

A Novel Method for Side Slip Angle Estimation of Omni-Directional Vehicles

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ABSTRACT

The omni-directional vehicle is an innovative vehicle, in which the in-wheel steering motor and in-wheel driving motor are integrated into each wheel of the vehicle so that each wheel can be independently controlled to have traction, braking, and turning motions to improve the vehicle's mobility, handling and stability. To realize good performance, various control strategies have been proposed, like the active steering control and the direct yaw moment control, where the accurate slip angle information is critical to these control strategies. However, in practice, the side slip angle is hard or expensive to be measured for a passenger vehicle, therefore, different estimation methods have been proposed in the literature. In this paper, a novel side slip angle estimation method is proposed for the omni-directional vehicle that has four independent steering motors. This method includes the estimation of total alignment torque and side slip angle, and only needs the measurements of steering angles and steering motor currents, which are available by using angle sensors and current sensors embedded with the in-wheel steering motors. Numerical simulations are used to validate the effectiveness of the proposed side slip angle estimation approach.

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INTRODUCTION

In modern society, traffic congestion is becoming a major problem in every metropolis, in particular, for the cities like Shanghai, Tokyo, and London, where the population is more than 10 million. According to Schrank, et al. [1], the cost of delays induced by the traffic congestion has risen from \$24 billion in 1982 to \$115 billion in 2009 in US, which becomes a serious economic cost. Verhoef and Rouwendal [2] stated that traffic congestion will have a significant impact on vehicle speed, traffic safety, and time cost. Shinar [3] also showed that driver aggression is increasing because of traffic congestion.

An innovative omni-directional vehicle has been suggested as a means of solving the traffic congestion problem because it has four independent steering wheels such that each wheel can have different steering angle to perform a small radius turn and thus save space. Omni-directional vehicles can also have enhanced stability and handling performance due to the available four wheels' driving, braking, and steering functions. The concept of omni-directional vehicle is initially referred to the research of advanced robotics, where many focused on the use of an omni-directional vehicle in situations [4,5,6] with slow speed and running on the smooth ground. In [7], the omni-

directional steering kinematic constraints were developed based on a simple four wheel vehicle dynamics model, and in [8], [9], and [10], a comprehensive vehicle dynamics model for the four wheel independent steering and four wheel independent driving road vehicle with relative high velocity was developed.

With the development of electric technology, the in-wheel driving and steering motors have been widely applied in the electric vehicles [11]. The omni-directional steering mechanism can be easily implemented in the electric vehicle with in-wheel steering motors and driving motors, and the comprehensive dynamics analysis of this kind of vehicle has been studied in [12].

Because the four wheel steering angles can be set differently for the omni-directional vehicle, the improved vehicle mobility, handling and stability performance can be realized and various control strategies have been proposed, like the active steering control and the direct yaw moment control, where the information about the side slip angle is critical to the performance of these control strategies. Due to the difficulty in directly measuring the side slip angle, accurate estimation of the side slip angle via available on-board sensors is becoming more important.

In the literature there are mainly three approaches to estimate the side slip angle. The method of integration of side slip rate which is available through the side slip rate sensor is affected by the error from sensors biases, road grade and bank angle [13]. The approach that designs the observer to estimate the side slip angle needs accurate information of vehicle velocity, road friction coefficient and some tire parameters, which are hard to be directly measured [14, 15, 16]. In addition, with the help of Global Positioning System (GPS) measurements, the side slip angle can be estimated. Ryu, et al., used the combination of GPS and Inertial Navigation System (INS) to accurately estimate the side slip angle [17]. However the GPS signal is not reliable due to the disturbance of satellite signal.

It is noted that using available and reliable signals to estimate the measured signal will be the best option for estimation. Motivated by this necessity, a new source of information from the in-wheel motor of electric vehicle, like the input current of steering motor or driving motor, has been considered by the researchers. Hsu et al. used the current of steering motor and pneumatic trail information to estimate the friction limit or lateral handling limit [18, 19, 20]. Xu et al. estimated the tire road friction coefficient and slip ratio by measuring the armature voltage and current of the in wheel driving motors [21]. However, no effort has been attempted to use the available motor current for the estimation of side slip angle so far, which motivates the current study.

This paper is organised as following. The vehicle dynamics model of omni-directional vehicle including the steering system model is introduced. Then a novel method is developed to estimate the total alignment torque and side slip angle. Finally simulation examples are used to validate the effectiveness of the proposed method.

VEHICLE DYNAMICS MODEL

In this paper, the four-wheel-independent-steering and four-wheel-independent-driving model as shown in Figure 1 is utilised to describe the dynamics behaviour and motion of the omni-directional vehicle [8][9][10][11][12]. This dynamics model will be regarded as a real vehicle and used to validate the performance of the proposed side slip angle estimator. The motion equations of this omni-directional vehicle are described as below.

Longitudinal motion:

$$m\dot{v}_x = mv_y r + F_{xfl} + F_{xfr} + F_{xrl} + F_{xrr} \quad (1)$$

Lateral motion:

$$m\dot{v}_y = -mv_x r + F_{yfl} + F_{yfr} + F_{yrl} + F_{yrr} \quad (2)$$

Yaw motion:

$$I_z \dot{r} = l_f (F_{yfl} + F_{yfr}) - l_r (F_{yrl} + F_{yrr}) + \frac{b_f}{2} (F_{xfl} - F_{xfr}) + \frac{b_r}{2} (F_{xrl} - F_{xrr}) \quad (3)$$

where v_x , v_y , r are the vehicle longitudinal velocity, lateral velocity, and yaw rate, respectively. F_{xfl} , F_{xfr} , F_{xrl} , F_{xrr} are the vehicle front left, front right, rear left and rear right longitudinal tire forces, and F_{yfl} , F_{yfr} , F_{yrl} , F_{yrr} are the vehicle front left, front right, rear left and rear right lateral tire forces. l_f and l_r are the front and rear wheel base lengths, while b_f and b_r are the front and rear track widths. I_z and m are the vehicle moment of inertia about yaw axis and vehicle mass.

The tire traction/brake force and side force are defined as F_{ti} , F_{si} , respectively, which can be related to the longitudinal and the lateral tire forces by the steering angle δ_i as:

$$\begin{aligned} F_{xi} &= F_{ti} \cos \delta_i - F_{si} \sin \delta_i, \\ F_{yi} &= F_{ti} \sin \delta_i + F_{si} \cos \delta_i \end{aligned} \quad (4)$$

where $i = fl, fr, rl, rr$, represent the front left, front right, rear left and rear right wheel, respectively.

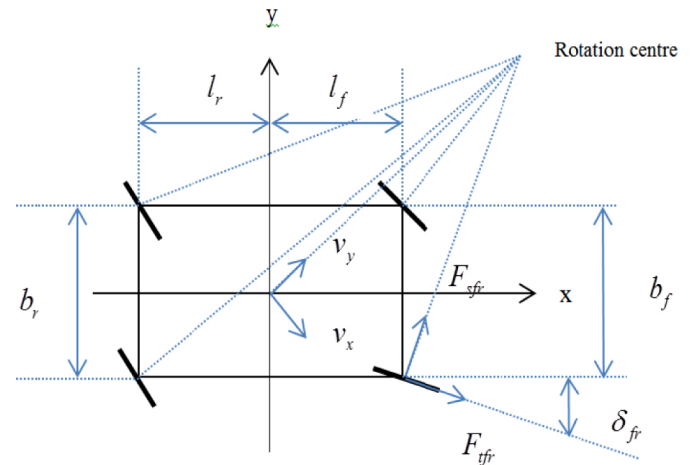


Figure 1. Omni-directional vehicle dynamics model

Vehicle Tire Model

The nonlinear Dugoff tire model is used in this paper, which is described by [22]:

$$\lambda_i = \frac{\mu F_{zi} \left[1 - \varepsilon_r u_i \sqrt{S_i^2 + \tan^2 \alpha_i} \right] (1 - S_i)}{2 \sqrt{C_i^2 S_i^2 + C_\alpha^2 \tan^2 \alpha_i}}$$

$$f(\lambda_i) = \begin{cases} \lambda_i (2 - \lambda_i) & \text{if } \lambda_i < 1 \\ 1 & \text{if } \lambda_i > 1 \end{cases}$$

$$F_{si} = \frac{C_\alpha \tan \alpha_i}{1 - S_i} f(\lambda_i)$$

$$F_{ti} = \frac{C_i S_i}{1 - S_i} f(\lambda_i)$$
(5)

where μ is the tire-road friction coefficient. F_{zi} is the vertical load of each wheel. C_i is the longitudinal cornering stiffness and C_α is the lateral cornering stiffness. S_i is the longitudinal slip and α_i is the lateral slip angle. ε_r is a constant value. u_i is the vehicle velocity component in the wheel plane which is defined for each wheel as

$$u_{fl} = \left(v_x + \frac{1}{2} b_f r \right) \cos \delta_{fl} + (v_y + l_f r) \sin \delta_{fl}$$

$$u_{fr} = \left(v_x - \frac{1}{2} b_f r \right) \cos \delta_{fr} + (v_y + l_f r) \sin \delta_{fr}$$

$$u_{rl} = \left(v_x + \frac{1}{2} b_r r \right) \cos \delta_{rl} - (l_r r - v_y) \sin \delta_{rl}$$

$$u_{rr} = \left(v_x - \frac{1}{2} b_r r \right) \cos \delta_{rr} - (l_r r - v_y) \sin \delta_{rr}$$
(6)

Traction/Brake Dynamics Model

As the omni-directional vehicle needs to be able to perform independent traction/brake motion for each wheel, each wheel will be integrated with the in-wheel traction/brake motor. Therefore, the wheel rotation dynamics can be described by the following equation [8]:

$$I_\omega \dot{\omega}_i = -R_\omega F_{xi} + T_i$$
(7)

where I_ω is the wheel moment of inertial and ω_i is the angular velocity of each wheel. R_ω is the wheel radius and T_i is the difference between the traction torque T_{di} and brake torque T_{bi} :

$$T_i = T_{di} - T_{bi}$$
(8)

The input of the wheel rotation dynamics model is the brake torque and the output of the model is the wheel angular velocity. According to the difference between the vehicle velocity and wheel angular velocity, the vehicle longitudinal slip S_i can be calculated as:

$$S_i = \frac{\omega R_\omega - v_x}{\max(v_x, \omega R_\omega)}$$
(9)

Steering Dynamics Model

Similarly, the omni-directional vehicle needs to be able to perform independent steering for each wheel such that the steering angle of each wheel can be different. Therefore, in-wheel steering motor needs to be installed at each wheel, and the steering dynamics model can be described as [19]:

$$J_{eff} \ddot{\delta}_i + b_{eff} \dot{\delta}_i = \tau_d + \tau_{act}$$
(10)

where b_{eff} is the steering damping coefficient and J_{eff} is the steering moment of inertial. τ_{act} is the torque generated by the steering motor. According to Hsu et al. [19], τ_{act} can be simplified as:

$$\tau_{act} = k_m i$$
(11)

where k_m is the armature constant and i is the motor current. τ_d is the total aligning moment of each wheel, which is described by the following equation:

$$\tau_d = -(t_m + t_p) F_{yi}$$
(12)

where t_m is the tire mechanical trail [23]. F_{yi} is the vehicle lateral force and can be obtained from the vehicle model. t_p is the pneumatic trail, which starts at t_{p0} and decreases to zero as slip angle increases.

$$t_p = t_{p0} - \text{sgn}(\alpha_i) \frac{t_{p0} C_a}{3 \mu F_{zi}} \tan(\alpha_i)$$
(13)

t_{p0} can be considered as the half length of the tire road contact length a [24].

NOVEL SIDE SLIP ANGLE ESTIMATOR

The proposed side slip angle estimator mainly includes two parts: the total aligning moment estimator and the side slip angle estimator as shown in Figure 2.

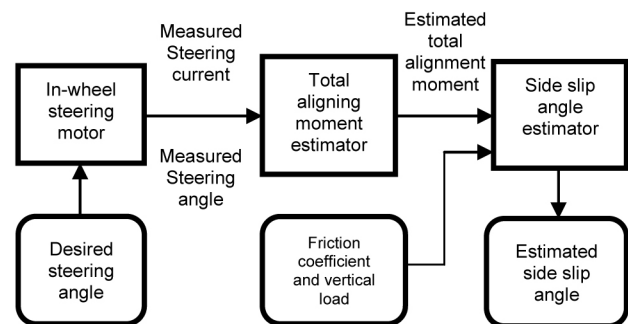


Figure 2. The working process of side slip angle estimator