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Towards agrobots: Identification of the yaw dynamics and trajectory tracking of an autonomous tractor

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

[a] Delft Center for Systems and Control, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands
[b] School of Mechanical & Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
[c] Department of Biosystems, Division of Mechatronics, Biostatistics and Sensors, University of Leuven (KU Leuven), Kasteelpark Arenberg 30, 3001 Leuven, Belgium

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ABSTRACT

More efficient agricultural machinery is needed as agricultural areas become more limited and energy and labor costs increase. To increase their efficiency, trajectory tracking problem of an autonomous tractor, as an agricultural production machine, has been investigated in this study. As a widely used model-based approach, model predictive control is preferred in this paper to control the yaw dynamics of the tractor which can deal with the constraints on the states and the actuators in a system. The yaw dynamics is identified by using nonlinear least squares frequency domain system identification. The speed is controlled by a proportional–integral–derivative controller and a kinematic trajectory controller is used to calculate the desired speed and the desired yaw rate signals for the subsystems in order to minimize the tracking errors in both the longitudinal and transversal directions. The experimental results show the accuracy and the efficiency of the proposed control scheme in which the euclidean error is below 40 cm for time-based straight line trajectories and 60 cm for time-based curved line trajectories, respectively.

1. Introduction

One of the most important tasks in tractor operation is the accurate steering during field operations, e.g. accurate trajectory following during tillage, to avoid damaging the crop or planting when there is no crop yet. Besides, the rows must be parallel, and the distance differences between them must be equal with respect to each other during the planting. Moreover, the tractor has to cover the full field without overlap during other operations. However, the steering accuracy decreases when the operator gets tired or does more actions than driving the tractor like operating/controlling the implements. In order to automate the trajectory following problem and also increase the steering accuracy, several automatic guidance systems have been developed to avoid the problems mentioned above.

There are various reasons why the control of tractors with a high efficiency is a challenging task. First, an autonomous tractor can be configured with different types of implements and also encounter various environmental conditions (such as humidity and temperature) during field operations. In such conditions, there is always a trade-off between performance and robustness when a conventional controller, e.g. proportional–integral–derivative (PID) controller, is used. Since conventional controllers have time invariant coefficients and do not have the ability to adapt to changing conditions, they are not appropriate to be used in such agricultural production machines. Second, these machines show many nonlinear behaviors such as saturation, dead-time and time lags, which are difficult to handle with conventional control algorithms. Third, tractor navigation involves two subsystems, namely: the yaw dynamics and the longitudinal dynamics which make the control operation more challenging. There is also interaction apart from the hydraulic driveline as a change in the longitudinal speed will change the yaw dynamics and vice versa.

In model-based control, the control performance highly depends on the accuracy of the model describing the system behavior. In the last decade, several models have been proposed where the yaw dynamics of a wheeled vehicle are described with a bicycle model. Simple kinematic models have been proposed in O'Connor et al. (1996). These models neglect the side-slip of the tires and the dynamics of the steering actuator. Therefore, they are not appropriate for slippery surfaces which are common in field conditions with loose or wet soil. As a solution to this problem, a bicycle dynamics model which takes the lateral forces into account is proposed in O'Connor (1997). As the effect of side slip can be taken into account by this model, it covers a range of

* Corresponding author. Tel.: +65 6790 5585; fax: +65 6792 4062.
E-mail address: erdal@ntu.edu.sg (E. Kayacan).

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slippery and hard surfaces. However, in the previous approach, side slip angles cannot be calculated when the longitudinal speed is equal to zero. As a solution to this problem, the relaxation length approach is proposed in Karkee and Steward (2010) to calculate the side-slip angles more accurately. Bevly et al. (2002) reported that the relaxation length for only the front tire is adequate in order to model the real-time system.

Modeling of side-slip angle, which is the difference between the real and effective steering angle, and determining cornering stiffness values are very important steps in analyzing the yaw dynamics of autonomous vehicles. In Fang et al. (2011), the cornering stiffness is estimated by a robust adaptive Luenberger observer and a sliding mode controller is designed based-on chained system theory. The proposed controller and observer were reported to be robust to time varying lateral disturbances and also inaccurate side-slip angles. As an alternative approach to controlling the agricultural production machines, model reference adaptive control approaches have been proposed in Derrick and Bevly (2009). It is observed that the model reference adaptive control algorithm is able to adapt itself to various implementation configurations properly to control lateral position of a tractor for a straight path. In Gartley and Bevly (2008), the effect of the hitch point loading on the tractor dynamics is investigated by using a cascaded estimator approach. The experimental results show that the online estimation for the changes in the system provides the ability of adapting the controller gain to maintain the consistent yaw dynamic control of the tractor.

Model predictive control (MPC) has been widely used in the chemical process industry since the 1980s. The main goal of MPC approach is to minimize a performance criterion with respect to constraints of a system's inputs and outputs. The future values of the system are calculated based on a model. The main advantages of MPC over conventional controllers for the control of agricultural machines are the ability to deal with constraints and with multi-input–multi-output controllers. Several successful applications on agricultural production machines have been reported in literature. An MPC design was implemented on the cruise control of a combine harvester (Coen et al., 2008) in which the speed model was developed based on relating the engine speed and the current to the hydraulic pump to the longitudinal speed. The engine speed and the pump settings were controlled simultaneously and this approach was tested experimentally on a New Holland combine harvester. The experimental results show that a satisfactory acceleration performance can be achieved even by keeping the engine speed low. In Lenain et al. (2005), an MPC strategy is described for the control of an autonomous tractor by using an extended kinematic model. This control scheme has been tested experimentally on a farm tractor whose realtime localization is achieved relying solely upon a real-time kinematic (RTK) global positioning system (GPS). However, the control accuracy is limited, because the model used is a kinematic model, and thus neglects the dynamic behavior of the system. As an extension to MPC, a nonlinear MPC (NMPC) is proposed to obtain better lateral position accuracy of a tractor-trailer system in Backman et al. (2012). The lateral position error of the trailer was reported to be less than 10 cm in straight paths for a space-based trajectory in real-time experiments. Moreover, centralized, decentralized and distributed NMPC approaches have respectively been proposed in Kayacan et al. (2015b, 2014a, 2015c). The drawback of these studies is the same as Lenain et al. (2005) which is that the model used does not include the dynamic behavior of the system. Another NMPC algorithm is proposed for the yaw dynamics control of an autonomous vehicle in Canale et al. (2011). Although it was reported that the proposed controller would allow to use hard constraints for obstacle avoidance strategies, it does not include any real time experiments. Since more advanced control algorithms and mathematical models bring not only more accuracy, but also more computational burden to the real time systems, there always exists a trade-off between the complexity of the method and the computational efficiency of the overall system.

The main contributions of this study beyond the state of the art are modeling the yaw dynamics of an autonomous tractor considering various definitions of side slip angles and controlling it with good computational efficiency. In order to achieve this, first, the yaw dynamics model of the autonomous tractor has been derived, the model structures have been validated, and model parameters have been estimated by using frequency response function (FRF) measurements. Finally, the nonlinear least square (NLS) frequency domain identification (FDI) approach is used to obtain the model parameters to determine which model is better for the tractor at hand. After the identification of the yaw dynamics, an MPC controller for the yaw dynamics is designed based on the identified model. Then, this yaw dynamics controller has been combined with a kinematic controller for the trajectory tracking in which the kinematic controller is used for compensating the errors both in the *x*- and *y*-axes.

This paper is organized as follows: The experimental set-up is described in Section 2. The kinematic model of the system and the mathematical model of the yaw dynamics are presented in Section 3. In Section 4, the identification of the yaw dynamics is described. In Section 5, the basics of the implemented MPC approach are given. The overall control structure and the real-time experimental results are presented in Section 6. Finally, some conclusions are drawn from this study in Section 7.

2. Experimental set-up description

The aim of this study is to track a time-based trajectory with a small agricultural tractor shown in Fig. 1. The GPS antenna is located straight up the center of the tractor rear axle to provide highly accurate position information for the autonomous tractor. The height of the antenna is 2 m above ground level. It is connected to a Septentrio AsteRx2eH RTK-DGPS receiver (Septentrio Satellite Navigation NV, Leuven, Belgium) with a specified position accuracy of 2 cm at a 20 Hz sampling frequency. The Flepos network supplies the RTK correction signals via internet by using a *Digi Connect WAN 3G* modem.

Fig. 1. The experimental set-up (CNH TZ25DA).