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Research paper

Determination of tire dynamic properties: Application to an agricultural vehicle

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ABSTRACT

This paper describes the methods for estimating a vehicle's dynamic parameters using a Global Positioning System implementing a Real Time Kinematic scheme (RTK-GPS) and an Inertial Measurement Unit (IMU). An RTK-GPS system and an IMU are used to estimate the vehicle's body sideslip angle and then obtain the relation between the tire's lateral forces and slip angles, and also the tire's cornering stiffness. In order to compare the experimental results two vehicle models are described; the bicycle geometric model and the bicycle dynamic model. The method of least squares was applied to the experimental data in order to obtain mathematical expressions that account for the nonlinearities of the system. It is shown that the measurements performed can be used to estimate the tire sideslip and the tire cornering stiffness. The experimental results are consistent to the predictions made by the models, which verifies the potential of this method to determine a nonlinear mathematical model.

1. Introduction

Aging and population decline have been progressing in Japanese society, and this tendency is more significantly seen in rural areas than in urban areas (Hashimoto et al., 2001). In order to protect food production in Japan, encouraging the development of technologies such as autonomous guidance systems for agricultural vehicles seems to be an effective strategy to deal with the dwindling farming labor force, in addition to increase production efficiency and safer operation (Kondo et al., 2011).

Agricultural vehicles, such as tractors, are designed to provide some drivability over fields and off-road surfaces. The counterpart is their propensity to roll over the ground. As a result, the development of on-board systems preventing agricultural machinery from rollover situations is encouraged. Several solutions (Anderson and Bevly, 2005) have already been proposed for road vehicles: steering and braking control or Electronic Stability Program (ESP) systems are some examples.

Information on the state of the vehicle such as its location, and tire parameters like the cornering stiffness can be estimated using a Global Positioning System (GPS). Methods using a GPS and an Inertial Measurement Unit (IMU) integration have been developed (Bevly et al., 2006a) to predict critical tire parameters in the limits of handling. Previously GPS/IMU solutions (Sienel, 1997) have been shown to estimate a vehicle's sideslip angle and tire slip angle. Using these estimates, the tire cornering stiffness can be estimated for the linear region of the tire (Bouton et al., 2007).

The tire's operating range is divided into three regions: linear, transitional and sliding. A linear tire model can be used to predict the properties in the linear region, but generally cannot be employed in transitional and sliding regions since they are nonlinear (Baffet et al., 2006).

Linear tire models that consider only the linear region of the tire's operating range have been successfully implemented in road vehicles. However, since road vehicles are supposed to move on high grip ground, such systems consider only pseudo-sliding phenomenon with constant parameters (Pepy et al., 2006). Most of active devices focused on vehicle stability concerns road cars and cannot be applied satisfactorily in an off-road context, as in path planning of autonomous agricultural vehicles like tractors and utility vehicles (Noguchi et al., 1998); since the variability and nonlinearities of the tire/ground contact are often neglected.

For off road vehicles, the nonlinearities of the interaction between the tires and the road surface gives as result a hysteresis loop in the linear region of the tire's operating range. For this reason, it is

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very complicated to model the lateral tire forces due to the nonlinear dependence of the lateral forces on several parameters, such as longitudinal slip, sideslip angle, normal load, camber angle, tire pressure, wear, and road surface characteristics (Koo et al., 2004). Even thought, the nonlinearities of the interaction between the tires and the road surface should not be ignored for off road vehicles. Therefore, there is a necessity of a precise vehicle model that does not depend on the parameters mentioned above; namely a "non-parametric" vehicle model, that fills the gaps existing in current models applied to autonomous vehicle development.

This work aims to expand the tire's dynamic properties research considering the nonlinear behavior of the tire by estimating the lateral force and tire slip angle over the tire's entire operating range (linear, transitional and sliding). We are interested into obtain a non-parametric vehicle model using mathematical expressions that account for the sliding nonlinear behavior in the vehicle dynamics. This tire information could be used to improve automatic steering controller systems applied to agricultural machinery.

2. Materials and methods

2.1. Test equipment

The test vehicle used is a conventional utility vehicle (John Deere, E-Gator) equipped with an on-board computer that logs the data from all the sensors. The RTK-GPS (Trimble, MS-750) provides the position, direction of travel and speed of the vehicle. The low latency configuration (update rate: 10 Hz, latency: 0.02 s, data link: 9600 Baud) was chosen for the RTK mode. This configuration provides a horizontal position accuracy of 2 cm + 2 ppm, a vertical position accuracy of 3 cm + 2 ppm and a speed accuracy of 0.16 kph. The RTK correction signal was obtained using a Virtual Reference System via an Internet Service Provider connected to the on-board computer that logs the data from the GPS receiver. The IMU (Vectornav, VN-100) provides the yaw rate (dynamic accuracy: 1.0 deg. RMS), heading (dynamic accuracy: 2.0 deg. RMS) and lateral acceleration (alignment error: ±0.05 deg., noise density: <0.14 mG/$\sqrt{\text{Hz}}$) readings. Due to the short duration of the test, the drift effects in the IMU can be neglected. Both the IMU and the GPS antenna are placed in the vehicle's center of gravity. A 10 kΩ Potentiometer (Midori Precisions, CPP-60, linearity ±0.05%) attached to the kingpin of one of the steering wheels provides the steering angle (alignment error: ±3.2 deg.). Fig. 1 shows the experimental vehicle and the sensors equipped for the experiment.

Both the GPS and the IMU have a direct serial port connection to the on-board computer. The potentiometer was connected to a microcontroller in order to process its analog signal. The microcontroller communicates with the on-board computer by serial port connection. The speed of all serial connections was 115200 bps. However, since the GPS NMEA data frames, the IMU data frames and the microcontroller data frames have different lengths, all the data was synchronized using the computer's time stamp. The result was a measurement update rate of 10 Hz for all the sensors, in order to make the IMU and potentiometer measurements coincide with the GPS measurement.

2.2. Vehicle models

Fig. 2 shows the typical configuration of the bicycle model for a four wheeled vehicle (Wong, 1993). The input of the system is given by the vehicle's velocity V and the steering angle δ. The output of the system is given by the vehicle's body sideslip angle β and the yaw rate ω.

2.2.1. Bicycle geometric model

We are interested into obtaining the trigonometrical relationships between the input δ and the outputs β and ω. As depicted on Fig. 2 taking the distance from the center of gravity (CG) to the front axle a, and the distance from the CG to the rear axle b; and due to the big difference between the steering angle δ and the turning radius ρ, we can make the approximation shown in Eq. (1) assuming that δ is very small ($\tan\delta \approx \delta$):

$$\tan\delta = \frac{a+b}{\rho}, \quad \delta = \frac{a+b}{\rho}, \quad \rho = \frac{a+b}{\delta} \tag{1}$$

Also, taking the distance from the CG to the rear axle b, and by assuming small angles ($\tan\beta \approx \beta$) we can make the approximation shown in Eq. (2):

$$\tan\beta = \frac{b}{\rho}, \quad \beta = \frac{b}{\rho}, \quad \beta = \frac{b}{\frac{a+b}{\delta}}, \quad \beta = \frac{b}{a+b}\delta \tag{2}$$

Fig. 3 shows the relation between the movement of the CG and the yaw rate ω.

Due to the big difference between ω and the turning radius ρ, we can make the approximation shown in Eq. (3):

$$V = \rho \sin\omega, \quad V = \rho\omega, \quad \omega = \frac{V}{\rho}, \quad \omega = \frac{V\delta}{a+b} \tag{3}$$

2.2.2. Bicycle dynamic model

In this model, we need to consider the sliding in the vehicle's lateral dynamics (Liljedahl et al., 1989). The most common model (Kim, 2009) is given Eq. (4):

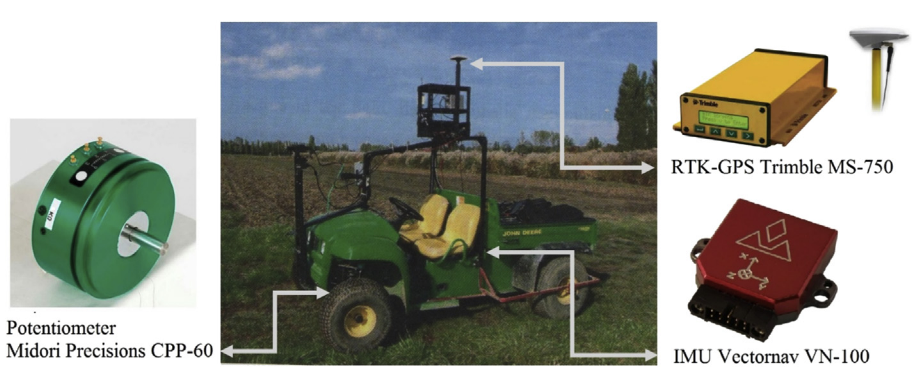

Fig. 1. Experimental vehicle and equipped sensors.