Preserving stability of huge agriculture machines with internal mobilities: Application to a grape harvester

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Abstract

This paper proposes an algorithm for estimating on-line the rollover risk of huge machines moving on natural ground. The approach is based on the reconstruction of lateral load transfer thanks to an observer, able to take into account terrain specificities (grip conditions and geometry). Capabilities are tested through experiments using a grape harvester.

Key words: Dynamic stability, Rollover prevention, grape harvester, observation, machine control.

1. Introduction

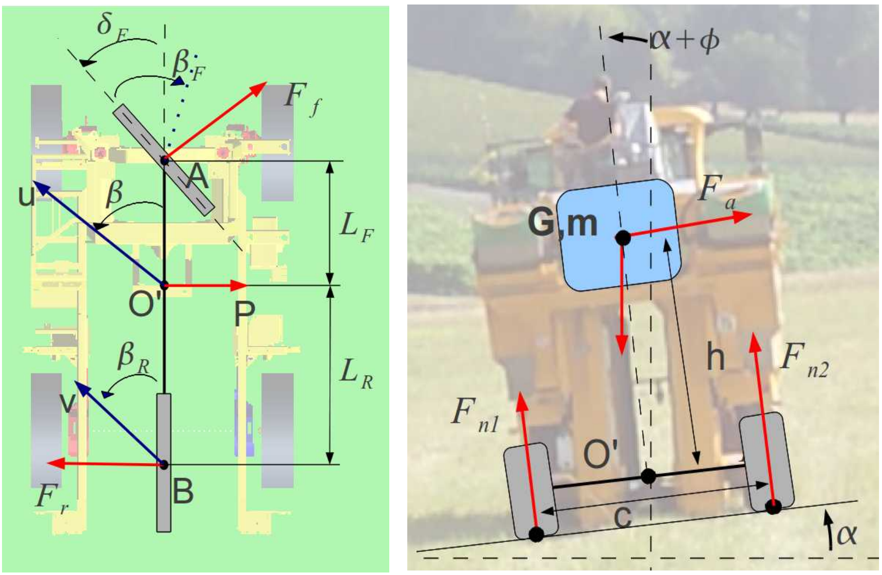
In order to meet the social expectations, agricultural machines have to be more and more efficient and cover larger areas[1]. As a consequence, such machines tend to be bigger, move faster and on more complex terrain. If it permits to extend capabilities of agricultural operations, such an evolution may also increase the risk of instability. This is especially true for machines dedicated to motion on complex terrains such as grape harvesters, mainly dedicated to act on sloping field.

If passive protection (ROllover Protective Structure - ROPS) are installed on tractors to reduce accident consequences, such structures cannot be embedded on bigger machines due to mechanical design limitations. Active security devices, allowing to warn the operator, or acting directly on control variables, then constitute a promising solution to reduce risks or avoid hazardous situations. Driving assistance systems (such as ESP or ABS [2]) have been deeply studied for on-road vehicles and successfully improve the safety. Nevertheless, such devices can not be directly applied to off-road machines, because of the complexity of the interactions with the environment. In this paper, an algorithm dedicated to estimate on-line the risk of rollover is developed, mainly dedicated to grape harvesters (as it uses the available hydraulic active suspensions). It is based on the on-line estimation and prediction of a stability metric, namely the Lateral Load Transfer (LLT). The algorithm takes advantage of machine modeling into two frames. The first one is the yaw frame, which permits to estimate the grip conditions thanks to an observer. This permits to feed equations of motion in the roll frame. As a consequence, a relevant estimation of the rollover risk can then be on-line derived accurately.

Thanks to adaption processes allowing to estimate the main parameters of the machine dynamics, the proposed algorithm is able to account for various situations, without requiring a huge perception system. In order to demonstrate capabilities of the algorithm, a grape harvester has been equipped with exteroceptive and proprioceptive sensors. The proposed driving assistance system is then investigated through full scale experiments on a harsh terrain.

2. Modeling

In order to describe the rollover dynamics of field vehicles, it is necessary to account for the grip conditions which impact the roll dynamics. As a result, a three dimensional model is mandatory when studying the roll motion. If this can be achieved directly by considering complete 3D dynamical models (such as [2]), it requires the knowledge of numerous parameters and complex interactions. They so appear to be hardly tractable for computation and need to be fed with complex and costly perception systems. In our approach, focused on lateral rollover, the vehicle dynamics is split into two 2D representations corresponding to the motion in the yaw frame (depicted in figure 1(a)), and the roll frame (depicted in figure 1(b)).



(a) Yaw projection (b) Roll projection

Figure 1: Vehicle modeling into two frames

2.1. Yaw projection

In the yaw projection the vehicle is considered as a bicycle (each axle is viewed as a wheel), and its motion is described perpendicularly to the inclination of the suspended mass. The velocity v of the center of the rear axle and the steering angle δ_F are the variable controlled by the driver. Since this paper is only interested in the lateral risk of rollover, the longitudinal forces are neglected. The lateral contact forces at each wheel F_F and F_R are solely considered. In order to avoid the use of complex tire/soil interaction models (such as [3]), these forces are assumed to be in linear relation with corresponding sideslip angles β_F and β_R , such as $F_{[F,R]}=C_e(.)\beta_{[F,R]}$. For observability reasons (explained in the forthcoming section), the linear coefficient $C_e(.)$ – namely the cornering stiffness – is supposed to be the same for the front and the rear axle. As grip conditions cannot be considered as constant in natural environment, the cornering stiffness is considered as variable and on-line adapted thanks to the observer detailed in section 3.1. The influence of suspended mass inclination (due to a slope or an action on active suspensions), is accounted by the force $P=m.g.sin\alpha$ where m is the suspended mass and α the robot inclination with respect to a vertical axes (see figure 1(b)). It is applied on the center of gravity, the position of which is defined longitudinally by the half wheelbases a and b . Finally, the interesting variables, which can be computed from this model are the yaw rate θ and global sideslip angle β , which can be expressed in a state space form as (see [6] for details):

$$\dot{X} = A(C_F,C_R)X + B(C_F,C_R)\delta_F \quad (1)$$

with : $X = \begin{bmatrix} \dot{\theta} \\ \beta \\ \sin\alpha \end{bmatrix}$, $A(C_F,C_R) = \begin{bmatrix} \frac{-L_F^2 C_F - L_R^2 C_R}{v I_z} & \frac{-L_F C_F + L_R C_R}{I_z} & 0 \\ -\frac{L_F C_F - L_R C_R}{v^2 m} - 1 & -\frac{C_F + C_R}{vm} & \frac{g}{v} \\ 0 & 0 & 0 \end{bmatrix}$ and $B(C_F,C_R) = \begin{bmatrix} \frac{L_F C_F}{I_z} \\ \frac{C_F}{vm} \\ 0 \end{bmatrix}$

Equation (1), exists under the assumption $v \neq 0$, which is assumed to be true in practice (algorithm is inactive if the velocity is very low). This set of equations introduces the vertical vehicle inertia I_z , which is computed thanks to the mass and vehicle dimensions.

2.2. Roll projection

The roll frame defines the vehicle motion along the roll axle. In this point of view the machine is viewed as a 2D system composed of a suspended mass, with a global inclination $\gamma=\alpha+\varphi$, attached to x axle. Four forces are applied on this system. First, the gravity, applied at the center of gravity, the position of which is defined in this frame by its elevation h . Secondly, two normal contact forces are applied on the two tires considered F_{n1} and F_{n2} (for the left and right side respectively). Finally, F_a is a restoring force representative of the tire elasticity, and acting as a suspension:

$$F_a = \frac{1}{h}\left(k_r\varphi + b_r\dot{\varphi}\right) \tag{2}$$

where k_r and b_r are the angular stiffness and damping coefficient obtained thanks to a preliminary calibration.
Using this point of view, equations relative to roll motion can be derived. In particular, as demonstrated in [6], the roll angle φ evolution can be written as:

$$\ddot{\varphi} \quad = \tfrac{1}{h}[h\dot{\gamma}^2\varphi + h\dot{\theta}^2\gamma + v\dot{\theta} + \dot{v}\beta + v\dot{\beta} - \tfrac{k_r\varphi + b_r\dot{\varphi}}{mh} + g\sin\alpha] \tag{3}$$

Thanks to this expression the vehicle roll angle can be estimated. As a consequence, it permits to express the risk of rollover using a representative metric (see [4, 5]). The Lateral Load Transfer [6] (hereafter denoted LLT) defined as following, is here considered.

$$LLT = \frac{F_{n1} - F_{n2}}{F_{n1} + F_{n2}} \tag{4}$$

It is representative of the mass repartition between left and right normal forces. The range of definition is comprised between [-1,1], the extremal values meaning that wheels of one side of the vehicle lift off. In practice, a threshold is chosen to consider an hazardous situation. Thanks to dynamical considerations, the LLT can be expressed with respect to roll angle in steady state conditions such as:

$$LLT \quad = \quad -\tfrac{2}{c}h\sin\varphi \tag{5}$$

As it can be seen on equations (1), (3) and (5), the two models are closely linked. Outputs of yaw model, indeed constitute some of the roll model inputs. This latter model then permits to describe the roll motion, comprising the forces, and finally the mass repartition, representative of the rollover risk. The knowledge of this global model need to be fed with cornering stiffness (representative of grip conditions), which can not be directly measured. As a result, an indirect estimation is mandatory, detailed in the following section.

3. Rollover risk estimation

3.1. Grip condition adaptation

In order to estimate the grip conditions for LLT evaluation, the indirect measurement of cornering stiffness C_e is here proposed. As described in section 4, the yaw rate and vehicle inclination are here supposed to be measured. The proposed observer, is then based on the dynamical model in yaw frame (1) and is decomposed into several steps following the scheme depicted on figure 2.

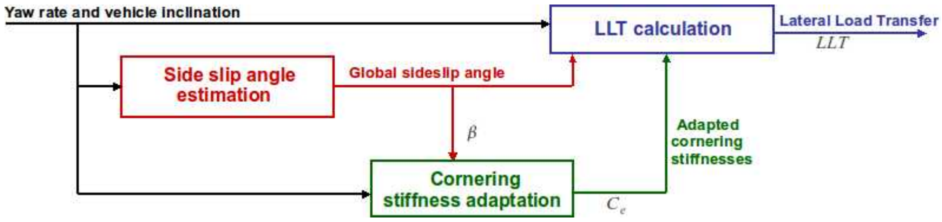


Figure 2: Observer Scheme for LLT estimation

First thanks to the first line of system (1), a value of the global sideslip angle β is computed in order to allow the convergence of estimated yaw rate $\dot{\theta}$ to the measured one. Once β is known, it can be used as a reference value to be reached by the second line of equations system (1). Indeed, if the cornering stiffness is known, the global sideslip angle computed from equations should be equal to the estimated one β . As a result, a value of the cornering stiffness ensuring the convergence of the global sideslip angle to the previously estimated one is computed.
As soon as the cornering stiffness is adapted, the model (1) is entirely known, allowing to estimate and predict the vehicle behavior. As a result, regarding to equations (2), (3) and (5), all the required variables for LLT computation are known.

3.2. Lateral Load Transfer Estimation

Thanks to the previously described observer, all the required variables to compute the roll dynamic equation (3) are known. As a consequence, the steady state value of the roll angle φ can be computed. Thanks to the computed roll angle and thanks to (5) a value of the Lateral Load Transfer is available, which constitutes a metric able to give some information about the rollover risk.

4. Results

4.1. Experimental vehicle and on boarded sensors

The experimental vehicle used to validate the proposed algorithm for the rollover risk estimation is a grape harvester manufactured by Gregoire SAS, depicted on figure 3. As it can be seen, it is equipped with active suspensions allowing to correct the inclination when

Figure 3: Experimental vehicle

moving on uneven ground. Regarding to the roll motion, the maximal inclination which can be imposed using active suspension is 16.5°. The total machine weight can vary during work from 9000 kg to 12000kg. The speed reached during work period is equal to 2m/s.

In order to feed the observer and the LLT estimation described in this paper, main on-boarded sensors are:

- a low cost IMU (Xsens), providing acceleration and angular velocity in three dimensions. It permits to measure the yaw rate in the vehicle frame $\dot{\theta}$. Thanks to the accelerations the vehicle inclination α can also be known. This angle is composed of the bank angle and vehicle inclination, bringing the same contribution into the vehicle dynamics.
- a Doppler radar, supplying together with the IMU the vehicle velocity v at the middle of the rear axle.

The last required variable (the steering angle δ_F) is measured via the CAN bus. The parameters (position of the center of gravity, roll damping and stiffness) are obtained by a preliminary calibration using weight measurement on each wheel in different conditions.

4.2. Tests description

In order to demonstrate the capability of the proposed algorithm to estimate the rollover risk, two tests are proposed, in the same conditions. In the two cases, the vehicle moves on a sloping field (around 10°), perpendicular to the slope. The trajectory achieved is composed of a straight line, a half turn and a straight line to go back to the starting point (see figure 4(c)).

(a) configuration during test 1 (b) during test 2 (c) path followed

Figure 4: Configuration during tests and trajectory followed

The difference between the two cases lies in the active suspension. The first test is achieved in a constant configuration for suspension, set to the lowest position (see figure 4(a)). On the contrary, during the second test, the driver can act on the suspension to correct the vehicle inclination to maintain α to almost zero (see figure 4(b)). This correction is not realized in real time, but require an action of the driver. During the second test this mainly appears during the half turn (at a distance comprised between 70-90m on the following figure). In both cases the velocity is almost constant and equal to 1m/s except during the half turns.

4.3. Results on LLT estimation

During the two tests, the Lateral Load Transfer has been estimated and results are compared on figure 5, related to the distance achieved in each of the tests. If the estimation obtained cannot be compared to actual forces measurement, their validation has been achieved thanks to preliminary static tests realized with mass repartition measure. It can be noticed that without inclination correction, the lateral load transfer reaches constant values of ±0.35 during the straight line parts (as inclination is constant and equal to 10°). On the contrary, when inclination correction is active (test 2), the lateral load transfer is considerably reduced and stays below 0.1, during constant conditions.

Nevertheless, during the half turn (and before the correction has been achieved), the LLT reaches punctually a value of 0.3. Moreover during the first test, the fact that no correction is present on vehicle inclination, generates some punctual overshoots during the half turn (at 80m), due to dynamical effects, potentially leading to an hazardous situation. These results show the logical influence of the inclination correction on the risk of rollover.

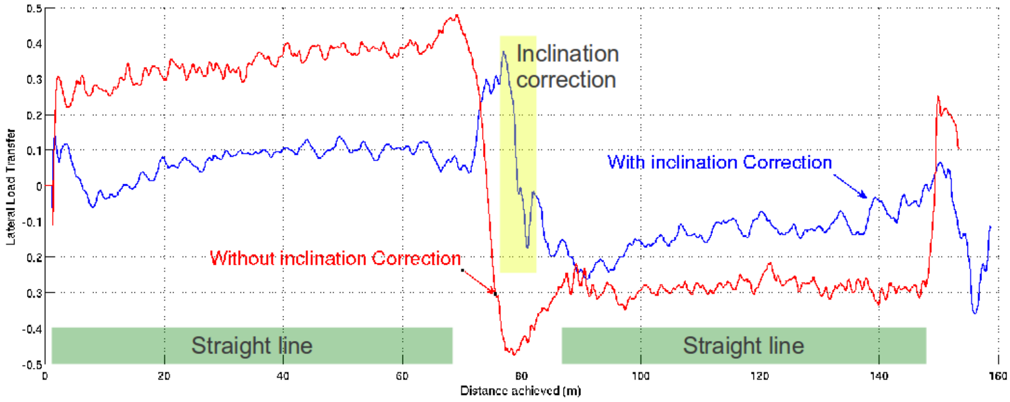


Figure 5: Comparison of LLT estimated during the two tests

5. Conclusion and Future Work

In this paper, an algorithm allowing to estimate the risk of rollover thanks to the reconstruction of Lateral Load Transfer is proposed. Based on an observer allowing to on-line adapt the grip conditions, such an algorithm is able to supply some information about an hazardous situation accounting for the vehicle configuration and terrain properties. To go further, output of this algorithm has to be compared during test with a sensor supplying the normal forces. If this comparison has been achieved thanks to differential mass measurement but without moving, a comparison with a ground truth during vehicle motion has to be done. For instance, the integration of cell measuring forces into the wheel are under investigation. The work proposed in that paper is part of the project ActiSurTT funded by the French National Research Agency (ANR).

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