ARTICLE IN PRESS

Engineering in Agriculture, Environment and Food xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Engineering in Agriculture, Environment and Food

journal homepage: www.elsevier.com/locate/eaef

Alternative method to model an agricultural vehicle's tire parameters

Ricardo Ospina[a], Noboru Noguchi[b,*]

[a] Graduate School of Agriculture, Hokkaido University, Kita-9, Nishi-9, Kita-Ku, Sapporo, Hokkaido, 060-8589, Japan
[b] Research Faculty of Agriculture, Hokkaido University, Kita-9, Nishi-9, Kita-Ku, Sapporo, Hokkaido, 060-8589, Japan

ARTICLE INFO

Keywords:
Agricultural vehicle
RTK-GPS
IMU
Lateral force
Tire slip angle
Nonlinear model
Soil moisture content
Cone index
Inflation pressure
Normal load

ABSTRACT

This paper introduces an alternative method to model the tire dynamic parameters of an agricultural vehicle from experimental data sets without the use of conventional test equipment. A Global Positioning System implementing a Real Time Kinematic scheme (RTK-GPS) and an Inertial Measurement Unit (IMU) are used to estimate the vehicle's body sideslip angle and to establish the relation between the tire's lateral forces and slip angles for different soil conditions; in terms of soil moisture content and cone index. To validate the method introduced in this paper, the results obtained from the experimental data sets were compared with an empirical modeling method; which uses a particular form of the relationship between lateral force, normal force and slip angle expressed as an exponential function. Results show that the method introduced in this paper can give a more accurate description of the relation between the tire's lateral forces and slip angles. This knowledge can be applied to improve automatic steering controller systems.

1. Introduction

Understating the interaction between the wheel and the ground is essential to study the performance and handling behavior of agricultural vehicles (Raheman and Singh, 2004). In order to perform vehicle motion analysis, a model of the interaction between the traveling tire and the ground surface is necessary. Describing the behavior of the lateral forces acting on a vehicle's tires through the use of a mathematical model make it possible to identify the directional stability of the vehicle during steering maneuvers. This knowledge can be applied to vehicle design in order to improve traction efficiency, enhance handling, and improve motion dynamic stability and steerability.

The interaction model or the tire model needs to adequately obtain the forces exerted on the tire based on the ground characteristics, besides being simple and easy to use (Yamakawa et al., 2014). Simple-to-use wheel–ground interaction models are also applicable to the computation of the necessary forces on the wheels for unmanned agricultural vehicle systems designed to perform agricultural labor.

However, there are several problems associated with the measurement of off-road tires (Crolla and El-Razaz, 1987), particularly in measuring and controlling the soil conditions. This has led some workers to use the controlled environment of a soil bin and conventional test equipment (Krick, 1973; Gee-Clough and Sommer, 1981) with the hope of obtaining repeatable, accurate results; whereas using more realistic field surfaces demands that many repeated runs must be carried out in order to obtain statistical accuracy.

This research introduces a strategy to avoid these measurements problems; it is shown how to construct a simple tire model for an agricultural vehicle traveling on soil by using an alternative measuring method. Information on the state of a vehicle such as its location and tire parameters can be measured by using a Global Positioning System (GPS). Methods using a GPS and an Inertial Measurement Unit (IMU) integration have been developed to predict critical tire parameters in the limits of handling for on-road vehicles (Bevly et al., 2006a,b). Previous GPS/IMU solutions have been shown to estimate a vehicle's lateral force, body sideslip angle and tire slip angle (Sienel, 1997). Related work (Ospina and Noguchi, 2016) has shown how these GPS/IMU solutions can be applied to agricultural vehicles as well; making it possible to estimate the tire dynamic properties of the vehicle and to obtain mathematical expressions that account for the sliding nonlinear behavior in the vehicle dynamics.

For this research, data sets were measured from experimental runs consisting in a vehicle traveling on soil; the purpose of these experimental runs was to find out the relation between different soil conditions (moisture content MC and cone index CI) and different vehicle conditions (normal load Fz and tire's inflation pressure P). Also, the experimental runs helped to establish how the soil and vehicle conditions affect the tire's lateral force and slip angle.

Finally, in order to validate the alternative method introduced in this paper, results were compared with a well-known empirical modeling method (Crolla and El-Razaz, 1987). Such method uses a particular form of the relationship between lateral force, normal force and

---

* Corresponding author.
E-mail address: noguchi@bpe.agr.hokudai.ac.jp (N. Noguchi).

http://dx.doi.org/10.1016/j.eaef.2017.10.001
Received 12 June 2016; Received in revised form 27 June 2017; Accepted 3 October 2017

Please cite this article as: Ospina, R., Engineering in Agriculture, Environment and Food (2017), http://dx.doi.org/10.1016/j.eaef.2017.10.001

slip angle expressed as an exponential function. The restrictions and limitations concerning this empirical method of modeling are also pointed out. Results show that the method introduced in this paper can give a more accurate description of the relation between the tire's lateral forces and slip angles, expressed as a hysteresis loop.

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) 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/√Hz) readings. Due to the short duration of the tests, which is 30 s for each run, 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, effective electrical travel 355°, independent linearity ± 0.05%, total resistance 10 kΩ, shaft diameter Φ62 mm, rated dissipation 4 W) attached to the kingpin of one of the steering wheels provides the steering angle (alignment error: ± 3.2 deg.). This potentiometer was chosen instead of a rotary encoder due to its high linearity over a limited rotation range and easy programming. 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.

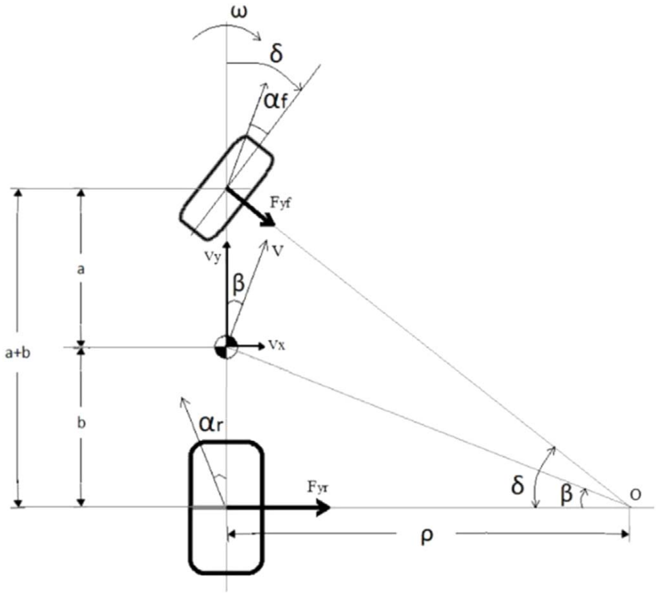

Fig. 2. Schematic of the bicycle model.

2.2. Bicycle model

The most simplified vehicle dynamic model is the bicycle model, describing the lateral and yaw motions. This model assumes symmetry in the dynamic behavior between right and left tires (Sienel, 1997). The reason for using this model relies in its simplicity; it is not necessary to describe the lateral forces effects on each one of the four tires of the vehicle because they are parallel, therefore the resulting lateral forces are in the same direction and can be described for the front and rear axle. This model is particularly useful to describe the lateral dynamic behavior of the vehicle in a simple way; ignoring longitudinal and vertical movements (Baffet et al., 2006).

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.

Where.

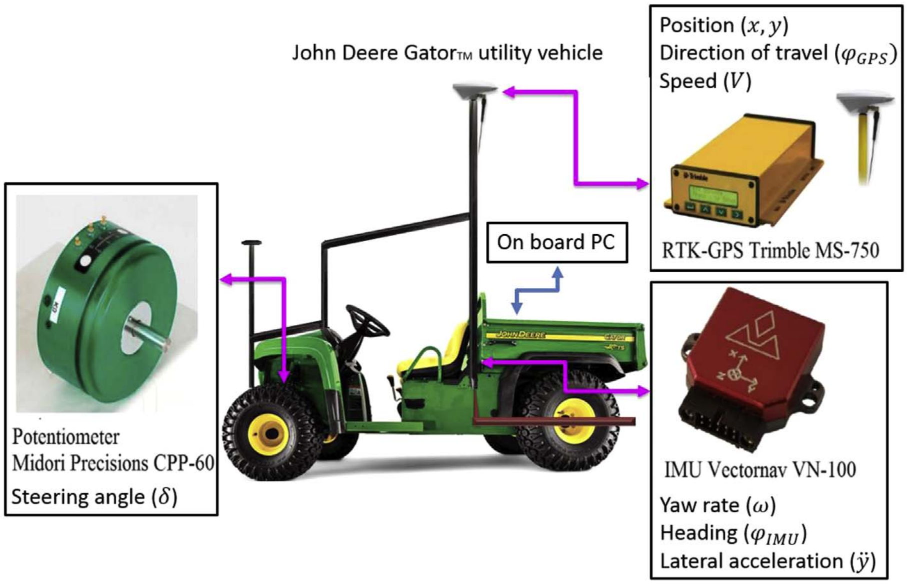

Fig. 1. Experimental vehicle and equipped sensors.