Autonomous Forest Vehicles: Historic, envisioned, and state-of-the-art

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ABSTRACT

The feasibility of using autonomous forest vehicles (which can be regarded as logical developments in the ongoing automation of forest machines), the systems that could be applied in them, their potential advantages and limitations (in the foreseeable future) are considered in this paper. The goals were to analyze: 1) the factors influencing the degree of automation in logging; 2) the technical principles that can be applied to autonomous forest machines, and 3) the feasibility of developing an autonomous path-tracking forest vehicle. A type of vehicle that is believed to have considerable commercial potential is an autonomous forwarder. The degree of automation is influenced by increased productivity, the machine operator as a bottle-neck, cost reduction, and environmental aspects. Technical principles that can be applied to autonomous forest vehicles are satellite navigation, wheel odometry, laser scanner, and radar. A new path-tracking algorithm has been developed to reduce deviations from the desired path by utilizing the driver's steering commands. The presented system has demonstrated both possibilities and difficulties associated with autonomous forest machines. A field study has shown that it is quite possible for them to learn and track a path previously demonstrated by an operator with an accuracy of 0.1 m on flat ground and also to detect and avoid unexpected obstacles. Although the forest machine safely avoids obstacles, the study shows that further research in the field of obstacle avoidance is needed to optimize performance and ensure safe operation in a real forest environment.

Keywords: *obstacle detection, path-tracking, robotic, system architecture, forest vehicle*

Introduction

A number of important steps in the mechanization of forest operations have been taken over the past 50 years. A forwarder with articulated steering inspired by the American "Blue ox" skidder was invented in 1962 (Staaf 1988). Machines for de-branching and log cutting were introduced in 1966–1967 (Nor-dansjö 1988), and machines for tree-felling in 1972 (Östberg 1990). Harvesters were invented in Sweden and Finland in 1972–1973 (Drushka and Konttinen 1997). The basic principles for cut-to-length (CTL) forest machines have remained the same since the 1990s.

The mechanization of logging can be divided into six phases according to Silversides (1997), in which the implements used were predominantly:
- hand tools and draught animals;
- various combinations of hand tools;
- motor-manual tools;
- manually operated machines;
- machines that automatically performed some repetitive work elements; and
- machines that use feedback from the process to control the next work element (e.g., a harvester with a bucking computer).

A further phase of mechanization, however, may occur when machines that can work autonomously without operators are developed (Gellerstedt et al. 1996). The machine presented by Golob (1981) that required no operator for tree felling, de-branching, and laying stems in piles can be seen as an early conceptual example of such a machine. The forces driving mechanization are a lack of workers, the aspiration to continue forestry operations year-round and for more hours per day, and the desires to reduce costs, the amounts of hard physical work involved, and the lead-times between logging and industrial processing (Sundberg 1978, Silversides 1997).

For the foreseeable future, humans will play a central role in the maneuvering of forest machines in harvesting operations because so many complex factors need to be considered in the work done by forest machines that full automation would be extremely difficult. The issues that must be addressed include:
- What trees should be harvested, and what are their optimal bucking lengths and assortments, according to both economic and environmental considerations?
- Where should the harvester be positioned, and what routes should be taken? These decisions are based on ground conditions, obstacles in the terrain, judgments regarding suitable driving routes in relation to the reach of the crane, the position and size of the trees, and the stability of the machine, which depends on the inclination of

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the ground, slant of the tree, wind affecting the tree, and environmental considerations.

- In what direction should a tree be felled? Tree felling has to be done without risks to humans, the machine itself, or surrounding objects. The decision is based on the slant of the tree, the wind, the risk of damaging remaining trees, and the planned positions of small piles of saw-logs and pulpwood for ease of extraction.
- The transportation of wood out of the forest to the roadside requires an ability to navigate, and thus the ability to follow a specific route. Navigation demands real-time knowledge with high precision about the surroundings as well as the position of the machine in each moment.

The complex work elements and decisions described above have to be automated before an autonomous forest machine can be constructed. This means that extensive research has to be conducted within the following three main areas.

Support for Decision-Making

The driver of a harvester has to make many decisions (regarding, inter alia, where the machine should be positioned, where the piles of logs should be placed, and which trees should be harvested), and systems that could facilitate decision-making could be extremely useful. The most complex decisions concern selective thinning, regarding which trees should be harvested depending on the species and quality of the individual trees, and the properties of the surrounding stand (density, tree sizes, species composition, etc.) (Vestlund 2005). A semi-autonomous way to solve this problem was presented by Kurabyashi and Asaman (2001), in which trees selected for retention were identified by discs attached to them. A decision support system for selective cleaning and thinning was developed by Vestlund et al. (2005), but sensors that are more capable of detecting the trees and measuring stand characteristics that the algorithm relies on need to be developed before it can be fully implemented (Vestlund 2005).

Extraction of logs to the roadside does not require many difficult decisions to be made. The route is roughly known because the harvester has already driven from the roadside to the harvesting site, and maneuvered at the site when harvesting trees. The harvester has also placed small piles of saw logs and pulpwood beside the route it took within the harvesting site. Therefore, before the extraction begins, it should be possible to acquire information about both routes and the positions of wood piles.

Automation of Work Elements

A number of repetitive work elements can be partly or fully automated, e.g., crane movements during loading, unloading, and sorting of assortments, positioning of the grapple or harvester head, and placement of the crane in a suitable position when driving the machine.

Autonomous Navigation in Terrain

All of the autonomous work tasks in a forest require an ability to navigate. An early attempt to develop an autonomous

navigation system was presented by Kourtz (1996). To be successful the vehicle must know where it is at any time and how it should maneuver to follow the decided route. Systems for detecting obstacles, humans, animals, other machines, and buildings are also needed, as well as advanced transmission systems to avoid unnecessary slippage.

Why Autonomous Vehicles in Forestry?

Autonomous vehicles have been considered, and tested, in various research and development projects, in efforts to make forestry operations more efficient. The main identified benefits are as follows.

Increases in Productivity

Increases in productivity per unit time are perhaps the most important potential benefits of automation: timber production will amount to 60,000 m^3 per year if a forest machine produces 20 m^3 per hour over an annual worktime of 3,000 hours (with two drivers working in shifts). To increase the annual worktime to more than 3,000 hours using the same machines more drivers would be required, and complex logistics with huge numbers of machine movements between harvesting sites. There is another way, however, to achieve the same annual production levels. A year has 8,760 hours, and if a machine can work autonomously it might be possible for it to work efficiently for at least 6,000 hours per year. The same annual production level (60,000 m^3) could then be delivered by a machine producing only 10 m^3 per hour. Furthermore, the cost per hour of an autonomous vehicle is not directly influenced by salary costs, because it has no driver.

Elimination of the Machine Operator as a Bottleneck

Crane speed is currently limited mainly by the speed their operators can handle, which equates to average productivity levels of approximately 20 m^3 per hour, while the load capacity of forwarders is currently limited solely by the weight the forest ground can support. A harvester can fell, delimb, and buck 60 to 100 trees per hour, and a large forwarder can carry a load of 18 tonnes. The machines are fast, but require an operator who constantly maneuvers its crane and harvester head and distinguishes differences in log quality classes both between and within trees. This makes the work environment stressful, since many decisions must be made at high pace, and the operator often becomes a production bottleneck. The operator can also be the limiting factor for rates of loading and unloading forwarders. A possible way to increase productivity is, therefore, to raise the level of automation and, if possible, use autonomous forest machines.

Cost Reductions

The salary of operators generally amounts to 30 to 40 percent of the hourly cost of a forest machine. Thus, there would be substantial economic advantages if a machine could work autonomously, or an operator could handle more than one machine at the same time.

Environmental Aspects

The size and load capacities of forwarders have increased to raise productivity, and the risks of damage to the ground have increased accordingly. Harvesters have also become larger. The damage could be reduced, while maintaining overall productivity levels, by using an autonomous harvesting system working 6,000 productive hours per year but at only half the hourly productivity rate of current forest machines. Thus, less advanced basic machines could be used (e.g., harvesters processing 30 to 50 trees per hour with slower crane movements). This also means reduction in mechanical stress, forwarders with gentler crane movements, slower driving speeds, and smaller loads. Generally, lower speeds require less engine power. Thus, an autonomous machine can be lighter since its speed and load can be reduced. The removal of the driver cabin alone can reduce the mass by approximately 1 tonne. It is also easier to optimize the weight distribution of a forest machine without a large cabin. For instance, it might be possible to place the crane of a forwarder in the middle of the machine, and piles of wood on both its front and rear parts. With such changes a forwarder should be able to carry a load of at least the same mass as itself. A 9 to 10 tonne forwarder would then be able to carry a load of 10 tonnes, and the total mass would still not exceed 19 to 20 tonnes. Such a machine will place considerably less stress on the forest ground and tires than current forwarders. A lighter machine, with a higher load/mass ratio, also consumes less fuel and generates less emission per m^3 handled.

Possible Scenarios on Automation

Due to the complexities of the problems involved, the current goal is not to fully automate the felling process, but rather to develop various types of semi-autonomous systems in which humans are still involved, especially in decision-making. Three examples of possible system designs are described below. Other possibilities have also been described in the literature (e.g., Hallonborg 2003).

Remote Supervision

This approach is based on a human remotely supervising a semi-autonomous system. If necessary, the operator can take control of the system. Such techniques already exist in the mining industry. LKAB have used unmanned loaders for several years that are capable of autonomously navigating. In forest applications, a process operator could supervise such systems from the mobile office, and to some degree remotely control a number of semi-autonomous harvesters and forwarders.

Semi-Autonomous Harvesters

In this scenario, a manned forwarder remotely controls one or more semi-autonomous harvesters. An example of this is the prototype system "Besten" [the Beast] (Bergkvist et al. 2006), which consists of an unmanned harvester remotely controlled from a manned forwarder. Studies performed indicate that this technique might reduce the costs of final felling by more than 20 percent (Bergkvist et al. 2006).

Autonomous Wood Shuttles

This is a system that has not been tested in practice yet. In a study by Hallonborg (2003), the system has been deemed to have the best ability to compete with the current harvester system. In this scenario, a manned harvester cuts the trees, but the logs are transported to the road by one or more autonomous shuttles.

Objectives

The goals of this study were to analyze the factors influencing the degree of automation in logging and to describe the technical principles that can be applied to autonomous forest machines as well as the feasibility of developing an autonomous path-tracking forest vehicle.

Material and Methods

The first and second of the goals listed above were addressed by literature studies and theoretical analysis, while the third was addressed in a field study. The techniques for path-tracking, localization, and obstacle detection were evaluated on a 10 tonnes Valmet 830 forwarder equipped with a LMS221 laser scanner for obstacle detection and a Javad Maxor RTK DGPS for estimating position and heading. To compensate for the effects of the vehicle's rolling and pitching on global positioning system (GPS) positional data, an AHRS400 gyro was used. An extensive software system comprised of more than 50,000 lines of source code was developed to implement the necessary functionality.

A 160-m-long reference path was driven by an operator-controlled forwarder on a flat gravel pitch. Thereafter the same path was driven four times autonomously by the path-tracking algorithm *Follow the Past* while measuring the distance to the reference path (path-tracking errors) with the GPS at intervals of 0.25 to 0.30 m (**Fig. 1**). The speed of the forwarder was 1.0 to 1.3 m/s. In addition, manual measurements were obtained by marking the ground at the rear tire of the forest machine at 5- to 6-m intervals during each run and then measuring the distance between the reference path and the new run with a measuring tape. The average and distribution of path-tracking errors was calculated individually for the GPS and manual measurements, respectively. The ground was covered by a thin layer of snow during the test.
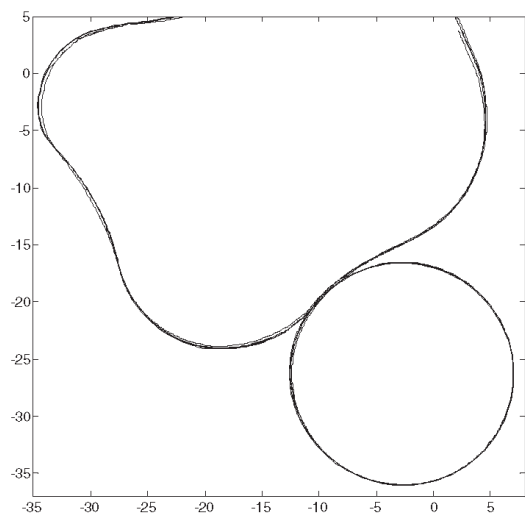
To test the autonomous vehicle's ability to avoid obstacles, a loading pallet was placed slightly to the left of the learnt path in one test, and slightly to the right of the path in another test. To detect obstacles, a laser scanner was used in combination with an occupancy grid. The obstacle-avoidance algorithm VFH+ was used to modify the direction of travel if any obstacles were detected along the planned path.

Results

Current Research Toward Developing an Autonomous Forest Vehicle

During the last several years the research group at the IFORcentre, Umeå University has been addressing various problems

that need to be solved before viable autonomous forest machines can be constructed and exploring systems that could be applied in them. Algorithms for controlling hydraulic cranes have been developed, which it is hoped will lead to semi-autonomous crane functions for next generation cranes of forest machines. The main goal for another project is to establish a solid research platform for investigating in detail the feasibility, optimal features, limitations, and prospective systems of autonomous wood shuttles such as those described in the previous section (Hellström et al. 2006, Ringdahl 2007). The project is based
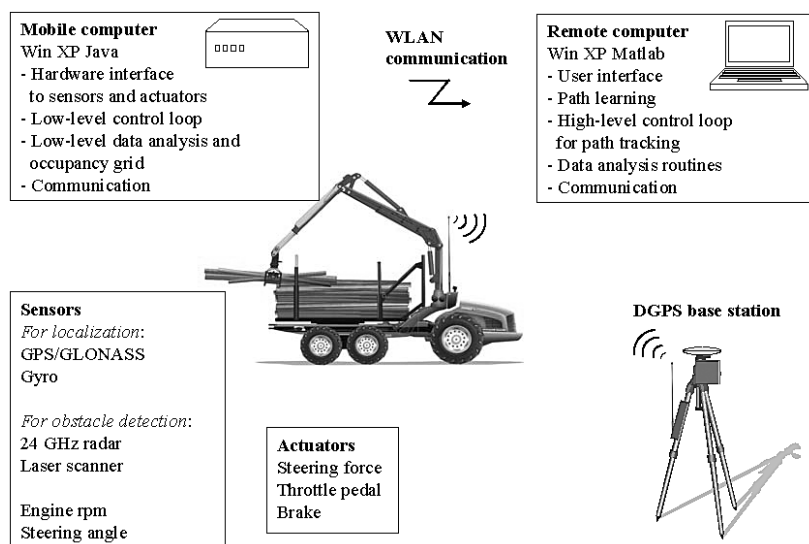
on a solution in which an operator demonstrates a path by driving the vehicle manually along it once, either by remote control or from the cabin (if still present). The computer in the shuttle records both the vehicle's pose and the operator's steering commands. Thus, the system can learn the adjustments to controls required to drive along the demonstrated path. Due to inaccuracies in signals from the position sensors in combination with unevenness of the ground, however, deviations from the path can occur. Consequently, the problems involved in autonomously tracking a demonstrated path are not easy to resolve, and interaction with the environment is required for satisfactory solutions. The scenario in which an operator initially demonstrates the path is, of course, a simplification and is not intended to be a final solution for use in a commercial product. An alternative to manual demonstration of the path could be to use information from a map. But, even in this case the ability to follow a predefined path is essential. The chosen scenario should, therefore, also provide a suitable test platform for further research relevant to these issues.

Figure 2 shows an overview of the system developed in the project to date. The computing power is split between two computers connected by a wireless local area network (WLAN). The primary computer is mounted in the autonomous shuttle and is responsible for hardware interfacing and communication with the vehicle. It also contains low-level routines for controlling velocity and steering angle, as well as processing sensor information. The secondary computer is used by the operator to initiate and supervise the autonomous shuttle's operation. Many different sensors are required, primarily to resolve the vehicle's pose and determine if there are any obstacles in the way. The sensors used are briefly presented in the next section.

Figure 1. ~ *Comparison of a 160-m-long reference path and four autonomous runs with the developed path-tracking algorithm Follow the Past. The data show that the runs coincide almost completely.*

Figure 2. ~ *System overview. Two computers share the computing tasks; one handles low-level tasks such as processing sensor information, while the other handles higher level tasks, including path tracking, learning new paths, and user interfaces. The forest machine shown is a concept of what a future autonomous shuttle could look like.*

Sensors

The main technical challenges that need to be resolved to enable autonomous navigation systems are more refined techniques for positioning and obstacle detection. For positioning, an accuracy of ± 1 m is regarded as both realistic and essential for safe operation in a forest environment. This is the required accuracy for estimates of the real position of the vehicle, so the positional information from the sensors must not deviate more than a few decimeters from true values to ensure safe control of a large forest machine.

Satellite Navigation

The main sensor used for positioning is an advanced Real-Time Kinematics Differential GPS (RTK DGPS) from Javad. With clear views of at least four or five satellites, this system has an accuracy of about 2 cm. The receiver is capable of receiving signals from both the American GPS system and the Russian GLONASS system. While providing lower accuracy than GPS, GLONASS provides important backup, especially at the high latitudes (64° north) where the work is being con-

ducted. The vehicle is equipped with two receivers and two antennas, which also makes it possible to determine the vehicle's heading. The system also includes a stationary receiver that compensates for common sources of errors in the satellite navigation system. This is done using the so-called differential-GPS technique (DGPS), which sends correction signals by radio to the mobile receivers. Hopefully in the near future, the European Galileo system will contribute additional positional information. But, all satellite navigation systems are sensitive to the reception conditions, and in a forest environment the accuracy can easily deteriorate to 0.5 m or less. In order to navigate even when the satellite navigation system does not provide sufficient accuracy, techniques for combining several sensors have been developed. Using this approach accuracy can be increased sufficiently to autonomously navigate the vehicle for a limited time, for example, through a dense part of the forest. The techniques used for this purpose are briefly described below.

Wheel Odometry

A vehicle's movement between two points can be estimated from measurements of its velocity and steering angles. To obtain information on the vehicle's position and heading, consecutive small movements are summed. The technique is called wheel odometry. One problem with this technique is that the vehicle's wheels can slip and slide considerably. Another source of error, related to the articulated joint design, is that the motions of the front and rear parts of the vehicle relative to the ground are uncertain. When the steering angle changes, the two parts move differently depending on factors such as weight distribution and ground conditions. Errors in position and heading estimates accumulate to total errors that increase with time. To improve wheel odometry, neural networks have successfully been used in the project (Ringdahl 2007). By training a neural network with velocity and steering angle data from the forest machine and using the exact positions obtained from the satellite navigation system, neural networks are able to learn the mathematical relationships between velocities/steering angles and changes in pose. The trained network can then be used as position sensors that are considerably less subject to drift than ordinary wheel odometry systems. In trials in a forest environment, the average time before the drift exceeded 1 meter was 13 seconds when a neural network was used, compared to 3 seconds when uncompensated wheel odometry was used.

Gyro

Normally the satellite navigation system is used to determine the vehicle's heading and, as for positional data, GPS signals provide highly accurate directional accuracy under normal circumstances. If the GPS antennas do not have clear views of sufficient satellites, a gyro with an internal compass is used instead (although the compass is not used since the magnetic material in a forest machine substantially affects the magnetic fields in and around it). The gyro we have been using in tests to date is an AHRS400CC from Crossbow Technology, based on MEMS-technology (Micro Electro-Mechanical Sensors). Instead of moving parts, vibrating ceramic plates are used to sense the angular rate. By multiplying the mean angular rate reported by the gyro in a given sampling period by its duration, a good estimate of the vehicle's change in heading during the sampling period can be obtained. The vehicle's current heading is calculated by summing these changes. Similar to the values provided by odometry-based methods for determining position, the values obtained here are subject to drift over time. The gyro system, however, is much more accurate than systems based on wheel odometry. Estimates of heading from the gyro can be used with sufficient accuracy ($\pm$ 5°) for movements lasting about 50 seconds.

Obstacle Detection

Detecting obstacles in forest environments is extremely demanding and raises problems that have not yet been satisfactorily resolved. In particular it is difficult to determine if a detected object is a real obstacle, such as a stone, or a traversable object, such as a bush. Rough terrain and "negative obstacles" (e.g., holes in the ground) present further challenges.

In this project, information from a laser scanner was used to create and update a local map of the environment. The resulting occupancy grid includes probabilities of obstacles in a fine-meshed grid and is created by weighing and integrating a large number of sensor readings.

Laser Scanner for Obstacle Detection

A LMS 221 laser scanner supplied by SICK, which operates by measuring the time of flight of laser light pulses, was used to detect obstacles in front of the forest machine. A pulsed laser beam is emitted from the scanner, reflected back if it meets an obstacle, and is then registered by the scanner's receiver. The time between transmission and reception of the pulse is directly proportional to the distance to the obstacle. The maximum range at which the scanner can detect an obstacle depends on the reflectivity of the object; the more reflective the object, the further away the scanner can detect it. A tree can be detected at about 60 m. The LMS 221 laser scanner has an accuracy of $\pm$ 35 mm and is able to complete a 180° scan in 13 to 53 ms, depending on the angular resolution.

Radar for Obstacle Detection

Another type of sensor for detecting obstacles is radar. An advantage with radar is its lower sensitivity to bad weather, such as fog, rain, or snow. The radar used in the project is manufactured by TYCO and is primarily used in the car industry. It has no movable parts, but emits pulses from two antennas with different lobe-characteristics. By comparing the relative strength of the radar echoes, the distance and bearing to several targets can be computed. The resolution is about 15 cm and the radar unit can detect obstacles up to 30 m away.

Path-Tracking

The vehicle has to be able to autonomously answer the following three questions in order to follow a route: Where am I? Where should I go? How do I get there? The first question is an-

swered with the help of positioning sensors and systems, of which the satellite navigation system is an important component. Where the vehicle should go, and how to get there are mainly defined by the operator who demonstrates the desired route. Both the final destination and the route are defined in this way. Algorithms for path-tracking are used to provide the ability to follow the learnt route. One of the simplest algorithms is named *Follow the Carrot*, which means that the vehicle steers straight toward a point further along the route, with no concern about the appearance of the route before that point (Barton 2001). This is analogous to a driver sitting in a cart pulled by a donkey and steering by dangling a carrot in the desired direction in front of the donkey using a fishing rod. The drawback of this, and most of the other standard algorithms, is that vehicles have a tendency to take short cuts around curves, which is inadvisable in a forest environment where trees and other obstacles are often situated close to a defined route. As part of our research efforts, a new algorithm *Follow the Past* (Hellström and Ringdahl 2005) has been developed. The idea is to utilize the driver's steering commands during a learning phase and compensate for any deviations from the route, which may occur if the machine has avoided an obstacle or if the positioning system is not sufficiently accurate. *Follow the Past* consists of three separate sub-functions:

1. Imitate the steering angles that the driver used during the learning phase,
2. Turn to travel in the same direction as during the learning phase, and
3. Turn toward the route if the machine is located beside it.

All of the sub-functions propose steering angles, which are then summed to obtain a value that is used to steer the vehicle. The developed algorithm works well, and the vehicle follows an intended route with good precision without taking short cuts around corners, provided that there are no obstacles nearby. A module based on the algorithm VFH+ (Borenstein and Koren 1991) is responsible for avoiding obstacles and has a higher priority than the route-following module. Steering angle is corrected if an obstacle is detected on the route. If the algorithm is unable to safely navigate around an obstacle, the vehicle is stopped while waiting for intervention by an operator.

Field Study

The average distance from the reference path in the four runs was 0.10 m according to the GPS and 0.07 m according to the manual measurements (**Table 1 and Fig. 1**) while the maximum distances were 0.38 m for the GPS measurements (**Fig. 3**) and 0.40 m for the manual measurements (data not shown). The differences in distances obtained by the two measuring techniques were well within the margins of error, given the accuracy of the GPS and the manual measuring procedure.

The probability of path-tracking errors less than 23 cm was 90 percent according to the GPS measurements (**Fig. 3**).

With the implemented algorithm VFH+, the vehicle was able to avoid obstacles and subsequently return to the learnt path 10 to 15 m after the obstacle (**Fig. 4**).

Table 1. ~ *Distances from the reference path presented as means and standard deviations (m) presented separately for manual measurements and GPS measurements.*

Run	Manual measurements			GPS measurements		
	Mean	SD	n[a]	Mean	SD	n[a]
1	0.09	0.09	30	0.10	0.09	548
2	0.09	0.08	27	0.10	0.09	590
3	0.06	0.05	29	0.10	0.09	593
4	0.07	0.06	26	0.10	0.09	647
Average	0.07	0.07	--	0.10	0.09	--

[a] n = the number of measurements in each run.
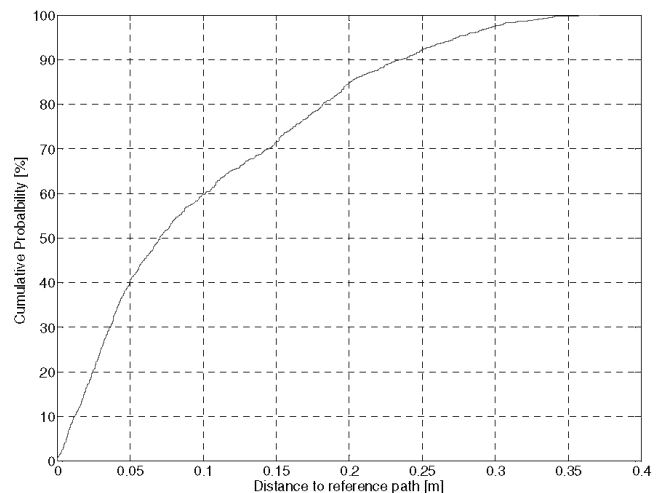
Figure 3. ~ *Cumulative distribution function (CDF) for the path-tracking errors (distance from the reference path) obtained using GPS.*

Discussion and Conclusions

The presented system has demonstrated both possibilities and difficulties associated with autonomous forest machines. It has shown that it is possible for them to learn and track a path previously demonstrated by an operator. The overall performance was very good in all four tests. For the future, the field study should be repeated in ordinary forest terrain with obstacles and slippery slopes in different directions and under a tree canopy.

A new path-tracking algorithm has been developed to reduce deviations by utilizing the driver's steering commands. It would also be possible to use information from a map to define a desired path, but further research is required before this becomes a realistic alternative to the operator demonstrating a safe path through the forest.

To determine the vehicle's position and heading, a highly accurate satellite navigation system was used. The results from the field study confirm the centimeter accuracy of the GPS claimed by the manufacturer. Although the costs of such systems will no doubt decline in the future, there is a need to develop less expensive techniques for determining position and heading. Another reason for developing such techniques is that the accuracy
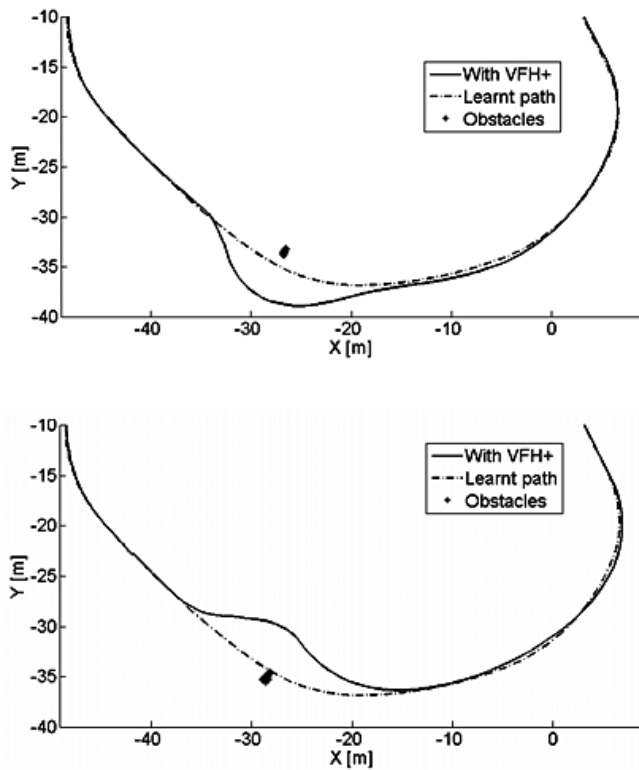
Figure 4. ~ *Obstacle avoidance. The obstacle is placed to the left of the center line of the vehicle (top). The obstacle is placed to the right of the center line of the vehicle (bottom). The vehicle's starting point is at the upper left corner of the figure. The obstacles were detected using a laser scanner and an occupancy grid.*

of satellite navigation systems can deteriorate considerably when the GPS-signals are obstructed by obstacles such as large trees. For these reasons, algorithms with neural networks have been developed to improve wheel odometry, and techniques for combining information provided by several sensors for position and heading. The neural network is usually able to increase the time that wheel odometry can be used before the errors grow too large. The gyro gives the most accurate heading information after the satellite navigation system.

Detecting obstacles is crucial for an autonomous vehicle. The task is quite difficult in a forest environment because the uneven terrain gives many "false positive" readings, i.e., detecting obstacles at times when the ground simply becomes visible to the sensors such as just before a steep incline. Distinguishing between an obstacle and something the machine can simply drive over, e.g., a large stone vs. a shrub, presents further challenges. Detecting "negative obstacles", e.g. a ditch or a steep slope, is also a problem to consider. To detect obstacles as reliably as possible, the system supports use of several different sensors, although to date the laser scanner, which is able to detect obstacles in front of the vehicle, has mainly been used. To keep track of obstacles and reduce the number of false positive readings, an occupancy grid based on Bayesian updating was used (Moravec 1988).

To avoid detected obstacles, the VFH+ algorithm was used. This works well for avoiding obstacles, but performs less well when there are narrow passages to negotiate with obstacles close to both sides of the vehicle. The behavior of the vehicle, for example the shortest allowed distance to an obstacle, can be controlled by parameters in the VFH+ algorithm. To ensure safe operation, the algorithm automatically reduces the speed of the vehicle when an obstacle gets closer than 4 m. The reduction is proportional to the distance to the nearest obstacle. The behavior when returning to the learnt path after avoiding an obstacle is a trade-off between speed and stability. If the vehicle returns too quickly to the path, it may overshoot it, with a risk of getting an oscillating behavior. On the other hand, too slow of a response is also undesirable. This behavior is determined by tuneable parameters in the path tracking algorithm. Major efforts to develop systems for avoiding obstacles in rough terrain are being made by various groups around the world (Iagnemma and Boehler 2006, Hellström and Ringdahl 2008).

A crucial factor that will strongly influence if and when autonomous forest machines are introduced in forestry is interest from machine manufacturers. Major efforts are required to proceed from academic research to products with acceptable performance for the end users. We estimate that this will take at least 10 to 20 years depending, of course, on the scale of resources invested in such efforts by both academic institutions and the forest industry.

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