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Nonlinear modeling and identification of an autonomous tractor–trailer system

Erkan Kayacan [a,*], Erdal Kayacan [b], Herman Ramon [a], Wouter Saeys [a]

[a] Department of Biosystems (BIOSYST), Division of Mechatronics, Biostatistics and Sensors (MeBioS), University of Leuven (KU Leuven), Kasteelpark Arenberg 30, 3001 Leuven, Belgium
[b] School of Mechanical & Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

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ABSTRACT

This paper presents the nonlinear modeling of the yaw and longitudinal dynamics of a tractor–trailer system. First, the yaw dynamic models of both the tractor and trailer are derived considering the lateral forces and side-slip angles. In order to be able to calculate the side-slips precisely, the relaxation length approach is preferred. Since the obtained yaw dynamic models are nonlinear, a constrained nonlinear optimization problem is formulated for the parameter estimation. Second, the longitudinal dynamic model for the system is derived based-on the static and dynamic responses. The static model consist of two inputs, the hydrostat position and the diesel engine speed, and one output, the longitudinal speed of the system. Afterwards, a dynamic model is proposed to define the dynamic effect between the output of the static model and the actual longitudinal speed. Third, the mathematical models of the steering mechanisms both for the tractor and trailer are identified. Consequently, a complete nonlinear dynamic model for the tractor–trailer system is obtained. The overall resulting model is thought to provide useful physical insight on such a complex mechatronic system, and can serve as the input for model based controller design.

1. Introduction

Automation of agricultural production machines is thought to be up-and-coming for farmers as it can lighten the job of the operator, especially now that more and more actions in addition to driving the vehicle, are asked from him. For instance, the operation of the trailer during tillage and planting can be mentioned as an additional action for an operator. Even in a single-task operation, in addition to time pressure, operators have to deal with challenging working conditions such as high temperature, and dust, in the field. In such cases, the accuracy and efficiency of the planting or harvesting decrease as he gets tired and loses his concentration over time. As a solution to the aforementioned problems, automatic guidance of agricultural production machines has been proposed benefitting from several advanced control algorithms to improve the efficiency and productivity of various field operations such as tillage, planting and harvesting.

Automatic guidance of agricultural production machines not only improves the accuracy of the field operations but also reduces the overlap resulting in less crop damage, compaction and rutting (Karkee and Steward, 2010). Without loss of generality, there exist two basic methods for the realization of off-road vehicle automatic guidance: local positioning systems (vision or laser-based sensors) and global positioning systems (GPSs). Whereas mostly the introductory applications in the 1970s relied on the former (Julian, 1971; Reid and Searcy, 1987), recent implementations in the 2000s have started using the latter method (Bell, 2000; Kraus et al., 2013) in which highly accurate GPSs are used inspired by several successful applications in the navigation of airplanes and marine vehicles. As a local positioning system, although the vision-based systems are relatively cheap to implement, they have major disadvantages in outdoor environments, e.g. to be very sensitive to light conditions (Hiremath et al., 2014). Real-time kinematic (RTK) GPSs have several advantages over local positioning systems such as the availability of the absolute position of the vehicle instead of the local coordinates, world-wide availability, ease of use as well as some disadvantages such as its relatively high cost, and the sensitivity to the presence of trees and buildings. In this investigation, two GPS antennas are used to determine the global positions of both the tractor and trailer.

There are two factors which determine the performance of a model-based controller: accomplishment of the model and well-tuning of the controller coefficients. So, a prerequisite for an

* Corresponding author. Tel.: +32 16 377089; fax: +32 16 321994.
E-mail addresses: erkan.kayacan@biw.kuleuven.be (E. Kayacan), erdal@ntu.edu.sg (E. Kayacan), herman.ramon@biw.kuleuven.be (H. Ramon), wouter.saeys@biw.kuleuven.be (W. Saeys).

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accurate performance of such controllers is the achievement of a precise mathematical model of the system to be controlled. Several researchers have investigated the automatic guidance of the agricultural tractors by using model-based controllers (Kraus et al., 2013; Backman et al., 2010, 2012; Matveev et al., 2013). The common point of the studies mentioned up to now is that all these controllers rely on the kinematic tractor and trailer models which do not include the dynamics of the system. From the implementation point of view, these models are easy and simple to be dealt with. However, since the kinematic models neglect the important dynamics, the performance of the designed guidance systems based-on such models is limited (Bevly et al., 2002). The reason for this poor performance is that the equipments to automate tractor–trailer systems are highly nonlinear; they include saturation and dead-band regions. In addition to their complex dynamics, these machines have to work under highly uncertain and variable soil conditions. In such cases, the model-based controllers, especially linear time invariant controllers, have to be tuned very conservatively. By this conservative tuning, robustness of the controller is obtained at the price of performance. On the other hand, to achieve an acceptable accuracy in a field operation, 1.5 cm guidance accuracy is needed (Rekow et al., 2001). The achievement of such a strict control specification under uncertain working environments with highly nonlinear vehicle and implement dynamics requires of a better understanding of the dynamic behavior of the systems to be controlled (Karkee and Steward, 2010). To promote the design of better model-based controllers, a dynamic model of a tractor–trailer system has been elaborated in this study. Particular attention is given to the analysis of the dynamics at longitudinal speeds within the range of 0–2 m/s where most of the field operations are realized except some special operations such a spraying.

In this study, a tricycle model, in which it is assumed that the lateral forces on the left and right wheels are equal and can be summed, is used to derive the equations of motion of the tractor–trailer system. The tricycle dynamic model in this investigation is similar to the ones in (Karkee and Steward, 2010; Feng et al., 2005). However, the main contribution of the proposed model in this study is that there are no small steering angle assumptions for the tractor, trailer and hitch point angle resulting in a fact that the overall system is capable of following curvilinear trajectories. These assumptions result in a nonlinear tricycle dynamic model for the tractor–trailer system.

The body of the paper contains six sections: In Section 2, the real-time system description is given. In Section 3, the dynamic equations of the autonomous tractor–trailer system are presented. The longitudinal dynamics model is given in Section 4, and the steering mechanism dynamics models for the tractor and implement are presented in Section 5. Finally, some conclusions are drawn in Section 6.

2. Experimental set-up description

The global aim of the real-time experiments in this investigation is to be able to model and identify the small scale agricultural tractor–trailer system shown in Fig. 1. Two GPS antennas are located straight up the center of the tractor rear axle and the center of the trailer to provide highly accurate positional information. They are connected to a Septentrio AsteRx2eH RTK-DGPS receiver (Septentrio Satellite Navigation NV, Leuven, Belgium) with a specified position accuracy of 2 cm at a 5-Hz sampling frequency. The Flepos network supplies the RTK correction signals via internet by using a *Digi Connect WAN 3G* modem.

The GPS receiver and the internet modem are connected to a real time operating system (PXI platform, National Instruments

Fig. 1. The tractor–trailer system.

Corporation, Austin, TX, USA) through an RS232 serial communication. The PXI system acquires the steering angles and the GPS data, and controls the tractor–trailer system by sending messages to actuators. A laptop connected to the PXI system by WiFi functions as the user interface of the autonomous tractor. The algorithms are implemented in *LabVIEW*™ version 2011 (National Instruments, Austin, TX, USA). They are executed in real time on the PXI and updated at a rate of 5-Hz.

The angle of the front wheels of the tractor is measured using a potentiometer mounted on the front axle yielding an angle measurement resolution of 1°. The position of the electro-hydraulic valve on the trailer is measured by using an inductive sensor with 1° precision. The longitudinal speed of the tractor is controlled by using an electro-mechanic valve. The wheel speed control system consists of a cascade of two PID controllers. The proportional-derivative-integral (PID) controllers in outer closed-loop and inner closed-loop are generating the desired pedal position with respect to the speed of the tractor and the voltage for the spindle actuator (LINAK A/S, Denmark) for the pedal position, respectively. In Fig. 2, the spindle actuator for the hydrostat position (Fig. 2(a)), the potentiometer for the steering angle of the tractor (Fig. 2(b)) and the electro-hydraulic valve for the trailer (Fig. 2(c)) respectively are shown. The rpm of the diesel engine has been measured by using a hall effect sensor (Hamlin, USA) which is connected to the shaft between the diesel engine and oil pump.

3. Modeling of the tractor–trailer yaw dynamics

As the driving speeds of the tractor–trailer combination is rather limited, it is reasonable to assume that the lateral forces on the left and right wheels are equal and can be summed. Therefore, the tractor–trailer system is modeled in 2D as a tricycle system (Karkee and Steward, 2010; Feng et al., 2005), which is schematically illustrated in Fig. 3. However, in contrast to previous studies no assumptions are made with respect to the size of the steering angles in order to also accurately describe the system behavior on curvilinear trajectories. This results in a non-linear dynamic model of the tractor–trailer system.

The tractor and trailer rigid bodies are mechanically linked to each other by the drawbar. There are two revolute joints which connect the drawbar to the tractor and the drawbar to the trailer as illustrated in Fig. 3. The dynamics of the drawbar are negligible due to its low weight, such that it can be assumed that there is only one revolute joint in the formulation. Therefore, only one revolute joint is included in the rigid multibody model.