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# Online adaptive observer for rollover avoidance of reconfigurable agricultural vehicles

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ABSTRACT

Tractor rollover is one of the main case of severe accident in agriculture. Since such vehicles move on natural ground with varying conditions and different kind of terrain, the risk of rollover is difficult to estimate and predict using classical on-road approaches. This paper proposes an online adaptive observer to assess and avoid rollover risk in agricultural vehicles which move in off-road terrain. In particular, the approach focuses on reconfigurable tractor dedicated to move in terrain with important slope (such as grape harvester). It is based on the coupling between an intermittent measurement and an estimation of a stability metric, namely the Lateral Load Transfer (LLT). Thanks to this adaptive method, terrain and vehicle parameters are updated in order to take into account for the effects of changes in center of gravity height and total vehicle mass. This then allows to monitor the stability of the vehicle whatever the state of the slope correction system, the soil type and the load of the machine. The algorithm capabilities are tested through experiments using a grape harvester equipped with hydraulic actuators.



## 1. Introduction

In order to meet the social expectations, agricultural machines have to be more and more efficient and cover larger areas (Blackmore et al., 2005). As a consequence, such machines tend to be bigger, move faster on more complex terrains. If field operations potentialities are extended, such an evolution may also increase the risk of instability. For instance, tractor rollover is the main case of severe accident in agriculture, which remains one of the most hazardous professional area (All-Terrain Vehicle Enforcement and Safety Report, 2011). This is especially true for vehicles with high Center of Gravity (CG) dedicated to move on complex soil.

In order to reduce the vehicle rollover risk, some manufacturers tool up their agricultural vehicles with correction slope systems. The correction is not realized automatically in real-time but it requires an action of the driver on the active suspension of the vehicle to correct the terrain slope. Because of this, the CG elevation varies significantly according to terrain slope and vehicle load changes. As already highlighted, the CG height is an important parameter affecting the rollover risk of the vehicle. A simple misinterpretation of the dangerousness of the situation by the driver can cause a serious accident with fatal injuries in certain cases.

On the other hand, passive protections (ROllover Protective Structures – ROPS) (ASAE, 1997) are installed on tractors to reduce accident consequences. However, protection capabilities of these structures are very limited (Cole et al., 2006) and the latter cannot be embedded on bigger machines due to mechanical design limitations.

Driving assistance systems (such as ESP Tahami et al., 2003 or ABS Guvenc et al., 2004) have been deeply studied for on-road vehicles and successfully improve safety. These systems usually assume that the vehicle CG height is low and the latter are operating on smooth and level terrain. As a result, such devices cannot be directly applied to off-road machines with high CG because of the complexity of the interactions with the environment.

Hence, active security devices allowing either to warn the operator or to act directly on vehicle control variables are promising solutions to reduce risks and avoid hazardous situations. Besides reducing the accident statistics in the agriculture field, the economic benefits of these systems would be also very important provided that these new solutions are at a reasonable cost for the purchaser (Owusu-Edusei, 2008). Thus, given the limited number of sensors required to evaluate the Lateral Load Transfer (hereafter denoted LLT), this metric has been here chosen as a

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relevant stability criterion among several rollover indicators described in the literature.

In previous work (Richier et al., 2011, 2012), it has been shown that LLT can be relevantly predicted over a short time horizon from an appropriate vehicle dynamical model and a basic sensor equipment supplemented by observers for the variables that cannot be measured. This predicted LLT can then be conveyed to the driver so as to warn him from an imminent rollover risk. This work has been extended in Lenain et al. (2013), Richier et al. (2015), where the range of vehicle velocities at current instant which ensures that the predicted LLT does not exceed some given threshold is evaluated on-line relying on Model Predictive Control (MPC) techniques (Richalet et al., 1987). It can then serve as a basis for an active rollover prevention device, specifically the velocity specified by the driver can be overstepped if it exceeds the range computed from MPC, so as to prevent against upcoming rollover risk. Experiments carried out with quad-bike vehicles and off-road autonomous mobile robots have clearly pointed out the relevance of such predictive approaches for rollover prevention in actual operating situations.

Since grape harvesters are vehicles with a high center of gravity operating on sloping fields, their propensity to rollover is also quite important. The approaches proposed above cannot however be transposed in a straightforward manner to these vehicles, since they are reconfigurable and therefore their dynamical model is not constant during operation. Specifically, these vehicles are equipped with a slope correction system and their total mass is also varying as the grape receptacle is filled. In order for rollover prevention devices to be efficient, the LLT prediction or the maximum velocity computation must be as accurate as possible and this can be obtained only if the vehicle reconfigurations are immediately reflected into the dynamical model used for the prediction or MPC computations. In this paper, the reconfigurations are described within the vehicle model by means of two parameters, namely the height of the center of gravity and the vehicle total mass. Since these two parameters cannot be measured online, it is here proposed to take advantage of an intermittent LLT measurement available from the pressure sensors used by the slope correction system (Section 2) to update these parameters, by means of a sensitivity based gradient search algorithm (Section 4) designed so that the current value of the LLT supplied by the vehicle dynamical model (Section 3) fits with the measured one. This update law ensures that the vehicle dynamical model used for LLT prediction or MPC is always relevant and so are the passive or active rollover prevention devices that can be derived from it. Full scale experiments with a grape harvester demonstrate (Section 5) the relevance of this update law whatever the state of the slope correction system, the soil type and the load of the machine.

## 2. Vehicle rollover risk measurement

### 2.1. Overview

The literature abounds in rollover metrics to quantify vehicle stability. The most suitable metric for the study of the stability of a vehicle can then be determined either on the basis of the conditions of the environment in which moves the vehicle itself or on its reliability and its ability to correctly retranscribe the rollover risk (anticipation, prediction) or on its computability, that is to say, depending on the number of parameters required to its computation. These metrics can be classified into two broad categories. The so-called static metrics and dynamic metrics.

Static stability criteria are purely geometric Weissler (2002) or Yu et al. (2008). As a consequence, they do not consider dynamic effects of the vehicle and the effects of terrain inclination and of grip conditions which are regularly encountered in off-road environments. Static metrics yield adequate results when the vehicle moves on flat terrain at low speed. But, their performances deteriorate when terrain conditions change or dynamical effects appear to be non negligible. Because of these and of the goal of this work, this category of metrics is ignored in favor of dynamic metrics.

Dynamic metrics can be subdivided into three main categories: geometric-based stability margins, energy-based stability margins and contact forces stability margins. The complexity and the requirements to calculate these margins vary. For geometric-based and energy-based stability margins respectively, Force Angle Stability Margin (Papadopoulos and Rey, 1996) and Dynamic Energy Stability Margin (Ghasempoor and Sepehri, 1998) are generally mentioned for their theoretical accuracy. However, they are difficult to compute and implement. Indeed, the calculation of these criteria requires numerous parameters and consequently numerous expensive sensors to measure them. As mentioned above, the purpose here is to develop a low cost active security device for the purchaser. Therefore, these classes of metrics will not be selected.

The last family of dynamic metrics is based on the distribution of the normal wheel-terrain contact forces, that indicates nearness to wheel lift-off (Odenthal et al., 1999; Chen and Peng, 2001). A common form of such metrics is expressed by Eq. (1). This class of metrics is distinguished by its physical meaning and its relative computational simplicity. Indeed, from common sense it is clear that the wheel lift-off is a necessary condition for rollover. Their assessment requires a relatively simple model of the vehicle. Conversely to the classes of metrics aforementioned, these stability criteria are easy to compute and require very few sensors for their implementation. These are the main reasons for the choice of *Lateral Load Transfer* metric which is formulated and interpreted below.

### 2.2. LLT formulation and interpretation

This simple and useful metric is defined as the difference in normal forces on the left and right sides of the vehicle (Odenthal et al., 1999; Chen and Peng, 2001). Specifically, let $F_{n1}$ (resp. $F_{n2}$) be the sum of the vertical component of front and rear forces on the right side (resp. the left side). Eq. (1) constitutes the literal expression of LLT, normalized with the overall normal contact forces in order for this metric to be dimensionless (see also Fig. 1):

$$\mathrm{LLT} = \frac{F_{n1} - F_{n2}}{F_{n1} + F_{n2}} \tag{1}$$

The LLT range of variation is comprised in $[-1\,1]$, the extreme values meaning that the wheels of one side of the vehicle lift off. In practice, it is considered that the rollover is imminent when $|\mathrm{LLT}|$ reaches 0.8, i.e., when 80% of the sprung mass is distributed on one side of the vehicle.

### 2.3. Rollover risk measurement

As indicated before, the LLT has a physical meaning and can then be measured directly knowing each of the vertical forces. This provides then a direct measure of the vehicle degree of stability in real time. Classically, these forces can be measured via dynamometers mounted between the wheels and the drive shafts of the vehicle. In this work, a reconfigurable vehicle is considered. As a result, an alternative may consist in exploiting the state of the actuators of the correction slope system devoted to reduce vehicle instability in order to measure the wheels–terrain interaction forces. Indeed, the active suspensions allow to couple the wheels to the vehicle chassis. Thanks to suitable sensors adapted to the active suspensions