned discussions, this paper is based on the modification of the approach taken in the paper [20]. For the designing of second sliding surface in [20], the currents in the left- and right- wheel motors are taken as direct state outputs to design the controller. Since the applied control input voltages to the motors are pulse width modulation (PWM) type, generally the frequency in the range of kilohertz, this causes chattering and unbounded first and second derivatives, ultimately causing poor speed and torque control [21]. Also higher switching gains (in range of thousands) were proposed in [20] which are not convenient to determine with unbounded derivatives of the direct states. To address these problems this paper utilizes the merger of the chassis dynamics of the robot with motor dynamics, making altogether a linear dynamic system while keeping the kinematic non-linear part separately [22]. Taking linear and angular velocities as outputs for linear dynamic equation provides an explicit solution for the input control voltages using second sliding surface. The desired linear and angular velocities are obtained from first sliding surface which is designed to track the trajectory or indirect states of the robot in a two-dimensional plane, based on non-linear kinematic model. The obtained control law and simulation results are different from the previous studies (e.g., [17–19] and [20]).

The work done in this paper is summarized as follows. At beginning, there is a different approach taken under consideration unlike previous studies (considering the whole system as non-linear thus making the solution unnecessarily complex to obtain control input) to simplify and separate the kinematic and dynamic part (incorporation of actuator dynamics as well while avoiding the non-linearities present in motors) of DDWMR including frictional disturbances and uncertainties. Secondly, based on these system's mathematical models, two sliding surfaces are constructed (first with three indirect states and second with two indirect states along with two direct states). Finally using Lyapunov's stability criteria, reference angular and linear velocities are obtained for the second sliding surface such that, under suitable condition indirect outputs asymptotically track the indirect reference input which is provided for a specific task (e.g. endpoint tracking, line tracking, circular tracking). Similarly, the indirect outputs of the linear dynamic model asymptotically track the reference input provided by the first controller's output under the suitable condition and desired input control voltages are obtained for left and right motors respectively.

The paper is organized as follows: In Section 2, system mathematical modeling and trajectory planning of a mobile robot is discussed. Section 3 describes proposed controller which consists of two sliding surfaces based on two state vectors (first for kinematic and second for a dynamic model of DDWMR). Simulation results and discussions are given for the selected system model in Section 4. In Section 5, experimental validation of the proposed controller is performed on a DDWMR. Finally, conclusions and further scopes of the research are discussed in Section 6.

2. Mathematical modeling and trajectory planning

To simplify the control law, the system model is represented in two separate but interconnected subsystems. The first part is the kinematic model of the system which represents the robot's rate of change of its position in global coordinate with respect to change in its linear and angular velocities. This relation is nonlinear with sine and cosine functions. The second part of the system model consists of the robot's dynamics which includes left and right DC motor and chassis of the robot. The following three subsections will show kinematic modeling, dynamic modeling and the trajectory planning.

2.1. Kinematic model

In Fig. 1, the following relation will hold for the rate of change of the robot's coordinate ($\dot{x}_{rw}$, $\dot{y}_{rw}$ and $\dot{\theta}_{rw}$) with respect to linear and angular velocities about point R

$$\dot{x}_{rw}(t) = v_{rw}(t)\cos(\theta_{rw}(t)), \quad \dot{y}_{rw}(t) = v_{rw}(t)\sin(\theta_{rw}(t)), \quad \dot{\theta}_{rw} = \omega_{rw}(t). \tag{1}$$