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Trajectory tracking control of Skid-Steered Mobile Robot based on adaptive Second Order Sliding Mode Control

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A B S T R A C T

This paper presents design and implementation of adaptive Second Order Sliding Mode Control (SOSMC) for a four wheels Skid-Steered Mobile Robot (SSMR). The control objective is to follow a predefined trajectory by regulating the linear and angular velocities, and in presence of external disturbance and parametric uncertainty. Adaptive Super Twisting (AST) algorithm is designed in order to build a robust controller with neglected chattering in steady state. The proposed controller is validated experimentally. The results show that the proposed controller guarantees the performance of the conventional SOSMC under external disturbance and parametric uncertainty with less chattering.

1. Introduction

Mobile robots are used extensively for tasks in dangerous and harsh environments, such as space exploration, military surveillance, security, etc. They are able to navigate and perform tasks in unstructured environments, without continuous human guidance. The Skid Steered Mobile Robot (SSMR) is a kind of mobile robot that has no dedicated steering mechanism. It generates curvilinear motion by applying differential torque to its wheels. The absence of steering system makes this robot robust and suitable for rough surfaces. However, trajectory tracking controller is very difficult for an SSMR vehicle especially when the reference trajectory is a curved path. In this case, the wheels need to skid laterally and cannot be tangent to the desired path.

Many recent research works have addressed the trajectory tracking control of SSMR. The robot model is usually described in the same way as the trajectory, consisting of a kinematic model and a dynamic model. Most of the developed controller design in literature is based on the kinematic model only. The dynamic model is more valuable to design a robust trajectory tracking as it highly depends on the robot parameters such as moment of inertia, mass, frictions, etc. In Caracciolo, de Luca, and Iannitti (1999), an exponential stabilizing state feedback with friction estimations is proposed as a robust controller. The controller performance was validated through simulation and proved only for straight line motion. In Kozlowski and Pazderski (2004), a new control law is proposed using Lyapunov analysis and backstepping technique. The method is susceptible to steady-state tracking error in both simulation and experimental results due to parametric uncertainty. A PID controller has been applied experimentally in Yu, Ylaya Chuy, Collins, and Hollis (2010). The controller is validated on a short trajectory path and shown good performance in closed loop but robustness study is not included. Adaptive Neural Network (NN) tracking controller is proposed in Boukens, Boukabou, and Chadli (2017), de Jesús Rubio (2017), de Jesús Rubio et al. (2017) and Park, Yoo, Park, and Choi (2009) for different application specifically for trajectory control, pendulums and magnetic levitation. The proposed controller performances have been proved through simulations or experiments. However, the NN technique has many disadvantages, and among of them implementation difficulty on a real setup and required greater computational source (Tu, 1996). In Begnini, Bertol, and Martins (2017), an adaptive fuzzy variable structure control integrated with a proportional plus derivative control is proposed as a robust solution. Moreover, the fuzzy logic controllers for the trajectory tracking have been point of interests in different works (Amer, Sallam, & Sultan, 2016; Asif & Junaid, 0000; Maalouf, Saad, & Saliah, 2006). However, the fuzzy logic control highly depends on the number of rules selected in the control design. In Serrano, Scaglia, Cheein, Mut, and Ortiz (2015) and Serrano, Scaglia, Rómoli, Mut, and Godoy (2014), a new method to find controller gains which do not exceed the actuator saturation limits, but this method is not robust against parametric uncertainty and steady-state error can be detected. In Chwa (2010) and Chwa (2016), a backstepping FeedBack Linearization (FBL) combined with PID controller is proposed but the control design is based only on the kinematic model. A feedforward controller with

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a proportional feedback controller is applied in Klančar, Matko, and Blažič (2009) and a PD controller with saturation function is applied in Martins, Sarcinelli-Filho, and Carelli (2017). An adaptive controller based on PI controller based on robot parameter observer is proposed in Martins, Celeste, Carelli, Sarcinelli-Filho, and Bastos-Filho (2008), while the observer is highly depending on the initial condition and the estimated parameters may not be accurate. Sliding Mode Control (SMC) is a well-tested and established technique for nonlinear control, known for its robustness under external disturbance and parametric uncertainty. The SMC has already been applied in different applications such as water level control, robot arm position control, single phase dynamic voltage control, helicopter, etc. (Biricik & Komurcugil, 2016; de Jesús Rubio, 2016; de Jesus Rubio, Soriano, Juarez, & Pacheco, 2017; Mohammadi & L'Afflitto, 2017; Precup, Radac, Roman, & Petriu, 2017). In Chen, Yan, Chen, and Yang (2016) and Keighobadi, Sadeghi, and Fazeli (2011), a SMC is applied for trajectory tracking control. The controller shown good performance specifically the steady-state tracking error is eliminated. The discontinuous function of the SMC produces chattering on the control input and that affects the motor and produces vibration during operation. There are different techniques for reducing chattering in SMC, for example, replacing the discontinuous control function by saturation or sigmoid, this technique was one of the traditional technique used to reduce chattering (Burton & Zinober, 1986; Slotine, Li, et al., 1991). Although this method reduces chattering but the controller becomes continuous and the features of the sliding mode such as finite time convergence and robustness cannot be achieved and steady state errors may also appear under parametric uncertainty variations. Another technique to reduce chattering is the use of second or higher order sliding mode control such as super twisting. This technique allows finite time convergence of the sliding variable and its first time derivative in the presence of disturbance and parametric uncertainty variations. In Becerra, Colunga, and Romero (2016), Salgado, Cruz-Ortiz, Camacho, and Chairez (2017) and Youssef, Martins, Pieri, and Moreno (2014), a Second-Order SMC (SOSMC) based on the Super Twisting algorithm (ST) is applied for this purpose. The chattering has been slightly reduced comparing to the SMC and the controller robustness is maintained. In Salgado et al. (2017) and youssef et al. (2014), the Super Twisting algorithm has been applied experimentally, and the controller performance has been compared with a first order sliding mode control. However, knowledge of the uncertainty bound is required (Pisano, Tanelli, & Ferrara, 2016).

The main contributions of this work is design and real time implementation of a robust adaptive controller, capable of working under parametric uncertainty, which does not require the knowledge of the uncertainties bounds and reduces chattering and maintains the classical advantages of SMC. Image processing has been used for validation of our implementation. The proposed controller is the Adaptive ST (AST) based on SOSMC (Shtessel, Taleb, & Plestan, 2012). This controller retains the robustness property of a ST algorithm while the controller gains can be dynamically adapted to the parametric uncertainty and external disturbance. The dynamic controller gains will decrease when the steady-state is achieved which involved in the chattering reduction. That results with two main benefits; the dc-motor will operate smoothly and it is protected from high oscillation, then no robot vibration. The main advantage of the AST is that the controller gains are independent of the system bounds. Moreover, a FBL is applied which allowed the proposed controller to have better transient performance in all the operating range. In this work, the model based on the work of Caracciolo et al. (1999) has been selected. This model is designed for trajectory tracking controller and takes into account the motion stability problem of SSMR. As the subject of this study is a commercial robot, low-level velocity control loops are already integrated. This has been taken into account in out model. Experimental validation of the proposed control strategy was carried out in 4-wheels SSMR Pioneer P3AT and a comparison between the proposed controller and other controllers is discussed.

This paper has been divided as follows: a description of the mathematical model of the SSMR dynamics has been presented in Section 2. In Section 3 the second order sliding mode controller has been described. Section 4 presents the control designs of the Super Twisting and Adaptive Super Twisting. Section 5 presents the real time experimental results that allow validating the proposed control scheme and comparison with conventional Super Twisting, Proportional Integral Derivative (PID) and SMC using saturation function controllers. Finally, conclusions have been presented in Section 6.

2. Problem formulation

In this section, the kinematic and dynamic models of a SSMR are presented along with the control objective. These models will be used in the control design. The parametric uncertainty is reformulated and included in the model in order to develop a robust controller.

2.1. Modeling of SSMR

The SSMR model used in this work is based on the work of De La Cruz and Carelli (2008), which is derived from the well known model (Caracciolo et al., 1999). The model was developed under the following assumptions:

- Vehicle speed below 10 km/h;
- Longitudinal wheel slippage neglected;
- Rigid vehicle moving on a horizontal plane;
- Tire lateral forces function of its vertical load.

The kinematic model is represented by the state vector $q = [x\ y\ \theta]^T$, x and y provide the center point position of vehicle corresponding to the earth frame and θ is the orientation of the robot. The dynamics of the state vector q is given as follows

$$\dot{q} = \begin{bmatrix} \cos(\theta) & -d\sin\theta \\ \sin(\theta) & d\cos\theta \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}, \tag{1}$$

where v is the linear velocity, ω is the angular velocity and d is the distance from the point of instantaneous center of rotation and robot center of gravity.

The dynamic model is represented by the state vector $\eta = [v\ \omega]^T$, and the dynamic equations are given as follows

$$\dot{\eta} = \begin{bmatrix} \frac{c_3}{c_1}\omega^2 - \frac{c_4}{c_1}v \\ -\frac{c_5}{c_2}v\omega - \frac{c_6}{c_2}\omega \end{bmatrix} + \begin{bmatrix} \frac{1}{c_1} & 0 \\ 0 & \frac{1}{c_2} \end{bmatrix} \begin{bmatrix} v_r \\ \omega_r \end{bmatrix} \tag{2}$$

where, $c_1, \ldots, c_6$ are positive parameters and they are given as a function of some physical parameters of the robot, such as the mass, moment inertia, motor parameters, etc. v_r and ω_r are the reference linear and angular velocities and they are the system control inputs. The two state vectors q and η are considered as measured variables.

2.2. Model uncertainty

The system parameters cannot be known precisely, especially when they are dependent on the hardware and the low-level velocity control loops. In order to make the controller robust against parametric uncertainty, the latter is formally described and included into the model in order to guarantee the robustness of the controller. All the system parameters have been considered as uncertainties. These parameters have been formalized in accordance with Laghrouche, Plestan, & Glumineau (2007), expressed as follows

$$\begin{aligned} c_1 &= c_{01} + \delta c_1 \quad , \quad c_2 = c_{02} + \delta c_2, \\ c_3 &= c_{03} + \delta c_3 \quad , \quad c_4 = c_{04} + \delta c_4, \\ c_5 &= c_{05} + \delta c_5 \quad , \quad c_6 = c_{06} + \delta c_6, \end{aligned} \tag{3}$$