Abstract: To improve the stability and controllability of vehicles, especially for wheel-driven field robot system, the friction between tire and road are investigated. For the commercial vehicle, various techniques including vehicle dynamic control, traction control, and anti-lock braking system have been developed and adopted. To accomplish these systems, the most important factor is to estimate the tire-road friction characteristics. Most of the tire-road friction estimation algorithms are based on the tire slip ratio and the tracking force obtained by a tire model. However, because the slip ratio and tracking force are difficult to be measured directly and defined strictly, additional estimation algorithms to get these values are required. Therefore, in this paper, in the view of traditional friction definition, we propose a tire-road friction estimation method that uses the traditional friction model. Also, to get normal force for the vehicle system, dynamic force distribution algorithm is suggested. The real car experimental result shows good performance of the proposed methodology.

1. INTRODUCTION

To enhance the vehicle safety, vehicle stability systems such as anti-lock brake system and vehicle dynamic control have been equipped. In addition to those stabilizing system, novel systems to increase driving ability and safety systems such as tire pressure monitoring system, traversibility analysis, and cruise control are researched in many ways. Especially for the autonomous unmanned field robot system, because there’s no driver to detect the road condition, these systems are more important than normal vehicles to recognize the driving conditions. Also, because there’s no danger to human, robot system is good platform to test these system performances.

In order to establish vehicle safety systems, tire-road friction is one of the most important parameter. The friction is used to predict running vehicle’s states that are essential to control safety system mentioned above. For the wheel-driven robot system, the estimated friction is also used to decide maximum available input torque to each driving wheel.

There are some difference between vehicle’s friction and general mechanical system’s friction. For vehicle, friction is positive factor to move a body by rolling. It means that if there’s no friction between tire and road, vehicle does not move to some position, it just slips on the same position. However, for general mechanical system such as hydraulic cylinder, the friction is negative factor to move mechanical system. Therefore, lubrication and bearings are equipped to reduce mechanical friction.

According to the some document about tire-road friction, the friction coefficient ranges 0.8~0.95 for the case of dry asphalt road. And many things can affect the tire-road friction such as road (asphalt, concrete, mud, etc...), road condition (dry, wet, icy, snowy, etc...), tire pressure, and so on. Most of the tire-road friction estimation methods are categorized as below.

(A) Estimation using slip ratio and tracking force generated by tire-model
(B) Sensing the road condition using optical or ultrasonic sensor
(C) Using vision sensor to see the road condition

(B) and (C) methods are good to recognize road condition. And if the controller knows exact value of tire-road friction of the various road, (B) and (C) methods are useful to get the friction value. However, because these sensors are expensive and require installing hardware, most of the related works are focused on (A) method.

To realize the vehicle friction estimation algorithm based on slip ratio, we have to measure tire’s slip-ratio and traction force. Usually, traction force is calculated using tire-model such as Pacejka’s model and Brush model. But, these tire models are defined with complex variables and these variables have to be obtained by experiment. Therefore, using only the tire model based method, to generate a general algorithm for friction estimation is very difficult. In order to overcome these difficulties, we propose novel methodology to estimate real-time tire-road friction using traditional simple friction model. Also, to calculate each road’s normal force, the vehicle dynamics are considered.

This paper is structured as follows: section 2 describes the suggested model of the tire-road friction. In Section 3, we show a vehicle dynamic model to estimate normal force using vehicle force distribution algorithm. Estimation algorithm is shown in section 4. In section 5, experimental setup and estimation results are shown. Concluding remarks are in Section 6.

2. TIRE-ROAD FRICTION MODEL

There are two types of friction model for mechanical system: static and dynamic. Coulomb, viscosity, and sticking are the characteristics of a static friction model. It is well summarized by Karnopp and Armstrong. And,
Fig. 1. The friction characteristics for a tire motion

Dahl’s model, Bristle model, and LuGre model are categorized as the dynamic friction model. The equations of the dynamic friction models are expressed by partially differential equations that come from the modeling of road or tire surface characteristics. Among dynamic friction models, the LuGre model is well matched to express the behavior of a tire-road friction. Although, differential equation model is a good friction model to simulate the characteristics of tire-road friction, because of the computation time and complex parameters, they make some difficulties to accomplish real time estimation.

The tire-road friction coefficient according to the tire’s motion is summarized as 2 cases in Fig. 1. Fig. 1(a) is a pure slip and no rolling motion and Fig. 1(b) is a rolling and no slip condition. To control robot’s path tracking exactly, Fig. 1(b) is an ideal driving condition. For the pure slip and no rolling case, the relationship between current friction and maximum friction is expressed as (1).

\[ F_x \geq F_f = \mu_{\text{max}} N \]  

where, \( \mu_{\text{max}} \) is a maximum friction coefficient of given tire-road, \( \mu_{\text{cur}} \) is a current friction coefficient while driving, \( F_x \) is a traction force, and \( F_f \) is a friction force.

Also, for the case of Fig. 1(a), the friction coefficient can be expressed as a Coulomb and viscosity, which is well known as a damping term, \( C \), in (2).

\[ J\dot{\theta} + C\dot{\theta} + K\theta = T \]

And for the case of pure rolling and no slip as in Fig. 1(b), the relationship between traction force and maximum friction coefficient is expressed as (3).

\[ \mu_{\text{cur}} N = F_x < F_f = \mu_{\text{max}} N \]

While driving, whether the tire motion is in the region of pure slip or pure rolling can be decided by slip ratio between tire and road. In real system, because the friction characteristics are shown as a complex behavior of slip and rolling, Slip ratio as well as friction coefficient is also important factor to estimate. Also, because the \( \mu_{\text{max}} \) is different from the tire and road condition such as asphalt, off road, dry, wet, icy, etc, current friction coefficient estimation is also required to define current road of a wheel-driven robot system.

We formulate the tire-road friction model using the traditional concept of static friction as (4)

\[ \mu(\lambda) = \frac{F_s}{N} \]

where \( F_s \) is the traction force and \( N \) is the normal force in Fig. 2, that is a simple schematic of wheel-driven robot system. It has 6 driving wheels and our friction model is adapted to each tire independently.

By the surveying of other researches, we assume that the friction, (4), is a function of slip ratio. Although, there’s a difficulty to get experimental data that enables to guess the relationship between slip ratio and friction, the concept of relationship between slip ratio and friction is very important to estimate maximum friction coefficient while normal driving. It is because, in a normal driving condition, rolling effect is bigger than slip effect, we can not observe maximum friction coefficient until braking.

Because (4) is a function of only normal force and traction force, it is relatively simple to accomplish real time estimation. Generally, the tire-road friction is formulated as an equation of slip ratio, camber angle, and normal force. Fig. 3 shows the single tire model of a vehicle. And assume that Fig. 3 is a simple model of a free rolling driven wheel. For that system, the slip ratio is defined as

\[ \lambda = \frac{R\omega - V_s}{R\omega} \]

where, \( R \) is a radius of a tire, \( V_s \) is the longitudinal velocity, \( \omega \) is the driven wheel angular velocity. An encoder measures the wheel angular velocity and the longitudinal velocity is assumed to be equal to the car velocity.

Fig. 2. A vehicle model with friction (1/4 model).

Fig. 3. A simple friction model of the free rolling tire.
Driving wheel dynamics are expressed as (6).
\[ J_w \ddot{\omega}_w = T_m - F_x r_w = T_m - \mu(\lambda)r_w N \quad (6) \]

Finally, friction estimation model for a tire can be obtained by (7).
\[ \mu(\lambda) = \frac{T_m - J_w \ddot{\omega}_w}{r_w N} \quad (7) \]

where, \( T_m = K_m I_m \) is a wheel driving torque that is obtained by input current to the driving motor. The difficulty to solve (4) or (7) is occurred to get normal force.

3. VEHICLE FORCE DISTRIBUTION ALGORITHM

For the commercial vehicle system, normal force estimation is other topic to conquered. The wheel-driven robot system of this paper has a 6-DOF sensor to monitor robot body states. Therefore, we suggest vehicle force distribution algorithm using this sensor and 6 wheeled body dynamics. Fig. 4 shows a free body diagram for our system.

The main idea is that the forces acting on the tire’s normal direction are occurred only by gravity, heave force, roll moment, and pitch moment, independently. So, while driving, the normal force is the sum of these forces altogether. If the robot body is on the plat surface, then only the normal force from gravity is acting on tire. If only heave force occurred, then, the normal force will be \( \frac{1}{6} Mg + \frac{1}{6} M \ddot{z} \), the sum of gravity and have force in Fig. 4 (b). And if there’s a positive direction roll moment in Fig. 4 (c), then force, \( \frac{J_{roll} \dot{\theta}_{roll}}{d_r} \), are added to right side of robot body and subtracted to left side of robot body. The separated forces acting on left and right side are equivalently distributed 3 wheels on each side of which amount is \( \frac{1}{3} J_{roll} \dot{\theta}_{roll} \). In the same way, if there’s a pitch moment, additional force, \( \frac{1}{2} \frac{J_{pitch} \dot{\theta}_{pitch}}{l_f} \), of pitch moment is added to front side of robot body and subtracted to rear side of robot body. Regarding the kinematics of robot body, \( F_{z_{nr}} \) and \( F_{z_{ml}} \) are attached to the center of robot body’s longitudinal \( x \)-direction that is the same position of the 6-DOF sensor. Summarized equations are (8).

\[ F_{z_{nr}} = \frac{1}{6} Mg + \frac{1}{6} M \ddot{z} + \frac{1}{3} \frac{J_{roll} \dot{\theta}_{roll}}{d_r} + \frac{1}{2} \frac{J_{pitch} \dot{\theta}_{pitch}}{l_f} \]

Fig. 4. A free body diagram to distribute normal force algorithm: (a) forces on the plat surface, (b) heave force (c) rolling moment, and (d) pitch moment
Finally the normal force on each tire is obtained and used to estimate friction coefficient. Because this algorithm is required a 6-DOF sensor, it has a limit to adapt to other commercial vehicle system. However, in some researches of suspension control, similar methodology of the force distribution algorithm to estimate normal force, using suspension displacement sensor, is available.

4. ESTIMATION

Fig. 5 shows a block diagram to estimate tire-road friction and maximum friction coefficient. To get normal force on each tire, sensor and force distribution method are used in section 3. Also, dynamics of arm actuator and suspension are applied to increase the reliability. Driving torque is obtained by input current to motor and angular velocity is measured from motor encoder. And then, using (4) or (7), current friction can be obtained.

For our wheel driven robot system, because a 6-DOF sensor can measure the traction force, we are going to use simplified estimation method using (4).

3 cases of estimation algorithm are investigated in this paper to compare the performance of estimation results as below:

Case A. Numerical calculation

\[ \hat{\mu} = \frac{F_x}{F_N} \]  

(9)

Case B. Low pass filter

\[ \hat{\mu} = \frac{4}{s^2 + 2 \cdot 0.55 \cdot 2 \cdot s + 4} \cdot \frac{F_x}{F_N} \]  

(10)

Case C. Gradient method

\[ \dot{\theta} = -u \cdot \hat{\theta} + u \cdot y \]  

(11)

where, \( \theta = \mu \), \( u = F_y = N \), and \( y = F_x \).

Because the (11) algorithm comes from a solution of minimization problem, \( J = \frac{1}{2} (y - \hat{y})^2 \), the stability of gradient method are easily verified. Also, the convergence of \( \hat{\theta} \) can be proved as below.

Let \( \phi(t) = \hat{\theta}(t) - \theta \), then,

\[ \dot{\phi}(t) = \hat{\theta}(t) = -u^2(t)\phi(t) \]  

(12)

Regarding the linear time varying system of the form \( \dot{x} = A(t)x \), the solution of (12) is

\[ \phi(t) = \phi(t_0)e^{\int_{t_0}^{t} u^2(\sigma)d\sigma} \]  

(13)

Concluding, \( \phi(t) \rightarrow 0 \) as \( t \rightarrow \infty \) if and only if \( \int_{t_0}^{t} u^2(\sigma)d\sigma \rightarrow \infty \) as \( t \rightarrow \infty \). It shows that \( \hat{\theta}(t) \rightarrow \theta \).

Finally, to get the maximum friction coefficient while driving, we utilize the database from experiments that contains the relationship between slip ratio and friction coefficient like Fig. 6. It contains the relationship between slip ratio and friction coefficient for a known sampled driving condition. If we calculate the slip ratio and estimate current friction coefficient, we can guess road condition as a friction coefficient value. And then, maximum value can be defined. Although there are many difficulties to choose sample road and test many times, experiment based method is the only reliable way to estimate tire friction coefficient, because until braking, the maximum friction can not be measured.
5. EXPERIMENTAL RESULTS

To prove the validity of the suggested concept of tire-road friction while normal driving, we had conducted vehicle tests on some sampled roads. Fig. 7 shows the tire and sensors. To obtain exact forces on each tire, we setup the SWIFT sensor that measures forces on the tire ($F_x$, $F_y$, $F_z$), moments of wheel ($M_x$, $M_y$, $M_z$) and angular velocity for each tire, directly. And an optical vision sensor to get the car velocity is attached in the rear side of the vehicle. To get maximum friction characteristics as well as current friction coefficient, after normal driving with 60KPH speed, emergency braking was done.

The measured forces are used to calculate (9), (10), and (11) to compare estimation performance. The results are shown in Fig. 8. For a constant speed driving condition, the slip ratio is 0.02–0.025 and friction coefficient is 0.2–0.3. And for the condition of emergency braking, the slip ratio is 0.8–0.9 and the friction coefficient is 1. This result shows that, while normal driving condition, the friction force varies with very small quantity because of the low slip ratio. It means that tire moves only by rolling with very little slip, while normal driving. However if emergent braking condition, as the slip becomes bigger and slip ratio becomes higher, the maximum tire-road friction coefficient becomes also high value that is pure friction coefficient of tire on this road. If the road changed to icy or wet condition, friction coefficient can be observed low value. By this experiment, that maximum friction coefficient on dry asphalt is 0.9–1.0 which is similar to other researches based on a tire-model. Therefore our simplified model is good to adapt wheel-driven robot system.

Also, from the comparison results among suggested estimator, there’s not much difference in the view of performance. However, to guarantee the stability of estimator and to reduce noise effect, gradient method is better than others.

In order to prove the force distribution algorithm to get the normal force on each tire, more experiment will be required and be shown in future work.

Fig. 7. Experiment setup for vehicle test: SWIFT sensor.

Fig. 8. Experimental results while driving and braking from 60KPH to 0KPH on dry asphalt: (a) car speed profile, (b) measured traction force (lower) and normal force (upper), (c) slip ratio and friction coefficient profile, and (d) friction estimation results.
6. CONCLUSION

In this paper, we suggest a simplified tire-road friction coefficient estimation method for a wheel-driven robot system using the traditional concept of friction model. Because the proposed friction model is expressed with simple equations, it enables to accomplish real-time friction estimation. Also to find tire normal force, we explain the force distribution algorithm. By the experimental results, we can decide that the proposed idea makes valid performance to be applied to real vehicle systems. This algorithm can be applied to our robot system that is equipped with a 6-D.O.F sensor at the gravity center of our autonomous vehicle.

However, maximum tire-road friction estimation using numerical method, while normal driving, will be discussed on future work.

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