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Trajectory tracking control of farm vehicles in presence of sliding

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Abstract

In automatic guidance of agriculture vehicles, lateral control is not the only requirement. Much research work has been focused on trajectory tracking control which can provide high longitudinal-lateral control accuracy. Satisfactory results have been reported as soon as vehicles move without sliding. But unfortunately pure rolling constraints are not always satisfied especially in agriculture applications where working conditions are rough and not predictable. In this paper the problem of trajectory tracking control of autonomous farm vehicles in the presence of sliding is addressed. To take sliding effects into account, three variables which characterize sliding effects are introduced into the kinematic model based on geometric and velocity constraints. With a linearized approximation, a refined kinematic model is obtained in which sliding effects appear as additive unknown parameters to the ideal kinematic model. By an integrating parameter adaptation technique with a *backstepping method*, a stepwise procedure is proposed to design a robust adaptive controller in which time-invariant sliding is compensated for by parameter adaptation and time-varying sliding is corrected by a Variable Structure Controller (VSC). It is theoretically proven that for farm vehicles subjected to sliding, the longitudinal-lateral deviations can be stabilized near zero and the orientation errors converge into a neighborhood near the origin. To be more realistic for agriculture applications, an adaptive controller with projection mapping is also proposed. Both simulation and experimental results show that the proposed (robust) adaptive controllers can guarantee high trajectory tracking accuracy regardless of sliding.

Keywords: Trajectory tracking control; Nonholonomic systems; Backstepping; Robust control

1. Introduction

Automatic guidance of farm vehicles develops with the requirement of modern agriculture. High-precision agriculture becomes a reality especially thanks to new localization technologies such as GPS, laser range scans and sonar. In agriculture fields it is quite common that several vehicles (including cropping, threshing, cleaning, seeding and spraying machines) compose a platoon for combined harvesting. In this case driving safety requiring constant longitudinal distances between the leading vehicle and following vehicles is an additional requirement along with the effort of improving lateral path-following performances. Therefore vehicle motions are specified not only by a geometric path but also by a time law with respect to the longitudinal direction. Since longitudinal-lateral control becomes more and more important, many research teams have paid their attention to trajectory tracking control, satisfactory results have been reported as soon as vehicles satisfy pure rolling constraints [1–7].

However due to various factors such as slipping of tires, deformability or flexibility of wheels, pure rolling constraints are never strictly satisfied. Especially in agriculture applications when farm vehicles are required to move on all-terrain grounds including slippery slopes, sloppy grass grounds, sandy and stony grounds, sliding inevitably occurs which deteriorates automatic guidance performance and even system stability.

Until now there are very few papers dealing with sliding. [8] prevents cars from skidding by robust decoupling of car steering dynamics, but acceleration measurements are necessary and the steering angle is assumed small. [10] copes with the control of WMR (Wheeled Mobile Robot) not satisfying the ideal kinematic constraints by using slow manifold methods, but the parameters characterizing the sliding effects are assumed to be exactly known. Therefore [8,10] are

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not realistic for agriculture applications. In [11] a controller is designed based on the averaged model allowing the tracking errors to converge to a limit cycle near the origin. In [15] a general singular perturbation formulation is developed which leads to robust results for linearizing feedback laws ensuring trajectory tracking. But above two schemes only take into account sufficiently small sliding effects and they are too complicated for real-time practical implementation. In [12, 13] Variable Structure Control (VSC) is used to eliminate the harmful sliding effects when the bounds of the sliding effects have been known. The trajectory tracking problem of mobile robots in the presence of sliding is solved in [14] by using discrete-time sliding mode control. But the controllers [12–14] counteract sliding effects **only** relying on high-gain controllers which is not realistic because of limited bandwidth and low level delay introduced by steering systems of farm vehicles. In [16] sliding effects are rejected by re-scheming desired paths adaptively based on steady control errors which are mainly caused by modeled sliding effects. Moreover a robust adaptive controller is designed in [17] which can compensate sliding by parameter adaptation and VSC. But [16,17] only care about lateral control.

In the references referred above most research works treated sliding as disturbances, but alternatively sliding can be also regarded specifically as time-varying parameters. On the other hand backstepping methods which are used widely in controller design have been proven powerful in controlling nonholonomic systems with uncertain parameters [18,21]. With this idea in our previous work [17] we have applied backstepping successfully to design an anti-sliding lateral controller. The purpose of this paper is to extend our lateral controller to a practical longitudinal-lateral controller in presence of sliding.

The main idea of this paper is that sliding effects are introduced as additive unknown parameters to the ideal kinematic model, based on *backstepping method* a robust adaptive controller is designed. Furthermore to be of benefit to actual applications the robust adaptive controller is simplified into an adaptive controller with projection mapping. This paper is organized as follows, in Section 2 a kinematic model considering sliding is constructed in the vehicle body frame. In Section 3 for an ideal kinematic model a trajectory tracking controller is designed. In Section 4 a robust adaptive controller is designed in presence of sliding by using backstepping methods. In Section 5 the robust adaptive controller is simplified into an adaptive controller with projection mapping. In Section 6, some comparative simulation and experimental results are presented to validate the proposed control laws.

2. Kinematic model for trajectory tracking control

2.1. Notation and problem description

In this paper the vehicle is simplified by a bicycle model, the kinematic model is expressed in the vehicle body frame (o, x', y') (see Fig. 1). Necessary variables appearing in the kinematic model are denoted as follows:

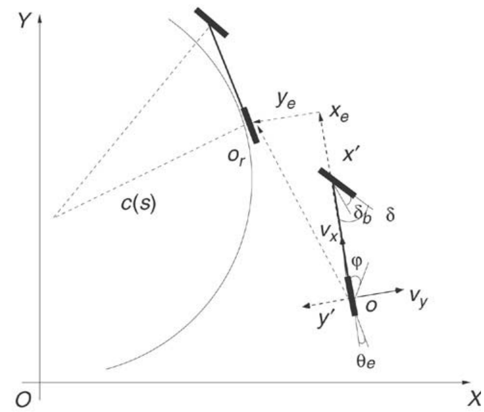

Fig. 1. Notations of the kinematic model.

- o (o_r) is the center of the (reference) vehicle virtual rear wheel.
- x' is the vector corresponding to the vehicle body centerline
- y' is the vector vertical to x'.
- (x_r, y_r) are the coordinates of the reference point o_r with respect to the inertia frame.
- (x, y) are the coordinates of the vehicle o with respect to the inertia frame.
- (x_e, y_e) depict the vector $\overrightarrow{oo_r}$ in the vehicle body frame (o, x', y').
- $c(s)$ is the curvature of the path, s is the curvilinear coordinates (arc-length) of the point o_r along the reference path from an initial position.
- θ (θ_r) is the orientation of the (reference) vehicle centerline with respect to the inertia frame.
- $\theta_e = \theta_r - \theta$ is the orientation error.
- l is the vehicle wheelbase.
- v (v_r) is the linear velocity of the (reference) vehicle with respect to the inertia frame.
- v_ω is the rear wheel rotating velocity.
- v_x is the longitudinal velocity of the vehicle in the direction of ox' w.r.t the inertia frame.
- v_y is the lateral velocity of the vehicle in the direction of oy' w.r.t the inertia frame.
- δ is the steering angle of the virtual front wheel.
- δ_b is the steering angle bias due to sliding.

So the trajectory tracking errors can be described by (x_e, y_e, θ_e). The driving velocity of the rear wheel v_ω and the steering angle of the front wheel δ are two control inputs. The aim of this paper is to design a controller (v_ω, δ) which can guarantee the longitudinal-lateral errors x_e, y_e approach to zero and the orientation error θ_e is bounded in presence of sliding.

2.2. Kinematic model

From Fig. 1, it is easy to obtain the following geometric relationship

$$\begin{pmatrix} x_e \\ y_e \\ \theta_e \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_r - x \\ y_r - y \\ \theta_r - \theta \end{pmatrix} \tag{1}$$