Guidance system for agricultural tractor with four wheel steering

Timo Oksanen, Juha Backman

Aalto University, School of Electrical Engineering, Department of Automation and Systems Technology, Otaniementie 17, 02150 Espoo, Finland (Tel: +358 9 4702 5562; e-mail: timo.oksanen@aalto.fi)

Abstract: In a typical automatic guidance system for agricultural machines, the guidance system controls only one degree of freedom; either the steering angle of the front wheels of the tractor or other steering equipment is used for steering. In a tractor with the multiple degrees of freedom, like four wheel steering, the guidance system may use both the degrees of freedom for path tracking. However, the implement connected has to support the additional degrees of freedom; otherwise kinematic constraints are addressed. This paper presents a path tracking algorithm for four wheel steered agricultural tractor that is designed to be autonomous. The path tracking algorithm utilizes the kinematic and dynamical model of the vehicle, dynamic prediction and linear control laws to steer both front and rear axles of the tractor. The kinematic model is used to separate the two-times-time control problem into two single-input single-output problems. Conventional linear controllers are used for feedback control together with feedforward part. The guidance system uses real time kinematic GPS receiver for global positioning and additional sensors to measure the attitude of the vehicle. The developed path tracking system was tested in an agricultural field with a mounted seeder; by sowing 2.4 ha winter wheat. The results show that in straight swaths the lateral tracking error was less than 0.05m and the angular tracking error less than 1 degree. The results show also that during the field experiment, the GPS positioning signal was within the quality limits 15% of time that caused number of interrupts for continuous autonomous drive. The longest continous period of valid signal was eighteen minutes while the average of continuous driving was five minutes.

Keywords: Navigation systems, global positioning systems, automated guided vehicles, mobile robots

1. INTRODUCTION

Automatic guidance systems have been available for commercial tractors more than a decade. Typically, these commercial guidance systems can do path tracking in swaths. Furthermore, these systems are typically configurable so that they can cope with different kinematic systems (like front-wheel steering, rear-wheel steering, a tracked vehicle or articulated steering) - by giving curvature command to the steering actuators.

Tractors with four wheel steering (4WS) are not common in agriculture, but there are some: CASE 1200 (1965) was one of the first, following CASE 4894 and CASE 9260 series. Currently, the best known tractor with four wheel steering is Claas Xerion. One of the challenges in these tractors is to provide an easy-to-use user interface for the driver, to handle two steering actuators at the same time – in Xerion this is solved by using driving modes. One of the driving forces introducing four wheel steering was to use rigid body chassis in a large tractor as an alternative to articulated steering. Four wheel steering system is especially beneficial to compensate lateral sliding without causing any heading error in guidance systems.

The path tracking methods for a vehicle under automatic guidance can be divided into three categories: a) simple geometrical algorithms (like the Pure Pursuit algorithm), b) algorithms relying on inverse kinematics and c) algorithms utilizing direct kinematics and dynamics in control law (like optimal control). (Snider 2009)

In geometrical algorithms, or target point algorithms, the idea is to look ahead in the path the fixed distance, use that point to compute the deviation from the target path and compute the steering angle based on that. Examples of the algorithms using a dynamics model and kinematics are presented linear Model Predictive Control (Vougioukas, 2007) or Nonlinear Model Predictive Control (Backman et al., 2012).

With an automatic guidance system, or an auto pilot, the four wheel steering is easier to handle than for a human driver. The increased degrees of freedoms allows more performance, if the implement allows those to be used – otherwise the additional kinematic constraints are set. Earlier studies with automatic guidance with four wheel steering have been presented e.g. by Cariou *et al.* (2008; 2009) or Zhou *et al.* (2005). The four wheel steering is a common choice in many research prototypes developed for autonomous agricultural robot operations in research institutes (Bak and Jacobsen, 2004; Takigawa *et al.*, 2002; Jørgensen *et al.*, 2007; Ruckelshausen et al., 2009; Bakker *et al.*, 2010; Godoy *et al.*, 2012).

In this paper, a new algorithm for path tracking with a four-wheel steering vehicle is presented. The new algorithm is based on the inverse kinematic model together with linear control laws.

2. MATERIALS

The agricultural tractor that was used to study four wheel steering is shown in Figure 1. The tractor was originally built by a Finnish company Modulaire Oy in the years 1990-1995. The tractor is equipped with 123 kW diesel engine and hydrostatic transmission. The wheelbase is 2.7 m and weight more than 5500 kg. Each wheel steers max 22 degrees and the control system keeps the steering angles synchronous, to realize the Ackermann steering principle. The control system for the steering and drive was refurbished in the years 2009-2012. (Oksanen, 2012a)

Fig. 1. A four wheel steered tractor, APU-Module.

The steering is based on a dedicated hydraulic pump, a hydraulic valve block with four directional valves and four steering cylinders, one for each wheel. The control system for the synchronous steering of four wheels was developed during the refurbishment process. The maximum steering rate is limited by the hydraulic pump that needs to produce flow for four cylinders, compared with traditional tractor design where only one hydraulic cylinder or actuator is used for steering. In the closed loop control system, the identified control delay was 400ms plus remarkable dynamics; the maximum steering rate is 8-12 degrees per second depending on steering directions if all the wheels are steered synchronously with 1500 RPM engine speed. Based on the field experiments, the hydraulic pump should be larger (volume per revolution) in order to do navigation in full speed, 3.0 m/s. (Oksanen, 2012a)

The positioning system for navigation purposes is based on a) a RTK-GPS receiver, b) a fiber-optic gyroscope in heading and c) an inclinometer for tilt compensation. Trimble 5700 RTK-GPS receiver was used for global positioning; with the virtual based station signal provided by Trimble. The positioning accuracy is claimed to be typically better than 5 cm, but if the view to the GPS satellites is poor, the positioning accuracy is lost. For the heading estimation, a fiber-optic gyroscope (KVH DSP-3000) is used together with odometry and GPS heading information. Inertial-Link 3DM-GX2 was used for tilt compensation. All the signals were fused together in an embedded controller; the GPS positioning is corrected to ground level, heading is estimated based on GPS heading, fiber-optic gyro and odometry information and all the relevant information is transmitted to the navigation system by using CAN-bus.

In this paper, the implement for automatic steering is a mounted seed drill: Tume KL-2500; see Figure 2. The seed drill is a combined seeder, both seeds and local fertilizing are applied at the same time. The working width of the seeder is 2.5 m. In the experiments, winter wheat was drilled at the beginning of September 2012 and it will be harvested 2013. The seeder is a 25-year-old machine without any electronic control, still in use for farming and in excellent condition.

Fig. 2. APU-Module with the seeder (Tume KL-2500).

3. METHODS

The objective is to keep the vehicle on the desired route, which is given as waypoints that form a polyline. Here it is assumed that the route planner above in the system gives these waypoints 5 seconds in advance before they are passed – in order to use prediction. In curves, the waypoints are given frequently, so that the polyline is smooth enough to follow. It is also assumed that the route planner gives feasible waypoints, so that the vehicle kinematic constraints are not violated – for instance the minimum turning radius is considered in the route planner.

As the vehicle knows its position and attitude in the global coordinate system by using the sensors, and the waypoints are given in the same coordinate system, the path tracking algorithm needs to consider two error variables: lateral error and angular error.

The path tracking algorithm records the waypoints it has passed successfully, and the path error computation is computed for the line segment that starts from the last passed waypoint to the next one. However, computing the error variables only for the current position and attitude do not provide enough information for steering controllers, as in curves a stiff vehicle would overshoot remarkably.

Therefore, the guidance system computes the error variables not only for the current position all the time, but also for all the predicted positions of the vehicle based on the current position, heading, speed and steering angles. The prediction relies on the kinematic model of the vehicle and it takes the dynamics of speed and steering actuators into account. The prediction horizon is a tunable parameter; the value used in the tests was five seconds. The predicated error variables are converted to single error variables by using weighed averaging; the weighting function was an exponent function;

the current state is weighted more than the predicted error five seconds ahead.

The structure of the path tracking algorithm is presented in Figure 2. In the first block the path error is computed including the prediction, described above. The Approach Filter (Eq. 1) tweaks the error signals in case the lateral error is very large (over one meter): it modifies the angular error signal in order to guide the vehicle quicker to the route – this is helpful in case when the automatic guidance is started. If the lateral error is less than one meter, the error variables are passed through as is.

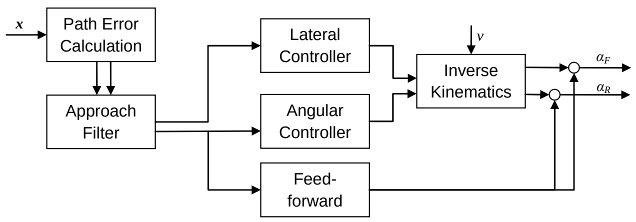

Fig. 2. Structure of path tracking algorithm.

$$\tilde{e}_a(t) = \begin{cases} e_a, \text{if } |\mathrm{e_p}| \le 1 \\ e_a + \dfrac{\pi}{3} \operatorname{sgn} e_p \dfrac{|\mathrm{e_p}| - 1}{10 - 1}, \text{if } 1 < |\mathrm{e_p}| < 10 \\ e_a + \dfrac{\pi}{3} \operatorname{sgn} e_p, \text{if } |\mathrm{e_p}| \ge 10 \end{cases} \quad (1)$$

Lateral Controller and Angular Controller are controllers in the feedback loop; the structure of both is PID. The feedforward part helps to stabilize heading control. The last block is Inverse Kinematics, that translates the desired lateral speed and angular speed commands to the steering angles in front and rear – by using the inverse kinematic model of the vehicle.

4. RESULTS

The preliminary results of the path tracking algorithm on hard terrain were reported in (Oksanen, 2012b). In earlier experiments on hard terrain it was found that the system is able to follow tight S-curves (radius 8 m) with maximum deviation 0.2 m and angular error 0.15 radians.

The path tracking abilities with the 4WS tractor and presented algorithm were tested all the season 2012. The final tests were made in early September. The tractor was equipped with 2.5m wide mounted seed drill; 24040 m^2 of winter wheat was drilled in a single field plot. Only the guidance system presented was used. In this phase of research, the full reference trajectory was generated by a script and only straight driving lines were used in the swaths. The reference trajectory is presented in Figure 3. First the field was driven 6 times counter-clockwise and reversing to the corners in order to create the headlands and after that looping the center area back-and-forth. The seeder tank was refilled once during the operation; the vehicle was manually driven to the service point to do that.

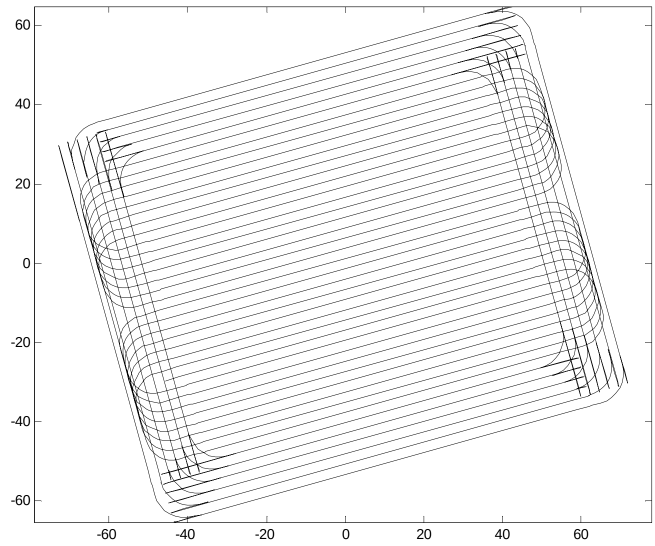

Fig. 3. Path trajectory in the field.

During the test, RTK-GPS signal was lost numerous times. There are various reasons for this: a) the field plot is located north (latitude 60.45°), the GPS satellites are low in the horizon; b) the field was bounded by trees that caused GPS satellite shadows and c) RTK-GPS correction signal was lost due to GPRS communication and/or service provider reasons. Statistically valid RTK-GPS signal availability was 85% of the time; the longest continuous valid period of the positioning signal was 18 minutes and the average was 5 minutes. The guidance system was programmed in a way that if the RTK-GPS signal is lost or the signal quality is below thresholds, the vehicle stops and waits until the signal is valid again.

The tuning of guidance system parameters was a challenge, as the parameters need to be different depending on the focus: curves with straights and gentle curves vs tight curves. However, in the case of seed drill, it is more important that the path tracking works accurately in swaths with the seeder down, than in turnings where the seeder is lifted. Therefore, the guidance system was tuned so that deviation may be larger and sharper curves were used for turnings (radius 7 m).

Figure 4 presents the path tracking errors in the continuous drive (three straight swaths two turnings at headlands; à 90 deg + straight + 90 deg). The first and second plot show deviance during the turnings and the third and fourth are the same but y-axis is zoomed in order to present the deviance during the swaths when the seeder is down, in the operating position. The sawtooth shape in the angular error is caused by the piecewise linear segments of the turning curve target trajectory; 8 segments per 90 degree turning.

Driving speed 1.8 m/s was used in swaths and 1.5 m/s in turnings; and 0.5 m/s when lifting or lowering the implement. The realized driving speed in the swaths varied between 1.7 and 1.9 m/s. The maximum velocity of the tractor is 3.0 m/s, but at this speed the path tracking accuracy decreases as the maximum steering rate is limited by the hydraulic system.

During a turn, the maximum deviation from the reference path is over 0.5 m and angular error over 10 degrees. However, in the swaths where the mounted seeder is down, the deviations are remarkably smaller, less than 0.05 m and 1 degree, respectively. As the inter row width of the seeder is 0.125 m, the guidance error less than 0.05 m guarantees that two drills are not overlapped.

Figure 5 presents the path tracking errors in straight swaths as a histogram; the turnings and the moments where RTK-GPS signal is lost were excluded. The mean angular error was -0.31° and the mean lateral error -0.01m; and the standard deviations 0.35° and 0.07m respectively. The reason for non-zero mean angular error is caused by the poor calibration of rear wheel angles and on the other hand tuning of the angular controller. However, the small deviation in the heading was not noticed during the seeding operation on the field.

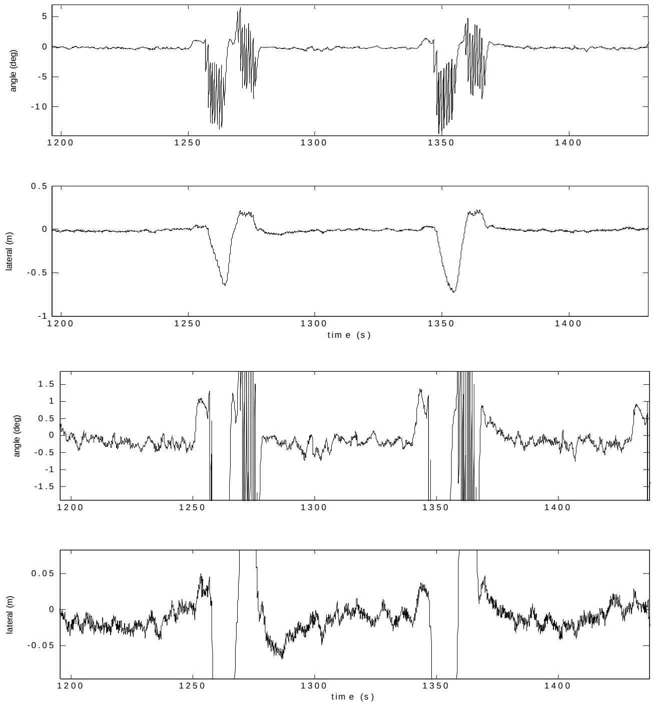

Fig. 4. Path errors in field tests (three swaths, two turnings).

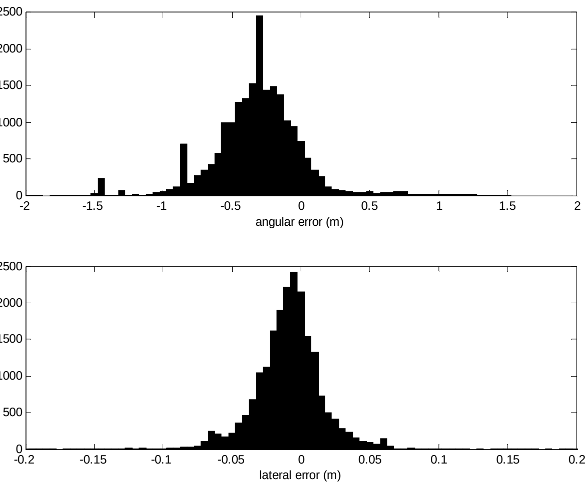

Fig. 5. Histograms of tracking errors in swaths.

No external positioning device was used besides the RTK-GPS used that was used for navigation. In the tracking analysis above, RTK-GPS position was considered as a true position of the vehicle. However, the germinated seeds reveal the true accuracy in the field. Figure 6 presents the field plot three weeks after sowing. The track of the support wheel of the seeder is seen in the middle of the picture; the seam is two drills to the right.

Fig. 6. The field three weeks after sowing.

5. DISCUSSION

As this paper presents, the automatic guidance systems relying on solely GPS positioning face a problem of GPS positioning signal availability. As presented in above, with this equipment and these conditions the RTK-GPS signal availability was 85% in time; which means that the vehicle may be in operation 85% of the time or less if no other positioning system is available.

Figure 7 presents which quality conditions caused interrupt for autonomous drive during a 80-minute run; the different quality thresholds are presented with different colours. The longest breaks were caused when losing the real time kinematic correction signal (fix); indicated by the GPS receiver. The other reasons for interrupts came from the number of satellites in view, HDOP value (representing the satellite geometry) and the pseudorange noise statistics (the major axis of the standard deviation error ellipse).

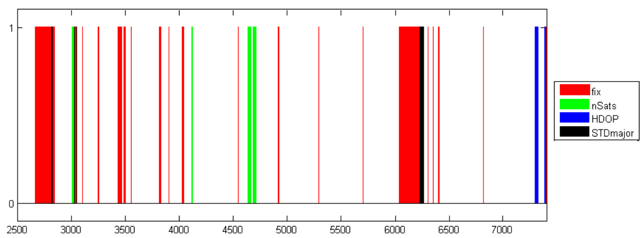

Fig. 7. GPS positioning signal errors during a 80-minute run.

It is crucial to take the RTK-GPS signal quality, properties and breaks into a consideration in the development process of a guidance system and algorithms. Simulation of GPS error is crucial in order to take all the cases into consideration as it is hard to repeat the conditions in the field. Backman *et al.*

(2010) presented a simulator model capable creating similar noise and quality signals than happened in real life. The simulator was utilized in the development process of the guidance system.

The results revealed a calibration error in the rear wheel angle that causes a small constant deviation in the heading of the vehicle (0.31°). This means that even if four wheel steered vehicle follows the route precisely, the heading differs from the course over ground and this affects the implement(s) connected to the vehicle. However, in this test, the stabilizer arms in the hitch allowed sideways movement for the mounted seeder, so the seeder was sowing 14mm out of the line. In practise this deviation cannot be notices in the field.

The real tracking accuracy was not measured; the results are based on RTK-GPS positioning that was used also for navigation. However, Figure 6 presented the result. Based on visual inspection three weeks after, the deviation seen in the field is in the same scale as the data presents (see Figure 4 and Figure 5).

The tractor used in the experiment to sow winter wheat with a mounted seeder is considered equally sized than the current human driven machinery in European farms. In the field experiment, the work efficiency was not as good as would have been achieved by using human driven machinery as the positioning system failed 15% of the time; this decreases the work efficiency at least with the same percentage. However, the size of the machine capable reaching similar work efficiency is pretty large that causes a risk for human beings in the neighbourhood; a runaway vehicle of this size may cause damages. In these field experiments, an operator was monitoring the vehicle with emergency stop function.

6. CONCLUSIONS

This paper presents a new path tracking algorithm for vehicles with four wheel steering. The results show that the guidance system is feasible for agricultural operations. However, the ability to follow tight and mild curves would require a more adaptive control method; with gain scheduling based on velocity and the state.

The positioning signal availability in practice causes problems in the systems solely based on GPS technology as trees and other obstacles next to fields cause shadows. The automatic guidance system would require additional means for positioning, to improve signal availability and reliability.

In a vehicle with four wheel steering the zero position in the steering angles must be calibrated in order to not cause error between the heading and the course of the vehicle. In this study, the bias was not estimated in the controller and therefore the small deviation was not noticed in the field experiments.

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