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Robust indirect-defined envelope control for rollover and lateral skid prevention

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ABSTRACT

This paper introduces a means to evaluate the severity of the lateral skid phenomenon based on a balance of forces applied to the vehicle. Derived from this analysis, a lateral Skid Index (SI) is proposed which, along with the well-known rollover index, is used to monitor the vehicle and to derive an indirect envelope specification. A robust control ensures the accident risk mitigation in spite of model uncertainty and perturbations from the driver. Speed and predictive dependent risk switching criteria are used to activate the control action. The proposed strategy is illustrated using Hardware-in-the-Loop experiments and its comparison with existing strategies is performed.

1. Introduction

According to the National Highway Traffic Safety Administration (NHTSA), crashes of land vehicles is one of the leading causes of death with 8998 fatalities associated to rollover, while most of the rollover accidents presented a previous lateral skid phenomenon. In Germany during 2005 (Otte & Krettek, 2005), 2–5% of all accidents were rollovers and 90% of these cases resulted in severe/fatal injuries. Frequently, the rollover constitutes a secondary event, with nearly 90% of the cases were preceded by a collision (88% in highways, straight country roads and rural curves (Otte & Krettek, 2005). A ditch and an embankment could be seen in 29% of the cases, as impact location. This resulted in the greatest risks for a rollover in case of a ditch running parallel to the side of the road, into which the skidding vehicle slid. Moreover, in 45.4% of all rollover accidents a sliding into an embankment downwards or upwards could be established. The data from the USA (1992–1996) is used in Parenteau et al. (2003) to perform a rollover classification. Specific tests are described to emulate in experiments the real causes of rollover; it is stated that tripped rollovers such as soil-trip, curb-trip and ditch fall-over increase representativeness to 83 % of passenger car and 75 % of light truck vehicle (LTV) rollovers reported in the field.

The presence or not of lateral skid or/and rollover depends on factors such as vehicle's height of the center of gravity (COG), type of soil, type of tire, the presence of obstacles, etc. In principle, the interaction between rollover and lateral skid has been widely accepted in the literature; however, in spite of these facts, the mitigation of both phenomenon has not been studied simultaneously. Ghandourda, Cunha, Victorino, Charara and Lechner (2011) introduces a prediction algorithm for the parameters of the vehicle dynamics, in order to foresee possible risky situations. The authors compute some risk indicators given by the lateral load transfer and a lateral skid indicator, by adopting assumptions regarding the trajectory, the velocity and the acceleration of the vehicle in future instants. Such indicators make use of the estimation of (i) the tire/road lateral and vertical forces, (ii) the maximum friction coefficient, (iii) the instantaneous friction coefficient as well as an observer to estimate the side slip angle.

In Yi, Li, Lu and Liu (2012) a dynamic Indirect-Defined Envelope Control for Rollover and Lateral stability and agility study of a pendulum-turn vehicle maneuver is presented. The use of the rear side slip angle is proposed as a state variable in order to define a stable region. The authors propose a vehicle lateral jerk and the acceleration information as agility metrics and suggest as future work, the design of control strategies to perform aggressive maneuvers by using the introduced agility metrics.

There exist in the literature some efforts to control lateral and roll dynamics of wheeled vehicles. These approaches are characterized by the type of actuator used to stabilize the system: active suspension, active front steering or differential braking. Among those, maybe differential braking is the cheaper and promptly implemented in the automotive industry; therefore, our proposal uses such approach.

Usually, the works dealing with the control of vehicle's lateral dynamics use active front steering (AFS) or steer-by-wire schemes and have as control objective to track a desired path as well as to improve

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vehicle stability. In Bernardini, Cairano, Bemporad, and Tseng (2009) the control objective is formulated as that to force the vehicle yaw rate to track a given reference, not known in advance. The reference is computed using the position of the steering wheel and vehicle's velocity. The control actuators are the steering and the differential braking system. The approach allows the authors to analyze visually the closed-loop stability region. Falcone, Borrelli, Asgari, Tseng, and Hrovat (2007) presents three different types of model predictive controllers: a nonlinear, a linear time varying (LTV) and a simplified LTV. Each of these approaches was proposed with the objective to gradually simplify the implementation burden of the control computation and model prediction. Authors show the effectiveness of their schemes through simulations and experiments. In Beal and Gerdes (2013) a model predictive envelope control that uses real-time state measurements as well as front steering actuation, is proposed. Experiments with a steer-by-wire test vehicle reveal that the approach provides a large operating region accessible by the driver and smooth interventions at the stability boundaries.

On the other hand, Hindiyeh and Gerdes (2014) designs a control for autonomous cornering with rear tire saturation ("drifting") of a rear wheel drive vehicle. The authors show a stability analysis based on a physically insightful invariant set around the desired drift equilibrium and experimental validation of their scheme. In Bobier and Gerdes (2013) the physical phenomena that should be taken into account when choosing an envelope is discussed. The authors design a control that limits the vehicle dynamics to a region of the state space bounded by the maximum and minimum rear slip angles. The presented controller results in a smooth, fast control response as the driver reaches the limits of handling. Experimental data is shown from a steer-by-wire vehicle.

In the literature, a variety of controllers has been proposed to detect and mitigate rollover. In Pearson (2002) the Rollover Index (RI) has been proposed as a dynamic measure of rollover risk which constitutes a normalized tire-road vertical forces balance. In Solmaz and Corless (2006) and Ku, Hsiao and Chen (2015) robust controllers that use differential braking as the control input are proposed in order to prevent rollover. In Dahmani, El Hajjaji, and Daraoui (2014) a fuzzy control design is proposed in order to improve vehicle stability and minimize rollover risk of the vehicle by manipulating the rear wheel steering angle. In Yim (2011) an output feedback preview controller is proposed for rollover prevention. In order to synthesize the optimal control law for the active suspension, the authors use a performance index subject to a dynamic constraint given by the linear description of the vehicle. In Akar and Dere (2014) an adaptive switching controller to mitigate rollover is introduced that uses the total braking force as the control input. The description of the system is linear continuous and its parameters are updated to face changes in the operating regime via two algorithms. In Cervantes and Rodriguez Licea (2014) a robust switched controller is proposed to prevent rollover based on a polytopic description of the system. The control objective is achieved using a state-dependent feedback and a single polytopic description for the entire operation domain.

The main objective of this paper is to design a lateral skid/rollover prevention controller and to provide evidence of its capability to ensure stability in spite of model mismatches, and parametric uncertainty. To this end, a Skid Index (SI) is proposed, which is a measure of the loss of adhesion between the tire and the road, and it preserves the skid direction (left or right). SI and RI are used to evaluate the risk of a vehicle during a maneuver and to formulate the control objective. The proposed controller uses differential braking/traction actions and it has a supervisor structure with switching criteria depending on the risk prediction. This architecture allows to the proposed control, a non-invasive and safe interaction with the driver (envelope control).

The contribution of this work with respect to existing approaches is:

(i) To introduce a Skid Index (SI) to evaluate lateral skid risk. In particular, our approach can deal with sudden or unexpected perturbations such as obstacles. This approach does not require exact knowledge of the future front wheels angle nor of the tire-ground contact forces.

(ii) To propose a switched robust controller capable of preventing both lateral skid and rollover risks simultaneously. The switching structure allows the driver to maintain the brake/traction control of a vehicle until a risk is foreseen, and such control is recovered once the risk is over. The size of the invariant set is specified indirectly by a safety metric and it is proved to be robust against parameter uncertainty, switching rules and perturbations of the steering angle.

(iii) To study the stability of uncertain switched systems subject to an RI/SI-dependent switching criterion that rules the interaction between closed-loop and open-loop behaviors. A family of switching criteria is derived that also allows the inclusion of predictive switching criteria. Moreover, the stability analysis allows to relax the restrictions over the perturbations given by the driver; therefore, the maximum steering angle is not given by the open-loop conditions (as in Bobier & Gerdes, 2013) but by closed-loop conditions. The boundaries of the envelope are defined indirectly using a characterization of the vehicle risk given by the rollover and lateral skid risk indexes.

(iv) Finally, an advantage of the proposed scheme is that it departs from the rollover and lateral skid risk estimation to mitigate both phenomena irrespective of their causes. This point of view allows proposing a control scheme to prevent such phenomena, independently of the skills of the driver.

This paper is organized as follows. Section 2 describes the vehicle model and the lateral Skid Index (SI) derivations. The Section 3 is devoted to describing the structure of the proposed controller, while Section 4 presents the stability analysis. In Section 5 the implementation of the proposed controller using HIL experiments is presented; finally, Section 6 presents some conclusions.

2. Vehicle model

2.1. Rotational dynamics

Consider the nonlinear description of the rotational dynamics of a four-wheeled vehicle given as follows (see Fig. 1):

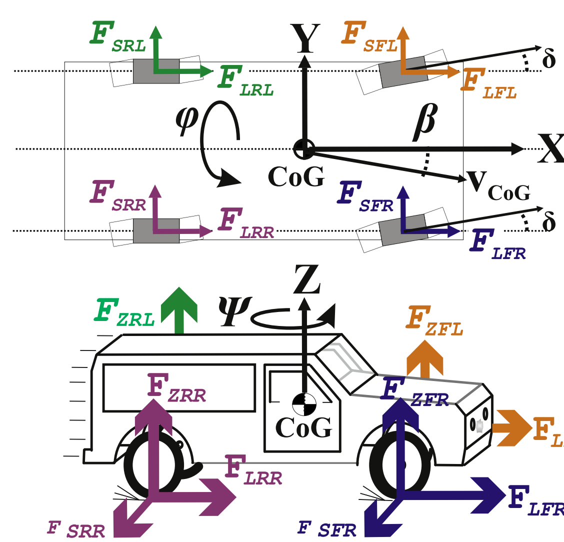

Fig. 1. Schematic diagram of the vehicle.