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Injured probability assessment in frontal pedestrian-vehicle collision counting uncertainties in pedestrian movement☆

Zhi Huang[a,b,*], Ying He[a,1], Yi Wen[a,1], Xiaolin Song[a,b,1]

[a] College of Mechanical and Vehicle Engineering, Hunan University, China
[b] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, China

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ABSTRACT

In probabilistic approaches, where uncertainties in pedestrian motion are counted, the distance model is important for the accurate and robust collision risks evaluation. Focusing on the typical frontal pedestrian-vehicle collision, the conflict distance model with the merit to distinguish front impacts from side ones is presented. Based on stochastic pedestrian model and Unscented Transformation (UT) method, the time-to-collision (TTC) and conflict distance are sampled, and their probability density functions (pdf) as well as the collision probability are deduced. The presented distance model and probabilistic method are verified with Monte Carlo (MC) as the reference, and show the high accuracy and potential for real-time application. Utilizing the estimated collision speed and its probability distribution, a unified model assessing the injured probabilities of pedestrian in front collision is proposed. A pedestrian-vehicle conflict scenario is constructed to evaluate the effectiveness of the probabilistic injury assessment. Simulation results show that the proposed method is sensitive to evasive maneuvers, and provides more useful cues for the optimization of collision avoidance control than the deterministic approaches.

1. Introduction

Pedestrians are the vulnerable group of road users. Approximately 1.24 million people died in road traffic accidents each year, and pedestrian fatalities account for 22% (World Health Organization, 2013). Pedestrian's safety is the great concern over the past few decades, with focuses mainly on the pedestrian detection, collision prediction and collision avoidance control (Gandhi and Trivedi, 2007). Pedestrian collision mitigation or avoidance systems (PCAS) with autonomous brake (Coelingh et al., 2010) are already available on the market, which warn or assist driver to evade collisions. Accurate risk assessments are critical for PCAS, which affect the system reliability, robustness and driver's acceptance to the assistance system. Furthermore, due to that the vehicle dynamics is restricted by tire-road friction characteristics, the accurate risk assessments are crucial for the objective of optimal expected benefit via evasive maneuvers, e.g. steering, braking and combination, with the limited lateral and longitudinal force from the road if a collision cannot be avoided.

Generally simplified and deterministic dynamics models are employed to assess the collision risk, e.g. constant velocity model (CV) for pedestrian and constant curvature and acceleration model (CCA) for vehicle (Zhang et al., 2014; Tamke et al., 2011; Hillenbrand et al., 2006). CCA model is rational since generally the driver does not change the operation abruptly if no danger is perceived. However pedestrian movements are influenced by various factors, e.g. destination, age, physical conditions, emotion, unpredictable environment changes and so on, and most of which are unobservable by sensors in PCAS. Practically, pedestrian may change his/her speed and direction frequently and randomly, therefore, more complicated or stochastic models should be used to predict the pedestrian's trajectory (Goldhammer et al., 2013; Keller et al., 2011; Makris and Ellis, 2002). Considering the random errors in pedestrian positioning and motion, the collision risks are described by collision probability (Braeuchle et al., 2013; Nicolao et al., 2007), and methods to solve the nonlinear transformation of random errors were studied, e.g. Monte Carlo (Eidehall and Petersson, 2008; Hafidi et al., 2008), polynomial fitting (Nicolao et al. 2007), stochastic researchable sets (Althoff et al. 2008), Hidden Markov Models (Nakatsubo and Yamada, 2010), Unscented Transformation (UT) (Berthelot et al. 2012;Huang et al. 2017).

In probabilistic approaches, distance between pedestrian and vehicle is employed to determine the risk levels and whether or not a collision occurs. In some studies, for simplification, Euclidean distance

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* Corresponding author at: College of Mechanical and Vehicle Engineering, Hunan University, 1st South Lusan Road, Yuelu District, Changsha, China.
E-mail addresses: huangzhi@hnu.edu.cn (Z. Huang), 1294565524@qq.com (Y. He), 2698887810@qq.com (Y. Wen), jqysxl@hnu.edu.cn (X. Song).
[1] Address: College of Mechanical and Vehicle Engineering, Hunan University, 1st South Lusan Road, Yuelu District, Changsha, China.

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is employed (Tamke et al., 2011; Hoffmann and Tomlin, 2008) by assuming these two objects as two circles enveloping their outlines and a collision is expected if the Euclidean distance is less than the sum of two radii. Obviously, the vehicle is generally rectangular, and then using circle simplification could result in conservative predictions. The maximum norm distance (Berthelot et al., 2011) is based on the fact that the vehicle is a rectangle, and is with the merit of low computation load. The frame distance (Itoh et al., 2011) is regarded as the distance between the rectangular frame of vehicle and pedestrian in the direction connecting the two centers of objects. If Frame distance is less than zero, a collision is expected. Although maximum norm distance and frame distance are more reasonable than Euclidean distance, however, both distance models cannot distinguish side collision from front collision. Regarding the injuries to pedestrian, the severity in side and front collision is totally different. In practice, side collisions are rare in traffic accidents, because side collision risk can be easily perceived and avoided with a stop by pedestrian, and that is also why injury to pedestrian in side collision can hardly be found in the past research. Both distance models count the side collisions into the total conflict events, and therefore, the estimated collision probability would be higher than the actual one.

When the probabilistic approaches are employed, the objective of PCAS is turned to the maximum expected benefit, in other words, minimum pedestrian's injury or costs for recovery (Braeuchle et al., 2013). There have been plenty of studies focusing on pedestrian's injury based on experiments, statistics and simulations (Mo et al., 2014, Rosén et al., 2011, Yao et al., 2008). However, fewer studies present a unified method to estimate the expected injury to pedestrian in front impact when pedestrian's uncertainties are counted, that is especially important for the decision of optimal evasive maneuver in case of collision being inevitable.

According to previous research, uncertainties in pedestrian positioning and movements were fully considered during the development of PCAS. However, the accurate estimation of risk probability and expected pedestrian's injury has not been well addressed yet. The objectives of this study are:

1. To construct a rational distance model discriminating the front collision from the side collision;
2. To present a unified method for the evaluation of the expected pedestrian's injury, in which the collision velocity and collision probability are counted.

This paper is organized as follows: The previous work is introduced firstly, and then the pedestrian model, vehicle model, conflict distance model and pedestrian's injury assessment are described. Finally, the results of simulation experiments and discussions are presented.

2. Previous work

This work is the extension to our previous research (Huang et al., 2017). In the previous work, the UT method (Berthelot et al., 2011; Pepy et al., 2006; Julier and Uhlmann, 1996) for the estimation of vehicle–pedestrian collision probability was proposed. Fig. 1 shows the skeleton of the presented method.

The uncertainties in the pedestrian's motion are described by ($\boldsymbol{X_{obj}}$, $\sum$). $\boldsymbol{X_{obj}}$ is the states of the pedestrian and described by the first-order Markov model, and $\sum$ represents uncertainties. Based on the discrete trajectory prediction and by assuming the outline of the pedestrian and vehicle as circles, the Euclidian distance is adopted for distance model, and the dichotomy is used to search the time at which the negative or minimum Euclidian distance occurs. The symmetric σ-sets of UT (see in the Appendix A) are used for *TTC* and minimum Euclidian distance sampling. The results of UT sampling are the means and variances of the minimum Euclidian distance and *TTC*. With the Gaussian distribution assumption, the probability density function (pdf) of distance and *TTC* can be deduced.

Here the *TTC* is defined as the earliest time at which a collision occurs. If no collision is expected, *TTC* is $+\infty$, then *TTC* is substituted by the pseudo TTC, i.e. $\underline{\overline{TTC}}$ (Berthelot et al., 2012) to overcome its uncontinuity. $\underline{\overline{TTC}}$ is the moment when the minimum distance d_{min} is reached (not the collision occurs) in the prediction horizon. Since the d_{min} is always available, therefore $\underline{\overline{TTC}}$ is finite, which satisfies the continuity condition to apply UT method. The collision risk is described by collision probability: $P(TTC \in \mathbb{R}) = P(d_{min} < 0)$. To evaluate the criticality of an imminent collision, $P(TTC \le t, TTC \in \mathbb{R})$ is employed, which equals the probability of $\underline{\overline{TTC}}$, $P(\underline{\overline{TTC}} \le t)$ multiplied by the collision probability $P(TTC \in \mathbb{R})$. This work presents an effective and efficient method to estimate the collision probability and its criticality, and more details can be found in the previous work (Huang et al., 2017). However, as discussed in the introduction, using circle simplification may result in conservative predictions and cannot distinguish the side collision from the front collision. To overcome this issue, more rational simplification and conflict distance model are proposed in this research.

3. Vehicle and pedestrian models

Assuming the driver keeps current maneuver, the CCA model is adopted. The vehicle states are described using

$$state_v = (x_v, y_v, v_{xv}, v_{yv}) \tag{1}$$

where x_v and y_v denotes the longitudinal and lateral coordinates of the vehicle respectively, using the location of the center of front bumper, v_{x_v} and v_{y_v} denotes the vehicle velocity in *x*, *y* direction respectively. All the states are defined in the ground-based *xoy* frame, where the *x* direction is along the road and the y direction perpendicular to the road (seen in Fig. 2). To calculate the relative position between the vehicle and the pedestrian, the $X'O'Y'$ frame, fixed on the center of front bumper, is constructed, with the X' direction along the vehicle heading and the Y' direction perpendicular to the vehicle heading. Obviously, the vehicle's coordinates in $X'O'Y'$ frame, e.g. X_v', Y_v', are zero.

The first-order Markov model is used to describe the uncertainties in pedestrian motion. The states of pedestrian in *xoy* frame are denoted using

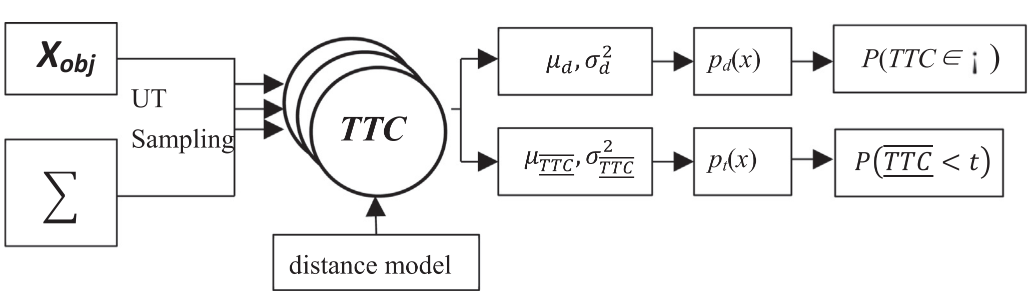

Fig. 1. Skeleton of collision risk estimation using UT algorithm.