Automation in Forestry – Development of Unmanned Forwarders

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PhD Thesis, May 2011
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Abstract

For the last 50 year, forestry operations have become more and more mechanized. In modern forestry in Europe two machines are typically used; a *harvester* that fells, debranches and cross-cuts the trees into logs and a *forwarder* that transports them to the nearest road. These machines are technically advanced and quite expensive, but have a very high production rate. In fact, the productivity is so high that the human operator risks becoming a bottleneck if the machines become even more efficient. One way of solving this is to change working methods such that some work tasks are not needed anymore. In this way, efficiency is improved without increasing the workload. Another way to solve the problem is to develop (semi-)autonomous vehicles.

One part of the work described in this thesis is an analysis of the economical performance of four potential systems based on the concept of integrated loading. Two of these systems use autonomous forest machines. Results from simulations with large amounts of real forest data show that a promising system is an autonomous forwarder switching loads with a manned *harwarder*, a combination of harvester and forwarder. Autonomous forwarders able to do the same work as conventional forwarders would be even more profitable than any of the other systems analyzed in this study.

The development of techniques and algorithms for autonomous navigation of forwarders that transport logs from the harvesting site to the nearest transportation road is a major part of the thesis. A novel path-tracking algorithm is introduced that is able to accurately guide a forest machine along a previously demonstrated path with high accuracy. To avoid obstacles, the VFH+ algorithm was modified to work on forest machines. However, tests with a forwarder showed that this algorithm performs unsatisfactory when there are narrow passages to negotiate with obstacles close to both sides of the vehicle. This led us to develop a real-time path-planner for off-road vehicles using a simulator to predict collisions in a window forward in time. The path-planner is able to safely navigate a forest machine around obstacles on and close to the path in a way that is hard or impossible to achieve with regular obstacle-avoidance algorithms that do not take the shape of the vehicle into account.

To handle a multitude of sensors, actuators, and other hardware in a systematic and uniform way and to enable communication between software modules, a software framework (often called robotics middleware) was developed. The system can be distributed over a network of computers if some software modules require more

computing power. The framework has shown to be a powerful tool for research and development of autonomous vehicles.

A problem in forestry operations is wheel slip causing ground damage and reducing trafficability of forest machines. Using data collected during experiments with the autonomous forest machine, a method for measuring slip was developed. It can be used to detect excessive wheel slip and may ultimately be used to control the machine transmission to reduce the amount of slip.

Sammanfattning

De senaste 50 åren har skogsbruket blivit alltmer mekaniserat. I det moderna skogsbruket i Europa används normalt två olika maskiner; en *skördare* som fäller, kvistar och kapar träden till stockar samt en *skotare* som transporterar dem till närmsta väg. Dessa maskiner är tekniskt avancerade och ganska dyra, men har samtidigt en mycket hög produktivitet. De är så effektiva att föraren riskerar att bli en flaskhals om produktiviteten ökar ännu mer. Ett sätt att lösa detta är att ändra arbetssätt så att ett eller flera arbetsmoment inte behövs längre. Därmed ökar effektiviteten utan att arbetsbördan ökar. Ett annat sätt att lösa problemet är att utveckla (halv-)autonoma fordon.

En del av denna avhandling är en analys av ekonomisk prestanda för fyra tänkbara system som alla bygger på konceptet integrerad lastning, varav två använder autonoma skotare. Resultaten visar att ett lovande system är ett lastväxlingssystem där en autonom skotare byter lastutrymme med en bemannad *drivare*, en kombination av skotare och skördare. Autonoma skotare som kan utföra samma arbete som konventionella skotare visade sig ha störst potential av de analyserade systemen.

Tekniker och algoritmer för autonom navigering av skotare för transport av stockar till närmaste väg är en viktig del i avhandlingen. En ny algoritm för att följa en tidigare demonstrerad väg med hög noggrannhet introduceras. För att undvika hinder modifierades algoritmen VFH+ så att den fungerar med skogsmaskiner. Tester med en skotare visade emellertid att algoritmen presterar otillfredsställande i trånga passager med näraliggande hinder på båda sidor av fordonet. Detta ledde till utvecklingen av en algoritm för ruttplanering för terränggående fordon som med hjälp av en simulator kan förutsäga kollisioner i ett fönster framåt i tiden. Ruttplaneraren klarar att navigera en skogsmaskin förbi hinder som finns på eller nära rutten på ett sätt som är svårt eller omöjligt att uppnå med standardalgoritmer för att undvika hinder, eftersom de inte beaktar formen på fordonet.

För att kunna hantera en mångfald av sensorer, styrdon och annan hårdvara på ett systematiskt och enhetligt sätt, och för att möjliggöra för kommunikation mellan mjukvarumoduler, implementerades ett programvarusystem (ofta kallat middleware). Systemet kan distribueras över ett nätverk av datorer om några programmoduler kräver mer datorkraft. Detta ramverk har visat sig vara ett kraftfullt verktyg för forskning och utveckling av autonoma fordon.

Ett vanligt problem i skogsbruket är hjulslirning som orsakar markskador och minskar framkomligheten för skogsmaskiner. Med hjälp av data som samlats in

under experimenten med den autonoma skogsmaskinen utvecklades en metod för att mäta hjulslirning. Denna metod kan användas för att upptäcka slirning mellan hjul och mark och skulle kunna användas för att styra maskinens transmission för att minska slirning.

Preface

A comment on working interdisciplinary

The work in this thesis began as a pure computer science/robotics project; developing techniques and algorithms for autonomous navigation of forest machines. As the work evolved, I began collaborating with SLU (the Swedish University of Agricultural Sciences) in Umeå to look more into the forestry side of the area of autonomous forest machines (why do we need them?; what is required of an autonomous forest machine? and so on). I soon noticed that the way of writing scientific papers differs a bit between computer science and forestry. In computer science, it is quite common to develop some software solution and then verify that it works as intended. In our case, a research task could for instance involve development of a path-tracking algorithm for a forest machine. This algorithm is then tested on a forest machine to verify that it works as expected. The result of the work is the algorithm itself, and the test is a verification of functionality. The research is motivated by forestry requirements: the need for working autonomous forest machines.

A forestry based viewpoint is typically somewhat different. The motivation could still be the same, but the software solution is regarded as *materials and methods*; as a tool used to produce the real results, e.g. how accurately can it track a path?, in how steep slopes?, in what kind of terrain?, and so on. It is sometimes difficult to fit the description of algorithms and software solutions into this format, where the major work effort is regarded as just a tool and not necessarily have to, or even should, be explained in detail. We want to describe/investigate the results from a forestry perspective, but also from a computer science perspective. Basically we want to describe results from two different scientific disciplines, and this is also the approach we have strived for in the interdisciplinary work included in this thesis.

It is important to mention that the difference in how to present research results is mainly a formatting task when writing joint publications, and not a real difficulty in collaborating with scientists from other fields. On the contrary, working interdisciplinary often gives new valuable perspectives, since colleagues from other fields may have different views on the joint work.

List of Papers

This thesis consists of an introduction to the field and the following seven papers:

Paper I: Thomas Hellström, Pär Lärkeryd, Tomas Nordfjell and Ola Ringdahl. Autonomous Forest Vehicles: Historic, envisioned, and state-of-the-art, *Int. J. of Forest Engineering*, Vol. 20, No.1, pp. 31-38, 2009.

Paper II: Ola Ringdahl, Thomas Hellström and Ola Lindroos. Potentials of possible machine systems for directly loading logs in cut-to-length harvesting. (Submitted manuscript).

Paper III: Thomas Hellström and Ola Ringdahl. Follow the past - a path tracking algorithm for autonomous vehicles. *Int. J. Vehicle Autonomous Systems*, Vol. 4, Nos. 2-4, pp. 216-224, 2006.

Paper IV: Thomas Hellström, Thomas Johansson and Ola Ringdahl. A Java-based Middleware for Control and Sensing in Mobile Robotics. In *International Conference on Intelligent Automation and Robotics* 2008 (ICIAR´08), San Francisco USA, pp. 649-654, 2008.

Paper V: Ola Ringdahl, Ola Lindroos, Thomas Hellström, Dan Bergström, Dimitris Athanassiadis, and Tomas Nordfjell. Path tracking in forest terrain by an autonomous forwarder, *Scandinavian J. of Forest Research*, 2011, 1-10, iFirst article.

Paper VI: Thomas Hellström, Ola Ringdahl. Real time path planning using a simulator-in-the-loop, *Int. J. of Vehicle Autonomous Systems*, Vol. 7, Nos. 1/2, pp. 56–72, 2009.

Paper VII: Thomas Hellström, Ola Lindroos, Ola Ringdahl and Iwan Wästerlund. Estimating wheel slip for a forest machine using RTK-DGPS. (Submitted manuscript).

Other publications by the author

In addition to the papers included in this thesis, the following papers have been published by the author:

1. Dimitris Athanassiadis, Dan Bergström, Thomas Hellström, Ola Lindroos, Tomas Nordfjell and Ola Ringdahl. Path tracking for autonomous forwarders in forest terrain. In *proceedings of the International Precision Forestry Symposium, Stellenbosch, South Africa*, pp. 42-43, 2010.

2. Thomas Hellström and Ola Ringdahl. *Path planning for off-road vehicles with a simulator-in-the-loop.* Technical Report 08.07, Department of Computing Science, Umeå University, May 2008.

3. Thomas Hellström, Pär Lärkeryd, Thomas Nordfjell, and Ola Ringdahl. *Autonomous forest machines - past, present and future.* Technical Report UMINF-08.06, Department of Computing Science, Umeå University, April 2008.

4. Ola Ringdahl and Thomas Hellström. *Autonomous Forest Machines - Techniques and Algorithms for Unmanned Vehicles.* VDM Verlag Dr. Müller, 148 pages, 2008. ISBN 978-3-639-04343-3.

5. Ola Ringdahl. *Techniques and Algorithms for Autonomous Vehicles in Forest Environment.* Licentiate thesis, Department of Computing Science, Umeå University, 2007. ISBN 978-91-7264-373-4.

6. Thomas Hellström, Thomas Johansson, and Ola Ringdahl. *A software framework for control and sensing in mobile robotics.* Technical Report UMINF 07.05, Department of Computing Science, Umeå University, April 2007.

7. Ola Ringdahl and Thomas Hellström. Autonomous navigation in forest environment. In *Proceedings from the 23rd Annual workshop of the Swedish Artificial Intelligence Society (SAIS06),* 2006.

8. Thomas Hellström, Ola Ringdahl, and Arsalan Siddiqui. Path tracking and localization in forest environment. In *Proceedings of the Israel Conference on Robotics (ICR06)*, 2006.

9. Thomas Hellström, Thomas Johansson, and Ola Ringdahl. *Development of an Autonomous Forest Machine for Path Tracking,* volume 25 of *Springer Tracts in Advanced Robotics*, (pp. 603-614). Springer Berlin Heidelberg, 2006.

10. Fredrik Georgsson, Thomas Hellström, Thomas Johansson, Kalle Prorok, Ola Ringdahl, and Urban Sandström. *Development of an autonomous path tracking forest machine — a status report.* Technical Report UMINF 05.08, Department of Computing Science, Umeå University, February 2005.

11. Thomas Hellström and Ola Ringdahl. Autonomous path tracking using recorded orientation and steering commands. In *Proceedings from Towards Autonomous Robotic Systems (TAROS05)*, pages 81–87, London, UK, 2005. ISBN 0-905247-03-5.

12. Thomas Hellström and Ola Ringdahl. Follow the past - a path tracking method using recorded orientation and steering commands. In *The Third Swedish Workshop on Autonomous Robotics (SWAR05)*, 2005.

13. Thomas Hellström and Ola Ringdahl. *Follow the past — a path tracking algorithm for autonomous forest vehicles.* Technical Report UMINF 04.11, Department of Computing Science, Umeå University, 2004.

14. Ola Ringdahl. *Path tracking and obstacle avoidance for forest machines.* Master's thesis, Department of Computing Science, Umeå University, April 2003.

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Ola Lindroos taught me that there are numerous ways of interpreting how to calculate time-consumption, costs and other factors regarding systems analysis. I think I went through them all before I finally managed to do it the way it is supposed to be done. Let us hope I get it right already from the beginning the next time we do something like this together.

Thanks to all co-authors of my papers, without you this thesis would have been a lot thinner. Some would perhaps argue that this would not necessarily be a bad thing, but I am grateful to you nonetheless.

Thank you Erik Billing for enduring me as your office neighbor for all these years and for answering all of my stupid questions (and some really smart ones). I also want to thank all of my other co-workers at the department. You all make it a great working environment.

A special thanks to our industrial partner Komatsu Forest AB for modifying and letting us use their forest machine. In particular, thanks to Per Lärkeryd and Bengt-Arne Walldén who supported the project throughout the years. Thanks to André and the other guys at Komatsu prototype workshop, and Dennis and Fredrik for helping us out when performing tests with the forest machine.

I would also like to thank my family and friends for making life so much better.

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Umeå, April 2011
Ola Ringdahl

Contents

Chapter 1

Introduction

For the last 50 year, forestry operations have become more and more mechanized. The first steps in mechanization were to go from using hand tools and draft animals to using motor-manual tools for felling, and tractors for transportation. In Europe today the *Cut-To-Length (CTL)* system dominates, where a single-grip *harvester* fells, debranches, and cross-cuts trees into logs. A *forwarder* is then used to pick up the processed logs from the ground and transport them to a landing area close to a road accessible by timber-trucks. These technically advanced machines are quite expensive, but have a very high production rate. In fact, the productivity is so high that the human operator risks becoming a bottleneck if the machines become any more efficient, as discussed in Paper I.

One way of solving this is to change working methods such that some work tasks are not needed anymore. In this way, efficiency is improved without increasing the workload. Paper II examines the potential of four different machine systems that enable this by placing logs directly in the load spaces of transporting machines as they are cut, thereby removing the need for picking up logs from the ground.

Another way to solve the bottleneck problem is to develop (semi-) autonomous vehicles. Autonomous harvesters are very hard to implement due to the many difficult decisions that have to be made, e.g. which tree to fell, in which direction to fell the tree, where to position the harvester, and where to put the logs (Paper I). In the experimental system *Besten* , an unmanned harvester is remotely controlled by the forwarder, loading directly onto the bunk. This could be an alternative to developing fully autonomous harvesters.

The forwarder is less difficult to automate. The route between the harvesting site and the landing is roughly known because the harvester has already driven there. Information about where the harvester has left the logs on the ground is available through GPS-information from the machine. There are (at least) three different possible machine systems when using autonomous forwarders:

1. **Fully autonomous forwarder.** Able to pick up logs from the ground, transport and unload them at the landing exactly as today's forwarders but without an operator controlling it. An advantage with this technique would be that it is independent of the harvester. A difficulty with this system is

how to find and load logs from ground.

2. **Direct-loading system.** In this system a manned harvester harvests trees and loads them directly onto the autonomous forwarder. When the forwarder is full, it will go to the landing to unload. Both driving and unloading is done automatically with no human intervention. To avoid that the harvester has to wait, two or more forwarders will have to be used. In this scenario the forwarder does not have to go around and pick up the logs from ground, which could be hard to do fully autonomously.

3. **Load-changing system.** Comprising a manned *harwarder* that cuts, processes and places processed trees directly into its own bunk. When fully loaded, the harwarder switches bunks with an autonomous forwarder, which then moves to the landing and unloads. Since this system has a buffer in the form of the harwarder's bunk, harvesting could be conducted, without waiting time, with one forwarder under certain conditions.

Valuable work in the field of autonomous off-road vehicles has been done in many areas. Research in automation of agriculture machines has come quite a long way, and several applications have been developed. Automation in forestry poses a larger challenge since forest terrain is rarely straight or flat and usually contains many obstacles such as trees and logging debris. The bearing capacity of the ground can sometimes be a problem in forestry, with high wheel slippage and risk of getting stuck as a result. Compared to agriculture, forestry operations include more complex in-field decisions. Most decisions have to be made in real-time, and are often based on prior knowledge and experience.

Another area in which automation has come a long way is autonomous military vehicles, where a lot of resources are spent. The competition DARPA Grand Challenge (Iagnemma & Buehler, 2006), where autonomous vehicles navigated a difficult 280 km long course, is probably one of the best examples of the forefront of the applied research within autonomous off-road vehicles (see Chapter 3). Although many valuable lessons can be learned from previous work, the forestry application is still challenging and a lot of research has to be done in order to realize autonomous forest machines.

In order to make autonomous navigation of forest machines possible, a number of components are needed. First of all, the vehicle has to be controlled somehow. Most modern forest machines are already controlled by computers communicating by CAN-bus. This makes interfacing easy since commands can be sent to the built-in computers to control the vehicle. To navigate autonomously, a path has to be planned (Paper VI) and algorithms to follow this path while avoiding obstacles has to be developed (Paper III). The most common way to determine the vehicle's location is to use GPS. To get accurate position estimation, the GPS-antenna has to have line-of-sight to at least four satellites (Drane & Rizos, 1998). This can be a problem in a forest where there are many trees potentially blocking the satellite signals (Durrant-Whyte, 2001). When this occurs, the position has to be estimated by other means, e.g. wheel odometry or an inertial navigation system (INS). To detect obstacles that the vehicle has to avoid, sensors like laser scanners, radars, cameras, and stereo vision are commonly used, c.f. Thrun et al. (2006). An additional use of obstacle sensors is for building maps of the surroundings that can be used for path planning or for localization. In the latter case, two maps built from consecutive sensor readings can be compared to each other to calculate the relative movement from the previous pose (Hellström et al., 2006b). Another way is to save several maps along the recorded path and then compare each new map to the saved ones to calculate an absolute position.

To investigate if autonomous forest machine systems would at all be profitable, a system analysis was made (Paper II). The result showed that autonomous systems have potential to be more profitable than today's systems. The work with developing the autonomous forwarder described in this thesis began with design and development of a simulator environment and path tracking and obstacle avoidance algorithms for a simulated forwarder (Ringdahl, 2003; Hellström et al., 2006a; Paper III). The next step was to implement a software platform supporting all the necessary hardware such as sensors, actuators and vehicles (Paper IV). The platform and all algorithms where tested and tuned on a small Pioneer robot before moving everything to a full-size forest machine. Some diagnostic routines for both hardware and software components were developed along the way to ensure safe operation of the autonomous forest machine.

Initially, the algorithm VFH+ (Ulrich & Borenstein, 1998) was used to avoid obstacles. This algorithm was originally designed for small circular robots, and our tests on a full-size forest machine showed that the algorithm did not perform well in narrow passages. The path-planning algorithm described in Paper VI was developed to enable the forest machine to safely navigate between obstacles without colliding with them. It uses a simulator that, in real-time, tries to predict collisions in a window forward in time. If a collision is predicted, the simulator tries to find a new, collision-free, path for the forest machine to follow.

Wheel slip causes ground damage and reduces trafficability of forest machines. Paper VII proposes a method that measures slip and can be used to detect excessive wheel slip, and may ultimately be used to control the machine transmission to reduce the amount of slip.

1.1 Outline

This thesis describes the development of some of the components needed for autonomous forest machines, in particular forwarders that transport logs from the harvesting site to a nearby road. Some reasons why we want to develop autonomous forest machines are given and an analysis of the economical viability, based on extensive simulations, is given. The thesis consists of an introductory part followed by seven papers, numbered I to VII. The rest of the introductory part is organized as follows:

Chapter 2 contains a short historical background of mechanization in forestry, followed by a section about automation in modern forestry and the possibilities to develop it even further. Chapter 3 describes three major techniques needed to enable autonomous navigation; path planning, path tracking, and obstacle avoidance. An example of how far development of autonomous off-road vehicles has come is also given in the chapter. The introductory part of the thesis is concluded in Chapter 4 which contains a short summary of the included papers and some conclusions of the achieved results.

Chapter 2

Forest technology

This chapter contains a short historical background to the mechanization of forestry, followed by a section about the technology used in modern forestry and the possibilities to develop it even further.

2.1 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 mechanization of forestry started much later than the mechanization of agriculture (Sundberg, 1978; Silversides, 1997), with the introduction of the chainsaw for harvesting and tractors for extraction. Nevertheless, there were some early examples of technical forestry innovations.

The first chainsaws 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 chainsaws in 1938, six in 1942 and thirty in 1949 (Silversides, 1997). The definitive breakthrough for chainsaws occurred 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 chainsaws, but by 1960 this proportion had increased to almost 100% (Silversides, 1997). Trends in the European countries were similar, and a number of chainsaw factories were built in Sweden and Germany. Chainsaws were still used by full-time 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 and onward to use tractors in forestry for hauling cut trees out of the forest (Brown, 1949; Silversides, 1997). An important step in mechanization 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 of logs were invented in the Soviet Union around 1950 and in North America during the 1950s (Andersson, 2004). A *skidder* with articulated steering was invented in North America 1959 to transport cut trees out of the forest (Silversides, 1997).

In addition, several machines for mechanized 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 mechanization 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 at the beginning of the 1930s (Drushka & Konttinen, 1997).

Total global sales of forest machines in 1966 amounted to ca. 400 Cut To Length (CTL) machines (generally used in Scandinavian forestry) and more than 5500 machines for stem- or tree-cutting methods (generally used in North American and 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).

The mechanization of forestry was rapid in the 1960s. Horses were still used for extraction of more than 80% of the total volume of logs extracted in Sweden 1960. By 1970 mechanized extraction was totally dominant with 95% of the total 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 mechanized. Harvesters, which fell trees, debranch and cross-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 chainsaw). 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 optimizing the cross-cutting of the trees into logs. The mechanization of logging can be divided into six phases according to Silversides (1997), in which the equipment used were predominantly: hand tools and draft 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 mechanization 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 mechanization are lack of workers, aspiration to conduct forestry operations year-round and for more hours per day, and a desire to reduce costs, the amounts of hard physical work involved, and the lead-times between logging and industrial processing (Sundberg, 1978; Silversides, 1997).

2.2 Modern Forestry

The export value of forest products in Sweden 2009 was 12% of the total export value (Anon, 2010), making forestry one of the most important business in Sweden. This is possible because the developments in Cut-To-Length (CTL) forest technology has been world leading in Sweden and the neighboring Finland since the sixties. CTL is the most common logging system used in European countries today. The system utilizes two machines: a *harvester* and a *forwarder*. The harvester fells the trees, delimbs them and finally crosscuts them in the desired length. This is a highly automated process with just a little intervention from the operator to get as high productivity as possible. A modern harvester can handle up to 100 trees per hour. The forwarder then picks up the logs from ground and transports them to a roadside landing for further transportation to the saw- or pulp-mill.

A relatively new concept is the combi machine (or *harwarder*) that replaces the harvester and forwarder. It processes the trees directly onto its bunk and drives to the roadside landing to unload when the bunk is full. Some combi machines first harvest all the trees, leaving them on the ground. Then the machine is slightly modified to work as a forwarder that picks up and hauls the logs to roadside landing. According to Hallonborg & Nordén (2000), the key advantage of a combi-machine to that of a conventional system is to not have to first leave the timber on the ground. By depositing it directly to the bunk instead, the system can be more profitable than a harvester-forwarder combination. According to Bergkvist (2007), the harwarder is profitable when used in stands with small diameters, close to the road. When used in stands with larger diameters and/or further away from the road the traditional harvester-forwarder combination is more profitable. Because the loading is done directly, the risk of logs being left behind on the ground (e.g. under the snow) is avoided. Fuel consumption per harvested volume is lower, which means this method is more environmental friendly. When moving the machine between sites, you only have to consider one machine, making the transport easier and less expensive.

The forest industry is under keen competition, and must therefore constantly develop its products to make them more profitable. Since the modern harvester is able to make use of almost 100 % of the trees' value, the harvesting speed (m^3/h) must be increased to make it more efficient. A problem with this is that the operator works under stressful conditions today, and if the harvesting speed rises even further, the operator risk becoming a bottleneck. To solve this, the operator will have to be replaced by a fully autonomous machine, or at least get help from semi-autonomous systems. Papers I and V discusses some reasons for developing autonomous forest vehicles and also some of the challenges involved.

2.2.1 Boom-tip control

An operator of a forwarder crane has to manually control each hydraulic cylinder to position the boom-tip at the desired position. With boom-tip control the forwarder operator simply points the joystick in the direction he wants the machine's knuckle boom to go. The Smart-Crane lab at Umeå University is currently developing methods for boom-tip control of forwarder crane (Hera et al., 2008). A study by Löfgren (2006) shows that this system is easier to learn than a conventional system, resulting in reduced time for new operators to become productive. The study also shows that the system reduces the perceived workload of the operators. Boom-tip control could also open up for automated functions for loading and unloading, allowing the driver to get micro pauses which help relieve stress (Shiriaev et al., 2008). Due to softer crane movements, the mechanical stress on the crane can also be reduced, prolonging the life span of the crane system.

2.2.2 Automation of forest machines

Löfgren (2006) has analyzed the effects on logging of three possible future unmanned harvesting systems, and compared the costs of these with those of today's harvester and harwarder systems. The first system consists of one or two forwarders remote-controlling an unmanned harvester that cuts the trees and loads them directly onto the forwarder, which then unloads at the nearest road. A system similar to this, called Besten ["the Beast"], has been developed in Sweden (Bergkvist et al., 2006). The second system analyzed was a harvester operating with one or two unmanned shuttles. The harvester loads directly onto the shuttle, which then takes the timber out of the forest. Lastly a harwarder operating with one or two unmanned forwarders was compared. In this scenario, the harwarder loads onto its own bunk and then switches bunk with the unmanned forwarder.

The study found that logging costs may increase, compared to conventional harvesting systems, if waiting time occurs because of the harvesting and extraction machines being out of phase. In systems using a remote-controlled harvester or autonomous forwarders, the machines are tied to each other during harvesting/loading, which automatically give rise to waiting times unless two forwarders are in use, and harvesting and extraction are in phase.

The conclusion of Löfgren's study was that the most competitive system, compared with today's harvester/forwarder system, is using two unmanned shuttles in combination with a conventional harvester. The technology required for autonomous shuttles will take time (and money) to develop, while the technology required for the remote-controlled harvester system in principle is already available. According to the study, this makes the difference in competitiveness between these two systems much smaller. In Paper II, a simulator was used to study the competitiveness of the above mentioned systems. The results differ somewhat from Löfgren and shows that the system with a remote-controlled harvester was the least competitive of the analyzed systems.

Chapter 3

Navigation for Autonomous Ground Vehicles

Work on autonomous vehicles for indoor use has been conducted since the late 1960s (mostly with different sorts of robots), but in later years vehicles for outdoor use, referred to as Autonomous Ground Vehicles (AGV), have been developed. Applications are mostly in military reconnaissance, automated machines for agriculture, mining, and construction, and automation equipment for passenger cars. Some tasks can be hard to render fully autonomous and may require some kind of supervisory or *semi-autonomous* control. This can be done in two different ways (Murphy, 2000). In *continuous assistance systems*, an operator delegates a (sub-) task to the AGV and only has to monitor ensuring that nothing goes wrong. If the vehicle is unable to complete the task, the operator can take over and remote-control it to overcome the difficulties.

The other approach to semi-autonomous control is *control trading*. Much like in continuous assistance, the operator assigns a task to the AGV, but does not have to monitor the vehicle while it performs its task. This enables the operator to control several vehicles simultaneously because he/she only has to give new orders when a task is done and can then leave the AGV to its work.

The two major reasons for developing autonomous vehicles found in most works about AGVs are cost efficiency (less labor cost) and safety (e.g. in hazardous environments).

The military is in the fore front in development of autonomous vehicles, mainly in order to reduce risks for personnel. The United States Army has a goal that one-third of the operational ground combat vehicles should be unmanned by 2015. To promote research in the area of autonomous vehicles, DARPA (Defense Advanced Research Projects Agency) has held a competition called The Grand Challenge (Iagnemma & Buehler, 2006). The challenge consisted of building a robot capable of navigating 280 kilometers through desert terrain in less than 10 hours, with no human intervention. The first competition was held in 2004, but none of the 15 participating robots managed to navigate more than 5% of the entire course.

The Challenge was repeated in 2005 and this time 5 of 23 participants managed to complete the whole course. The vehicles passed through three narrow tunnels (thereby loosing GPS coverage) and negotiated more than 100 sharp turns. The race concluded through Beer Bottle Pass, a winding mountain pass with sheer drop-offs on both sides. The winner was Stanford's robot Stanley (Thrun et al., 2006) making it in just under 7 hours. The path was defined by a number of GPS coordinates (lat-long) and corresponding width of the path. This meant that the teams did not have to do any global path planning, as the path was already defined by DARPA.

The Stanley robot was a modified four-wheel-drive car with many sensors to perceive the environment and estimate the position of the vehicle. To be able to scan the environment in front of the car, they used five SICK laser range-finders. The lasers measured cross-sections of the approaching terrain at different ranges up to 25 meters in front of the vehicle. The vehicle was also equipped with a color camera for long-range road perception. For long-range detection of large obstacles, Stanley also held two 24 GHz radar sensors to cover the frontal area up to 200 meter, with a coverage angle in azimuth of about 20 degrees. The Stanford team used an online path planner to decide the optimal path inside the corridor given by DARPA. This was done by applying a search algorithm that minimizes a linear combination of continuous cost functions, subject to a fixed vehicle model. The cost functions penalize running over obstacles, leaving the path corridor, and the lateral offset from the current trajectory to the sensed center of the road surface.

The conclusions drawn by Stanford's team were that, although the DARPA Grand Challenge was a milestone in the quest for self-driving cars, a number of problems still need to be solved to get reliable autonomous vehicles. The race environment was entirely static. However, to be able to construct autonomous cars, they must be able to perceive and interact with moving traffic. Even when driving in static environments, the Stanley robot can only handle limited types of obstacles. It cannot distinguish between a rock and tall grass, for example.

In 2007 the DARPA Urban Challenge was held at a closed down air force base and involved a 96 km urban area course, to be completed in less than 6 hours. This event required teams to build an autonomous vehicle capable of driving in traffic, performing complex maneuvers such as merging, passing, parking and negotiating intersections. Rules included obeying all traffic regulations while negotiating with other traffic and obstacles and merging into traffic. Of eleven competitors, six managed to complete the whole course.

The remainders of this chapter describes three major techniques needed for autonomous navigation; path planning, path tracking, and obstacle avoidance.

3.1 Path planning

A purely reactive vehicle is able to move around in the world without colliding with obstacles, but in an unstructured environment it has no way to know where it should go to reach the goal other than just wandering around until it reaches it. To be able to move a vehicle from start to goal in a safe and efficient way, a planned path is required between these points. Path-planning techniques are usually divided into two categories (Murphy, 2000):

- **Topological Path Planning**
  A path is planned between several landmarks that the vehicle has to recognize. This method is usually used indoors because it is easier to perceive the landmarks (for example an intersection in a corridor). In our tests with laser odometry (Hellström et al., 2006b), we found that it is very hard to compare two “images” taken by a laser scanner in a forest environment. We found that the laser odometry is sensitive to the large movement of the forest machine’s front end, occurring when the steering angle is changed or driving over a large stump for example.

- **Metric path Planning**
  Instead of using landmarks, this planning technique utilize waypoints, represented by (x,y)-coordinates. These coordinates could for instance be measured using GPS.

In many applications the vehicle builds a map of the world by itself, by driving around in the environment while recording sensor data and generating (or updating) a map from it. Combined with the task of localizing the vehicle in the environment, this is called *SLAM, Simultaneous Localization and Mapping.*

In the case of a forest machine, it would be best to use a geographical map to generate a suitable path from. Another source of information could be an aerial photo of the area. The problem with using a geographic map for path planning is that it is difficult to generate a path that is really traversable for the vehicle. In a forest there could be obstacles such as fallen trees or large boulders that do not show on the map, and the ground could be mire, for example.

Irrespective of the source, a representation of the world must be used that enables a search for the optimal path. The most popular representation is a regular grid. Many solutions have been suggested for solving the problem of partially known environments. Lumelsky & Stepanov (1986) initially assume the environment has no obstacles and simply plans a path straight between start and goal. If an obstacle appears in front of the vehicle, it moves around it and then continues straight towards the goal again. Stentz (1994) developed a more optimal way of planning, called D*. The planner begins with an *a priori* map (the world map known from the start) and computes the optimal path from every location to the goal. This is implemented by doing in advance an A* search from each possible location to the goal. This means that if the vehicle has to go around an obstacle, it knows the optimal path to the goal from the new position. The algorithm also re-plans continuously as the vehicle moves along in the world, and adapts from changes in the environment not on the a priori map.

In Paper VI we developed a path-planning algorithm based on a simulator that tests different alternative ways to go between two points and finds the best one in terms of avoiding obstacles while staying as close to the original path as possible.

To perform global path planning, i.e. plan a route from start to goal and not just a few meters ahead, an accurate map of the surroundings is needed. Digital terrain maps are available from Lantmäteriet (Swedish Land Survey) containing information about houses, roads, rivers and lakes, and type of terrain. The resolution is 5 meters, meaning that each pixel corresponds to 5x5 meters on the ground. This is not enough for accurate path planning. Laser scanning from the air to do inventory of the forest is becoming more and more common. In addition, this technique can be used to create high resolution (about 10-20 cm) terrain maps, and showing the position of individual trees (Hollaus et al., 2007). This map can then be used for path planning in 3D.

3.2 Path tracking

The aim of path tracking is to guide a vehicle along a geometric path by applying appropriate steering motions. The goal of a path tracking controller is to minimize the lateral distance between the vehicle and the path, minimize the difference in the vehicle's heading and the defined path's heading, and limit steering inputs to smooth motions while maintaining stability (Snider, 2009). Geometric trackers exploit geometric relationships between the vehicle and the path resulting in control law solutions to the path tracking problem. These techniques often make use of a look-ahead distance to calculate error ahead of the vehicle and can extend from simple circular arc calculations to more complicated computations involving screw theory (Wit, 2000).

The Pure-Pursuit method (Amidi, 1990; Wallace et al., 1985) and variations of it are among the most common approaches to the path tracking problem for mobile robots (Snider, 2009). A circular arc is fitted between the vehicle and a goal point on the path, located on a look-ahead distance in front of the vehicle, as illustrated in Figure 3.1. This circle is uniquely defined by adding the condition that the heading of the vehicle should be along the tangent line of the turning circle. The Pure-Pursuit method enables a smoother steering control, and improves the vehicle's ability to handle curved paths with lesser short-cuts than Follow the Carrot, which is another common method for path planning (Barton, 2001). The reason is that the vehicle normally moves along circular arcs when turning, rather than along straight lines, hence trying to follow a circular arc is more natural than a straight line. An analogy is a driver of a car who looks at a point further ahead on the road and then tends to steer smoothly toward that point, thereby driving in circular arcs on a curved road.

Another method, called the Stanley method (Thrun et al., 2006), was developed by Stanford University in connection with their participation in the DARPA Grand Challenge (Iagnemma & Buehler, 2006). The key error metric is the cross-track error x, i.e. the lateral distance between the vehicle and the path. If the vehicle has a heading error ψ_e, the steering angle ϕ at time t is calculated as:

$$\phi(t) = \psi_e(t) + \arctan\left(\frac{kx(t)}{v(t)}\right) \tag{3.1}$$

where $v(t)$ is the vehicle's velocity at time t and k is a gain parameter. The first term matches the steering angle to the path's heading. The second term adjusts the steering angle proportional to the cross tracking error $x(t)$. Having velocity in

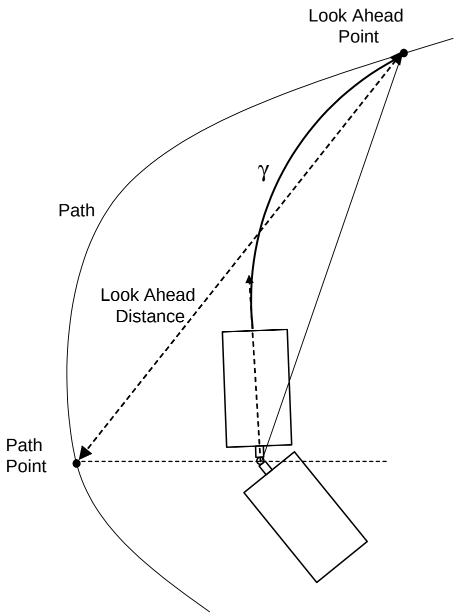

Figure 3.1: Pure Pursuit fits a circular arc (γ) between the vehicle and the look-ahead point. The steering angle is then derived from the curvature of this arc.

the denominator limits the steering angles when driving at high speeds. However, when driving very slow (v close to 0) the model breaks down due to this. Because this method does not use a look-ahead point, it tends to overshoot the path, rather than "cut corners" as Pure Pursuit does (Snider, 2009). The Stanley method outperforms Pure Pursuit in most cases, but is not as robust to large errors on non-smooth paths. The basic idea behind this method is similar to the Follow-the-Past algorithm we developed (refer to Paper III).

To enable more sophisticated algorithms, the geometric model can be extended with vehicle kinematics and dynamics. This increases path tracking performance when speed is increased and path curvature is varying (Snider, 2009). The added complexity of this method increases the computational work needed to calculate steering angle and the reported improvement over the simpler Stanley method is small. The fact that the Stanford team managed to win the DARPA Grand Challenge 2006 using (among many other components) the Stanley method shows that it is able to perform quite well for guiding autonomous off-road vehicles. Paper III describes the development of Follow the Past, a path-tracking algorithm able to very accurately follow a previously demonstrated path.

3.3 Obstacle avoidance

For an autonomous vehicle operating in real terrain, obstacle avoidance is a key issue. The most primitive form of obstacle avoidance stops the vehicle short of an obstacle when detecting it, to avoid collision. In applications for avoiding obstacles in indoor environments (typically long corridors) it is common to use the wall-following method. Here the vehicle follows the wall of the corridor at a certain distance. If an obstacle is detected, the vehicle regards it as just another wall and follows it around at a safe distance until the vehicle resumes its previous course. The drawback with the wall-following method is that it is less versatile and most often not suitable for outdoor applications.

A vehicle in forest environment demands a completely different kind of obstacle avoidance. Here we must be able to detect the size of and range to all obstacles, steer around (or between) them, and then continue on the correct path again. This means that obstacle avoidance must be combined with path planning to know which side of each obstacle it's best to go (depending on where the path is), and where to go after the obstacle has been safely avoided. Obstacle avoidance relates to path planning in the way that both aims at avoiding obstacles. However, obstacle-avoidance algorithms typically are more reactive while path planning involves long-term planning of an obstacle free path that a path tracking algorithm then can guide the vehicle along. Another difficulty in forest terrain is that some obstacles, such as small stone or trees, should not be avoided but simply driven over. Obstacles can also be things such as slopes or ditches, which can be hard to detect.

We have implemented and tried out the algorithms VFH (Borenstein & Koren, 1991) and VFH+ (Ulrich & Borenstein, 1998), of which the latter was chosen for use on the real forest machine experiments.

Chapter 4

Summary of Contributions

This chapter contains a brief summary of the contributed papers in this thesis. Some general conclusions about the the achieved results are presented as well.

4.1 Papers

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

The mechanization of logging has gone from hand tools and draft animals, through motor-manual tools, manually operated machines to today's machines that use feedback from the process to control the next work element (e.g., a harvester with a bucking computer). The next logical step would be to develop autonomous forest machines. We have identified several benefits with this:

- To increase the productivity from today's level, the annual work time could be increased from today's 3 000 hours. To do this with manual machines, more drivers would be required, as well as complex logistics involving huge numbers of machine movements between harvesting sites. An autonomous machine may be used efficiently for at least 6 000 hours per year. The same annual production level could then be achieved by a machine producing slightly less per hour. Furthermore, the cost per hour for an autonomous driverless vehicle is not directly influenced by salary costs.

- Crane speed is currently limited mainly by the speed of their operators. The work environment is very stressful, since many decisions have to be made at high pace, and the operator often becomes a production bottleneck. The operator can also be the limiting factor for the rates of loading and unloading forwarders. A possible way to increase productivity is therefore to raise the level of automation and, if possible, to use autonomous forest machines.

- 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.

- 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 twice as many productive hours per year but at only half the hourly productivity rate of current forest machines.

In addition to the analysis summarized above, Paper I also contains a field study of a developed autonomous forwarder used on a flat open field. The machine was able to follow a previously learnt path with less than 10 cm tracking error in average, using the new algorithm Follow the Past (see Paper III). The maximum deviation from the learnt path in four runs was 38 cm. The vehicle's ability to avoid obstacles using the VFH+ algorithm was also evaluated. The results showed that the algorithm 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.

4.1.2 Paper II - Potentials of possible machine systems for directly loading logs in cut-to-length harvesting

In the cut-to-length system (CTL), a single grip harvester is used to fell, debranch and cross-cut trees into logs. A forwarder then picks up the logs and transports them to the nearest road where it unloads the logs. The machines are highly efficient, but also expensive. A common strategy to improve cost efficiency is to change working methods such that some work tasks are not needed anymore. This paper examines four different systems that remove the need for picking up logs from the ground and thereby reducing the number of work tasks needed:

- **Harwarder.** This manned machine does the work of both harvester and forwarder: felling, processing and transporting.

- **Autonomous load-changing system, *ALC*.** Comprising a manned harwarder that cuts, processes and places processed trees directly into its own bunk. When fully loaded, the harwarder switches bunks with an autonomous forwarder, which then moves to the landing and unloads. Since this system has a buffer in the form of the harwarder's bunk, harvesting could be conducted, without waiting time, with one forwarder under certain conditions.

- **Autonomous direct-loading system, *ADL*.** In this system a conventional harvester cuts, processes and places processed trees directly into the bunk of an autonomous forwarder. When the forwarder is full it moves to the landing to unload. Both driving and unloading are done automatically with no human intervention. Since the system does not involve the use of a harvesting buffer, two or more forwarders have to be used to avoid letting the harvester wait.

- **Remote-controlled direct-loading system, *RDL*.** In principle, the same as the ADL system outlined above, but with manned forwarders whose operators take turns to remotely control one unmanned harvester (as in the Besten system (Bergkvist et al., 2006)).

A discrete event simulator was developed and implemented to capture the dynamic and stochastic nature of interactions between machines using integrated loading of logs. The simulator was implemented with one Finite State Machine for each forest machine and produced data representing time consumption for the different systems. This data was used to compare the economical performance of the above four potential systems for CTL harvesting and a conventional harvester-forwarder system in final felling. The main conclusion of this work was that harwarders have a large theoretical potential at the same time as rather limited technical innovations are required to realize the system. The ALC system also shows large potentials but cannot compete with today's CTL systems in regions containing stands with smaller trees. The RDL and ADL systems were shown to have less potential in this study.

4.1.3 Paper III - Follow the Past - A path tracking algorithm for autonomous vehicles

This paper describes the derivation of the Follow the Past path-tracking algorithm. It compares results from simulated runs as well as tests with a physical robot (a Pioneer 2-AT8) with traditional path-tracking algorithms. Traditional algorithms like Follow the Carrot (Barton, 2001) and Pure Pursuit (Coulter, 1992) use position information only, and sometimes run into problems that can be avoided by taking into account additional information from the human driver. Follow the Past uses information from a learning phase, where a human operator drives the path once while a computer continuously records the vehicle's position, velocity, orientation, and steering angle. The recorded information is used to later follow the demonstrated path in the best possible way. The idea is to utilize the driver's steering commands during the learning phase and compensate for any deviations from the route, which for example may occur if the machine has maneuvered to avoid an obstacle. The Follow the Past method consists of three separate behaviors:

1. Imitate the steering angles of the driver during the learning phase,

2. Turn to move in the same direction as during the learning phase, and

3. Turn towards the path if the machine is not already on the path.

The three behaviors propose three steering angles, which are then added together to obtain a steering command to the vehicle. The developed algorithm works well, and the vehicle follows an intended path with good precision without taking short cuts around corners.

4.1.4 Paper IV - A Java-based Middleware for Control and Sensing in Mobile Robotics

Nav2000 is a mobile-robot middleware implemented in Java, allowing efficient configuration of the robot's sensors and actuators. In many ways it has the same functionality as ARIA, the software shipped with the AmigoBot and Pioneer robots. The main difference is that Nav2000 is more general and works better in Java than ARIA's Java API does. The Nav2000 system can be distributed over a network of computers if some software modules require more computing power, i.e. more hardware can be added to the system without any software changes. It supports many different sensors and it is fairly easy to add new sensors as well. A dedicated health monitor system keeps track of all software modules running on the local computer, and also communicates with health monitors in all other computers running the system. The overall health of every module, as well as a more detailed description of possible problems, is presented graphically. In addition to this, the system uses advanced logging features to enable debugging and performance analysis of hardware and software modules. Currently the system supports four different robot platforms; a Valmet 830 forest machine, a 3D forest-machine simulator, and the AmigoBot and Pioneer robots.

4.1.5 Paper V - Path tracking in forest terrain by an autonomous forwarder

An autonomous forwarder able to follow a previously demonstrated path and avoid obstacles was described in Paper I. The path-tracking capacity of that machine was evaluated on a flat and even, open field. The study presented in this paper aimed at evaluating the path-tracking capability in a real forest environment. A gyro was used to compensate for the effect of the vehicle's roll and pitch on the GPS position when driving on uneven ground. To verify the accuracy, manual measurements of the vehicle position were also conducted. In the study, the forwarder operated at an average speed of 1 ms^{-1}, which is very close to the one expected in real work situations

The results showed that the autonomously tracked path deviated very little from the path initially learned. The mean absolute lateral deviation from the reference run in one of our tests was 6 cm and the deviation never exceeded 28 cm. According to the GPS measurements, 90 % of the path-tracking errors were less than 14 cm. Deviation patterns were generally similar over runs and also over measuring methods (manually and GPS), indicating that deviations were systematic and not random. A probable cause is that the forest machine's steering response is slow, such that it takes some time for the machine to reach a new set angle. This may cause the algorithm to overcompensate the steering angle, leading to the vehicle oscillating around the path. To reduce this effect, some parameters in the path tracking algorithm can be tuned. However, this tuning is a trade-off between quickly returning to the reference path and avoiding oscillating behavior.

The path deviations were generally lower in this latter study than in Paper I, even though the environment was more unstructured. One explanation is that the algorithm was better tuned in the latter study. Another reason could be that some of the software functions involved in path-tracking were further developed and optimized after the initial study.

4.1.6 Paper VI - Real-time path planning using a simulator-in-the-loop

In our work with autonomous forest machines there was a need for an obstacle-avoidance and path-planning system. In Paper I the obstacle-avoidance algorithm VFH+ was evaluated. The result showed that the algorithm performs less well when there are narrow passages to negotiate with obstacles close to both sides of the vehicle. As this algorithm is not well suited for large forest machines, a new algorithm had to be developed.

This paper describes the development of a real-time path planner for off-road vehicles, using a simulator. The general idea with the presented system is to extend a regular path-tracking algorithm with a simulator that, in real-time, tries to predict collisions in a window forward in time. This simulation is based on current sensor data giving information about the environment around the vehicle. If a collision is predicted, the vehicle is stopped and a path-search phase is initiated. Variants of the original path are generated and simulated until a feasible path is found. The real vehicle then continues, now tracking the replanned path. In simulated tests, this way of using a simulator to predict and avoid collisions works well.

The system is able to safely navigate around obstacles on and close to the path in a way that is hard or impossible to achieve with standard obstacle-avoidance algorithms that do not take the shape of the vehicle into account. Another scenario, also envisioned in forest environment, is off-line path planning of a longer route, based on map information. An approximate path given as a straight line from start to goal is then modified in the same way as described above.

Our tests show that using a simulator to predict and avoid collisions works well. The system is able to safely navigate a large forest machine around obstacles on and close to the path. The main advantage compared to VFH+ is the handling of narrow passages and the fact that the whole vehicle is taken into consideration, not only the front part.

4.1.7 Paper VII - Estimating wheel slip for a forest machine using RTK-DGPS.

This paper shows that the equipment and algorithms developed for the autonomous forest machine can also be used for other tasks, such as calculating wheel slip. This is done by comparing the wheel velocity reported by the machine and velocity measured with an accurate DGPS system. Slip is defined as the deviation between the speed of the traction elements and the forward speed of the vehicle. Most forestry machines are made for good mobility in uneven terrain, and the basic principles have been adopted by most machine manufacturers over the years. Lately, with increased focus on trafficability, some of the previously accepted design principles have been questioned. Some amount of slip is needed for good traction, but too much slip may increase the risk for wheel rutting in the forest. Large slip may tear up ground vegetation and superficial roots, thereby decreasing the bearing capacity of the ground floor and also reducing the growth of nearby trees. With increased slip, energy is consumed for making wheel ruts in the ground with increased fuel consumption as a result. The tests made in this paper showed that in a forest environment, 10-15 % slip was common for a regular forest machine.

The proposed method of using GPS-measured speed and wheel speed to compute slip can be used to detect excessive slip of the whole machine, and automatically activate differential locks to restore the all-wheel-drive operation. Combined with a more advanced transmission control it would be possible to adapt transmission forces to current loading of the machine (e.g. empty versus loaded with 10-18 tonnes of timber in the rear part), and thereby reducing both fuel consumption and ground damages.

4.2 Conclusions

As the machines becomes more and more efficient, the human operators risk becoming a bottleneck as discussed in Paper I. One way of approaching this problem is to develop autonomous forest machines. Can such machines become economically viable? In Paper II we tried to answer this question by performing a system analysis of two possible autonomous systems (and two manned). The result showed that a manned harwarder switching loads with an autonomous forwarder would harvest timber at a lower cost than today's systems. A manned harwarder without load-changing capabilities (and thereby no forwarder) was even more promising in our analysis. However, the combination of a regular harvester and an autonomous forwarder capable of doing the same work as today's manned forwarders would probably be the most cost effective system. On the other hand, autonomous forest vehicles capable of driving around and picking up logs from ground will take longer time to realize than autonomous systems switching loads with a manned harwarder. The conclusions in Paper II differ somewhat from similar studies. The strength with our study is that we used dynamic modeling of the harvesting and transporting systems and data from real harvesting operations to simulate how the systems would behave in real-life conditions.

To enable autonomous navigation, we need algorithms able to control the vehicle along a desired path. Paper III describes the development of a novel path-tracking algorithm able to accurately follow a previously defined path. During the development of this algorithm we did not have access to a physical forest machine, so to test and verify the path-tracking accuracy we used a forest-machine simulator and a small Pioneer robot. The result showed that our algorithm is superior to traditional algorithms such as pure pursuit.

An autonomous forest machine consists of many components, such as different sensors and actuators, that may reside on different computers. To support this we developed a robotic middleware called Nav2000 (Paper IV). This software framework supports interchangeability between components, i.e. a sensor or actuator can easily be replaced by a similar, yet not identical, component without any software modifications. It also has support for several target vehicles (Valmet forest machine, Pioneer robot, Amigo robot, and a 3D simulator have been implemented so far). The system can be distributed over a network of computers. In our project we run low-level routines on one computer and high level algorithms on another for reasons of computational power. Sometimes a third computer is used for modules like the path-planning algorithm described in Paper VI, which requires quite a lot processing power. Later developments of software frameworks have adopted a similar design as ours, showing that the design ideas were sound and relevant.

In Paper I, experiments with a real forest machine were made on a large open field. We let the vehicle track a previously defined path and placed artificial obstacles along it. The VFH+ algorithm (Ulrich & Borenstein, 1998) was used for obstacle avoidance. The experiments were quite successful; the path-tracking accuracy was 10 cm in average and the vehicle was able to successfully avoid the obstacles we placed on the path. An observed drawback with the VFH+ algorithm was that a large vehicle such as a forest machine has problems in narrow passages with close obstacles on both sides. We concluded that a different algorithm would have to be used for better performance. In Paper V, the path-tracking capabilities of the forest machine was tested in a real forest environment with good results. It actually performed even better than the test on a flat open field, probably due to improvements in some of the code controlling the forest machine and better tuning of parameters in the path-tracking algorithm. The results clearly show that it is possible to develop an autonomous forwarder able to accurately follow a previously defined path in a forest environment.

In Paper VI we tackled the problem with poor performance of the VFH+ obstacle-avoidance algorithm. The forest machine uses articulated steering, and thereby changes shape when it changes steering angle. VFH+ does not take this into account, as well as the fact that the machine consists of two parts. Therefore, another algorithm had to be developed to successfully avoid obstacles. It uses a previously developed 2D-simulator to determine if a series of steering commands would safely navigate the vehicle around obstacles or if it would hit (or come too close to) them. The simulator runs continuously in the background, tracking the path 5 meters ahead of the real vehicle. If a collision is predicted, the real vehicle is stopped and a replanning phase is initiated. The simulator then tries out several different paths 10 meters ahead to find one that avoids all obstacles while at the same time minimizing the deviation from the original path. The algorithm can be used online in real-time for short term path planning, i.e. more or less as a traditional obstacle avoidance algorithm. Another application is offline path planning. In this scenario a rough path is defined from start to goal (it could even be a straight line). Instead of the real vehicle, a simulator tracks the suggested path while another instance of the simulator continuously runs ahead to check if the path is clear and replans if necessary, exactly as in the previous scenario. When the simulated vehicle reaches the goal, a new path that avoids all obstacles has been generated. It can then be used as an a priori path for the real vehicle (which could still use the path planner if unforeseen obstacles should appear). The current Matlab implementation is a bit slow, such that the replanning takes too long time (depending on the number of nearby obstacles). This could be solved by using for example C or Java instead of Matlab. Using a faster computer to run the simulator would be another approach. A major problem is that the simulator is not mimicking the real forest machine's behavior accurately enough. Even if the algorithm finds a path such that the simulated vehicle avoids all obstacles, the real forest machine may not be able to avoid them. We have tried to improve the simulator, but the behavior of the forest machine is difficult to model and also depends on e.g. ground conditions and current load on the machine. A physics-based 3D simulator would probably mimic the forest machine's behavior better since it can take the machine-ground interaction into consideration. However, the question is whether such a simulator would be fast enough, (the 2D version runs more than 100 times faster than real time).

In Paper VII we showed that equipment and algorithms from development of the autonomous forest machine can be used also for other tasks, such as estimating wheel slip. If the wheel slippage is high, fuel consumption goes up, increasing the cost of harvesting operations. Wheel slip can also lead to soil damage by tearing up ground vegetation and superficial roots, reducing the bearing capacity of the ground and growth of nearby trees. In addition, it often leads to deep rutting which is esthetically displeasing and often leads to complaints from the public. Measuring wheel slip is a first step towards developing more advanced transmission control to reduce wheel slip.

To conclude, the work described in this thesis shows that it is possible to develop an autonomous forwarder able to accurately follow a previously defined path and avoid obstacles along the way. We have also showed that autonomous forest machines can be economically viable. However, there is still quite a lot of work to be done before fully autonomous forest machines can become a product with acceptable performance and safety for end users. In particular, methods to accurately detect and classify objects in the vicinity of the forest machine have to be further developed. We estimate that it will take at least 10-20 years to realize such a product depending on the amount of resources spent by both the forest industry and academia. However, the methods presented in this thesis can be used for partly automating forest machines much sooner. For example, a forwarder could autonomously drive from one pile of logs to the next, while the operator may focus on loading. The operator would still decide when the forwarder should move, but the machine takes care of steering and looking out for obstacles. In this way, technology has a chance to mature over time and gradually take over more and more tasks, and at the same time improving the operator's working conditions.

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