

Based on the Unscented Kalman Filter to Estimate the State of Four-Wheel-Independent Electric Vehicle with X-by-Wire

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ABSTRACT

As a new form of electric vehicle, Four-wheel-independent electric vehicle with X-By-Wire (XBW) inherits all the advantages of in-wheel motor drive electric vehicles. The vehicle steering system is liberated from traditional mechanical steering mechanism and forms an advanced vehicle with all-wheel independent driving, braking and steering. Compared with conventional vehicles, it has more controllable degrees of freedom. The design of the integrated vehicle dynamics control systems helps to achieve the steering, driving and braking coordinated control and improves the vehicle's handling stability. In order to solve the problem of lacking of vehicle state information in the integrated control, some methods are used to estimate the vehicle state of four-wheel-independent electric vehicles with XBW. In order to improve the estimation accuracy, unscented Kalman filter (UKF) is used to estimate the vehicle state variables in this paper. At the same time, simulations in several typical working conditions have been carried out based on the simulation models of four-wheel-independent electric vehicle with XBW, which are established by CarSim and Simulink together. The simulation results show that: Unscented Kalman Filter can achieve a high-precision in the estimation of vehicle state.

CITATION: Gu, X., Chen, G., and Zong, C., "Based on the Unscented Kalman Filter to Estimate the State of Four-Wheel-Independent Electric Vehicle with X-by-Wire," *SAE Int. J. Commer. Veh.* 8(2):2015, doi:10.4271/2015-01-2731.

INTRODUCTION

With the development of automotive electronic technology, most of the mass-produced vehicles are equipped with Active safety systems, such as ABS (Anti-lock Braking System), TCS (Traction Control System), ESP (Electronic Stability Program) etc. The wide application of the chassis electronic control systems plays an important role in ensuring driving safety and stability of automobiles. The realization of these chassis electronic control systems is based on some key state variables of the vehicles (such as vehicle longitudinal velocity, lateral velocity, yaw rate etc). The accuracy and reliability of these vehicle states directly affects the performance of electronic control systems for vehicle chassis control.

Some general methods use signals of sensors which have been equipped on the vehicles to calculate the vehicle states directly, they are: wheel speed method (the maximum wheel speed law, the minimum wheel speed law etc), integral method and combined method. These methods are simple and have high reliability, but they also have some shortcomings. The maximum wheel speed law is mainly suitable for the vehicle braking conditions and the minimum wheel speed law is mainly suitable for the vehicle driving conditions, but the two methods are not suitable for four-wheel drive vehicles. The integral method is a method that obtains the vehicle speed by the integral of the acceleration signal collected by the sensors. With the accumulation effect of time, the error caused by the acceleration sensor accuracy and noise will become gradually larger and the estimated vehicle speed may diverge away from the true value.

Commonly, Kalman filter(KF), extended Kalman filter(EKF) and unscented Kalman filter(UKF) are used to estimated vehicle variables. KF only can be applied to linear systems. EKF can be used in weakly linear systems, but it is poor in real-time performance for solving the Jacobian matrix. UKF can be used for non-linear system and has the capable of real-time performance and high accuracy.

As a new form of electric vehicles, there are many differences between four-wheel-independent electric vehicles with XBW and conventional vehicles in mechanical structure and chassis electronic control systems. For these special characteristics, the traditional methods which are used to estimate vehicle states can't be used for the electronic control systems of four-wheel-independent electric vehicles with XBW. So some researchers propose advanced methods which use the technology of vehicle states estimation (or state observation technology) to estimate the required vehicle states accurately.

RELATED WORKS

7 Degree-of-Freedom Vehicle Dynamic Model

In this paper, UKF algorithm is used to estimate the vehicle states. UKF is a filtering algorithm based on the model. As a part of the UKF estimation algorithm, the model is used for iterative computation. The vehicle dynamic model, which includes the longitudinal velocity, lateral velocity, yaw rate and four wheel steering angle, is built to estimate vehicle states. As shown in figure 1, the vehicle model ignores the vehicle's pitch, roll motion, and the motion in vertical direction. Where v_x is the longitudinal velocity.

is the vehicle lateral velocity, r is the vehicle yaw rate, δ_{fl} , δ_{fr} , δ_{rl} , δ_{rr} are the wheel angle, F_{xij} , F_{yij} are the longitudinal forces and lateral forces, α_{fl} , α_{fr} , α_{rl} , α_{rr} are the tire sideslip angle respectively, fl , fr , rl , rr represent the left front wheel, right front wheel, left rear wheel and right rear wheel respectively.

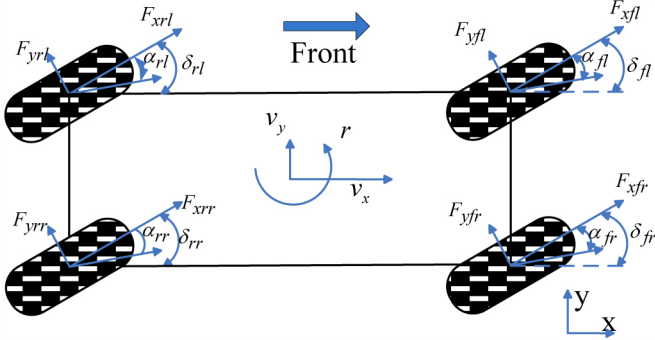


Figure 1. 7 Degree-of-Freedom vehicle dynamic model

The equations of vehicle dynamic model are as follows:

$$m(\dot{v}_x - v_y r) = \sum F_x \quad (1)$$

$$m(\dot{v}_y + v_x r) = \sum F_y \quad (2)$$

$$I\dot{r} = \sum M_z \quad (3)$$

$$\begin{aligned} M_z = & a(F_{xfl} \sin \delta_{fl} + F_{yfl} \cos \delta_{fl}) - \frac{t_f}{2}(F_{xfl} \cos \delta_{fl} - F_{yfl} \sin \delta_{fl}) \\ & + a(F_{xfr} \sin \delta_{fr} + F_{yfr} \cos \delta_{fr}) + \frac{t_f}{2}(F_{xfr} \cos \delta_{fr} - F_{yfr} \sin \delta_{fr}) \\ & - b(F_{xrl} \sin \delta_{rl} + F_{yrl} \cos \delta_{rl}) - \frac{t_r}{2}(F_{xrl} \cos \delta_{rl} - F_{yrl} \sin \delta_{rl}) \\ & - b(F_{xrr} \sin \delta_{rr} + F_{yrr} \cos \delta_{rr}) + \frac{t_r}{2}(F_{xrr} \cos \delta_{rr} - F_{yrr} \sin \delta_{rr}) \end{aligned} \quad (4)$$

Where m is the weight of vehicle, r is yaw the rate, $\dot{v}_x$ is longitudinal acceleration, $\dot{v}_y$ is lateral acceleration, F_x is longitudinal force of the vehicle, F_y is lateral force of the vehicle, M_z is torque around the Z axis of the vehicle, I is moment of inertia of the vehicle about the Z axis. a , b are distance between the center of mass and the front, rear axles, t_f , t_r are the wheel track of the front and rear axles, Equations of $\dot{v}_x$ and $\dot{v}_y$ are as follows:

$$\begin{aligned} \dot{v}_x = & \frac{1}{m}(F_{xfl} \cos \delta_{fl} - F_{yfl} \sin \delta_{fl} + F_{xfr} \cos \delta_{fr} - F_{yfr} \sin \delta_{fr} \\ & + F_{xrl} \cos \delta_{rl} - F_{yrl} \sin \delta_{rl} + F_{xrr} \cos \delta_{rr} - F_{yrr} \sin \delta_{rr} - F_w) \end{aligned} \quad (5)$$

$$\begin{aligned} \dot{v}_y = & \frac{1}{m}(F_{xfl} \sin \delta_{fl} + F_{yfl} \cos \delta_{fl} + F_{xfr} \sin \delta_{fr} + F_{yfr} \cos \delta_{fr} \\ & + F_{xrl} \sin \delta_{rl} + F_{yrl} \cos \delta_{rl} + F_{xrr} \sin \delta_{rr} + F_{yrr} \cos \delta_{rr}) \end{aligned} \quad (6)$$

Where F_w is the wind resistance of vehicle.

Tire Model

In this paper, HSRI tire model is used to calculate tire forces. This tire model is established by Highway Safety Research Institute of Michigan University in the US. It is a semi-empirical tire model which is got through a lot of tire tests. This tire model has three kinds of expressions and the simpler form is used in this paper. The reason why we choose this model is that HSRI tire model is simple and convenient, which has little parameters to be identified and doesn't need to consider tire aligning moment. It also can achieve higher precision. Tire coordinate system as shown in [figure 2](#).

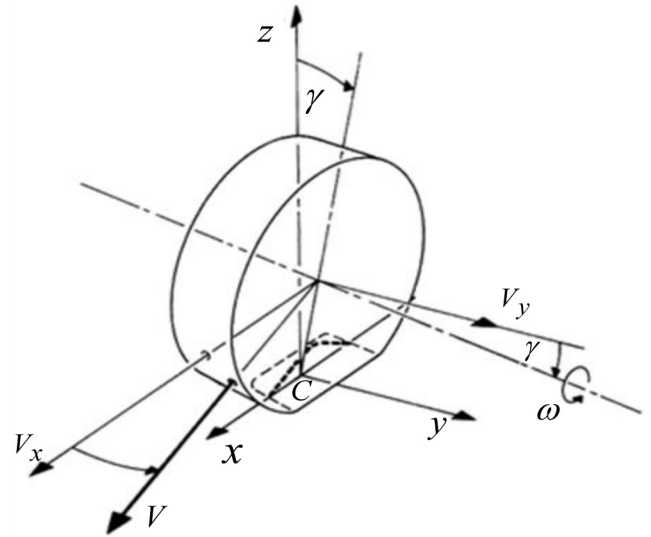


Figure 2. HSRI tire coordinate system

In HSRI tire model, we need to reference two parameters named the tire longitudinal slip ratio and the lateral slip ratio. Their definitions are as follows:

$$s_x = \frac{v_{cx}}{v_x} = \frac{v_x - v_r}{v_x} = \frac{v_x - \omega R}{v_x} = 1 - \frac{v_r}{v_x} \quad (7)$$

$$s_y = \frac{v_{cy}}{v_x} = \frac{v_y}{v_x} \quad (8)$$

Where v_x , v_y respectively represent the speed of tire in the direction of X, Y axis, v_r is the rolling speed of tire, which is $v_r = \omega R$, v_{cx} is longitudinal slip speed of tire, which is $v_{cx} = v_x - v_r = v_x - \omega R$, v_{cy} is lateral slip speed of tire.

$$\lambda = \frac{\mu F_z (1 - s_x)}{2\sqrt{(C_s s_x)^2 + (C_\alpha s_y)^2}} \quad (9)$$

In addition, we reference another parameter λ . It is the ratio of “limit of adhesion region” and “non-slip contact length”. Where C_s , C_α are the longitudinal slip stiffness and the lateral slip stiffness of tires. μ is coefficient of road adhesion, F_z is the vertical force of vehicle.

The calculation formulas of the longitudinal force and the lateral force in HSRI tire model as follows:

$$F_x = \begin{cases} -C_s \frac{s_x}{1 - s_x}, \lambda \geq 1 \\ -C_s \frac{s_x}{1 - s_x} \lambda (2 - \lambda), 0 < \lambda < 1 \\ -C_s \mu F_z \frac{1}{\sqrt{C_s^2 + (C_\alpha s_y)^2}}, \lambda = 0 \end{cases} \quad (10)$$

$$F_y = \begin{cases} -C_\alpha \frac{s_y}{1 - s_x}, \lambda \geq 1 \\ -C_\alpha \frac{s_y}{1 - s_x} \lambda (2 - \lambda), 0 < \lambda < 1 \\ -C_\alpha s_y \mu F_z \frac{1}{\sqrt{C_s^2 + (C_\alpha s_y)^2}}, \lambda = 0 \end{cases} \quad (11)$$

Where F_z is wheel vertical force. $\lambda = 0$ is complete sliding (only at wheel lock), $\lambda = 1$ is complete adhesion, $0 < \lambda < 1$ is adhesion and sliding.

The Unscented Kalman Filter

UT transform is core part of UKF. This paper uses symmetric sample as an example to introduce the working principles of the UT transform in detail.

The mean and covariance of x are $\bar{x}$ and P_x . The mean and covariance of y can be obtained as follows: Constructing a matrix X which contains $2L + 1$ vectors, they are X_i .

$$X_0 = \bar{x} \quad (12)$$

$$\lambda = \alpha^2 (L + \kappa) - L \quad (13)$$

$$X_i = \begin{cases} \bar{x} + (\sqrt{(L + \lambda) P_x})_i, & i = 1, 2, \dots, L \\ \bar{x} - (\sqrt{(L + \lambda) P_x})_{i-L}, & i = L + 1, L + 2, \dots, 2L \end{cases} \quad (14)$$

Weight of the mean:

$$W_0^{(m)} = \lambda / (L + \lambda) \quad (15)$$

Weight of the covariance:

$$W_0^{(c)} = \lambda / (L + \lambda) + (1 - \alpha^2 + \beta) \quad (16)$$

$$W_i^{(m)} = W_i^{(c)} = 1 / [2(L + \lambda)], i = 1, 2, \dots, 2L \quad (17)$$

Where λ is scale parameter, K is the second parameter, β is state distribution parameter ($\beta = 2$, for Gaussian distribution), α is represent a nearby stretch range of sigma points set.

The set of Sigma points spreads by the nonlinear function:

$$Y = g(X_i), i = 0, 1, 2, \dots, 2L \quad (18)$$

The mean and covariance of y can be calculated as follows:

$$\bar{y} \approx \sum_{i=0}^{2L} W_i^{(m)} y_i \quad (19)$$

$$P_y \approx \sum_{i=0}^{2L} W_i^{(c)} \{y_i - \bar{y}\} \{y_i - \bar{y}\}^T \quad (20)$$

This paper establishes the state equation and measurement equation on the foundation of vehicle dynamics model and tire model. The system noise and measurement noise are assumed as Gaussian white noise. In the UKF algorithm, the state variables equation is $x(t) = [v_x, v_y, r, \dot{v}_x, \dot{v}_y, M_z]^T$ and the observed variables equation is $y(t) = [\dot{v}_x, \dot{v}_y, r]^T$. The above two equations use continuous signals. The equations should be discretized firstly for the computer can only deal with discrete signals. Then the discrete form of state equation and observed equation are as follows: