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Advances in using robots in forestry operations

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1 Introduction

Forestry is a term that spans a wide range of activities, from the agricultural-like cultivation of rapidly growing trees to the harvesting of pristine forests. Hence, the operations related to forestry are similarly diverse. When focusing on managed forests, the fundamental processes are similar to the cultivation of any product: to establish, manage and harvest a particular crop. However, the time span for the rotation cycle and the size of the harvested crop differs

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substantially for forestry compared with other cultivated products. Moreover, how forestry operations are carried out varies greatly around the world. Current practices are adapted to complex, locally variable conditions, such as geophysical characteristics (terrain), management regimes, tree properties, climate, ownership structure, industrial infrastructures, labour availability and capacity, and societal rules for acceptable practices.

Since the twentieth century, timber harvesting has progressed from being entirely manual and animal-powered to being fully mechanized and to some extent automated (Silversides, 1997). Although many aspects of forestry operations are highly mechanized, there are still some that are rarely mechanized (e.g. planting), and many geographical regions where mechanized options are not applied or viable (e.g. tree felling in steep terrain and of large trees).

An interest in automated forestry operations developed soon after the first applications of mechanization. Examples can be seen in the symposium on 'Forest Harvesting Mechanization and Automation' held in 1974 (Silversides, 1974) by a division of the International Union of Forest Research Organizations (IUFRO) and a Swedish workshop on 'Automation and Remote Controlling of Forest Machinery' held in 1983 (Uusijärvi, 1985). More than a decade later, ideas for fully automated, but supervised, logging systems were described (Hallonborg, 1997). More recent publications have summarized state-of-the-art developments and considered possible future steps (e.g. Bayne and Parker, 2012; Billingsley et al., 2008; Hellström et al., 2009; Lindroos et al., 2017; Milne et al., 2013; Parker et al., 2016). There have been plenty of innovative projects over the years attempting to automate the technology used in forestry operations. Some early examples are machines aimed at autonomously carrying out tree felling, delimbing and piling of stems (Golob, 1981), and robots aimed at autonomously performing weeding, pre-commercial thinning and thinning of young coniferous stands (Kourtz, 1996). However, few innovations involving automation technology have successfully reached the market.

Forestry falls within the category of outdoor applications, which is still a challenging area for the robotics community. Forest is a highly unstructured environment, and very few developments seen in the field of robotics are directly applicable to this situation. Most developments in current robotics research take place in simpler outdoor applications than those existing in forestry, for example driving cars, rescue missions, exploration of hazardous environments and surveillance. The main focus in these applications is the ability to provide precise data, such as global and local positioning, as most of them are for use around cities, with easy access to the internet or some other type of communication. The technology to achieve this within forestry

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operations does not yet exist. Unlike other industries, forestry is still a young research field in the application of robotics, because the data needed to develop advanced autonomous or semi-autonomous applications is still absent. For instance, there is lack of computer vision ability, and global and local positioning capability; additionally, current forestry machines have little or no sensing equipment to understand their own work. Hence, most research effort is aimed at acquiring this type of data, such as research focusing on developing sensors and carriers for forestry machinery (e.g. Lideskog et al., 2015). Advances in methods of collecting, handling and using data are, then, the stepping stones to smart machines and eventually automation. Although there is still a long journey to go before some level of fully automated machines is reached, there are plenty of interesting advancements within the field of forestry operations.

This chapter presents the current state of robotics in advanced, but yet conventional, forestry operations. The focus is on commercially available products, with some selected examples of ongoing research as an indication of what can be expected in the near future in terms of teleoperated, semi-autonomous and fully autonomous forestry machines. Less attention is given to the many creative and futuristic concepts that constantly arise across various media, because of the less likely chance that they will someday actually become part of forestry operations. However, the trends and possible directions for future technologies are discussed in Section 13.

When addressing automation it is important to mention that the factors that need to be taken into account to achieve automation coincide with efforts to improve the current, manual, forestry operations, such as occupational health and safety issues and improving work efficiency (by analysing and improving work methods and providing decision support systems (DSS)). Thus, development efforts will directly benefit operators in many ways, even before, in the far future, resulting in fully autonomous forestry operations.

To be able to understand the automation process for forestry operations, it is necessary to be familiar with the conditions under which the processes take place. Thus, Section 2 describes the particular challenges to automation of forestry operations. We then present different sections based on the different fields of research required to solve those challenges. The chapter focuses primarily on timber harvesting systems, although automation of planting and silvicultural machinery is addressed to some extent in Section 13. Automating forestry operations is a global activity, but this chapter focuses particularly on the Nordic cut-to-length (CTL) harvesting system, which uses harvesters (Fig. 1) and forwarders (Fig. 2). That is partly because the authors are based in Sweden, but also because the Nordic CTL system is the most technologically advanced in the world.

Figure 1 A Nordic CTL harvester, Komatsu 901XC, in an unstructured, sloping environment demonstrating a self-levelling cabin function. Photo courtesy of Komatsu Forest AB.

Figure 2 A Nordic CTL forwarder, Ponsse ElephantKing, in an example of harsh work conditions encountered during forestry operations: darkness, snow and an unstructured environment. Photo courtesy of Ponsse Oyj.

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2 Challenges to using robots in forestry operations

Within the field of forestry operations research, the themes of Forestry 4.0 and Internet of Things are hot topics. In this respect, research is keeping up with contemporary technological development. This might seem at odds with the fact that there are still parts of the forestry operations that are not even mechanized, and that there are limited possibilities for automatically monitoring production within some mechanized operations. In fact, within a global context, most forestry operations rely on robust low-tech equipment, which is far from being connected to the internet. This global variation in levels of technology can also be found in agriculture, but the reasons for this are somewhat different.

The major challenge to using autonomous machines in forestry operations is the work environment, which is off-road, covers rough terrain and is located in remote areas. Outdoor work over rough terrain makes automation extremely difficult, compared with automation in controlled environments. The appearance of the forest environment can also vary greatly, as a result of light conditions, precipitation, wind and so on. Thus, a given location might look very different depending on whether, for instance, the surrounding trees are fully leaved, still and well lit, or whether the leaves have been shed and the branches are moving yet barely visible because of a snowstorm. Moreover, the time span of forest management means visits to any particular forest area are rare, so investment in infrastructure is normally kept to a minimum. When any work is carried out, it involves challenging decisions related to production as well as management of environmental impacts and social values.

The actual work carried out by forestry operations has not only many similarities with agricultural operations but also many essential differences. When focusing on managed forests, the re-establishment of a forest stand involves many familiar cultivation processes, such as soil preparation (scarification), planting or sowing, suppression of unwanted plants (e.g. weeding and pre-commercial thinning) and the management of pests and diseases.

Although a very important part of forestry operations, the early phases of the silvicultural cycle (e.g. the rotation cycle) are given little attention in this chapter, because the processes are either too similar to agricultural practices (e.g. mechanical site preparation) to warrant a separate focus or they have not yet been mechanized within forestry (e.g. planting, weeding and pre-commercial thinning). There are exceptions, but they normally occur in plantations with relatively short rotation periods and management regimes that make them similar to agriculture.

The latter part of the silvicultural cycle includes the harvesting of various sizes of tree. With large-sized trees, there are obviously specific demands for the machines used to handle them. Hence, these operations differ substantially from harvesting operations in agriculture. The main focus of this chapter is therefore operations related to tree harvesting.

Tree harvesting can be divided into five distinct work elements: (1) accessing/reaching the tree, (2) felling the tree, (3) debranching the tree, (4) cross-cutting the stem/tree (bucking) and (5) transporting the stem/log/tree to a roadside landing. All five elements have to be carried out to enable the delivery of roundwood logs for further processing, but in what order and where they are carried out can differ greatly between operations. Irrespective of which work element(s) a given machine is designed to carry out autonomously, one of the first technological challenges is being capable of advanced localization and decision-making. For instance, the machine should be capable of knowing where it is located, and the status and location of its parts. It should also be aware of the surrounding environment, and how the work objects (trees/stems/logs) are placed within it, their qualitative features and so forth. Consequently, it should possess the computing ability to decide how to carry out the work. In other words, an intelligent machine has to possess basic human operator abilities through sensing and computing. And, as mentioned, this needs to be possible under the most challenging conditions possible: an unstructured and highly variable outdoor environment.

Forestry machines need to be robust to endure the demanding conditions in which they operate. The automation challenges that need to be overcome are in many cases, similar to those encountered in the development of space and military applications (unstructured, unknown terrain to be navigated under extreme conditions), but with a much smaller research budget. As only a few thousand dedicated forestry machines are produced around the globe annually, the resources available for development are limited. And, naturally, the machines must be cost efficient, which has resulted in two distinct types of product: cheap low-tech machines and expensive high-tech machines. Nordic CTL machines are an example of the latter, for which the philosophy is that an expert operator with a higher salary needs a highly productive machine that can output at a low cost per unit. Thus, the more advanced machines are rather expensive, costing several hundred thousand euros, with small margins for increasing machine costs. Thus, the cost of any additional function has to be covered by increased machine or operator productivity. However, with autonomous machines the cost of the operator will be excluded, which can allow for higher machine costs at the same productivity, or lower productivity at the same machine cost if the machine can work for longer days.

This short overview just skims the surface of the conditions under which forestry operations are conducted, with the aim of introducing the main challenges encountered in the automation of forestry operations. It also serves as an introduction to the structure of this chapter, in order to discuss the advances in automation of forestry operations. Readers interested in more information on the challenges of forestry operations and the drivers for technological advancement are directed to, for example Häggström and Lindroos (2016) and Lindroos et al. (2017).

3 Knowing the state of the machine

Most forestry machines, irrespective of whether they are more or less advanced, share some common features. A diesel engine generates the power to operate hydraulic cranes and tools, and often the locomotive transmission also includes a hydraulic step.

Many machines are still controlled by very old, but robust, techniques (e.g. an electro-mechanical open loop hydraulic control), with the help of distributed controller area network (CAN)-based control systems. In the more advanced machines there has been, however, rapid development of hardware and software to improve the human–machine interaction. Current developments are addressing the need to monitor daily operations automatically in terms of, for instance, production levels and fuel consumption (Manner et al., 2016a,b; Pierzchała et al., 2018b). To this end, machines are equipped with traditional sensor hardware, similar to many other machines in different industries. Nordic CTL machines can provide detailed information on their performance, including fuel consumption, production and idling time (e.g. Eriksson and Lindroos, 2014; Manner et al., 2016a,b). Such data is saved automatically and can be transferred wirelessly, if such facilities are available at the work site. Thus, automatic follow-up of conventional operations is advancing rapidly, although many challenges remain. Ownership of the data produced, for instance, is under discussion for the Nordics.

At the other end of the spectrum, current developments involving the actual use of automation technology are largely focused on the use of intelligent hydraulic valves: a technology that has only recently appeared on the market. This type of valve is equipped with digital electronics and dedicated sensing hardware, with the potential for the software to be improved for dynamic motion control of the machine (Mathworks, 2016; Danfoss, 2015). Such sensors enable analysis of the operators' conventional work as well as the possibility of improving the working methods and automating the movements of the crane. This will be addressed further, mainly in Section 8.

Automatically levelling cabins is a standard function of many forestry machines (Fig. 1), which can be seen as an early application of a sensor feedback control system. Forestry machines have also been equipped with sensors in research projects to identify, for instance, the position of the crane (Hyyti et al, 2018; Lindroos et al., 2015), wheel slippage (Ringdahl et al., 2012b; Suvinen and Saarilahti, 2006), soil damage (Melander and Ritala, 2018) and machine slope (Visser and Berkett, 2015). With such information, it is possible to adapt the driving to compensate for the encountered conditions. For example, some machine manufacturers are starting to use sensor feedback control algorithms to improve the working performance of machines.

4 Knowing where the machine is located

The ability to locate the machine within the forest is improving, and satellite navigation systems are standard equipment for conventional Nordic CTL machines. The location of the machine's movement is automatically logged and saved, together with information on the production at each location (e.g. volume of various assortments). Global mapping is normally not a problem in current state-of-the-art operations. However, autonomous operations will also require high-precision local mapping. For this, the standard global navigation satellite system (GNSS) equipment of current forestry machines suffers from the challenge of locating the machines correctly under the forest canopy. Thus, high localization accuracy currently requires additional effort, and is normally only carried out at an experimental level (Melander and Ritala, 2018; Lindroos et al., 2015).

Such experiments include efforts to develop simultaneous location and mapping (SLAM) algorithms suitable for the highly variable forest environment. There have been several experimental platforms in forest environments investigating the possibility of equipping forestry machines with such a technique (e.g. Pierzchała et al., 2018a). The use of unmanned aerial vehicles (UAVs) as scouts to compile local maps for forestry machines has also been suggested (Talbot et al., 2017). However, so far there has been no progress with commercially available products.

5 Knowing the location of surrounding objects

Currently, no conventional forestry machine is able to sense its surroundings. However, there are plenty of ongoing research into detecting trees (Fig. 3) (e.g. Brunner and Gizachew, 2014; Hauglin et al., 2017; Oveland et al., 2018; Wells, 2018), obstacles (Lideskog, 2018; Puliti et al., 2018), people (Ostovar et al., 2016) and what effects the machines have on the terrain (Marra et al., 2018; Melander and Ritala, 2018; Salmivaara et al., 2018). There is a huge variation in the methods used, with typical techniques including computer vision via two-dimensional (2D) and three-dimensional (3D) terrestrial laser scanners (Talbot et al., 2017). Thanks to recent advancements in the areas of computer vision, technological development is expected to progress rapidly within forestry as well. The expectation is that ultimately the operator will be informed about the location and amount of trees that are surrounding the machine as well as receiving suggestions about which trees should be harvested. Similar

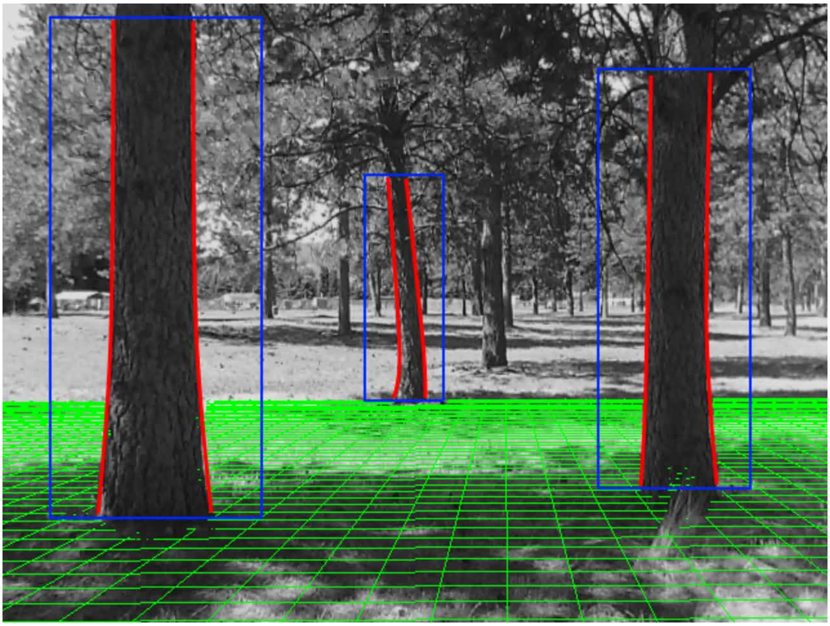

Figure 3 A photometry-based example of ongoing research on tree identification. Image courtesy of Lucas Wells.

technology will be fundamental for the automation of crane work. Although advancing fast, the research within this field is still at an early stage, and identifying objects in the forest is very challenging. Commercial products are not likely to be available within the coming decade.

6 Knowing how to plan the work

Because of the rapid progress in remote sensing as well as sensor technology, there has been progress with computational planning. Contemporary research comprises a plethora of DSS for various aspects of forestry work. The development of DSS will in the first instance support operators, but, more importantly in the context of this chapter, the algorithms of DSS can also be used for autonomous decision-making. Thus, the successful development of DSS can be seen as a prerequisite for autonomous forestry operations. Here, we will focus on the decisions needed to choose which trees to harvest, how to plan the movements during the harvest and where to take the harvest.

The challenges of tree selection are well-known for human operators because of the variability in tree features and the conditions in which they grow, and there are only simple heuristics for addressing this task (Vestlund and Hellström, 2006; Vestlund et al., 2005, 2006; Contreras and Chung, 2013).

Thus, given that there are difficulties in even sensing trees reliably and rapidly in research settings, DSS for tree selection is not likely to enter conventional forestry operations within the next decade.

When it comes to DSS for which paths to take during forestry work, there has been more progress, and this topic has received much attention during the last decade because of increasing concerns about soil damage. Soil damage is likely to be reduced if the operator can be guided into making better choices of where to drive, and how often. Aerial light-detecting and ranging (LiDAR) data has enabled high-precision digital elevation maps, which in turn has enabled depth-to-water (DTW) maps (e.g. Ågren et al., 2014). To provide even more information on soil-bearing capacity, machine learning has been used to combine aerial data with field-measured data (Pohjankukka et al., 2016). Although successful to a certain level of prediction accuracy, the conclusion is that the accuracy would be improved substantially with real-time data (e.g. from sensors mounted on the machine). Digital DTW maps are currently used in Nordic CTL machines to provide the operator with information about the expected soil conditions of an area; however, the operator still needs to plan the driving manually.

Algorithms for computational planning of where machines should be driven during harvesting are under development for Nordic CTL machines (Mohtashami et al., 2012; Flisberg et al., 2007). However, it is a complex problem when trying to produce an optimum route for the full operation of, for example, forwarding the harvested logs in a stand while simultaneously considering both environmental and economic factors (Hosseini et al., 2019). Software that finds the best (especially the driest) main path from the roadside landing to given points in a stand is already available, and there is ongoing research to produce DSS that takes the full network into consideration.

DSS for locating the roadside landing, to which the harvest can be taken, is comparatively well developed. Such location problems are often integrated with an analysis of the road network design, where the challenge is the trade-off between road construction costs and off-road extraction costs (e.g. Contreras and Chung, 2007; Grigolato et al., 2017; Søvde, 2015). Thus, there is relatively good support for knowing where the machine should start and where to extract the harvested products. In practice, however, the machines are not usually equipped with such DSS because the location of roadside landings is not normally an operational problem, being solved at earlier planning phases.

7 Moving around in the forest

Once there is a planned path, the next challenge is to be able to follow it. In forest environments paths are rarely straight or flat and obstacles are common. In addition, the vehicle itself is likely to have problems moving about because

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of the large quantity of logging residue (branches, treetops etc.) on the ground surface and potentially high variability in traction and soil-bearing capacity. Furthermore, the possibility of adapting the environment so that it complies with automation requirements is strongly limited in forestry because of ecological and social concerns. Thus, forestry operations include more complex in-field decisions than typical agricultural operations. The challenges can be divided into the machine's ability to move in rough terrain, and to follow a specified path.

7.1 Locomotion in rough terrain

Forestry operations can be executed by either ground-based machines or non-ground-based machines. Conventional ground-based machines are wheeled or tracked.

For some time there has been an abundance of impressive robotic concepts that can move in outdoor environments, such as the walking robots from Boston Dynamics (e.g. Raibert et al., 2008) and the ANYmal (Hutter et al., 2017). These are important stepping stones towards the automation of forestry operations, but their focus is often general in character. However, there are a few walking concepts that are dedicated to forestry operations, such as the PlusTech Ltd (now John Deere Ltd) harvester of the 1990s (Billingsley et al., 2008) and the more recent Portalharvester (Fig. 4) (Anon., 2013; Erler, 2013). The

Figure 4 The Portalharvester, a walking concept machine with two tripod legs and a sliding cab. Photo courtesy of Christian Knobloch.

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benefits of walking machines, compared with wheeled and tracked machines, include improved negotiation of some obstacles and terrains, although such machines are limited in terms of complexity, fuel consumption and so on (Billingsley et al., 2008). From a soil damage perspective, the benefit is that only soil compression points are created and not continuous tracks. Thus, avoidance of tracks prevents the risk of blocking off roots and water from certain areas by walls of compacted soil.

Conventional Nordic CTL machines are wheeled, often with bogies and various systems to improve operator comfort when driving over sloping and uneven terrain. Self-levelling cabins have long been available (Fig. 1) and the latest commercial enhancement is active suspension (Ponsse, 2017), such that dynamic motion control is employed to make the hydraulic suspension system even out over obstacles.

Aerial forestry operations take place around the globe, but because of higher costs they are mainly used when ground-based operations are not an option. There are several conventional systems available, such as cable yarding (Lindroos and Cavalli, 2016) and heli-logging (Bigsby and Ling, 2013). Balloons were an option until the 1970s (Peters, 1973), while recent advances in UAVs mean they can be used in forestry for various monitoring purposes (Torresan et al., 2017). Given the large loads that have to be carried when harvesting or extracting trees, current UAV technology is unlikely to be used for such purposes, at least in the near future.

Tree-based locomotion is a solution that falls between ground and aerial locomotion. The brachiating (tree-to-tree moving) robot developed in New Zealand was inspired by the way monkeys move (Parker et al., 2016) (Fig. 5). As with aerial systems, it avoids soil damage and is not affected by how rough or steep the terrain is. However, as with UAVs, the work that can be carried out by climbing machines is probably limited in relation to harvesting purposes. The development of a tree-to-tree moving machine capable of tree felling might be feasible; however, the weight of logs that could be carried while climbing is probably limited, although some innovative solutions have been proposed by having several machines that can co-operate (see Section 13).

7.2 Following a planned path

An autonomous vehicle must know where it is at any time, and how it should manoeuvre to follow the chosen path. Systems for detecting obstacles, human beings, animals and other machines are also needed. Moreover, changed or unexpected conditions necessitate the ability to react and adapt to the input, in terms of re-planning the path as well as manoeuvring to follow the new path.

Although there is a plethora of research on how to plan suitable and efficient paths in unstructured terrain (e.g. Norouzi et al., 2017) and on how

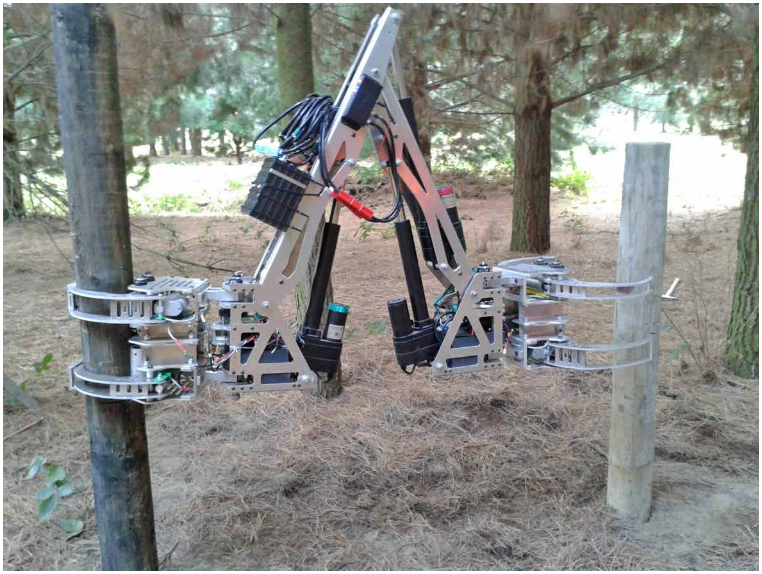

Figure 5 The brachiating robot is designed to move from tree to tree. Photo courtesy of Richard Parker.

to follow given (human-made) paths in forest terrain by using various kind of sensors (e.g. Leidenfrost et al., 2013; Giusti et al., 2016), little has been implemented in actual forestry settings. In fact, most research has been focused on following actual paths (roads) in the forest, in which there is a distinct difference between the path and the surrounding forest. During forestry operations, however, planned paths are seldom visible. Thus, it is not surprising that there is currently no conventional forestry machines that are able to follow planned paths autonomously (apart from some cable-guided systems, see Section 10). However, it has been shown that a conventional forwarder equipped with some additional hardware and software can autonomously repeat a previously driven path with centimetre precision (Ringdahl et al., 2011). In fact, it would probably be difficult for professional human operators to have better path-tracking accuracy than the autonomous machine in that study.

Path following normally requires a combination of techniques to assess the vehicle's current position, velocity, steering angles and goal position. A major problem is that the vehicle's wheels can slip and slide considerably on the unstructured terrain. Another source of error, related to the articulated joint design, is that the motions of the front and rear parts of the vehicle relative to the ground are uncertain. When the steering angle changes the two parts move differently depending on factors such as weight distribution and ground conditions. The errors in position and heading estimates accumulate into total errors that increase with time.

8 Reaching and handling the trees

Most ground-based forestry machines are equipped with a manipulator in the form of a hydraulic crane by which the trees are reached and handled. Traditionally, the cranes are operated by controlling each link separately, which is an advanced task for an operator because there are many possible combinations of link movements that can result in the same overall movement and final position of the tool at the end of the crane. However, there has been rapid advancement in how cranes are controlled. Over recent years, several entry-level products have appeared on the market, such as the following:

- *Cranes equipped with motion sensors*, providing entry-level products that use improved motion control software (Cranab, 2015).
- *Hydraulic valves equipped with digital electronics*, providing entry-level products that use improved software for dynamic motion control of the machine (Mathworks, 2016; Danfoss, 2015).
- *Basic boom-tip control*, where the operator receives computer support in order to carry out expertly co-ordinated end-effector movements with less effort (John Deere, 2013).
- *Reduced crane vibrations*, making the operation of the crane more comfortable (John Deere, 2013; La Hera and Ortiz Morales, 2015).

Among the examples listed above, the concept of boom-tip control has long been anticipated. In 2013, John Deere became the first forestry machine manufacturer to offer their solution: smooth and intelligent boom control (SBC & IBC) systems, first for forwarders and then for harvesters. At the same time, Cranab released their Cranab Intelligent System (CIS), comprising cranes with integral sensors. Simultaneously, different producers of hydraulic valves have released products involving sensors and computers, resulting in a technology known as 'intelligent valve'. This combination of sensors in cranes and intelligent hydraulics provides sufficient technology for more machine manufacturers to develop their own automated crane functions. All these examples are entry-level solutions, opening the door to automation. Various concepts for automated crane functions have been trialled and/or implemented in test beds (Ortiz Morales, 2015; Hansson and Servin, 2010). For example, in relation to intelligent boom control, there is a large number of different boom-tip control algorithms that can be implemented with a machine, because these algorithms respond to selectable optimization options such as minimum kinetic energy control, minimum potential energy control, failure recovery, strength optimization and fuel consumption (La Hera, 2011; Westerberg, 2014; Ortiz Morales, 2015).

9 Converting trees into products

9.1 Decision support for processing

The development of value optimization algorithms for the processing of felled trees into logs (delimbing and bucking) was initiated during the 1960s (e.g. Smith and Harrel, 1961; Pnevmaticos and Mann, 1972). In the late 1980s, the algorithms became commercially available as computerized DSS (Anon., 1988), and since then algorithms have been part of the standard equipment in Nordic harvesters. The input is continuous measurement of diameters along the length of the stem, by use of the feeding rollers and/or delimbing knifes. The measured diameters are used to calculate a stem's taper and to predict the shape of the remaining part of the stem. Thus, optimization decisions for the assumed stem can be taken without first measuring the whole stem's diameter and then going back and bucking the logs. The optimization process is carried out continuously and updated based on the flow of new diameter recordings, while the stem is fed through the harvester head at a speed of circa 5 m/s.

This DSS can already be used for autonomous delimbing and bucking under rather simplistic conditions. The system could, for instance, be set to process trees automatically based on predefined log length(s). However, in most situations the value of bucking optimization depends on the tree species and quality, which are currently recorded by the operator. Thus, until sensors can replace the operator's input for that information, the current processing system will remain a DSS. Although there is no apparent advancement with such sensors, developments related to tree recognition are likely to be transferable and of benefit to processing activities.

9.2 Improved characterization of product properties

Data collected by conventional harvesters can already provide some industry-relevant information regarding tree features (sizes, volumes, assortments etc.), but at an aggregated level because individual logs are not tracked. Moreover, technological developments have made it possible for harvesters to gather data while bucking trees into logs, including data on wood properties that had not previously been considered, such as stiffness (Murphy, 2014).

Although this avenue of development might not lead directly to advances in automation, the ongoing development of new wood products and processes such as bio-refining means that it may become increasingly important to identify, select and sort trees with desirable chemical properties. Indeed, trees of the same species can vary in their chemical composition (e.g. Arshadi et al., 2013). Data on the chemical composition of wood has hitherto rarely been used during industrial processing, but the ongoing development in tree recognition is likely to enable detection of detailed tree and wood properties before harvest. However, it is not obvious that such features should be identified in the forest. With the increasing number of desired characteristics from a given tree and from given stands, it is less likely that sorting can be carried out efficiently in the forest. Thus, the future might see machine systems focused on harvesting and delivering stems (maybe even with branches) to centralized wood yards, where the products are then identified, captured and delivered to customers. If so, it will be easier to automate the work of processing trees, because that work will be carried out in a controlled environment. However, the rest of the workflow will be just as, or even more, problematic, if larger units (whole stems with branches) are to be handled.

10 Extracting logs or trees to roadside landings

Extraction work follows a cyclic procedure, in which the machine travels out unloaded, accumulates the load, travels back loaded and unloads at a roadside landing. Cable yarders, which are used for extracting timber on steep terrain, have for some decades been available commercially in semi-autonomous versions. The carriage autonomously travels the cable out and in, but is loaded and unloaded with operator input. The input of the former cable yarder operator has now been overtaken by two other operators involved in the cable yarding. During the accumulation and unloading phases, the choker-setter and the processor, respectively, have complete control of the yarder by means of a wireless radio remote controller.

In addition to increased worker productivity (with one less operator), the advantages of automation include improved management of acceleration and deceleration and speed management along the extraction path. Moreover, the computer can stop the movement of the carriage in 1/100th of a second if the tension-monitoring system detects that a turn is stuck. Conversely an operator is likely to take up to 2 s, and in that time the machine can become severely shock-loaded. Examples of remotely controlled tower yarders with autonomously travelling cabins include the Konrad KMS 12Uxii, the Valentini V1500 and the Griefenberg TG 1100.

A similar concept, but ground-based, is the Konrad 'Pully', which is a semi-autonomous/remotely operated forwarder or skidder that runs along a wire rope that connects the steep-slope harvester and the landing/roadside area (Konrad, 2017). The Pully requires operator input to be loaded in the forest and to be unloaded at roadside.

The existing products all rely on a cable for guidance along the path to travel autonomously. Self-navigating extracting forest machines are still only at an early experimental stage (see the examples in Section 7.2).

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11 Remote-controlled operations

Being able to control the machine remotely can be seen as an important step in making a machine autonomous, in the sense that it enables new designs and technological solutions to be considered when operator safety and comfort do not have to be taken into account. Moreover, it is likely to facilitate a transition to controlling (or rather supervising) several machines from one centralized control hub. However, research into teleoperated forestry machines (Milne et al., 2013; Westerberg and Shiriaev, 2013) and unmanned self-navigating vehicles (Ringdahl et al., 2011; Hellström et al., 2009; Vestlund and Hellström, 2006) has highlighted the challenges in making sensors perceive and understand the structure of the 'natural' forest landscape. Nevertheless, a number of forestry machines already have remote-controlled operating systems in place, for productivity and safety reasons. These remote-controlled forestry machines range from those that rely on the operator's own direct vision, to those that rely on camera vision.

A number of European skidder manufacturers provide a remote-control feature as a complement to cab control. During operations, this is typically used to reposition the skidder while the operator is out of the cab, for example when pulling out the winch rope while setting chokers.

In New Zealand, a teleoperated winch-assisted John Deere 909 feller-buncher has been trialled. The machine has been retrofitted to enable full teleoperation from a purpose-built control booth trailer (Fig. 6). To provide the operator with a sense of the terrain slope, the system includes an artificial horizon line and a 'heads-up display' overlaid on one of the screens. It has been tested successfully during harvesting operations (Parker et al., 2016). With the operator taken out of the cab, the system can be pushed onto steeper slopes, but the remote-control system itself does not improve stability and tractability on steep slopes.

Larger specialist companies are also involved in retrofitting machines with remote controls or teleoperation. For instance, the Applied Research Associates' Modular Robotic Appliqué Kit (M-RAK) has been used to teleoperate a Caterpillar 521B feller-buncher at the Fort Bragg army site to clear timber on firing ranges without putting the workers in danger. The M-RAK provides video of both the operation and the surrounding environment, and enables control at a range of about 2.4 km.

In experimental settings, the range for control is not a problem. Forwarder cranes have been set up and controlled worldwide. However, to enable successful teleoperation of conventional operations problems of information presentation and visibility need to be solved. For instance, the viewing angle and abstraction level have been shown to affect operator performance (Westerberg and Shiriaev, 2013).

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Figure 6 The control booth for a teleoperated winch-assisted John Deere 909. Photo courtesy of Keith Raymond.

Another example of a remote-controlled forest machine was the Swedish 'Beast system', in which an unmanned harvester was controlled from a forwarder located in direct proximity to the harvester. The remote control worked well, but to have a harvester and forwarder co-operating for direct loading of logs has proved to be unsuccessful (e.g. Lindroos, 2012; Ringdahl et al., 2012a).

A recent development in commercialized remote control is the HiVision system for self-loading timber trucks (Hiab, 2018). An operator is still present in the truck but, by using augmented reality goggles, the crane can be operated from the truck cabin instead of from a crane cabin.

12 Conclusion

Ongoing research and development in the automation of forestry operations is contributing to the sustainable supply of fossil-free raw material for circular bio-economies of the future. Smart machines in forestry operations will facilitate the much-needed growth of feedstock and sustainable harvest, with better consideration of economic, ecological and ergonomic needs. The advances already made in particular address needs related to labour shortage, increased safety requirements and increased productivity targets. The current level of automation in forestry operations is very low, as even the level of mechanization is low in many parts of the world. There are logical reasons for the slow rates of development, but there has nevertheless been substantial progress, and there is no shortage of innovation. Indeed there is a great range of innovation focus, which is to be expected because forestry practices are a complex mixture of adaptations to complicated, locally variable conditions.

There is, however, a large step from innovation to a commercial product for forestry operations. The automation challenges that need to be overcome are in many cases similar to those encountered in the development of space and military applications (unstructured, unknown terrains to be mastered under extreme conditions), but with a much smaller research budget. Moreover, to be commercially viable, the innovations need to be profitable compared to conventional forestry operations.

The challenges to developing the first stages of automated forestry operations are related to the availability of data, so there is currently a strong focus on the integration of sensor technology and development of control systems, to manage machine movements efficiently. The difficulty lies in making sensors perceive and understand the structure of the 'natural' forest landscape, to enable both remote-controlled and autonomous operations. Moreover, development in the automatic detection of qualitative features of trees and logs is needed, to enable automated decisions on where and how to move in the forest, which tree to harvest and what products can be processed from a given tree.

Current research is starting to consider the hardware requirements and initial software needed for automation. However, transitioning towards this technology will not be easy, because developing software and redesigning all the hydraulics and embedded electronics in conventional forestry machines will be challenging, particularly when trying to make a profit during the process.

Therefore, as we enter the world of operator-assisted operations, this could still take at least a decade to complete. During this time, however, improvements can be expected in control performance, particularly precision boom movements using motion sensors and operator-assistance software.

However, the operator will still have an essential role in the correct use of these tools, and many difficult movements will still need to be carried out manually.

13 Future trends

The use of autonomous machinery for forestry operations is still considered to be several decades away. Naturally, there will have to be a gradual transition to systems with a decreased level of operator input. It is also likely that some forestry operations will be automated earlier than others because of the nature of the work. Naturally, the advances will benefit in general advances in robotics on how to make machines plan and execute actions autonomously. However, in this section we address some forestry-related challenges that is likely to not be covered in general robotics.

There will probably be rapid development of machines that can gather forestry information (e.g. UAVs). However, it will likely take some time before there are unmanned and autonomous machines that can carry out some actual physical forestry work. Activities that require the fewest decisions will be easiest to carry out autonomously. For instance, automating the process of scarification has good potential, because it is 'only' about navigating and creating suitable regeneration spots. Moreover, it is an activity that can be ergonomically challenging for the operator, so there is motivation for removing the operator from the machine. However, the work does require a machine that is able to traverse the ground and adapt the scarification to soil conditions.

Some operations have not yet been successfully mechanized, like planting on natural soils. Technically, mechanical planting can be carried out, but the logistics of efficient handling of fragile plants remains a challenge to complete mechanization (e.g. Ersson et al., 2011, 2014). Once mechanized, hitherto theoretical advances on automated planting might be implemented (Lideskog, 2018).

When it comes to pre-commercial and commercial thinning, the challenges relate to the choices of which trees to harvest and which to leave, as well as what products to make. As with the harvesting of mature trees, tree sizes can be a challenge, not least because failing to handle a large tree successfully is likely to be harmful to the machine and anything in its proximity.

It will therefore probably be easiest to automate operations in which all trees within a stand need to be felled, but without any product recovery. This should preferably be done without having to traverse the ground, and the trees should be small. Hence, using UAVs to help weed out small trees in areas where no trees should be growing may be the first autonomous forestry operation. This process 'only' requires the capacity to navigate a defined area, identify the trees and use a tool to cut the trees. For small trees, small tools and UAV carriers would suffice. A typical application would be weeding under power lines and along rights of way. An operator could supervise a swarm of autonomous machines, and

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move with them along the area to be weeded. Naturally the required robotic advances would be substantial, especially in the area of computer vision, but the forestry-related challenges would be considerably small.

When it comes to harvesting activities, it is likely that automated extraction work will be expanded to vehicles without cable guidance. Such 'shuttles' would autonomously transport logs or stems to the roadside. However, the work of loading and unloading will probably take time to automate, because of the challenges in automating the gripping work as well as identifying different tree assortments.

To be economically viable, any innovations in automation need to cut costs in some way, or increase income. As the hardware is likely to be more expensive initially, operator productivity has to be increased, or running costs such as fuel consumption has to be decreased. The first step is likely to be semi-automation, in which some processes can be carried out quickly, efficiently and autonomously, while an operator will continue to carry out the work that is more difficult to automate, such as the gripping of logs, and locating logs on the ground correctly. Eventually, the operator will co-ordinate a number of work units, either by controlling several cranes on a machine or controlling several machines remotely. The challenge will then be to reach a level of automation, that means the operators have a supervisorial role rather than carrying out the work themselves.

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15 Where to look for further information

15.1 Journals and conferences

The ongoing development in forestry operation robotics is taking place within two different branches of research: robotics and forest operations. The latter is an applied field for advances in forestry, and the scientific work is often published in journals such as the *International Journal of Forest Engineering*, *Croatian Journal of Forest Engineering* and more general forestry journals. Applied, but not necessarily forestry related, advances can also be found in journals such as the *Journal of Field Robotics*. Naturally, basic advances in robotics can be found in journals such as the Institute of Electrical and Electronics Engineers' (IEEE) *IEEE Transactions on Robotics*, *IEEE Transactions on Mechatronics* and *IEEE Transactions on Automatic Control*, and at conferences such as the IEEE

International Conference on Robotics and Automation (ICRA) and the IEEE International Conference on Intelligent Robots and Systems (IROS). However, as it is assumed that readers will be able to find general, basic robotics-related information relatively easily, we are providing further information on the more limited, and probably less familiar, field of forestry operations.

Forest operation research networks are formed predominantly through organizations and conferences in which applied advances in forestry operations robotics are presented.

The IUFRO's Division 3 – Forest Operations Engineering and Management unites people with an interest in advancing forestry operations. Among other networking activities, Division 3 arranges sessions within the IUFRO World Congress, which is held at 5-year intervals and is one of the largest global forest events, attended by more than 2000 participants. The next congress will be held in 2019 in Brazil. More information about IUFRO and Division 3 can be found at https://www.iufro.org/.

There are a number of international Anglophone conferences dedicated to advances in forestry operations, for example:

FORMEC, which is held annually in Europe, www.formec.org.

COFE, which is held annually in North America, http://cofe.org/.

The Precision Forestry Symposium is dedicated to new technology for data collection, automation, robotics and information and communications technology (ICT). It is held every 2 or 3 years in the southern hemisphere; the most recent, fourth, symposium, was held in 2017, https://www.sun.ac.za/english/faculty/agri/forestry/upcoming-conferences/precision-forestry-symposium.

The Forest Engineering Conference rotates across the globe, and is held every 3 or 4 years. The seventh conference will be conducted in 2021 in Italy, and the most recent one was held in 2018 in New Zealand, http://www.foresteng.canterbury.ac.nz/FEC2018.shtml.

For those interested in regular updates on advances in forestry operations, the free newsletter *Logging On* is available at https://loggingon.net/.

15.2 Futuristic concepts

The internet abounds with exotic and thought-provoking robotic concepts, although there are not many focusing on forestry operations. A small selection of concepts is presented here; they are far from being implemented, but might serve as inspiration for potential development.

The now almost 20-year-old animation of STINA, the pre-commercial thinning robot, demonstrates some of the challenges in forestry. It is not actually mentioned in the video, but Sten Gellerstedt was one of the researchers for the concept: https://www.youtube.com/watch?v=t8Qb5t3NIyc.

Scion's brachiating robots provide an interesting take on possible methods of tree-to-tree harvesting: https://www.youtube.com/watch?v=mzzE70ymuTU&t=22s.

For work that is difficult to mechanize, the operators themselves could be strengthened to carry out the work in a less strenuous and safer way, as exemplified by Aegis, an exoskeleton for logging workers: www.jasonplee.com/#/aegis/.

The SLOPE project (www.slopeproject.eu) spans a wide range of possible uses of sensors and digitization, although not specifically for automation. However, its video provides a good exposé of some of the technologies and applications tested, especially in the fields of planning and product quality identification: https://youtube/Ml8nQzf17Mc.

The Virtual Forest project (http://www.virtueller-wald.de/en/the-virtual-forest/) draws on the potential of gathering detailed data to model and visualize forests and forestry operations to provide decision support: https://www.dw.com/en/the-virtual-forest/av-17904981.

Interested readers would also like to keep an eye on the two Swedish projects Auto^2 and Mistra Digital Forest, both with the aim to advance the automation in forestry operations and with strong engagement from forest industry, machine manufacturers and academic institutions.

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