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ORIGINAL ARTICLE

Path tracking in forest terrain by an autonomous forwarder

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Abstract

Autonomous navigation in forest terrain, where operation paths are rarely straight or flat and obstacles are common, is challenging. This paper evaluates a system designed to autonomously follow previously demonstrated paths in a forest environment without loading/unloading timber, a pre-step in the development of fully autonomous forwarders. The system consisted of a forwarder equipped with a high-precision global positioning system to measure the vehicle's heading and position. A gyro was used to compensate for the influence of the vehicle's roll and pitch. On an ordinary clear-cut forest area with numerous stumps, the vehicle was able to follow two different tracks, three times each at a speed of 1 m s^{-1} , with a mean path tracking error of 6 and 7 cm, respectively. The error never exceeded 35 cm, and in 90% of the observations it was less than 14 and 15 cm, respectively. This accuracy is well within the necessary tolerance for forestry operations. In fact, a human operator would probably have a hard time following the track more accurately. Hence, the developed systems function satisfactorily when using previously demonstrated paths. However, further research on planning new paths in unknown unstructured terrain and on loading/unloading is required before timber transports can be fully automated.

Keywords: Robotics, autonomous vehicles, automation.

Introduction

Automation of harvesting operations has been applied in many areas of the agricultural sector (e.g. Pedersen et al., 2006; Pilarski et al., 2002; Stoll & Kutzbach, 2000). Starting with the structured and stable greenhouse environment, automation has now successfully moved on to the variable and semi-structured outdoor environment that only partly can be tailored to simplify the requirements of robotic systems. Precision is a key issue in navigation of autonomous systems. In agricultural applications, a precision of $\pm 0.20 \text{ m}$ has been reported for all kinds of ground conditions (Lenain et al., 2007). Agricultural path-tracking addresses, however, mainly straight paths on flat and even, but somewhat soft and slippery, grounds (e.g. Cariou et al., 2009; Nagasaka et al., 2009; Pilarski et al., 2002; Tillet et al., 2008). In comparison to agriculture, the forest environment is much more challenging for autonomous machine navigation since operation paths are rarely straight or flat and obstacles are common. In addition, the vehicle itself has more problems in

moving due to high amount of logging residues on the ground surface and sometimes high variability of the soil-bearing capacity. Further, the possibility to adapt the environment according to robotic requirements is strongly limited in forestry due to environmental concerns. Forest operations include more complex in-field decisions than typical agricultural operations. Most decisions have to be made in real time and are often based on experience and prior knowledge (Hellström et al., 2009).

In forestry the forces driving mechanization and automation are a lack of workers, the amount of hard physical work involved, the aspiration to continue forestry operations year-round and for more hours per day, and the desire to reduce costs and the lead times between logging and industrial processing (Silversides, 1997; Sundberg, 1978). For example to operate a forwarder in the transportation of roundwood from the harvesting site to the roadside is a monotonous, repetitive handwork with joysticks and buttons. Already in the early days of mechanization it was found that even light, short cycle

movements of hands and arms may cause repetitive stress injuries that are characterized by complaints and injuries to the neck, shoulder, arms and cervical spine. Axelsson and Pontén (1990) point out that about 50% of the logging machine operators showed more or less serious repetitive strain injury symptoms. Hence, the working conditions would improve if a part of the work operations could be performed autonomously. Moreover, human performance can be limiting work efficiency; for instance the technical potential is not fully used in many machine movements as humans have difficulties to precisely guide machines or machine parts at high speeds for long periods of time (Hellström et al., 2009; Pilarski et al., 2002). Even though the automation process in forestry is rather slow compared to agriculture, some advances have been made towards a partial or full automation of as well tree harvest as transportation. A machine presented by Golob (1981) autonomously conducted tree felling, delimiting and piling of stems, while robots designed to develop and demonstrate autonomous control were built to perform weeding, pre-commercial thinning and thinning of young coniferous stands (Kourtz, 1996). The latter machinery was also used to study forest environment sensing and to test mobility concepts, which was also addressed in the evaluation of an autonomous log skidder that was guided by six sonar rangefinders (Anderson et al., 2005). The present research mainly focuses on the development of the decision management of support systems, automation of specific work tasks to relieve the operator from both physical and mental pressure (shared control) and automation of navigation in terrain (Hellström et al., 2009).

Compared to the advanced harvester work with its multitude of operator input in terms of both machine control and active decisions (e.g. Vestlund et al., 2005), work of the forwarder would be feasible to perform autonomously. The key issue is navigation, which requires a real-time knowledge of the current machine position as well as of the coordinates for loading in the forest and unloading at the landing. Moreover, knowledge of how to travel between those points in the most economically and ecologically beneficial way is crucial. A bad choice of route might not just result in excessive time spending but also result in contact with obstacles (trees, stones, holes, etc.), which might cause damage to crop trees and the machinery. The presence of a physical path enables navigation by sensors that identify the path (e.g. Aghkhani & Abbaspour-Fard, 2009; Anderson et al., 2005; Kim & Slaughter, 2008; Kise et al., 2005; Søgaard & Lund, 2007), while virtual paths have to be created and followed in the lack of physical ones. Global positioning systems (GPSs) that use satellite signals are commonly

employed for virtual paths (e.g. Cariou et al., 2009) and are often combined with path-identifying sensors (e.g. Nørremark et al., 2008) as each navigational mode has its advantages and disadvantages (Pilarski et al., 2002). Virtual path tracking is dependent on a priori information on the environment and the path to follow. Thus, such operation is blind in the sense that it relies on the positional input and the employed map without validating it with the surrounding physical environment. Uninterrupted positional input is thus required, which, in the case of GPS technology, is troublesome when working under dense tree canopies (e.g. DeCesare et al., 2005; Naeset et al., 2000). Fortunately for the automation of forwarder work, its desired travel route is roughly known because the harvester has already driven from the roadside to the harvesting site and manoeuvred at the site when harvesting trees. The harvester has also placed small piles of sawlogs and pulpwood beside the route it took within the harvesting site. Therefore, before the transportation of logs begins, it should be possible to acquire information about the route and the positions of wood piles. Moreover, when forwarding at final felling sites there is no tree canopy that might obstruct GPS signals.

Traditional path-tracking algorithms, such as Follow the Carrot (Barton, 2001) and Pure Pursuit (Coulter, 1992), use position information only and sometimes run into problems such as cutting corners. By taking into account additional information from a human driver during the learning phase, the algorithm Follow the Past (Hellström & Ringdahl, 2006) can avoid these problems. This algorithm enabled an autonomous forwarder to follow a previously driven path and avoid unexpected obstacles (Hellström et al., 2006). To ensure accurate navigation despite poor GPS coverage, it was developed to be able to continue to run autonomously even when the GPS signal was lost for short periods of time (Ringdahl & Hellström, 2008). The technique was based on a neural network combining information from a gyro with the forwarder's speed and steering angle. This increased the time the vehicle could run correctly without receiving a GPS position compared to the ordinary odometry system commonly used. On a flat and even open field, the machine followed a path demonstrated by an operator with a mean lateral deviation of ± 0.1 m, without taking short cuts at sharp turns (Hellström et al., 2009). To work satisfactorily on uneven forest terrain, the path-tracking algorithm must be able to compensate for the vehicle slipping and sliding in the rough terrain. Furthermore, driving on slopes and over large stumps may cause errors in the position estimates owing to displacement of the GPS antennas. A brief

survey of more path-tracking control algorithms can be found in Mäkelä (2001).

The present study aims at evaluating the path-tracking capability of an autonomous forwarder in a real forest environment and comparing the results with previous tests on the flat and even ground.

Materials and methods

Vehicle and path-tracking equipment

The trial vehicle was a 10-tonne Valmet 830 forwarder (Figure 1). The vehicle consisted of two parts joined through articulated steering with double acting cylinders. The maximum steering angle was 43° . The front part comprised cab, engine, main hydraulic system, front bogie axle and hydraulic and fuel tanks. The rear part comprised the bunk area and the rear bogie axle. The forwarder had an eight-wheel drive hydrostat-mechanic transmission. For more details about the vehicle, see Hellström et al. (2009). For positioning of the vehicle, a Javad Maxor real-time kinematic differential GPS (RTK DGPS) system with three receivers was used. This system has a much higher accuracy than regular GPS receivers (in the order of ± 2 cm with clear views of at least four or five satellites). One reason for the improved accuracy is the use of a reference station, which is a stationary GPS receiver (differential GPS, DGPS) able to send correction data to the two mobile receivers. Another reason is the basic measuring technique real-time kinematics, in which the carrier wave of the signal received from the GPS satellites is used. The carrier wave has a relatively

short wavelength, enabling more accurate position estimates (Zhao, 1997). One advantage with the used GPS model is its compatibility with both the Russian GLONASS system and the American GPS system. This provided an important backup and also increased the accuracy, especially on the high latitudes (64°N) where the tests described here were conducted. The GPS position was available during the entire test, so no other positioning system had to be used.

In addition to position, the GPS system accurately measured the vehicle's heading. The heading was calculated by comparing the position of two GPS antennas mounted next to each other at approximately 1.2-m distance. The antennas were placed on the roof of the forest machine 3.77 m above ground level. The reported position and heading referred to this point while the path-tracking algorithm needed coordinates at ground level. A coordinate transformation was therefore necessary and for this the vehicle's roll and pitch had to be taken into account. The AHRS 400 CC gyro (Crossbow Inc., USA) was used to measure these angles dynamically with an accuracy of approximately $\pm 2^\circ$. The angles were then used to calculate the position of a reference point, located at ground level below the center of the front part of the vehicle. Ground level was defined as being 3.77 m below the position given by the GPS. In order to determine the steering angle, the forwarder was equipped with a sensor in the hydraulic cylinders controlling the articulation link. An extensive software system comprising more than 50,000 lines of source code was developed to implement the necessary functionality



Figure 1. The studied Valmet 830 forwarder equipped with an RTK DGPS for localization and heading measurements and a gyro determining the vehicle's roll and pitch angles.

Photo: Ola Ringdahl

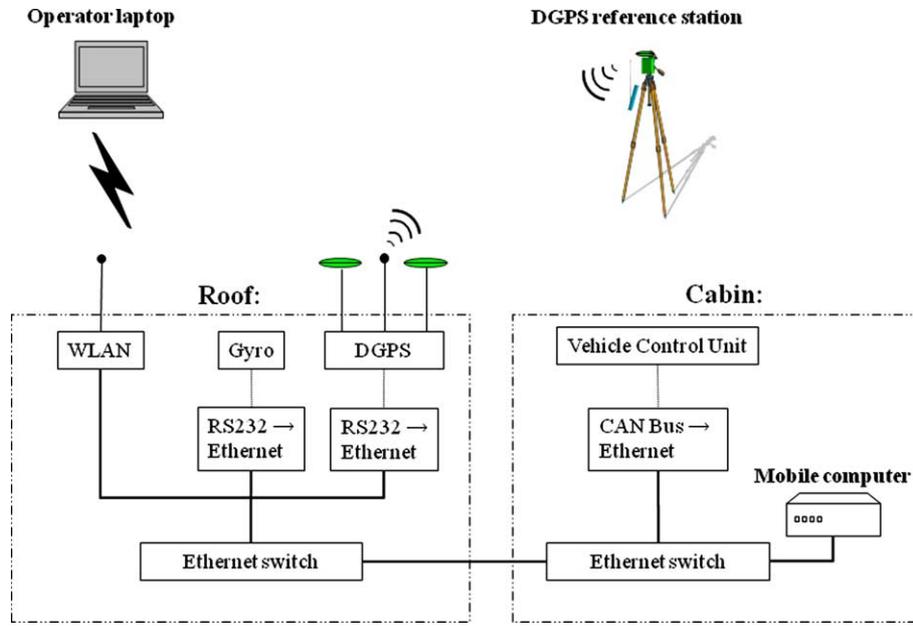


Figure 2. Block scheme of hardware for the autonomous forest vehicle used in the presented experiments. The DGPS reference station was placed on the ground nearby the forest machine.

(Hellström et al., 2008). An overview of the hardware used in the tests can be seen in Figure 2.

The operator initiated and supervised the autonomous machine through a laptop. In addition to user interface, this laptop contained high-level routines for path tracking and functions for learning a new path. Data recorded from various sensors on the autonomous machine were collected here. On the vehicle, the hardware was placed on the roof and in the cabin. A mobile computer responsible for low-level control and data analysis was placed in the cabin. The forest machine was interfaced via its vehicle control unit, which was connected to our system through a device converting signals from the vehicle's CAN bus to Ethernet (and vice versa). Control signals for requested speed and steering angles were transmitted to the vehicle, and the current speed and steering angle were reported back to the system. The Ethernet switch connected the equipment in the cabin to the equipment on the roof. Gyro and GPS provided data in RS232 format and were therefore converted to Ethernet format. The RTK DGPS system was connected to the two GPS antennas on the vehicle and a radio antenna for communication with the DGPS reference station placed on the ground in close proximity to the path (see Figure 2). The hardware on the forest machine communicated with the operator laptop via wireless LAN. The previously developed path-tracking algorithm Follow the Past (Hellström & Ringdahl, 2006) was responsible for keeping the vehicle on the previously demonstrated path. The algorithm consisted of three separate subfunctions suggesting one steering command

each, which were then fused together. The first subfunction imitated the steering angles that the driver used during the learning phase. The second subfunction aimed at turning the vehicle to the same direction as during the learning phase. The last subfunction turned towards the route if the machine was located beside it. In this study, the algorithm was improved by tuning the quickness that the vehicle returned to the path. If it returns too slowly, the path-tracking errors will become larger. If the vehicle returns too fast, it risks oscillating around the path.

Stand and track data

The study was performed 10 km west of Umeå in Northern Sweden (63.78 N, 20.07 E) during a 2-day period in December 2008. The forest stand was situated 45 m above sea level in an area dominated by coarse-textured sandy till soil and with no visible groundwater. Just days before the study, the stand had been harvested (final felling by clear-cutting). In addition to roundwood, logging residues (tops and branches) were to be recovered for bioenergy and had therefore been piled. The area contained approximately 1000 fresh stumps ha^{-1} with a mean diameter of approximately 28 cm in addition, but there were very little loose tree parts on the ground.

Two tracks were selected on the clear-cut area. Track 1 (Figure 3, left pane) had a length of 74 m and was oriented in the same direction as the main slope of the almost level terrain. The track's orientation in the terrain resulted in elevation differences equal to a downhill slope of on average 2.3° during

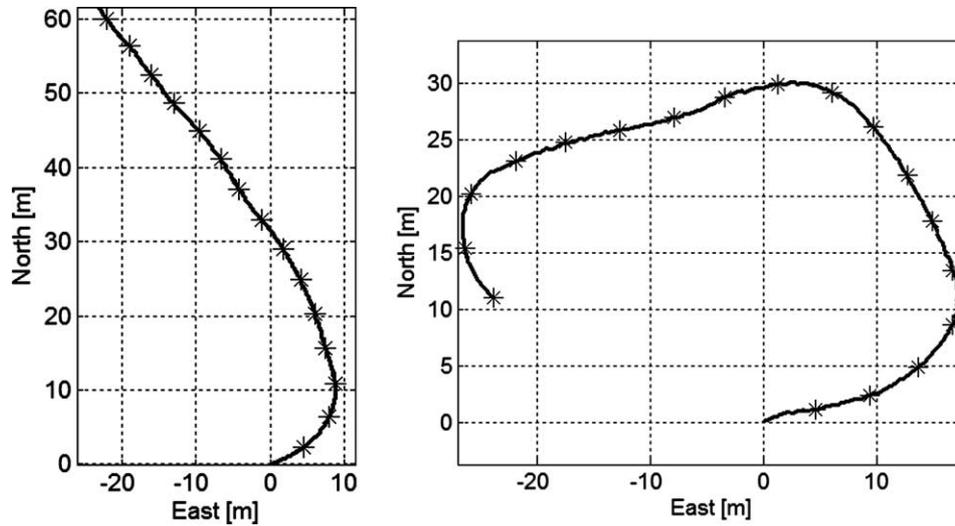


Figure 3. Trajectories of reference paths 1 (left pane) and 2 (right pane). The vehicle started at position (0, 0), i.e. in the lower part of the figure. The paths were, respectively, 74 and 85 m long. Every fifth meter of the paths is marked with an asterisk.

the first 50 m and the remaining distance on level ground. The vertical difference was 2 m. Track 2 (Figure 3, right pane) had a length of 85 m, and its almost circular orientation made the vehicle travel down, parallel and up the main slope direction (north-east). The main slope was 5.3° and the track's orientation resulted in elevation differences equal to a downhill slope of on average 3.7° during the first 40 m and an uphill slope of on average 3.9° at the remaining part. The vertical difference between the lowest and the highest part of the track was 3 m. Side slope and obstacles (stumps) together gave the forwarder an inclination of maximum $7\text{--}8^\circ$ for both tracks during short periods. The forwarder had a side inclination of more than 2.5° during 5% of the distance on track 1 and 30% of the distance on track 2. There was no ground frost or snow cover during the test, only a thin layer of rime on the ground surface. During the study the temperature was approximately 0°C and no precipitation occurred.

Stump heights and diameters varied between 14 and 43 cm and between 11 and 49 cm, respectively, for the two tracks (Table I). On average, the machine passed over a stump every 3–5 m of the driving distance. In track 1, 60% of the stumps were passed over by the left side of wheel pairs, while equally

many stumps were passed over by each side of wheel pairs in track 2.

On both tracks the forwarder performed the first run (reference run) driven by an operator. Thereafter, the same path was driven three times autonomously by the path-tracking algorithm while measuring the lateral distance to the reference path (path-tracking errors) with the GPS at 5 Hz intervals (approximately each 0.25–0.30 m). In addition, manual measurements were obtained by marking the ground at the left rear tire of the forest machine at approximately 4-m intervals during each run and then measuring the lateral distance between the reference path and the new run with a measuring tape. Since the GPS antennas were placed on the roof of the machine, they moved considerably sideways when going in rough terrain, resulting in an incorrect estimate of the forest machine position. The reason for doing manual measurements was to verify that the technique to compensate for this error worked as well as expected. In previous studies, path-tracking errors have been reported either as absolute mean values (e.g. Aghkhani & Abbaspour-Fard, 2009) or as root mean square errors (e.g. Nagasaka et al., 2009). For comparability, these two formats as well as the standard deviation (SD) and

Table I. Characteristics of stumps that wheels rolled over.

	N	Diameter (m)			Height (m)		
		Mean	SD	Min–max	Mean	SD	Min–max
Path 1	25	0.27	0.10	0.12–0.43	0.27	0.08	0.14–0.39
Path 2	18	0.29	0.10	0.11–0.49	0.26	0.08	0.15–0.43

Table II. Lateral deviations from the reference path presented as means and standard deviations (SDs) of absolute values and as root mean square errors (RMSEs) in meters presented according to the manual measurements and the GPS measurements.

Track	Run	Manual measurement				GPS measurement			
		<i>n</i>	Mean	SD	RMSE	<i>n</i>	Mean	SD	RMSE
1	1	18	0.06	0.07	0.09	321	0.08	0.06	0.10
	2	18	0.06	0.06	0.08	316	0.07	0.06	0.10
	3	18	0.06	0.06	0.09	321	0.07	0.05	0.09
	Mean	54	0.06	0.06	0.09	958	0.07	0.06	0.09
2	1	21	0.05	0.04	0.07	342	0.05	0.04	0.06
	2	21	0.04	0.05	0.07	322	0.06	0.05	0.08
	3	21	0.05	0.04	0.07	320	0.07	0.06	0.09
	Mean	63	0.05	0.05	0.07	984	0.06	0.05	0.08

Note: *n* is the number of measurements.

distribution of the absolute mean were calculated individually for the GPS and manual measurements.

Results

For the three runs of the first track, the mean absolute lateral deviation from the reference run was 0.07 m according to the GPS and 0.06 m according to the manual measurements (Table II; Figure 4). The maximum deviations were 0.35 and 0.20 m according to the GPS and the manual measurements, respectively (Figure 4). The large deviations in the beginning of the runs that can be seen in Figure 4 are due to difficulties in placing the vehicle at exactly the same starting position as the reference track. For the second track the mean absolute lateral deviation from the reference run was 0.06 m according to the GPS and 0.05 m according to the manual measurements (Table II; Figure 5). The maximum deviations were 0.28 and 0.19 m according to the GPS and the manual measurements, respectively (Figure 5). According to the GPS measurements, 90% of the path-tracking errors were less than 15 cm in track 1 and 14 cm in track 2.

Manually recorded travel time for the reference run was 68.7 s for track 1 and 83.9 s for track 2, resulting in average speeds of 1.08 and 1.05 m s⁻¹, respectively. When autonomously tracking the path, the corresponding manually recorded mean speeds per run were 1.11 (SD 0.01) m s⁻¹ in track 1 and 1.05 (SD 0.01) m s⁻¹ in track 2. Compared to the reference run, the path-tracking speed was slightly higher (0.02 m s⁻¹) in track 1 (*df* = 2, *T* = 13.77, *p* = 0.005) and equal in track 2 (*df* = 2, *T* = -0.83, *p* = 0.493).

Discussion

Our results show that it is possible to modify a conventional forwarder so that it is able to

autonomously follow a previously demonstrated path with high accuracy even in a normal Scandinavian forest environment. In fact, lateral path-tracking errors were similar to many errors reported when autonomously following paths in agricultural conditions (Lenain et al., 2007; Nagasaka et al., 2009; Zhu

et al., 2007). Surprisingly, the path-tracking errors were generally smaller in the present study compared to when the same system was tested on the flat and even ground (Hellström et al., 2009). One plausible explanation is that the path-tracking algorithm was better tuned in the present study and some of the software functions supporting path tracking have been further developed and optimized since the previous study. Path-tracking errors were generally similar over runs, indicating that the errors were systematic and not random (Figures 4 and 5). The lateral path-tracking errors from the two different measuring methods (manually and GPS) were also quite similar, indicating that the systematic errors were not due to low accuracy in GPS signals (e.g. positioning errors when demonstrating the path to follow). Concordance between manual and GPS observations also indicate that the technique to minimize the negative effect of vehicle roll and pitch on GPS position worked well. Periodically, changed lateral errors have previously been observed when using an RTK GPS for path tracking (Kise et al., 2005) and were then suggested to be caused by the non-linearity of the steering system and/or poor performance of the steering controller. This also seems to be the probable cause in this study. The forest machine's steering response is slow, such that it can take several seconds for the machine to reach a new required steering angle. This may cause the algorithm to overcompensate the steering angle, leading to the vehicle oscillating around the path. To avoid this, some parameters in the path-tracking algorithm can be tuned. However, this tuning is a

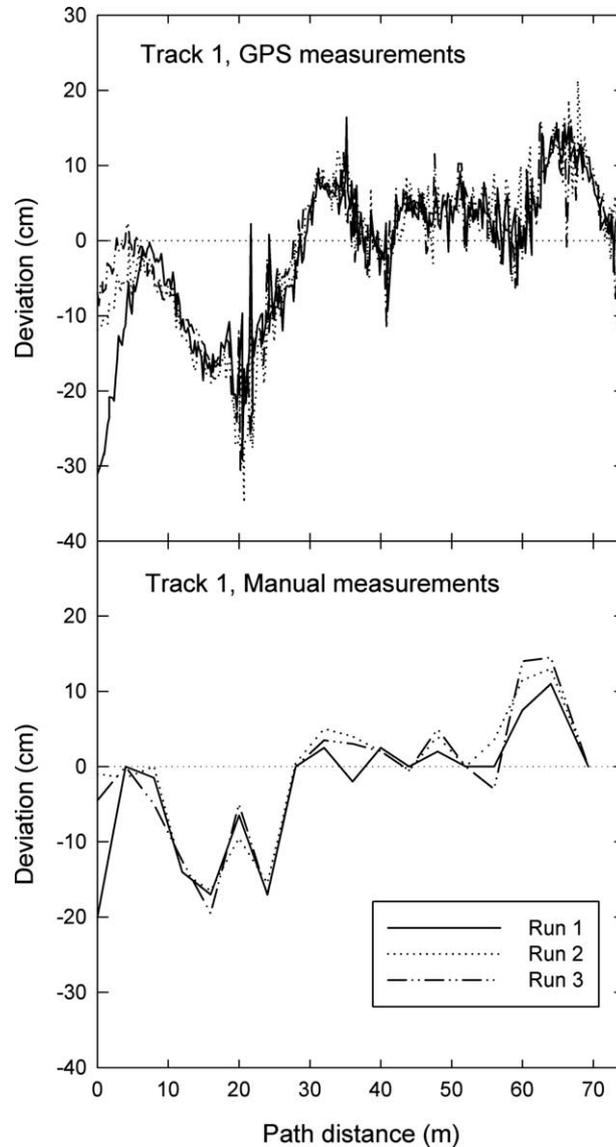


Figure 4. Lateral path-tracking deviations from the reference path in track 1 measured with a GPS and manually. Negative and positive values indicate deviations to the left and to the right, respectively, of the reference path. Measurements were taken at the same path distances, but path length differed since the GPS and the manual measurements were recorded in the front and in the rear of the vehicle, respectively. The large deviations in the beginning are due to the machine not being placed exactly on the same starting position as the reference track.

trade-off between quickly returning to the reference path and avoiding the oscillating behavior. Figures 4 and 5 suggest that the deviation could depend on how much the vehicle steers. However, no significant relation could be found between path deviation and steering angle when analyzing them graphically. Another possible source for positional errors is the accuracy of the gyro. Because of the GPS antennas' placement almost 4 m above ground level, driving over a 40-cm high stump will cause the vehicle to roll almost 9° and the GPS antennas to move 58 cm to the side. The gyro is used to compensate for this effect, but its reported $\pm 2^\circ$ accuracy corresponds to ± 13 cm positional error in this case. However, in

the recorded data, path deviation has no significant relation to roll according to graphical analyses. This shows that the error in measured roll is random and results only in increased positional noise. The observed noise in path deviation is in the order of ± 2.5 cm (cf. Figures 4 and 5) and can be partly caused by this inaccuracy in roll measurements. Another cause for the noise could be discrepancies in timing between position readings from the GPS and roll readings from the gyro.

In this study the forwarder operated at an average speed of 1 m s^{-1} , which is very close to the one expected in real work situations (Nordfjell et al., 2003). The study gave no indications that deviations

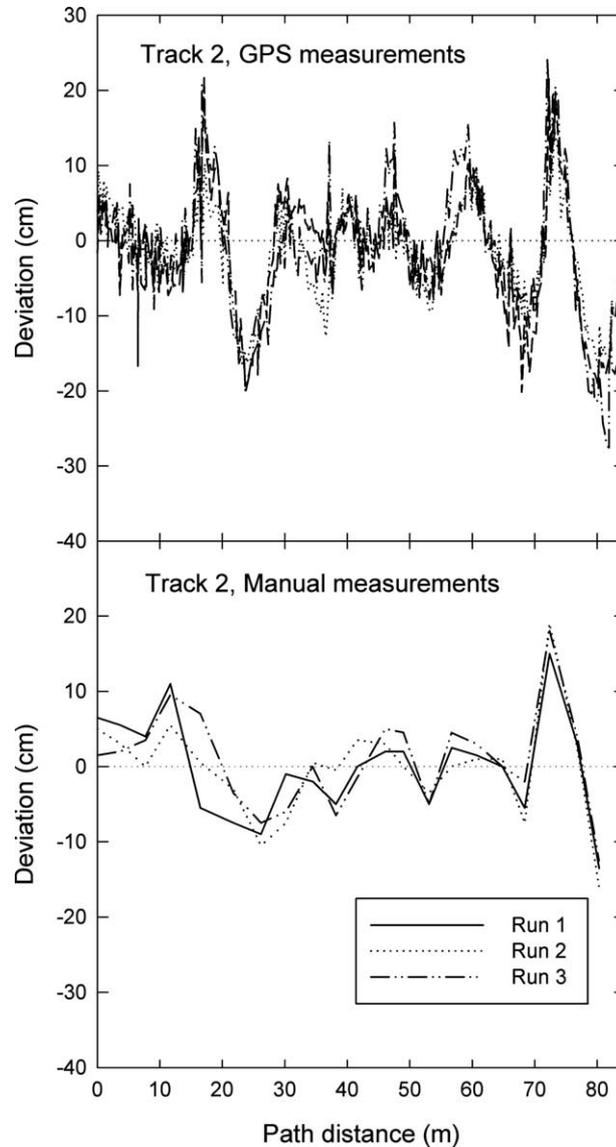


Figure 5. Lateral path-tracking deviations from the reference path in track 2 measured with a GPS and manually. Negative and positive values indicate deviations to the left and to the right, respectively, of the reference path. Measurements were taken at the same path distances, but path length differed since the GPS and the manual measurements were recorded in the front and in the rear of the vehicle, respectively.

would increase substantially with increased speed. Accurate path tracking is thus probably technically possible at higher speeds with an autonomous forwarder. In conventional forwarders, however, increased speed would result in a poor operator environment due to whole-body vibrations (Rehn et al., 2005).

Concerning the two methods for measuring path-tracking errors (GPS and manually), it should be noted that the path-tracking algorithm works with positions given by the GPS and transformed to a point at ground level below the center of the front part of the vehicle. The path-tracking errors reported by the GPS refer to the deviation for this point. The manual measurements, on the other hand, refer to

the rear part of the vehicle. Because of the articulated joint architecture, these two errors are not necessarily the same. However, the study indicates that the two ways of measuring path deviations give similar results.

In precision agriculture, navigational errors in the order of millimetres are both required and feasible (e.g. Belforte et al., 2006; Kim & Slaughter, 2008; Nagasaka et al., 2009; Sogaard & Lund, 2007; Tillett et al., 2008). In a forest environment such a high accuracy is unfeasible because of the many obstacles and changes in surface characteristics. Thus, the vehicle can slip sideways from an obstacle even if the correct path is followed, as was also observed during the study. Furthermore, requiring

such high accuracy would lead to unacceptably many corrections in steering angle. On the other hand, the need for path-tracking precision in forwarding might not be as high as in many agricultural operations. Whereas agricultural crop densities often require centimetre and even millimetre precisions, the distance between Scandinavian crop trees is typically 2 m (2500 trees ha⁻¹) in planting and 3–5 m (500–1000 trees ha⁻¹) in final felling. We estimate that the precision in the presented work (errors <0.3 m) is enough for safe navigation of an autonomous vehicle when performing forestry operations. In fact, it would probably be difficult for professional human operators having better path-tracking accuracy than the autonomous machine had in this study. A GPS system, such as the one used in the presented work, delivers more than sufficient positioning accuracy if signals from sufficiently many satellites can be received. However, a fully autonomous system operating in forest environment must be equipped with additional positioning systems to complement GPS if the satellite signals are occluded. Suitable choices are inertial navigational systems or systems based on visual odometry. In a real-life application, the path-tracking algorithm described here would have to be combined with a system for avoiding obstacles such as trees or human beings (Hellström & Ringdahl, 2009).

In the future, we will challenge the studied system with additional conditions normally found in the forest work environment. In boreal forests, forestry machinery must be able to function under tree canopy (with bad GPS coverage), in slippery slopes, in snow and in temperatures far below 0°C. Moreover, it is essential to evaluate the system's performance when carrying out its actual work – to transport logs. With the basic functionality of system granted, vehicle load and its effect on vehicle dynamics will be evaluated. The ultimate aim of future studies would be to contribute in the development of a forwarder that is not dependent on initial operator guidance to find its path. Information from a priori maps is a possible solution and could be created in simulations (Hellström & Ringdahl, 2009). This makes the task a bit easier compared to navigating in unknown unstructured areas. However, using information from the harvester would be a more desirable solution since it has always travelled the area before the forwarder. Knowing where the harvester has driven and where it left the log piles, a system planning which route the forwarder should take to pick up the piles can be developed (e.g. Flisberg et al., 2007). Even with this kind of planning software, a method to guide the vehicle along the planned path, like the one presented in this paper, is still required.

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