

AUTONOMOUS FOREST MACHINES – PAST, PRESENT AND FUTURE

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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 their limitations (in the foreseeable future) are considered here. The aims were to analyse: (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 class of such vehicles that are believed to have considerable commercial potential is autonomous wood shuttles (forwarders). 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, laser odometry, wheel odometry, laser scanner and radar. The presented system has demonstrated both possibilities and difficulties associated with autonomous forest machines. It is in a field study shown that it is quite possible for them to learn and track a path previously demonstrated by an operator with an accuracy of 0.1m on flat ground. A new path-tracking algorithm has been developed to reduce deviations by utilizing the driver's steering commands.

Keywords: Forest technology, obstacle detection, path-tracking, robotic, system architecture.

1. INTRODUCTION

The aims of this study were to analyse: (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.

The first and second of the aims listed above were addressed by literature studies and theoretical analysis, while the third aim was addressed in a field study.

The paper is organized as follows: Section 2 gives a historical background to automation in forestry. Section 3 analyzes the major driving forces behind the urge to develop autonomous forest machines while Section 4 summarizes the basic requirements for such systems. In Section 5, a number of basic system design scenarios for semi-autonomous vehicles are described. In Section 6, the experiences from a pilot project aiming at developing an autonomous forest vehicle are discussed. The results from the field study are presented in Section 7 and conclusions regarding state-of-the-art and future development in the area are given in Section 8.

2. HISTORICAL BACKGROUND

For a long time forestry operations were largely performed manually, but the scope for further improvements to the tools used, such as saws, axes and horse-drawn sledges, had become very limited by around the year 1900 (Ekman 1908, Brown 1949, Sundberg 1978, Silversides 1997). However, the mechanisation of forestry started much later than the mechanisation of agriculture (Sundberg 1978, Silversides 1997), with the introduction of the chain-saw for harvesting and tractors for extraction. Nevertheless, there were some early examples of technical forestry innovations. The first chain-saws light enough to be handled by just two persons were developed in the USA and Sweden in the years 1916-17 (Sundberg 1978, Silversides 1997). In USA, a single factory was producing chain-saws in 1938, six in 1942 and 30 in 1949 (Silversides 1997). The definitive breakthrough for chain-saws occurred in around 1950, when they became sufficiently light to be handled by a single operator (Sundberg 1978, Drushka & Konttinen 1997, Silversides 1997). In 1952, only 20% of the pulp wood produced in eastern Canada was harvested with chain-saws, but by 1960 the proportion had risen to almost 100% (Silversides 1997). Trends in the European countries were similar, and a number of chain-saw factories were built in Sweden, and Germany. However, chain-saws were still being used by fulltime professional operators at thinning operations in Scandinavia until the beginning of the 1990s (Lidén 1995).

Many attempts were made in North America from the 1920s onwards to use tractors in forestry (Brown 1949, Silversides 1997). An important step in mechanisation was that from 1925 tractors could be equipped with winches (Brown 1949). More than 8000 machines were in use in Canadian forestry in 1950; three times more than in 1945 (Silversides 1997). Many tracked vehicles for extraction were invented in the Soviet Union around 1950 and in North America during the 1950s (Andersson 2004), where a skidder with articulated steering was invented in 1959 (Silversides 1997). In addition, several machines for mechanised tree felling, loading and extraction were invented during the 1950s, as well as machines for debranching and cutting logs at road-side (Silversides 1997).

The large-scale mechanisation of extraction and harvesting operations occurred somewhat later in the Scandinavian countries than in North America, although some early examples of Scandinavian tractors for extraction were produced by the beginning of the 1930s (Drushka & Konttinen 1997). Total global sales of forest machines in 1966 amounted to ca. 400 CTL machines (generally used in Scandinavian forestry) and more than 5500 machines for stem- or tree-cutting methods (generally used in North American or Soviet Union forestry) (Drushka &

Konttinen 1997). In 1957 the first Swedish tailor-made forest tractor was introduced, and manufactured in large numbers (Östberg 1990). The introduction in 1959 of the first hydraulic grapple loaders, mounted on tractors, was a highly important development for Scandinavian forestry (Malmberg 1988). A forwarder with articulated steering, inspired by the American “Blue ox” skidder and invented in 1962, was the next important Swedish breakthrough (Staaf 1988). Nevertheless, in the year 1960, the horse was still used for extracting more than 80% of the total volume of logs extracted in Sweden, but by 1970 mechanised extraction was totally dominant with 95% of the volume (Andersson 2004). Machines for debranching and log cutting were introduced in the years 1966-67 (Nordansjö 1988) and machines for tree-felling in 1972 (Östberg 1990). The whole CTL-harvesting operation was then mechanised. Harvesters, which fell trees, debranch and cut logs, were invented in Sweden and Finland in the years 1972-73 (Drushka & Konttinen 1997). In 1982 in professional forestry in Sweden, 51% of the volumes from final fellings were cut with a two-machine system (one for tree felling and one for debranching and log cutting), 21% of the volume was cut with a harvester and 24% was cut motor manually (using a chain-saw). The corresponding values five years later were 25, 44 and 15%, respectively (Fryk et al. 1991).

The basic principles for CTL forest machines have remained the same since the 1990s. Developments since then have been mainly focused on raising productivity, reducing costs and optimising the division of the trees into logs.

The mechanisation 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). However, a further phase of mechanisation may occur when machines with no operators that can work autonomously are developed (Gellerstedt et al. 1996). The machine presented by Golob (1981) that required no operator for tree felling, debranching and laying stems in piles can be seen as an early conceptual example of such a machine. The forces driving mechanisation 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).

3. 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 m³ per year if a forest machine produces 20 m³ per hour over an annual work-time of 3000 hours (with two drivers working in shifts). To increase the annual work-time to more than 3000 hours using the same machines more drivers would be required, and complex logistics with huge numbers of machine movements between harvesting sites. However, there is another way to achieve the same annual production levels. A year has 8760 hours, and if a machine can work autonomously it might be possible for it to work efficiently over perhaps 6000 hours per year. The same annual production level (60 000 m³) could then be delivered by a machine producing only 10

m³ 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 bottle-neck

Crane-speeds are currently limited essentially by the speeds their operators can handle, which equate to average productivity levels of ca. 20 m³ 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 – 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 manoeuvres 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 taken at high pace, and the operator often becomes a production bottle-neck. 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 30-40% 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. This damage could be reduced, while maintaining overall productivity levels, by using an autonomous harvesting system working 6000 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 30-50 trees per hour with much slower crane movements, and consequent reductions in mechanical stress, and 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 speeds and loads can be lower, and the removal of the driver cabin alone can reduce the mass by ca. a tonne. It is also easier to optimise 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 9-10 tonne forwarder would then be able to carry a load of 10 tonnes, and the total mass would still not exceed 19-20 tonnes. Such a machine would place considerably less stress on the forest ground and tires than current forest machines. A lighter machine, with a higher load/mass ratio, would also consume less fuel and generate less emission per m³ handled.

4. WHAT IS REQUIRED FOR AUTONOMOUS WORK SYSTEMS IN FORESTRY?

For the foreseeable future human beings will play a central role in the manoeuvring 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 the following:

- ❖ 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, judgements 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 the ground, slant of the tree, wind affecting the tree and environmental considerations.
- ❖ In what direction should a tree be felled? The tree-felling has to be done without risks to human beings, the machine itself or surrounding objects, for example power transmission lines. 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 road-side 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 three following main areas.

Support for decision-making

The driver of a harvester has to take many decisions (regarding, *inter alia*, where the machine should be positioned, where small piles of logs should be placed and what trees should be harvested), and systems that could facilitate the 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.) (cf. Vestlund 2005). A semi-autonomous way to solve this problem was presented by Kurabyashi & 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 the stand characteristics that the algorithm relies on need to be developed before it can be fully implemented (Vestlund 2005).

Extraction of logs to the road-side does not require many difficult decisions to be taken. The route is already roughly known because the harvester has already driven from the road-side to the harvesting site, and manoeuvred at the site when harvesting trees. The harvester has also placed small piles of saw-logs and pulp-wood 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 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 all times, and how it should manoeuvre to follow the decided route. Systems for detecting obstacles, human beings, animals, other machines and buildings are also needed, as well as advanced transmission systems to avoid unnecessary slippage.

5. POSSIBLE SCENARIOS

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

Remote supervision

This approach is based on a human remotely supervising a semi-autonomous system. When necessary, the operator can take control of the system. Examples of this can be found in the mining industry, for example LKAB have used unmanned loaders for several years that are capable of autonomously navigating in mines. In forest applications, a process operator could supervise such systems from his or her 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 indicate that this could 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 yet been tested in practice, but has been deemed in a study by Hallonborg (2003) 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.

6. CURRENT RESEARCH TOWARDS DEVELOPING AN AUTONOMOUS FOREST VEHICLE

During the last few years we have 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, at the IFOR-centre, Umeå University. 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 aim 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. However, due to inaccuracies in signals from the position sensors in combination with unevenness of the ground, 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. However, 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 1 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.

The main technical challenges that need to be resolved to enable autonomous forest vehicles are more refined techniques for positioning and obstacle detection. Solutions for these problems are needed for the main task of path tracking. A few possible approaches for these areas are presented below.

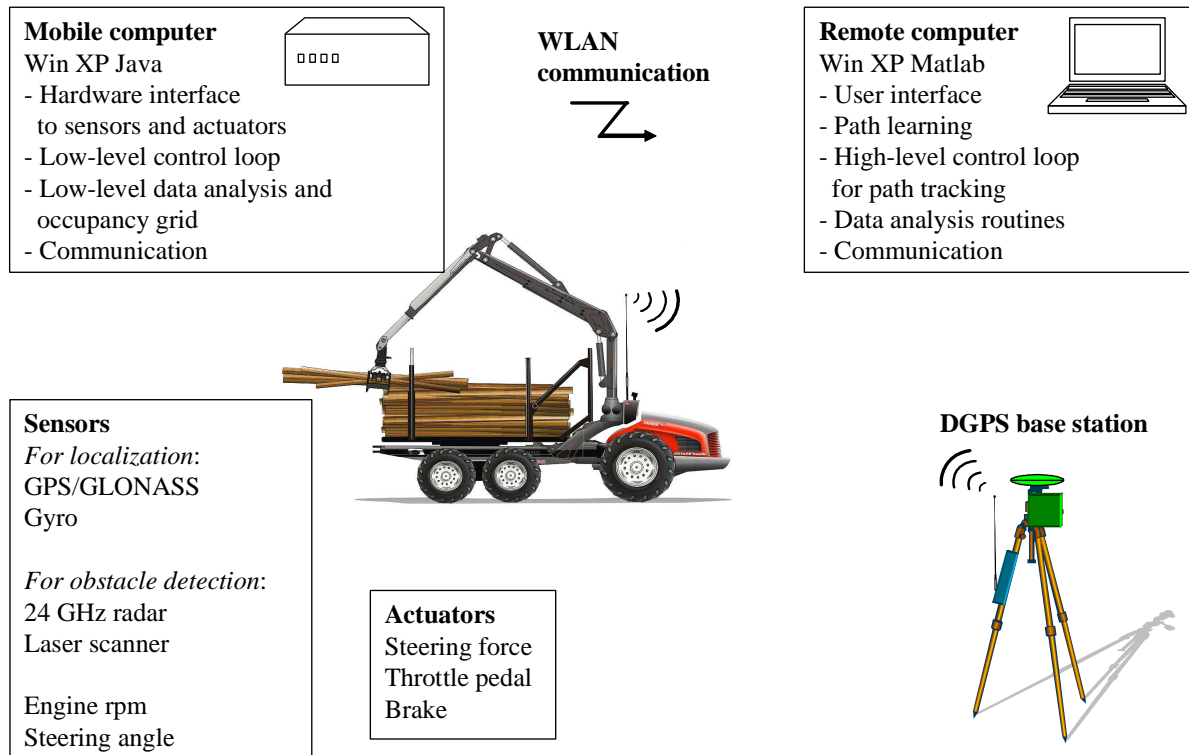


Figure 1. System overview of prototype machine. Two computers share the computing tasks; one handles low-level tasks such as processing sensor information, while the other handles higher level tasks, including path tracking, learning new paths, and user interfaces. The forest machine shown is a concept of what a future autonomous shuttle could look like.

Positioning

For positioning, an accuracy of ± 1 meter 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 couple of decimetres from true values to ensure safe control of a large forest machine. The following sensor techniques have been tested in the project:

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 centimetres. 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 degrees north) where the work is being conducted. 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. In the near future, the European Galileo system will hopefully contribute additional positional information. However, all satellite navigation systems are sensitive to the reception conditions, and in a forest environment the accuracy can easily deteriorate to 0.5 metres or worse. In order to navigate even when the satellite navigation system is not providing sufficient accuracy, techniques for combining several sensors have been developed. Using this approach the accuracy can be increased sufficiently to autonomously navigate the vehicle for

a limited time, for example through a dense part of the forest. The sensing techniques used for this purpose are briefly described below.

Laser odometry - Algorithms for a positioning technique called *laser odometry* have been developed and evaluated in the project. A laser scanner mounted at the front of the vehicle emits pulsed laser beams in a 180-degree sweep and measures the distance to any object that reflects the beam back to the scanner. This results in a picture of the nearest surroundings consisting of 181 points. More technical details on the laser scanner are given below. To calculate how the vehicle has moved between the times that two pictures were acquired, they are compared to each other. In simplified terms, the algorithm that does this translates and rotates one picture until as many as possible points in the two pictures coincide. This translation and rotation correspond to the changes in the vehicle's pose between the two measurements. To obtain information on the vehicle's position and heading, all movement changes are summed. A drawback associated with this method is that many small errors accumulate, aggregating to total errors that increase with time. This drawback also affects many other localization techniques. Consequently, sufficient accuracy can only be maintained for short periods of time. Poor accuracy has been obtained in initial tests of laser odometry in a forest environment, but further tests are needed to determine how well this technique could work in practice.

Wheel odometry - A vehicle's movements can be calculated from measurements of its velocity and steering angles. A problem with this technique is that the vehicle's wheels can slip considerably, resulting in reduced accuracy. Another problem, 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, leading to the introduction of small, cumulative errors in each step of the calculations when the machine is changing heading, and thus drift similar to the drift affecting laser odometry, as described above. 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 metre 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. However, 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 we can obtain a good estimate of the vehicle's change in heading during the sampling period. The vehicle's current heading is calculated by summing these changes. Like the values provided by odometry-based methods for determining position, the values obtained here are subject to drift over time. However, the gyro system is much more accurate than systems based on either

wheel odometry or laser odometry. Estimates of heading from the gyro can be used with sufficient accuracy (± 5 degrees) 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, like a stone, or a traversable object like a bush. Rough terrain and “negative obstacles” (e.g. holes in the ground) present further challenges.

In the project, information from a laser scanner and a radar sensor is being used to create and update local maps 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 - An LMS 221 laser scanner supplied by SICK, which operates by measuring the time of flight of laser light pulses, is 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 metres. To reduce the scanner’s sensitivity to rain or snow, the scanner takes several consecutive scans in the same direction. By comparing these scans, it is able to determine whether there is a real obstacle at a spot from which it detected a signal or if the signal was due to something temporary like a snow flake. The LMS 221 laser scanner has an accuracy of ± 35 mm and is able to do a 180 degree scan in 13-53 ms, depending on the angular resolution.

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 centimetres and the radar unit can detect obstacles up to 30 metres away.

Path-tracking

The vehicle has to be able to answer autonomously 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 answered with the help of positioning sensors and systems, an important component of which is the satellite navigation system. 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 towards 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, 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
3. Turn towards 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, Koren 1991) is responsible for avoiding obstacles and has a higher priority than the route-following module. The steering angle is corrected if an obstacle is detected on the route. The vehicle then waits for an intervention by an operator if too large a correction is needed to avoid collision.

7. FIELD STUDY

The techniques for path-tracking, localization, and obstacle detection described above were evaluated on a 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 GPS positional data, an AHRS400 gyro was used.

To assess the performance of the developed system in general and the path-tracking algorithm *Follow the Past* in particular, a 160 metres long path was tracked four times while measuring the distance to the reference path with the GPS. In addition, manual measurements were obtained by marking the ground at the rear tire of the forest machine at intervals during each run and then measuring the distance between the reference path and the new run with a measuring tape. The tests were performed on flat ground to minimize the effect of vehicle roll and pitch. The ground was covered by a thin layer of snow.

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 is used to generate pictures from which an occupancy grid is derived, and the obstacle-avoidance algorithm *VFH+* is used to modify the direction of travel if any obstacles are detected along the planned path.

The average distance from the path in the four runs was 0.10 metres according to the GPS, and 0.07 metres according to the manual measurements while the maximum errors were 0.35 metres and 0.4 metres, respectively (Table 1; Fig. 2). The differences in distances obtained by the two measuring techniques are well within the margins of error, given the accuracy of the GPS and the manual measuring procedure.

Table 1. Distances from the reference path presented as means (m) and standard deviations (σ) for each run and for all measurements together. The values are presented separately for the manual measurements (man) and the GPS measurements (gps). N is the number of measurements in each run.

RUN	m_{man} [m]	σ_{man} [m]	N_{man}	m_{gps} [m]	σ_{gps} [m]	N_{gps}
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	-

The probability of path-tracking errors less than 23 centimetres is 90% (Figure 3). Errors larger than 38 centimetres were never observed during any of the four test runs, in which a total of 2378 measurements were obtained.

With the implemented obstacle avoidance algorithm VFH+, the vehicle is able to avoid obstacles and subsequently return to the learnt path (Figure 4). The obstacles were detected using a laser scanner and an occupancy grid.

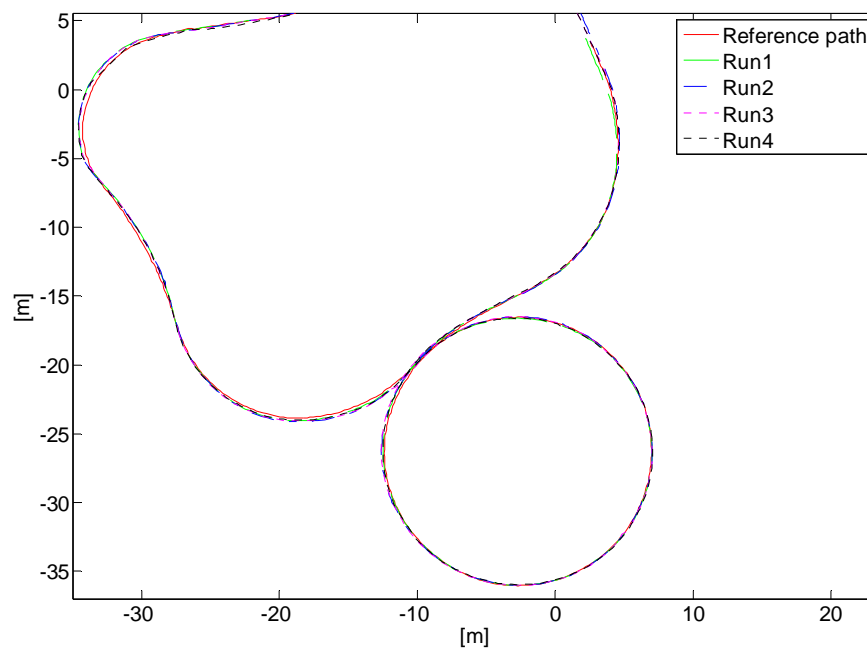


Figure 2. Comparison of a 160-metre long reference path and four autonomous runs with the developed path-tracking algorithm Follow the Past. The data show that the runs coincide almost completely.

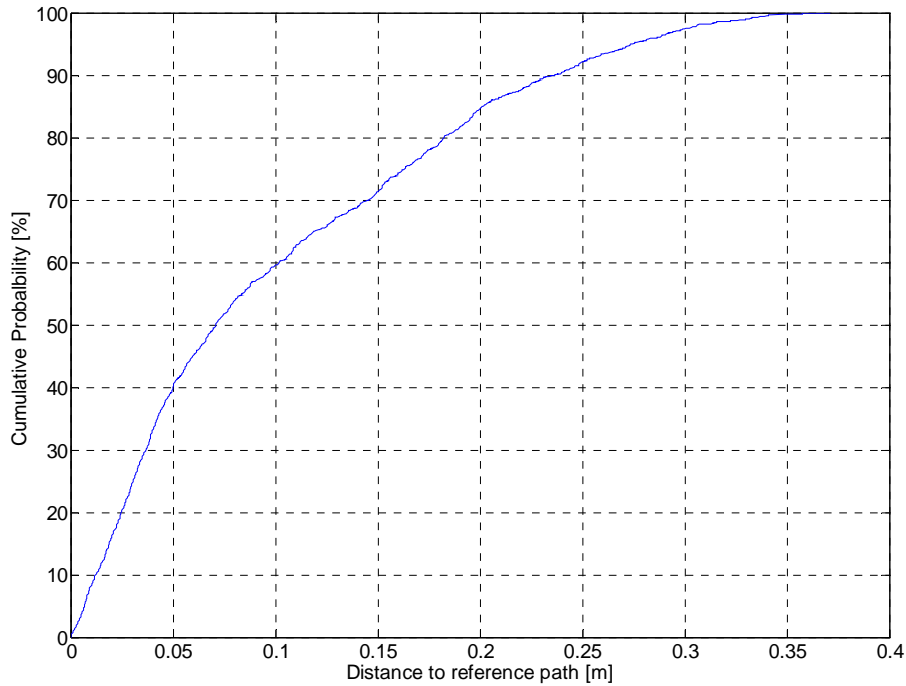


Figure 3. Cumulative distribution function (CDF) for the path-tracking errors (distance from the reference path), obtained using the GPS.

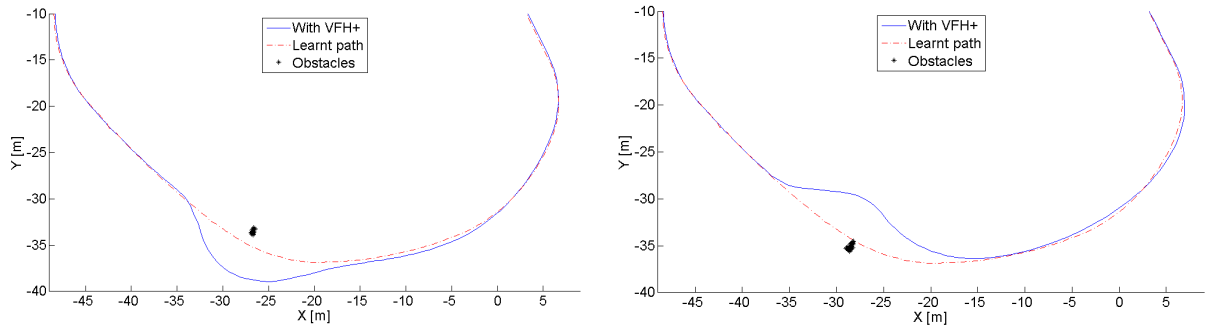


Figure 4. Obstacle avoidance. (Left) The obstacle is placed to the left of the centreline of the vehicle. (Right) The obstacle is placed to the right of the centreline of the vehicle. The vehicle's starting point is at the upper left corner of the figure. The obstacles were detected using a laser scanner and an occupancy grid.

8. DISCUSSION AND CONCLUSIONS

The presented system has demonstrated both possibilities and difficulties associated with autonomous forest machines. It is shown that it is quite 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 is used. The results from the field study confirm the centimetre 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 of satellite navigation systems can deteriorate considerably when the GPS-signals are obstructed by obstacles such as large trees. For these reasons we have developed algorithms for laser odometry, neural networks to improve wheel odometry, and techniques for combining information provided by several position and heading sensors. The laser odometry system is highly sensitive to inaccurate readings, and tests in forest environments have shown that it is difficult to make it more accurate than wheel odometry. 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. This 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, for example just before a steep incline. Distinguishing between an obstacle and something the machine can simply drive over, e.g. a large stone versus a shrub, presents further challenges. Detecting "negative obstacles", e.g. a ditch or 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 we have mainly used the laser scanner, which is able to detect obstacles in front of the vehicle. To keep track of obstacles and reduce the number of false positive readings, an occupancy grid based on Bayesian updating is used.

To avoid detected obstacles, the VFH+ algorithm is used. We have found that 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 behaviour of the vehicle, in terms of variables such as how close to an obstacle it will go, can be altered by changing parameters in the VFH+ algorithm. Major efforts to develop systems for avoiding obstacles in rough terrain are being made by various groups around the world (cf. Iagnemma & Bohler 2006.).

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 10-20 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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