A novel design for vehicle rollover warning system based on advanced image processing

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Abstract
This paper investigates a novel type of intelligent rollover warning system. Particularly, this study focuses on the speed based rollover warning messages for vehicles in a potential rollover situation on sharp curves or exit ramps. The vehicle rollover warning system (VRWS) estimates the maximum rollover threshold speed in real time according to the curvature detection of road and the vehicle dynamic sensing parameters such as slip angle, vehicle speed, vehicle acceleration, roll angle, tire model, height of gravity center. Consequently, there are two key techniques. First, we use image recognition technology to calculate the radius of the curve. It had the advantage of real-time detection with road environment than the Global Positioning System method which is according fixed digital map. Finally, we provide the maximum rollover threshold speed by the rollover index prediction model. Compared with Electronic Stability Program (ESP), this technique may provide 2 or 3 seconds early warning before the vehicle rollover occurs. It can reduce the risk of vehicle rollover on curved ramp. The effectiveness of VRWS is presented in the test results.

Keywords: rollover warning system, curvature detection, rollover index
1. Introduction

Rollover accidents are a serious and too frequent incident at many locations on the road. Especially in the condition of trucks or Sport Utility Vehicles (SUV) travelling at high speeds require a greatly reduced speed when meeting the exit ramps and tight curves. The usual cause of rollovers is driving behaviour, typically excessive speed while cornering which adversely affects the stability of the vehicle. Sudden or severe changes in direction can create a potential risk to rollover. By the time drivers see or feel something wrong, it is usually too late to prevent a rollover.

One method proposed to reduce rollovers is the Anti-Rollover Braking System (ARB) [1]. This system monitors the proximity to rollover of the vehicle. When the vehicle is about to rollover, Anti-Rollover Braking system applies the front brakes. The application of the front brakes reduces the cornering capability of the front tires and causes the vehicle to turn less sharply. This allows the vehicle to turn as sharply as possible without rolling over. The scenarios include slippery road or unsuitable driving behaviour. Various rollover tests of ARB’s method have been developed and verified [2]. Many papers assumed that a driver's steering input is previewed with a Global Positioning System (GPS) and an inertial measurement unit (IMU) [3-5], or with an automatic steering system for collision avoidance. Based on a linear vehicle model, a linear optimal preview controller is designed. Vehicle maneuvers are performed on a test track and a computer vehicle simulation is used to compare the experimental results from the scaled vehicle with passenger vehicle dynamics. The simulation was able to accurately predict the dynamic behavior of the scaled vehicle, providing a link between full size vehicle roll dynamics and scale vehicle roll dynamics.

Although the above methods can eliminate the rollover phenomenon, it could not provide early warning for the driver. These systems usually work in the condition of slipping or near rollover. To overcome the problem, an alternate approach is to incorporate an image-based detection technique with rollover prediction model. To estimate the rollover threshold, Gillespie initiates Loading Transfer Ratio (LTR) [6]. When a vehicle encounters a sudden drop in pavement height on one side of vehicle, there is a transient response which decays, leaving some steady-state load transfer. The relative importance of the transient effect can be determined by comparing the maximum LTR that occurs during the event with the steady-state LTR. The maximum LTR that occurs during the manoeuvre is \[ LTR = \frac{F_R - F_L}{F_R + F_L} \]

\( F_L, F_R \) respectively represent the total loads on the left and right sides of the vehicle. If the vehicle is suffering from rollover, the load on one side is zero, i.e. LTR=1 or -1. Thus, LTR represents roughly how close a vehicle comes to rolling over. Later, the new predictive Loading Transfer Ratio (PLTR) is derived based on the simplified LTR presented earlier. The
simulation results of the PLTR show the effectiveness of this new index to predict impending rollover [7]. The PLTR approach is compared against the commonly used LTR estimation algorithm that utilizes lateral acceleration and roll angle.

In this paper, we combined a predictive model based on PLTR with curve lane recognition. As described in [8, 9], the inverse perspective mapping (IPM) approach is adopted to generate the bird’s eye image of the road plane so as to remove the perspective effect and extract lane markings through some constraints of road geometry. This method is time-consuming due to its complex computation. Other research combines road model and Hough Transformation to estimate the initial lane boundary and improve the availability of lane detection without the ability of curve lane recognition [10]. The proposed vision-based driver assistance system in this research can detect lane radius through a CMOS camera and an image-processing unit simultaneously. By means of adopting road geometry model, the deviation to lane boundary and road radius will be calculated. The proposed image recognition method not only can reduce the noise interference from the roadway image but also can utilize the settings of dynamic region of interest (ROI) to enhance real time processing. When the vehicle begins to drive towards exit ramps and tight curves, the system will issue early warnings with sound and screen, warning the driver to reduce the vehicle speed to prevent from potential rollover accidents.

2. System structure

In an attempt to increase the effectiveness of a rollover warning system, vehicle parameters that affect a vehicle in a rollover situation, such as speed, can be incorporated into a rollover system. Systems that include vehicle configuration provide a more detailed analysis of the vehicle than a strictly speed based system to determine whether a warning condition applies. By incorporating a larger number of vehicle parameters that are directly related to the rollover of the individual vehicle, the rollover warning system will become more effective and reliable in the long run. A Digital Signal Processor (DSP) is used as the operating core in this research to implement the real-time lane radius recognition. An algorithm that can keep away the noise interference from the background of road images is adopted to precisely recognize the lane ahead. In the meantime, a setup of DROI (Dynamic Region of Interest) is taken to increase the speed in processing the images and reduce the misjudgment rate from the image-processing algorithm so that the system is able to normally recognize any lane forms.

2.1 Rollover threshold speed

Consider the vehicle roll dynamics as shown in figure 1, the effect of lateral forces can be formulated as:

$$\frac{a_y}{g} = -\frac{F_y}{mg} + \frac{2l}{mgh} \quad (1)$$
where $a_y$ is lateral acceleration, $g$ is gravity acceleration, $l$ is longitudinal distance from c.g. to axle, $h_r$ is roll center height, $r_i$ is distance from sprung mass CG to ground, $F_{yi}$ is tire longitudinal force, $m$ is vehicle sprung mass, $\phi_v$ is roll angle. When the lateral acceleration is increasing, the loading of the internal tire $F_{yi}$ is decreasing. When $F_{yi}$ is zero, all the loading shifts to the outer tire. At this time, the vehicle will be rollover, and the threshold of the acceleration is called Rollover Threshold (RT):

$$\frac{a_y}{g} = \frac{t}{2} + \frac{\phi_v h_r}{h_i}$$

where $t$ is track. Ignore super-elevation, i.e. $\phi_v = 0$, the rollover threshold is relative to $t$ and $h_i$.

\[\text{Figure 1 – Vehicle roll dynamics}\]

Consider torque equilibrium in the point of roll center in figure 1, The maximum values of lateral acceleration which the vehicle will be rollover is calculated as follows:

$$\frac{a_y}{g} = \frac{l}{h_i} - \frac{\phi_v (h_i - h_r)}{h_i}$$

where $a_y = \frac{V_{\text{max}}^2}{\rho}$, $\rho$ is radius of the curve. $V_{\text{max}}$ is the maximum rollover threshold speed which is determined from the following equation:
The rollover threshold varies according to the type and make of vehicle and load being
carried. The vehicles with higher centre of gravity are at higher risks. Therefore, the
measurement for the actual height centre of gravity is very important. This paper follows ISO
10392 to measure the location of centre of gravity longitudinally. The height of the centre of
gravity above ground, $z_{CG}$ is determined by the equation:

$$z_{CG} = \frac{l(m'_f - m_f)}{m_v \times \tan \theta} + r_{stat}$$  \hspace{1cm} (5)

where $l = 0.5(l_{left} + l_{right})$, $l_{left}$ is left wheelbase, $l_{right}$ is right wheelbase, $m_f$ is front load,
$m_v$ is total mass of vehicle, $\theta$ is the corresponding lifting angle, $r_{stat}$ is static loaded radius,
$m'_f$ is axle load at front of the axle remaining on the ground while the vehicle is inclined.

2.2 Lane radius detection

The relation between the global coordinates and the planar coordinates of image is shown
in figure 2. Since the lane detection must be performed in the image coordinates, the 2-D
information derived from the image-processing for lane mark should be transformed into 3-D
spatial information through the Inverse Perspective Mapping (IPM) in order to obtain the
position of lane in a real space (global coordinates). Parameters needed in the algorithm and
thereof definitions are shown in table 1. Because the image recognition for lane detection is
undertaken in the image plane, the objects in image plane is converted into a real object in
global coordinates by Equation (6), (7) and (8).

$$X = \frac{uH}{e, m_\theta - v}, e_v$$  \hspace{1cm} (6)

$$Y = \frac{e_\theta H}{e, m_\theta - v}$$  \hspace{1cm} (7)

$$Z = \frac{e, m_\theta H}{e, m_\theta - v}$$  \hspace{1cm} (8)
In order to detect the road curvature from its driving lane, firstly it is necessary to identify the position of lane mark from the image plane. Some features of the roadway itself should be taken as the basis for image recognition when detecting the curvature of lane marks that mainly covers the following four cues for lane mark recognition. Regardless of the white or yellow lane markings appeared in the roadway image, all of them have a higher gray value than the road surface. Therefore, the statistics of gray scale can be utilized to identify the threshold value of lane marks and differentiate the lane marks from road surface. A noticeable edge characteristic at the connecting point of the lane marks and the road surface can be taken to compute and mark the possible range of lane mark. The Sobel’s horizontal edge-based detection technology was applied to detect the edge of lane marking in every row of image by
The following equation:

\[
E(u, v) = \begin{cases} 
S^*[I(u, v)] & \text{if } I(u, v) > 0 \\
0 & \text{otherwise} 
\end{cases}
\]  

(9)

In the equation, \(I(u,v)\) is the original image, \(E(u,v)\) is the edge image. \(S^*[I(u,v)]\) represents the Sobel’s operation, and its horizontal mask is \([-1 -2 -1; 0 0 0; 1 2 1]\). The actual lane mark width will be shown in the image plane through a conversion from the Equation (10) at a constant ratio. A determined interval can be used as the basis for determining if it is the lane mark or not even though it is a roadway with a very unstable marking quality.

\[
\Delta u = \Delta X_w \cdot \frac{e_v m_\theta - v e_u}{H} 
\]  

(10)

In the equation, \(\Delta u\) is the width of lane marking in the image while \(\Delta X_w\) is the actual lane marking width. Lane marks usually appear within a specific range in the screen in a manner of segment-by-segment continuity and form the lane boundary accordingly that becomes an important cue for identifying if they are lane marks or not. Figure 3 exhibits the result after processing the images for lane recognition. The left line and the right line are the desired results from detection while the middle line is the estimated center line of the lane according to the left & right lines. Thus, the subsequent estimation for the amount of lane departure and the curvature of roadway is performable. Once the lane marks were recognized in the image plane, an iterative method can be taken to derive a lane-fitting equation as shown in Equation (11) to finish the lane modeling:

\[
x = k \cdot y^2 + m \cdot y + b 
\]  

(11)

where \(x\) and \(y\) are the axis of ordinate and the axis of abscissas respectively; and \(k\), \(m\) and \(b\) are parameter values that vary with the time factor. Thus, the slope of the driving lane and the curvature of roadway can be calculated from Equation (11) as shown in Equation (12) and Equation (13):

\[
\varepsilon = 2 \cdot k \cdot y + m 
\]  

(12)

\[
\rho_L = \frac{2 \cdot k}{(1 + (2 \cdot k \cdot y + m)^2)^{1/2}} 
\]  

(13)
3. Verification tests

3.1 Simulation results

To analyze vehicle dynamic systems is very complicated. In this paper, we use vehicle analysis software to simulate dynamic behavior of sport utility vehicle. Simulations conducted in CarSim on various car types to better define the precision and accuracy of vehicle models. Figure 4 shows the simulation results of maximum rollover threshold speed with different loads. The triangle line is the curve of maximum rollover threshold speed of SUV with loading 1500 kg. The other lines denote the curve of maximum rollover threshold speed of truck with different loads.

![Figure 4 – Simulation results of maximum rollover threshold speed with different loads](image)

3.2 Experimental results

The developed rollover threshold speed algorithm was validated with experimental measurements on a test vehicle. To obtain objective test results, the vehicle was instrumented to record the relevant values from CAN network with communication at the baud rate of 500 kbits/sec. We refer to the maximum rollover threshold speed in figure 4 as the criterion. In order to maximize the effectiveness of rollover warning system, the scenario is potentially dangerous for vehicles that are in real danger and need to be warned of that danger. First, the
accuracy of the lane radius detection is a very important factor. Figure 5 shows the radius detection of the curve. The test environment is with a regular curvature 238 m. The triangle line denotes the calculated radius of the road, the plus sign line shows the maximum rollover threshold speed, the rhombus line denotes the vehicle speed. The average error is about ±6m. According to equation (4), it only makes up 3% error of the maximum rollover threshold speed.

![Figure 5 – Measured radius of the curve](image)

To ensure the quality of rollover alarms, the validity of rollover threshold speed is another issue. In this paper, we measure the slip angle to demonstrate that the vehicle is near the situation of rollover. From [7], we have known that the car sideslips before the rollover occurs. When the vehicle sideslips, the slip angle is approaching 5 degrees. Figure 6 shows the measured the variation of roll angle and lateral acceleration with vehicle speed 65 kph. The scenario is that the test vehicle was driven across S-type curve with radius 40 meters after 4th second. The predictive rollover threshold speed results in about 5 degrees of slip angle. Therefore, the predictive rollover speed is verified. Figure 7 shows the human interface of the rollover warning system, where 85 denotes the calculated maximum rollover threshold speed, 104 is the current vehicle speed, 191 is the detected radius of the road. In this case, the current vehicle speed is larger than the calculated maximum rollover threshold speed. Therefore, the status is warning.
Figure 6 – The variation of roll angle and lateral acceleration with vehicle speed

Figure 7 – Human interface of the rollover warning system

4. Conclusion

In this paper, the maximum rollover threshold speed and lane radius detection approach is proposed and demonstrated the effectiveness that utilizes slip angle. The average error of
image recognition is within ±6m and affects 3 % error of the maximum rollover threshold speed. It detects the lane radius effectively. The predicted value of the maximum rollover threshold speed is verified by measured slip angle. Compare to traditional methods, we could offer 2 or 3 seconds early warning before the vehicle rollover occurs, and hence the proposed approach is potentially suitable for application in rollover prevention systems.

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References