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Dynamic path tracking control of a vehicle on slippery terrain

Eric Lucet [a,*], Roland Lenain [b], Christophe Grand [c]

[a] Robosoft, Bidart, France
[b] Irstea, Aubiere, France
[c] ISIR - UPMC/CNRS (UMR 7222), Paris, France

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ABSTRACT

This paper deals with accuracy and reliability for the path tracking control of a four wheel mobile robot with a double-steering system when moving at high dynamics on a slippery surface. An extended kinematic model of the robot is developed considering the effects of wheel–ground skidding. This bicycle type model is augmented to form a dynamic model that considers an actuation of the four wheels. Based on the extended kinematic model, an adaptive and predictive controller for the path tracking is developed to drive the wheels front and rear steering angles. The resulting control law is combined with a stabilization algorithm of the yaw motion which modulates the actuation torque of each four wheels, on the basis of the robot dynamic model. The global control architecture is experimentally evaluated on a wet grass slippery terrain, with speeds up to 7 m/s. Experimental results demonstrate enhancement of tracking performances in terms of stability and accuracy relative to the kinematic control.

1. Introduction

1.1. Context and background

Advances in autonomous ground vehicles control in slippery context arises as a promising solution in many areas, especially for surveillance, agriculture or rescue (see Luettel, Himmelsbach, & Wuensche, 2012). As an example, in the agricultural sector “Hands-off” driving tractors are already used to reduce onerous work, cost and pollution by achieving a more accurate navigation in nominal conditions (i.e. achieving straight lines on an even field). However, the fast and precise autonomous navigation of vehicles on uneven grounds with water and vegetation remains an open issue. In particular, the vehicle is exposed to the low grip conditions of the soil, which are furthermore variable (see Bakker, Nyborg, & Pacejka, 1987 or Gonzalez, Fiacchini, Guzman, Alamo, & Rodriguez, 2011). In this situation, classical motion control laws as proposed by Micaelli and Samson (1993) or by de Wit, Bastin, and Siciliano (1996), that assume a motion without slippage, are not suitable to handle such perturbations which lead to a loss of controllability. Therefore, the design of a path tracking control law should take into account the low dynamical grip conditions in order to address these difficulties.

The solution of considering sliding as a perturbation to be rejected by robust control (see for instance Hamerlain, Achour, Floquet, & Perruquetti, 2005 or Zhang, Chung, & Velinsky, 2003) may constitute a first alternative. Nevertheless, such approach appears as conservative given the dynamic effects encountered in the context of this work. As a result, a model-based control addressing explicitly the influence of sliding is favored in this paper. Mainly two distinct approaches can be identified in this framework: the first one relies on an accurate modeling and estimation of the wheel–soil interactions and their use in the control law; the second one is based on the estimation of the grip conditions to define unstable and forbidden domains in the system state space. In Lhomme-Desages, Grand, Ben Amar, and Guinot (2009), an on-line estimation procedure of the wheel–ground slippages based on terramechanic models has been proposed. The resulting slippage estimator was included in a trajectory controller in order to improve mobility on natural terrains (Lhomme-Desages, Grand, & Guinot, 2007). However this approach needs an accurate estimation of the vehicle motion, which is not always possible. Similarly, numerous results taking into consideration the tyre road interaction are published in automotive chassis control (see for instance Di Cairano, Tseng, Bernardini, & Bemporad, 2013). Another approach with a prediction model of the vehicle slip is proposed by Rogers-Marcovitz, George, Seegmiller, and Kelly (2012). This model requires a precise and specific calibration phase, making this solution inappropriate to transition between different types of soil. Assuming that the grip conditions are known, the off-line definition of a stability

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[*] Corresponding author. Tel.: +33 169082711; fax: +33 169080701.
E-mail addresses: eric.lucet@cea.fr (E. Lucet), roland.lenain@irstea.fr (R. Lenain), christophe.grand@upmc.fr (C. Grand).

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domain (velocity/steering angle), as proposed by Spenko, Kuroda, Dubowsky, and Iagnemma (2006) or by Peters and Iagnemma (2008), could be an alternative solution. But these studies are focused on the controllability only, and they generally assume known and constant grip conditions. Furthermore, many other works address the problem of controllability of vehicle in slippery conditions. Several marketed systems such as Electronic Stability Program (see Farmer, 2006 for instance) offer some innovation for road vehicles, but are not compatible with robotics on natural soils where a large drift is recorded.

1.2. *Proposed control strategy and previous work*

In this work, a generic mobile robot with four driven and steered wheels, that includes an absolute position and heading measurement system, is considered. More and more off-road vehicles, especially in agriculture with inter alia, the Claas Xerion and the JCB Fastrac, are indeed equipped with double-steering systems in order to increase their mobility. Popular vehicles with four driven wheels are moreover already showing the applicative interest of considering such a kinematic structure. Thus, an adaptive and predictive controller for the path tracking of double-steered robot is proposed. It is based on the complementarity between several types of input: steering angle (s) and differentiated wheels velocities. Variables to be controlled are consequently the lateral tracking error, and the angular deviation (between robot heading and path orientation). The longitudinal control, including longitudinal slip, sinkage and tire-force estimates (see Baffet, Charara, & Lechner, 2009; Fang, Fan, Thuilot, & Martinet, 2006 or Wang & Low, 2008), is not investigated here, and the lateral controller is designed to be relevant whatever the measured speed. Thus, this work mainly considers the effects of lateral slippage on the stability and the accuracy of path tracking control. The contributions presented in this paper are partially based on some works previously published by the authors that have been largely extended and modified to improve the controller performances.

In Lenain, Thuilot, Cariou, and Martinet (2010), the capability of an accurate control is demonstrated at a speed with important dynamic effects (compatible with delay in the low-level control loop), by integrating lateral slippage effects in the steering control, and by using an adaptive and predictive approach. However, this strategy was designed for car-like mobile robots moving on a flat ground. Moreover, singularities may occur during the adaptation of grip conditions in straight line. Finally, such an approach estimates and tries to compensate for sliding but does not improve the grip conditions or address loss of controllability. As a result, if the wheels side slippage becomes too significant, the robot may become unstable and start spinning around. To avoid this phenomenon, an original method was proposed in Lucet, Grand, Salle, and Bidaud (2008), which consists of controlling each wheel individually and modifying their actuation torque in order to limit the skidding effect. However, it does not permit us to achieve a highly accurate path tracking when used alone. Therefore, a global controller, based on research lines presented above, has been designed and successfully implemented in Lenain, Lucet, Grand, Benoit Thuilot, and Ben Amar (2010), showing the feasibility of this approach. Based on a simple dynamic model, it was dedicated to vehicles with only one steering axle. However, in this previous version, the stabilization algorithm output was only a conservative modulation of the torque of one selected wheel. Dynamic properties of the system were not properly considered and the control loop stability was not analyzed.

Thus, in this paper a new control architecture based on previous contributions (Cariou, Lenain, Thuilot, & Berducat, 2009; Lenain, Lucet, et al., 2010; Lenain, Thuilot, et al., 2010; Lucet et al., 2008) is presented by considering the independent control of the four wheel velocities and the use of a double-axle steering system. This control architecture can be divided into two cascaded sub-systems (see Fig. 1). The first one deals with the accurate path tracking control. It uses the localization information to compute the tracking error (lateral and heading deviations), and then implements a non-linear adaptive and predictive controller for the front and rear steering angles. This controller is coupled with an observer that estimates the wheels sideslip angles. The second sub-system is dedicated to the stability control. The stabilization algorithm uses an inertial measurement unit and evaluates the dynamic behavior of the vehicle along the yaw motion. Then, a modulation of the four wheel velocities is computed in order to generate a variation in the wheels–ground interaction forces transmission, and so limits the wheels slippage and avoids harsh swing-around. These two control parts are associated to form a stable and accurate servoing of the mobile robot motion, with respect to a desired path followed at a constant speed and regardless of grip conditions. The resulting control architecture is then evaluated on different experimental trials.

1.3. *Contributions*

The paper is organized as follows. In Section 2, major extensions of previous work (Cariou et al., 2009; Lenain, Lucet, et al., 2010; Lenain, Thuilot, et al., 2010) to a double Ackermann steering system are investigated, while a new backstepping observer of the sideslip angles is proposed with the following contributions: (i) the lateral slope in equations is now considered and (ii) a new adaptation algorithm for grip conditions estimation has been developed avoiding singularities. This allows further investigation of the independent wheel control by considering a simplified dynamical model adapted to real-time conditions, ensuring the

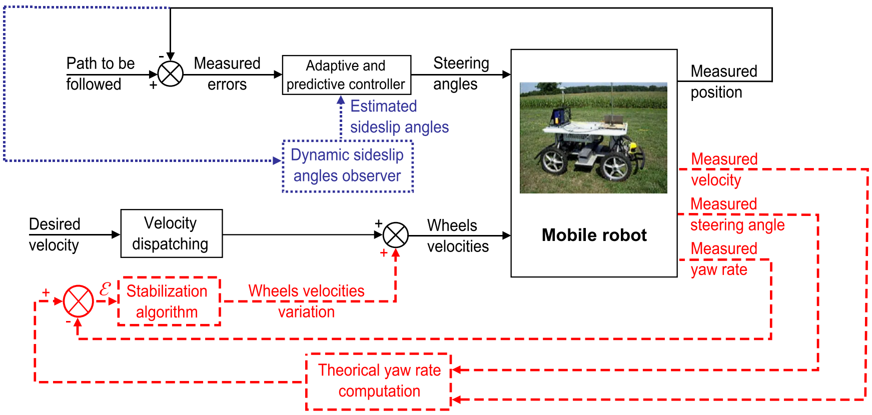

Fig. 1. Control block diagram of the overall controller. (For interpretation of the references to color in this figure, the reader is referred to the web version of this paper.)