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Nonlinear Path Tracking Controller for Bi-Steerable Vehicles in Cluttered Environments ⋆

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Abstract: This paper presents a nonlinear path tracking controller for autonomous bi-steerable (four-wheel steering or 4WS) vehicles, allowing high precision tracking even when the reference path proposes fast varying curvature. Indeed, such paths are very common as soon as vehicles have to avoid obstacles in cluttered environments. Considering the well-known bicycle model, the sole reference path usually defined for the rear wheel is replaced by two synchronized paths, introducing a new way to calculate the expected yaw rate of the vehicle without numerical derivatives. Equations describing the motion of the vehicle with respect to this "dual-path" are presented and used to design the proposed control law. Then, simulations and experiments with the electrical public transport vehicle EZ10 demonstrate the controller ability to precisely follow complex trajectories.

Keywords: Autonomous vehicles, Four-wheel steering, Path tracking, Nonlinear control.

1. INTRODUCTION

Automated vehicles are progressively introduced into the manned flows of cars where they are facing the challenging problem of the traffic rules but also the security issues and public acceptance of autonomous maneuvers for obstacle avoidance. In urban scenarios, such maneuvers often lead to complex paths with high curvature, in order for the vehicle to squeeze through the obstacles. To address this issue, alternative kinematics are currently investigated by manufacturers. For instance, in the field of urban vehicles, the Easymile company proposes a bi-steerable bus shown in figure 1. To take advantage of such kinematics, both path planning algorithms and steering control laws have to be enhanced. This work is specifically concerned with the control aspect and proposes a new path tracking steering law dedicated to 4WS vehicles, where the reference path is defined by two synchronized paths describing the front and rear axle trajectories.

Different control approaches have been explored for this class of nonholonomic vehicles. The first one relies on a speed dependent coupling function between front and rear steering angles. A commonly implemented one is a fixed ratio of -1. It allows any front-wheel steering (FWS) law to be directly adapted to 4WS vehicles, the vehicle center becoming the controlled point instead of the center of the rear axle. Alternative coupling functions have been developed, see for example the work presented by Akita and Satoh [2003]. This approach is the one currently

Fig. 1. EZ10, the bi-steerable vehicle used to evaluate our proposal

implemented in high-end cars to increase maneuverability as well as stability. This coupled bi-steerable kinematic is also considered in Hermosillo and Sekhavat [2003] work, where the flatness property is used to design a control law by means of a chained transformation and exact linearization. However, in this case the controlled point is no longer fixed in the vehicle frame. Finally, coupled kinematics deprive bi-steerable vehicles of the ability for crabwise motion and other asymmetric steering modes which are necessary to navigate in cluttered environments, see for example the path planning algorithm of Nizard et al. [2016].

Lyapunov approaches have also been used in the work of Micaelli and Samson [1993] or Petrov [2009] to design feedback control laws, and Thuilot et al. [1996] provides

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a dynamic feedback linearization method for the general case of wheeled robots. But it requires the knowledge of the trajectory of the instantaneous center of rotation of the vehicle along the desired path, which turns out to be problematic as soon as pure rolling without sliding assumptions are not perfectly satisfied. Recently, single path tracking methods and complementary references were also proposed by Silva et al. [2013].

Another controller proposed by Cariou et al. [2009] enables bi-steerable vehicles to follow a path with an arbitrary desired offset angle. It relies on chained form transformations (De Luca et al. [1998]) and is instrumental in agricultural applications where the front and rear wheels of a machine must not pass several times on the same track to prevent soil compaction. Unfortunately, the regulation of the offset angle is not designed to support fast variations, as it is the case when obstacles have to be avoided. Indeed, simplifying assumptions have been introduced to make the controller robust to noisy numerical derivatives which is detrimental to its reactivity.

The controller proposed in this paper has been developed to address the need for bi-steerable vehicles to precisely follow paths with rapidly varying curvature and heading setpoint. The path tracking problem is modified with the introduction of a "dual-path" and the controller designed via feedback linearization.

First, the vehicle model proposed by Cariou et al. [2009] is recalled to highlight the limitations of the associated controller. Then, new model parameters are introduced and the control law is designed in section 3. Finally, sections 4 and 5 propose simulation and experimentation results.

2. PREVIOUS WORK

2.1 4WS path tracking model

Figure 2 presents the bicycle model, where each axle is reduced to a centered virtual wheel distant from each other by the wheelbase L. The vehicle is localized in a Frénet frame moving along the reference path. Its origin is M, the closest point on the path to the rear wheel R, with s_R being the curvilinear abscissa of M and $c_R(s_R)$ the curvature of the path at M (called c_R from here). The absolute heading of the Frénet frame is θ_{tR} while θ is the heading of the vehicle. Then, the angular gap between the vehicle and the reference frame is $\overline{\theta} = \theta - \theta_{tR}$. The vehicle configuration can be described without ambiguity by three state variables: s_R, y_R, and $\overline{\theta}$, the curvilinear abscissa, the lateral gap, and the angular gap respectively. The vehicle control inputs are δ_F and δ_R, the front and rear steering angles. The rear wheel velocity $\overrightarrow{v_R}$ is here considered as a parameter possibly varying. For FWS vehicles (i.e. $\delta_R = 0$), $\overline{\theta}$ has to be null when the path is perfectly followed. In contrast, for 4WS vehicles, a desired heading offset with respect to the path tangent may be specified. This offset angle is called $\tilde{\theta}_{off}$, the desired absolute vehicle heading is then $\theta_d = \theta_{tR} + \tilde{\theta}_{off}$ and the absolute heading error is $\tilde{\theta} = \theta - \theta_d$.

In order for the model to account for slipping phenomena, the front and rear side-slip angles β_F and β_R are introduced. Such angles are defined as: the angle between the wheel plane and the actual direction of the linear velocity of the wheel center, see figure 2. In practice, side-slip angles of a few degrees are common. They can be indirectly measured by means of observers (Cariou et al. [2009]) and compensated within the steering control law to increase tracking performances.

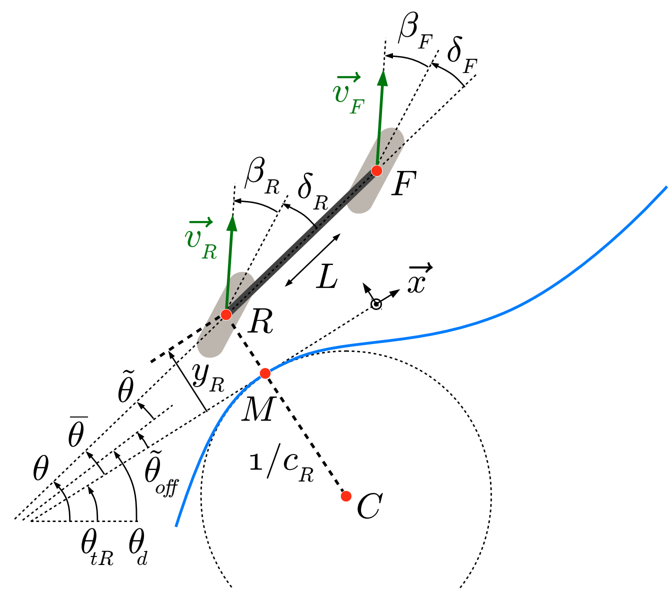

Fig. 2. The existing two tracks bicycle vehicle model representing tracking errors parameters

Cariou et al. [2009] express the motion of the vehicle as:

$$\begin{cases} \dot{s}_R &= v_R \frac{\cos(\overline{\theta}+\delta_R+\beta_R)}{1-c_R y_R} \\ \dot{y}_R &= v_R \sin(\overline{\theta}+\delta_R+\beta_R) \\ \dot{\overline{\theta}} &= v_R \Big[\cos(\delta_R+\beta_R)\frac{\tan(\delta_F+\beta_F)-\tan(\delta_R+\beta_R)}{L} \\ & \qquad - \frac{c_R \cos(\overline{\theta}+\delta_R+\beta_R)}{1-c_R y_R}\Big] \end{cases} \tag{1}$$

This model is singular for $y_R = \frac{1}{c_R}$, i.e. when points R and C are coincident. In the considered applications, y_R is always small compared to the radius of curvature of the path. Then, the assumption: $|y_R| < \frac{1}{|c_R|}$ is reasonable.

2.2 4WS control law

The control law developed by Cariou et al. [2009] has been designed to regulate the lateral gap y_R to zero and the angular gap $\overline{\theta}$ to $\tilde{\theta}_{off}$. First, model (1) has been converted into a chained form (Samson [1995]) and next, the backstepping techniques have been considered: the front steering law (2) has been designed to ensure the convergence of y_R with zero:

$$\delta_F = -\beta_F + \arctan\Big[\tan(\delta_R+\beta_R) + \frac{L}{\cos(\delta_R+\beta_R)} \times \\ \left(\frac{c_R\cos(\overline{\theta}_2)}{\alpha_R} + \frac{A\cos(\overline{\theta}_2)^3}{\alpha_R^2} + \frac{\dot{c}_R y_R \sin(\overline{\theta}_2)}{\alpha_R v_R} - \frac{\dot{\delta}_R - \dot{\beta}_R}{v_R}\right)\Big] \tag{2}$$