Longitudinal and Lateral Velocity Estimation based on Covariance Inverse Robust Fusion

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Abstract. Accurate estimation of vehicle longitudinal and lateral velocity is meaningful for internal system. Aiming at improving the accuracy of velocity estimation, the Covariance inverse (CI) based fusion method is applied. A vehicle dynamics model is established and the CI method is analysed. Finally, a joint simulation of CarSim and MATLAB/Simulink is conducted and the results show the advantages of proposed method.

1. Introduction

The application of automobile electronic control system has a good effect on the active safety of automobile, in which vehicle sensors play an important role. The on-board sensor can directly measure part of the driving state information, but because of the external environment interference or the error of the sensor itself in the driving process, it cannot accurately measure the important information such as the sideslip angle of the centre of mass, the longitudinal and lateral speed, the longitudinal and lateral force of the tire. Based on the information fusion technology, it is becoming the focus of people's attention to estimate the key state information of automobile, accurately acquire the motion state information which is difficult to measure directly, and realize the product application of active safety products in mass production vehicles [1].

The characteristics of multi-sensor information fusion are: through performance complementation, the time coverage, space coverage and frequency coverage of sensor detection are expanded; through performance redundancy, the confidence of target detection decision-making is improved, the fuzziness is reduced, the false alarm rate is reduced, the reliability and fault tolerance of the state monitoring system are enhanced, and the anti-interference ability of the system is improved [2].

2. Vehicle dynamics model

The first task of establishing vehicle dynamics model is to establish a proper vehicle body coordinate system. In this paper, the car body coordinate system is specified as follows, as shown in Figure 1, where absolute coordinate system \(X-O-Y\) represents geodetic coordinate system, and \(X-O-Y\) represents car body coordinate system (consolidated on car body). The origin of the coordinate is consistent with the centre of mass of the vehicle. The \(x\)-axis represents the longitudinal coordinate axis of the vehicle, and the driving direction of the vehicle is the positive direction of the coordinate axis; the \(y\)-axis represents the lateral coordinate axis of the vehicle, which is perpendicular to the longitudinal driving direction of the vehicle, and it is specified that the left-hand direction is positive when the vehicle is driving.
2.1 Key driving state parameters

In this paper, the key driving state parameters for ESP control are estimated. First of all, three degrees of freedom, longitudinal, lateral and yaw, should be considered in the active safety control esp. Secondly, in order to improve the accuracy and simplify the model, the wheel differential control is considered, so the rotational degrees of freedom of four wheels need to be considered. Based on the above factors, this paper establishes a seven degree of freedom vehicle model as shown in Figure 1, and makes the following assumptions: (1) the origin of vehicle coordinate system coincides with the centroid of vehicle model; (2) the degrees of freedom of vehicle pitch, roll and vertical direction are ignored; (3) the suspension is simplified as a rigid body, and the transmission system is a linear system. Under the control of steering wheel, the two front wheel angles are the same; (4) The influence of longitudinal friction resistance on state estimation is ignored.

Table 1. Vehicle parameter symbol meaning

| Parameter symbols | Parameter names          | unit |
|-------------------|--------------------------|------|
| $v_x$             | longitudinal velocity    | m/s  |
| $v_y$             | lateral velocity         | m/s  |
| $r$               | yaw rate                 | rad/s|
| $\beta$           | sideslip angle of centroid | rad  |
| $\omega_i$        | wheel angular speed      | rad/s|
| $T_{bij}$         | wheel braking torque     | N/m  |
| $\delta$          | front wheel corner       | rad  |

2.2 Establishment of state estimation model

According to the vehicle model, the state vector is defined as

$$ X_k = [v_x, v_y, r, \omega_i, \omega_j, \omega_p, \omega_r] $$

$$ U_k = [\delta, T_{bij}, T_{bij}, T_{abl}, T_{abl}] $$

The following relationship exists between the vehicle’s sideslip angle and the longitudinal and lateral speeds

$$ \beta = \arctan \frac{v_y}{v_x} $$

Combined with the idea of state parameter estimation and tire model, the above vehicle dynamics model is sorted into state equation and measurement equation.

The standard form of the equation of state is as follows:
The standard form of measurement equation is as follows:

$$Z_k = [a_x, a_y, r, \omega_x, \omega_y, \omega_z]^T$$

$$= h(X_k, F_k, U_k) + V_k$$

where $W_k$ represents the process noise of the system state equation and $V_k$ represents the measurement noise of the system measurement equation. $a_x, a_y$ represents the longitudinal and lateral acceleration.

### 3. Covariance Cross Robust Fusion

The CI algorithm proposed by Julier [3] and Uhlmann [4] can realize the fusion estimation without knowing the cross covariance. The algorithm can improve the accuracy and robustness of the fusion estimation.

CI fusion Kalman filter is defined as

$$\hat{x}_{Cf} = \Omega_1 \hat{x}_1 + \Omega_2 \hat{x}_2$$

$$P_{Cf} = \omega P_1^{-1} + (1-\omega) P_2^{-1}$$

where $\Omega_1 = \omega P_{Cf}^{-1}, \Omega_2 = (1-\omega) P_{Cf}^{-1}, \omega \in [0,1]$

The minimum performance index is

$$\min_{\omega} tr P_{Cf} = \min_{\omega \in [0,1]} tr \left[ \omega P_1^{-1} + (1-\omega) P_2^{-1} \right]^{-1}$$

The optimal weight coefficient matrix can be obtained by 0.618 method.
\[ \Omega_i = \omega_i \mathbf{P}^{-1} \]
\[ \omega_1 + \omega_2 + \ldots + \omega_n = 1, \quad \omega_i \in [0,1] \]

Using CI algorithm, the state estimation result and covariance matrix can be obtained.
\[ X_{\text{est}}(k) = \sum_{j \in \Omega(k)} \Omega_j \hat{X}_j(k) \]
\[ P_{\text{est}}(k) = ( \sum_{j \in \Omega(k)} \omega_j P_j(k)^{-1} )^{-1} \]

where
\[ \Omega_j = \omega_j P_j^{\text{est}}(k) P_j(k)^{-1} \]
\[ \sum \omega_j = 1, \quad \omega_j \in [0,1] \]

4. Experimental results

In order to verify the effectiveness of the above estimation algorithm, the joint simulation of CarSim and MATLAB/Simulink is carried out. The input of the system is the output of the CarSim simulation module, namely: longitudinal and lateral acceleration, yaw rate, steering wheel angle, etc.; the simulation module is established by using Matlab/Simulink. Finally, the simulation is carried out under typical working conditions, and the estimated value of this algorithm is compared with the simulation results of CarSim under the same working conditions. The vehicle working condition is set as double shift line, where there is a period of violent acceleration and deceleration in the process of vehicle driving.

The longitudinal and lateral velocity estimation relative error are shown in Figure 3 (a) and (b).

![Figure 3. Relative estimation error](image)

According to Figure 3, the relative error of velocity estimation with proposed method is smaller than the UKF and EKF [5], which means a better estimation accuracy and performance.

Table 2 shows the MSE (mean square error) of the three methods. Consistent with the previous results, the MSE of the proposed algorithm in estimating the longitudinal and lateral velocity are 3.1050 and 3.3715, showing a better performance comparing with the UKF and EKF method.

|                | UKF    | EKF    | Proposed |
|----------------|--------|--------|----------|
| Longitudinal   | 5.7542 | 5.9127 | 3.1050   |
| Lateral        | 5.9512 | 6.1423 | 3.3715   |

5. Conclusion

In this paper, the CI based fusion method is applied in vehicle longitudinal and lateral velocity estimation. A vehicle dynamics model is established and the CI method is analysed. Finally, a the joint simulation of CarSim and MATLAB/Simulink is conducted and the results show the advantages of proposed method. Due to the limitation of the conditions, the road conditions selected in this paper are
typical. The following research work should select more complex conditions, such as fishhook condition, single line transfer condition, etc., to carry out simulation verification and real vehicle verification for the performance of each algorithm, so as to make the conclusion more representative.

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