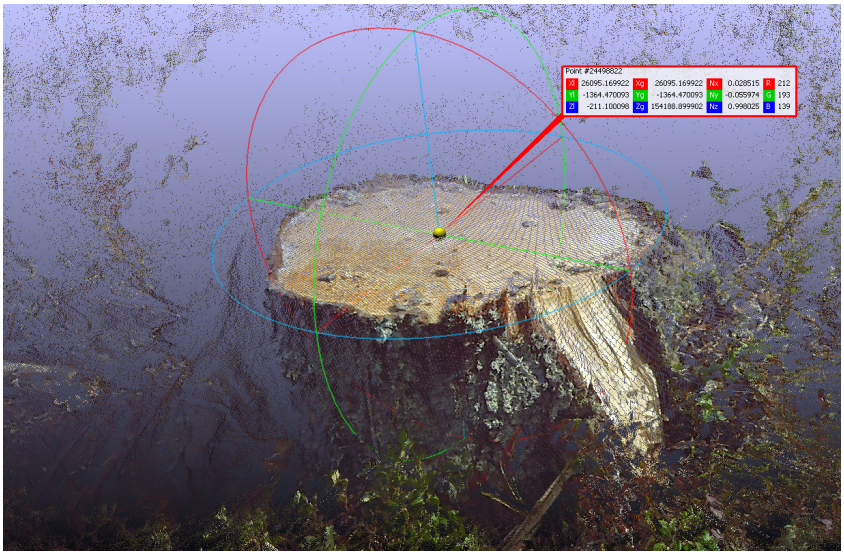
DOCTORAL THESIS

A Methodology for Automation of Mechanized Forest Regeneration



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Computer Aided Design

LULEÅ UNIVERSITY OF TECHNOLOGY

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A Methodology for Automation of Mechanized Forest Regeneration

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PREFACE

The research presented in this thesis was conducted within the research subject of Computer Aided Design at the Division of Product and Production Development at Luleå University of Technology. The research has been funded by the Kempe Foundations, the Faste Laboratory; a Vinnova Excellence Centre, the Swedish research council Formas, and by Smart Machines and Materials; an area of excellence in research and innovation at Luleå University of Technology.

The seed from which this doctoral thesis work originates was planted years ago with me doing a master's thesis work for the Swedish University of Agricultural Sciences about how to improve mechanized planting. The master's thesis was a work supervised by Magnus Karlberg at LTU, Lars-Göran Sundblad at Skogforsk and Urban Bergsten at SLU; people who later would turn out to be some of my "partners in crime". Later, I got the opportunity to start working as a PhD student in Computer Aided Design, launching my research career in the Faste Laboratory. As chance also would have it, a research collaboration with LTU, SLU and Skogforsk was initiated where I was privileged to learn stuff like how suitable microsites are created, why you would ever want to measure something in m^3fub, or what those angry little pine weevils were up to and how to stop them. This research world also taught me that you learn the most being out in the field (in any weather) and see it for yourself, whether it is watching steep terrain logging in sunny Alsace or clearcut stump removal in the outskirts of a rainy Suonenjoki. This was a research world that I came to appreciate very much, which was not only because of sunny and rainy field trips, but also because of the people around me:

First and foremost, thanks to my dedicated supervisor Magnus Karlberg for your patience and support through these years. Thanks also to my co-supervisor John Lindström for helping me understand the research world.

Thanks to all researchers at SLU and LTU who I have come to know throughout the years, with many extra thanks to Urban Bergsten and Back Tomas Ersson at SLU and L-G Sundblad on Skogforsk for showing me the world of forestry.

Many thanks goes out to the entire PPD division, those still left and those whose watch is ended; a group of amazing people that have allowed me to work in a stimulating and creative environment. Special thanks to my roommate Jonas Pavasson that stood up with me for so long.

Lastly, thanks to my family for your never-ending love and support that have kept me going.

Luleå, March 2018

ABSTRACT

High quality forest regeneration is typically performed by a combination of site preparation through mounding and deep planting. These operations are performed either by mounders with subsequent manual planting, or by mechanized tree planting devices that creates mounds and, simultaneously, plant seedlings. These forest regeneration strategies are sustainably beneficial and have high development potential particularly regarding efficiency. Recent development in digitalization, sensing, IoT etc. has enabled new forest regeneration strategies. Hence, the objective of this thesis is therefore to develop a methodology for how automation can be used to improve sustainability in forestry and in forest regeneration operations in particular. The research has followed the Design Research Methodology in which success criteria was identified concurrently with analysis of the as-is situation. Then different sub-solutions forming the automation methodology was prescribed and validated in subsequent descriptive studies. To enable automation, it was found that data needs to be retrieved from surroundings while performing mounding or mechanized planting, whereby analyses of this data need to be used to make improved decisions of the machines' working procedures. First, properties and characteristics of the surroundings on a clearcut were defined. Then, different ways to retrieve data from the surroundings were tested and evaluated. In addition, several ways of analysing such data for improved decision making were found and validated. The information gained from data collection of surroundings and subsequent analyses further has potential to be improve activities beyond forest regeneration e.g. smart forwarding, customer adapted assortments, history tracking etc. To use as support for how decision making can be improved from such information, an experimental offroad vehicle platform for researchers and machine developers was developed to enable tests and validation of new solutions with special focus on autonomy and robotics, which requires a variety of data collected from both exteroceptive and proprioceptive sensors. The resulting methodology shows how forest regeneration can be automated in the short-term. Developed methods for data collection and analysis can enhance obstacle avoidance for mounding significantly, and thus contribute to increasing the share of continuously intermittent mounding conducted in Fennoscandia.

SAMMANFATTNING

Högkvalititativ skogsföryngring görs idag med dragen högläggare i kombination med manuell plantering, eller via maskinell plantering som både höglägger och planterar. Dessa sätt att anlägga ny skog anses hållbara och innehar även en hög utvecklingspotential, men är underlägsna kostnaden för kombinationen av harvning och manuell plantering. Målet med denna avhandling har därför varit att utveckla en metodik för hur nya teknologier, främst automation, kan nyttjas för att förbättra hållbarheten i skogsbruket och skogsföryngring i synnerhet. Forskningen har följt metodiken kallad Design Research Methodology, där man först kartlägger ett antal framgångsfaktorer, success criteria, och sedan kartlägger dagens situation, i detta fall skogsbruk och skogsvård och hur automation används i dessa och relaterade områden. Potentialen för automatiserad kontinuerligt intermittent högläggning simulerades för att motivera vidare arbete, samt för att fokusera metodik-utvecklingen. För att möjliggöra automation konstaterades att data måste samlas in från omgivningen under pågående markberedning och plantering, samtidigt som analyser av insamlad data används som beslutsstöd för effektivare makrberedningsprocedur. Initialt definierades kvantitativa egenskaper och karakteristik hos de objekt som befinner sig i och på de marker där maskinerna vistas. Därefter kartlades olika sätt att samla in data från omgivningen med syfte att öka kunskapen om objekten under drift. Vidare utvärderades och testades olika alternativ till dataanalys kopplat till hur objekten ska identifieras för att ge beslutsstöd till en mer hållbar markberedning, och i förlängningen, plantering. för att stödja hur sådan insamlad data kan användas till fler syften inom skogsbruket togs en mobil forskningsplattform fram för maskintillverkare och akademi med fokus på automation och robotik, områden som kräver stora mängder insamlad data från både interna och externa sensorer. Den resulterande metodiken visar ett sätt att på kort sikt automatisera skogsföryngring i synnerhet. Metodiken har potentialen att göra högläggningsproceduren signifikant mer hållbar, samt öka den totala andelen kontinuerligt intermittent högläggning i det boreala skogsbältet.

ABOUT THIS THESIS

This thesis comprises a description of the general research approach that has been used during this work, as well as how the resulting appended papers have contributed and are positioned in the larger context as a methodology for automation in forest regeneration. The main contributions are also presented and discussed, with suggestions for future work.

LIST OF APPENDED PAPERS

Paper A

Lideskog, H., Ersson, B. T., Bergsten, U. & Karlberg, M. (2014). Determining boreal clearcut object properties and characteristics for identification purposes. Silva Fennica 48(3).

Paper B

Lideskog, H. & Karlberg, M. (2016). Simulated continuous mounding improvements through ideal machine vision and control. Silva Fennica 50(2).

Paper C

Lideskog, H. & Karlberg, M. (2014). Automatic clearcut obstacle identification using a time-of-flight camera. Extended abstract and Poster presented at the International Symposium on Forestry Mechanisation: 23/09/2014 - 26/09/2014.

Paper D

Vingbäck, J., **Lideskog, H.**, Karlberg, M. & Jeppsson, P. (2016). Obstacle identification through fast vector analysis. In ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (Vol. 3). New York.

Paper E

Lideskog, H. & Karlberg, M. (2018). Clearcut stump detection using a time-of-flight camera. Submitted to Silva Fennica 2018-02-07.

Paper F

Lideskog, H., Karlberg, M. & Bergsten, U. (2015). Development of a research vehicle platform to improve productivity and value-extraction in forestry. Procedia CIRP 38, 68–73.

AUTHOR CONTRIBUTIONS

In Papers A, B, C, E and F, Lideskog is the main author of the paper and is main responsible for all parts of the research efforts as well as for writing the papers. In Paper D, Lideskog is second author and is responsible for writing most parts of the paper in collaboration with the main author and co-authors, as well as conducting the experimental work and analysing the results.

Related papers but not included in the thesis:

Lideskog, H., Karlberg, M., Lindström, J., Bergsten, U. & Ersson, B. T. (2012). Functional products in forestry : challenges and opportunities. In Proceedings of the 1st International Conference on Through-life Engineering Services.

Lindström, J., Sas, D., **Lideskog, H.**, Löfstrand, M. & Karlsson, L. (2015). Defining Functional Products through their constituents. International Journal of Product Development 20(1), 1–24.

Lindström, J., Plankina, D., **Lideskog, H.**, Löfstrand, M. & Karlsson, L. (2012). Functional product development : criteria for selection of design methods on strategic and operational levels. In The Philosopher's Stone for Sustainability : Proceedings of the 4th CIRP International Conference on Industrial Product-Service Systems, Tokyo, Japan, November 8th-9th, 2012 (pp. 25–30). Berlin Heidelberg.

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1 INTRODUCTION

Reforestation in Fennoscandia[1] is commonly done through mechanical site preparation, followed by manual outplanting of tree seedlings (Eriksson 2013, Granhus et al. 2013, Juntunen and Herrala-Ylinen 2013). Compared to disc trenching, intermittently created planting spots using mounding site preparation has proven efficient in terms of subsequent seedling survival and growth (Örlander et al. 1990, Sutton 1993, Saksa et al. 2005), and even better seedling survival has been noted using inverting preceding planting (Hallsby and Örlander 2004). Intermittently created planting spots also have the advantage of lower soil disruption than disc trenching, which is important for advance regeneration and other environmental, recreational, and archaeological values (Örlander et al. 1998). Compared to disc trenching, however, mounding execution is highly sensitive to obstacle occurrence on the clearcut. On average, every other mounding attempt fails (Larsson 2011). Consequently, when soil disturbance is not considered, disc trenching is chosen at the expense of mounding on obstacle-rich clearcuts (Lundmark 2006).

In today's forest regeneration, the need for productivity increase is much higher than previous decades (Rantala et al. 2009). Future forest regeneration processes need to utilize a larger share of mechanization in order to reduce costs and enhance productivity (Nilsson et al. 2010). Competitive mechanized processes in forestry require high production at low cost and high technological availability (Rantala et al. 2009). One way to improve productivity in forest regeneration processes is to automate machines (Ringdahl 2011). In forestry, processes are still mechanized (with manually operated machines) during harvesting or forwarding (Nordfjell et al. 2010), while in silviculture, manual labor is still common (Ersson and Petersson 2013) and the field of automation is poorly explored (Hallongren et al. 2014). Costs are still too high for mechanized planting compared to the combination of mechanized site preparation and manual outplanting (Hallongren et al. 2014).

In other industries, such as automotive and construction, machines and vehicles are already transitioning to semi-automation or full automation. Sensors suitable for outdoor data collection from moving vehicles have attracted interest in research and development in recent years, as car manufacturers and businesses continue to strive towards self-driving vehicles (Bengler et al. 2014).

In silviculture, semi-automated, continuously advancing planting machines already existed in the 1970s – the Swedish Silva Nova and the Finnish Serlachius planting machines - but were deemed too expensive to keep in use (Nilsson et al. 2010) despite decent planting quality (Kaila 1984, Hallonborg 1995). Today's planting devices are less automated than the continuous machines introduced in

[1] This includes Sweden, Finland Norway and the Russian parts of Karelia and the Kola Peninsula.

previous decades (Rantala et al. 2009) in order to reduce costs and increase technical availability.

Although researchers have stated that reforestation should be amenable to automation (Kemppainen and Visala 2013), very few forestry-dedicated solutions for obstacle avoidance and target identification exist (Vestlund and Hellström 2006). Other researchers have predicted that autonomous operations will soon be a reality during both silvicultural (Nilsson et al. 2010) and harvesting operations (Hellström et al. 2009), but this needs to be addressed more intensively within R&D in order to disruptively improve the forest industry and forest regeneration processes.

Such a paradigm shift requires the ability to remotely sense the surrounding environment and make better decisions based on collected and analysed data. Rantala et al. (2009) claimed that innovations in communication and sensor technology could offer solutions for mechanized planting. Such solutions did not exist in the previous semi-autonomous, continuously advancing planting machines, although development of new machines should adopt the principle of continuous working methods (Rantala et al. 2009). Hence, with such solutions, the degree of automation could possibly be increased to an extent that makes forestry operations competitive in terms of productivity and quality, which is expected to happen in the medium-term or long-term (Ersson 2014) with sufficient stimuli. At the same time, sometimes clashing with productivity needs, sustainable processes are required (WCED 1987) that could be addressed by reducing soil disturbance (Örlander et al. 1998) or GHG emissions from forest operations (Berg and Karjalainen 2003).

By utilizing solutions previously developed, primarily for the automotive and multimedia industries, the automation transformation of forestry operations could be significantly accelerated (Vestlund and Hellström 2006). Development of remote and proximal sensing technology will provide continuous data from which useful information can be extracted and used for decision support, monitoring and evaluation (Talbot et al. 2017).

However, although some sub-solutions may exist in other applications, research is still needed to adapt them and develop dedicated solutions for sustainable forestry operations, which is the focus of this thesis.

1.1 Problem formulation

Productivity of mechanized planting using mounding is not currently competitive. Meanwhile, intermittently executed site preparation cannot be used to the extent desired to enable lower soil disturbance, which is an environmental, recreational and archaeological need. There are no specific technological solutions and methods that can increase the execution performance of intermittent site preparation directly, so such automated solutions need to be tailored for that need.

1.2 Purpose, objectives and research questions

This thesis addresses the challenges of permitting forest regeneration activities to benefit from emerging technologies, such as exteroceptive (cf. proximal sensors; Talbot et al. 2017) sensors and associated methods and processes. Continuously advancing machines that create intermittent planting spots, Continuous Intermittent (CI) machines, have been identified as one important facilitator for higher sustainability in forestry and forest regeneration (see Section 3).

The purpose of the research presented in this thesis is to improve sustainability in forestry through automation. Further, the main objective is to develop a methodology[2] **for such automation, CI machines in particular.**

This thesis is focused primarily on how to collect data about the surrounding obstacles and targets (what should be measured?), and how to process these data (how should they be transformed?) to enable better decision-making in autonomous CI machines.

The thesis encompasses the following research questions (RQs):

1. What surrounding environmental information is needed in order to enable autonomous CI machine operations?
2. How should data from the surrounding environment be captured and transformed into information?
3. How should information about the surrounding environment be used to automate CI machines for increased sustainability?

The research has been focused on base machines that operate continuously and independently, while intermittent planting spots are found automatically (see Sections 3 and 4).

[2] A methodology can be interpreted as a holistic strategy that incorporates processes, methods and tools.

2 RESEARCH APPROACH

The research presented in this thesis has been conducted in a series of activities following the Design Research Methodology (DRM) described by Blessing and Chakrabarti (2009). The use of DRM is suitable since changes in design and working procedures are needed to reach the final objective. DRM suggest a series of descriptive and prescriptive stages (Figure 1) with iterations. Other potential methods that could have been used are circular/iterative or agile (e.g. Ambler 2002), but the DRM was chosen because of a heavy research content, not mainly design and development activities. It is also to be used in a general context.

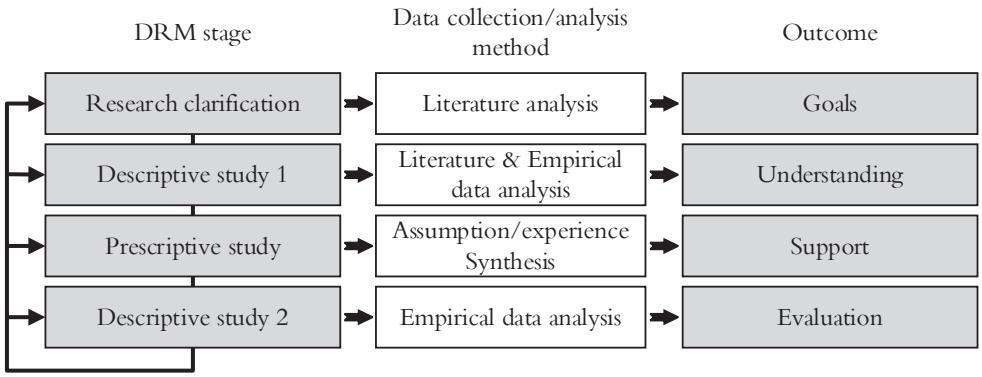

Figure 1. Design Research Methodology stages, methods and outcome. Based on Blessing and Chakrabarti (2009). Feedback arrows depict the iterative nature of DRM.

Throughout the research process, extensive literature reviews have been conducted iteratively to analyse scientific documents, product reviews, trends reports, industry reports, etc. In addition, several interviews (Patton 1990, Kvale and Brinkmann 2009) and workshops (Remenyi 2013) with academics and forest machine developers and manufacturers have been carried out to collect data for subsequent analyses. These analyses provided insights about the as-is situation on existing tools, methods and processes in sustainable forestry, forestry automation, etc. Hence, a deep understanding of the state of the art and its history, as well as best practice in industry, was gained (described in Section 3). The analyses further contributed to identification of important needs and challenges in forestry and other fields (see Section 3.4), which were corroborated through triangulation (Miles and Huberman 1994). These needs and challenges were used to position and formulate overall goals for the research presented in this thesis (see Section 1.2). Based on these goals, measurable criteria could be identified for evaluation of the proposed automation methodology. Additional empirical studies of existing forestry operation solutions were conducted to gain an understanding of the aspects of current solutions that affect success criteria. This information is necessary to focus on solutions that have a significant impact on the stated goals. Hence, the

research clarification and first descriptive study of DRM were iteratively conducted and refined throughout the research project.

The RQs were formulated in order to tell the researcher what was needed to know first, channeling energy in the right direction (Miles and Huberman 1994). As with the nature of DRM, the RQs were iterated to some extent. Miles and Huberman (1994) argue that an RQ might as well start out generally or vaguely and then get more "defogged" as the project progresses. The basic assumption is that data from the surroundings must be acquired and transformed in order to address the success criteria stated in Section 3.4, which is the goal of this thesis.

Based on the goals and RQs, the as-is situation and identified aspects that affect success criteria, a to-be scenario for future sustainable forest regeneration was prescribed to guide the research. Since new information emerged on a continual basis, the to-be scenario was updated throughout the research project.

Solutions that improve the aspects that are preventing forest regeneration systems from reaching the goals were then developed and evaluated (verified and/or validated) by using the identified success criteria at a higher level through different descriptive studies. Hence, solutions were prescribed and evaluated (descriptive study) iteratively. Papers A-F can be put in the context of DRM stages as seen in Figure 2, where further information is found in the papers.

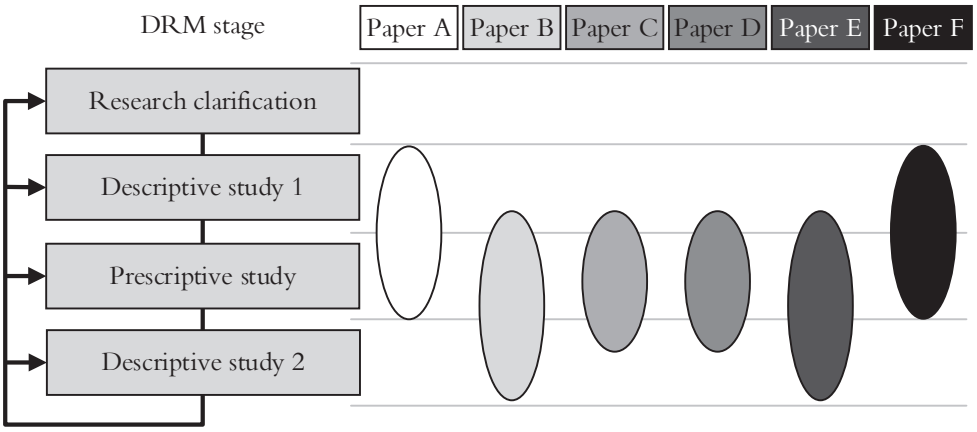

Figure 2. Depiction of how papers A-F relate to DRM stages.

2.1 Paper positioning

The research process illustrated in Figure 3 shows how this research project was systematically approached. The process starts with the identification of social and industrial needs whereby project goals and RQs are formulated. Since not all identified needs could be addressed due to competence profile, resource and time limitations, the research was narrowed down to include forest regeneration and automation opportunities only. In automation, two main areas were found in the

gap between the as-is situation and the to-be scenario, sensing and actuation. Sensing is connected to the information that is needed to collect for better decision-making, whereas actuation concerns subsequent activities (machine movements, etc.) during forest regeneration. The main focus of this thesis is the sensing part (papers A, C, D and E), while the potential of automation in forest regeneration was evaluated in paper B, and the prospects for automation in forestry were analysed in paper F. RQs 1-3 are also positioned in Figure 3.

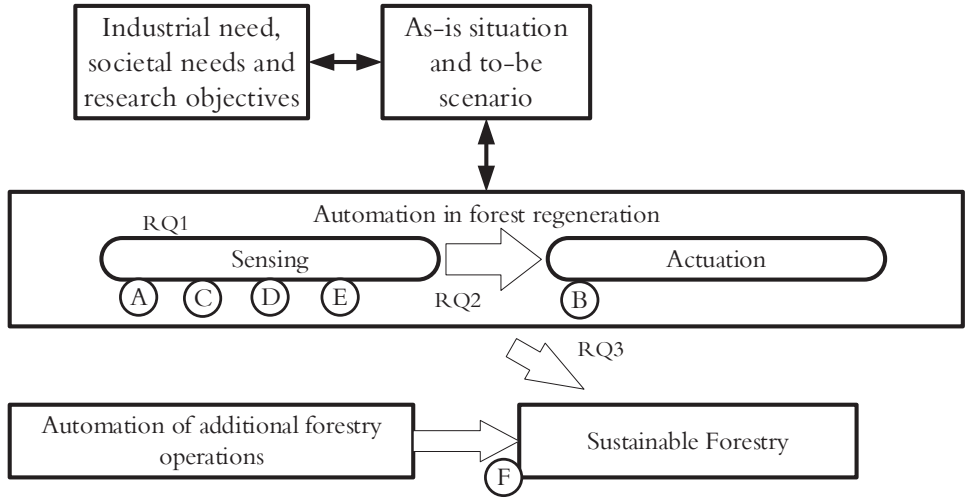

Figure 3. Relationships between papers, RQs and the context in which they have made a contribution. This process can also be identified in the various sections of the thesis.

In addition to the view presented in Figure 3, Bäckström (1978) and the Skogsarbeten research institute (now Skogforsk, Sweden) formed the ideal working method of a tree planting machine. In their view, as depicted in Figure 4, the steps for a tree planting machine working method account for the actuation part of the machine and should be completed as fast and autonomously as possible (Ersson 2010). What the working method does not account for is the full interaction needed with the surrounding forestland in order to determine where to mound and plant a seedling, i.e. the sensing part. Thus, an ideal tree planting machine is not only fast and autonomous (which has no intrinsic value), it makes the steps accurate too. In this context, the contribution of this thesis is mainly positioned in the area enclosed by dashed lines. In order to achieve high accuracy in actuation, a basis for decision-making is needed through sensing.

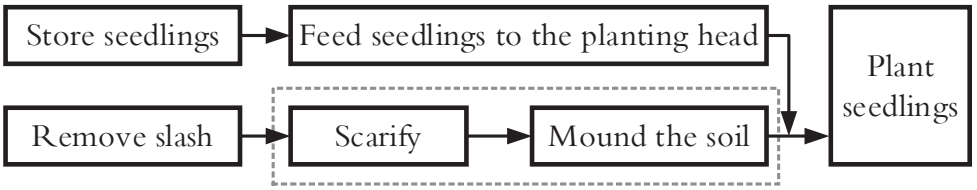

Figure 4. An ideal working procedure of a tree planting machine, from Bäckström (1978). The dashed area represents the section in which this thesis has contributed. These steps should be completed as fast, autonomously and accurately as possible supported by collected data and analyses.

2.2 Data collection and analysis

In this research project, data have been collected through both quantitative and qualitative methods. I distinguish between data and information such that data can be seen as 'raw', i.e. no filtering, transformation etc. has been conducted. Information, on the other hand, has been transformed into useful units.

The research process described in Figure 3 has been followed to ensure correct boundaries, i.e., that which will be studied (see 'focus' in Miles and Huberman 1994).

The concepts of reliability, validity and generalizability are crucial to both qualitative and quantitative research. Reliability is interpreted by Thorndike (1985) as "how accurately and precisely the test score assesses the domain from which the test does in fact draw a sample", while validity ascertains if the "test tasks match the attributes or domain of knowledge that we wish to assess." Similarly, Roberts and Priest (2006) define reliability in research as "how far a test, procedure or tool will produce similar results in different circumstances, assuming nothing else has changed", while validity "describes the extent to which a measure accurately represents the concept it claims to measure". External validity is ensuring that "conditions under which the study is carried out are representative of the situations and time to which the results are to apply" (Black 1999), i.e. that your sample is representative. One way of enhancing validity and reliability is known as triangulation, which Roberts and Priest (2006) define as "the combination of two or more theories, data sources, methods or researchers in the study of a topic." Generalizability can be defined as "an act of reasoning that involves drawing broad conclusions from particular instances, that is, making an inference about the unobserved based on the observed" (Denise and Beck 2010). Moreover, the researchers argue that "in quantitative research, generalizability is a major criterion for evaluating the quality of a study" and in qualitative research, "the issue of generalizability is even more complicated and more controversial" (Denise and Beck 2010).

For each part of methodology development, generalizability has been evaluated, with a basis in the defined delimitations in order to evaluate if a broader

generalization has been possible and whether the choices of data collection, methods etc. have been sufficient to cover the needed scope. The generalizability of the methodology developed in this thesis is discussed in Section 8.

A quantitative data collection approach was employed in several ways: as data collected from experiments, as computer-generated simulation data using a pseudo-random generator and literature searches in the databases of Scopus and Google Scholar using keywords that covered the properties of sustainability, automation, forestry and forest regeneration. 3D point cloud data collected from experiments were used in sensing methodological development. Data were used in an iterative process of implementation, testing different techniques and evaluating different algorithms using display of matrices and graphs (Miles and Huberman 1994) to draw conclusions. Computer-simulated data with defined probability distributions from literature and interviews and conclusions were drawn about converged results (see Metropolis and Ulam 1949) for e.g. mounding quality as a function of the chosen working strategy. External validity was addressed when chosen quantitative studies were planned in order to represent situations and times to which results were to be applied (see Black 1999). Reliability was addressed when several different sources were used for data collection.

In addition, to obtain sufficient information for the research, qualitative methods such as workshops and interviews were used to internally validate (or triangulate) collected quantitative data (such as variables for simulations derived from literature). To obtain an initial structure of interviews and minimize imposition of predetermined responses when collecting qualitative data, interviews were open-ended and semi-structured (Patton 1990, Kvale and Brinkmann 2009). Interviews about e.g. physical parameters that define clearcut obstacles were conducted with academics: people from experimental mechanics, geosciences and environmental engineering, both to corroborate literature findings and to identify new sources. To collect data to form an accurate as-is situation and a prescriptive to-be scenario, additional interviews were conducted with a leading manufacturer of forestry equipment for scarification and with people from forest science to collect data about

- the description of the as-is situation in forestry,
- the validity of the prescriptive to-be scenario,
- what objects are considered obstacles,
- how obstacles affect site preparation,
- what strategies will streamline site preparation and planting, and
- what site preparation strategies are realistic to develop, given ideal obstacle identification, and
- needs in industry and academia for automation testing and development.

This was used to verify views in literature and triangulate, e.g., the prescriptive to-be scenario from several sources.

Data analysis consist of three flows of activity: data reduction, display and conclusion drawing (Miles and Huberman 1994). Data reduction was embodied in the papers when literature reviews were focused and consciously selected to the scope. Data reduction was also used when new methods and tools were developed to best utilize data collection from surroundings using sensors. Data reduction (and transformation was a continuous work until a study was finalized. Data display was used e.g. when organizing literature review results or when visualizing algorithm efficiency on different setups. This allowed conclusion drawing and proper actions to be taken for further progression in the study.

3 AS-IS SITUATION

The following section summarizes the state of the art and best practice in the field of forestry operations in general and forest regeneration in particular. In addition, the fields of forestry automation and sustainability are reviewed in the relevant context. The outcome of this section has been the main basis for the success criteria in Section 3.4 and the to-be scenario described in Section 4.

3.1 Forestry Sustainability

"… the environment is where we all live, and development is what we all do in attempting to improve our lot within that abode. The two are inseparable." (WCED 1987).

Sustainability is achieved if development processes can meet the needs of the present without compromising the ability of future generations to meet their own needs (WCED 1987). There are limitations on sustainability however; our efforts are constrained by current technological and social organization and by nature's ability to accommodate human activities (WCED 1987). Our society requires the natural resource of wood to provide for our welfare. Meanwhile, we still want to preserve forest flora and fauna, its land and water, recreational values and cultural heritage. Managing forests sustainably is therefore a demanding and necessary task. Deficiencies in adopted policies, methods and mechanisms that maintain the ecological, economic, social and cultural roles of trees and forestlands (Sitarz 1993) must be addressed for the sake of both ourselves and future generations.

Human economic activities such as manufacturing, agriculture and forestry all rely on natural resources. With that in mind, some researchers argue that ecological sustainability deserves higher priority than sustainable economic development (Starik and Rands 1995). In fact, observers believe that ecosystem health has an intrinsic value apart from its human benefits; it has a right to exist with or without humans (Nash 1989).

A few countries have adopted regulations that require environmentally sustainable forestry operations and management. These countries have embraced the use of sustainable forest management (SFM) (Stupak et al. 2011). By introducing SFM, measurements are taken to stimulate participating companies and organizations to take actions (investments) to ensure the regrowth of harvested clearcuts and other measures that stimulate sustainability. Sustainable forestry is defined as solutions that lead to economic feasibility, ecological viability and social desirability (Salwasser et al. 1992, Lindenmayer et al. 2000). These solutions are regarded as crucial to recognize according to the Rio Forest Principles (1992), from which The Montréal Process (2015) originates; a number of countries that own around 50% of the world's forests have set goals to maintain a broad range of forest values indefinitely. In terms of the EU, similar processes came into play at the same time in the form of the Forest Europe process (MCPFE 1998). Since agriculture and

forestry represent 78 % of land cover in the EU, they play a big role in maintaining natural resources, such as quality water and soil, as well as biological and landscape diversity (European Union 2008). In principal, they comprise indicators for how maintenance, conservation and enhancement of forest functions such as forest ecosystems, soil and water can be measured in their interplay with productive functions (MCPFE 1998, Montréal process 2015). The Forestry Europe process has also formed operational guidelines for how aspects of sustainability in their member states' forests should be both addressed and measured in order to maintain and enhance the measured levels (Appendix 1).

3.1.1 Outlooks in forestry sustainability

Sustainability is considered crucial now more than ever. For example, the EU has some of the strictest environmental requirements in the world. Member states need to contribute to green economy, protection of nature and protection of health and quality of life. The EU 7th Environment Action Programme states that by 2050 legislation, an improved knowledge base, wiser investments and integration of environmental requirements have enabled people to live well within the planet's ecological limits such that natural resources are managed sustainably and biodiversity is protected, valued and restored (European Union 2008).

In some cases, goals may be contradictory, and working towards them all in a cohesive way is not straightforward. It will probably be necessary to introduce greater diversity in the way forests are managed to fulfil all of the goals of sustainable forest management. Some forests will continue to be managed according to traditional European silvicultural principles, while others will be managed according to e.g. principles of continuous cover forestry, natural conservation, community or social forestry, or to enable shorter rotation forestry (Backlund 2013).

To summarize, demands on ecology and aesthetics, recreation, i.e., ecosystem services other than wood production are increasing.

3.2 Forestry Operations

From the birth of mechanized forestry operations, timber harvesting in Fennoscandia has been practiced using clearcutting to organize sustained yield (Kuuluvainen et al. 2012). Clearcutting means that a limited area is cleared from trees, regardless of size and species (Kuuluvainen et al. 2012). This method is still common practice but with added measures to ensure that clearcut areas are reforested (Skogsstyrelsen 2016) and that negative effects on biodiversity are avoided (Skogsstyrelsen 2014, Metso 2014).

In the 1980s and onwards, final felling in Fennoscandia has used the two-machine system of a harvester and a forwarder (Nordfjell et al. 2010). Technological advancements have improved machine availability, lifting and carrying capacities,

etc., which have led to a total harvesting cost reduction from around 22 EUR/m^3 in 1985 to 10 EUR/m^3 in 1995, when the reduction stalled. Since 2003, there have been indications of decreasing productivity (Nordfjell et al. 2010). Development for forest machine manufacturers depends on progress in other vehicle industries (Nordfjell et al. 2010), since very few machines are produced annually (Drushka and Konttinen 1997), which means that the development costs are distributed over only a few sales. These machines are now lighter, faster and more accurate than ever before but basic technologies and operation have remained the same since the system was introduced (Öhman et al. 2008).

Pirnazarov (2015) argues that the challenge for forestry machine manufacturers is to meet global harvesting competition, new customer demands and legislation while addressing harvesting and log transportation productivity (see Nordfjell et al. 2010), fuel consumption (see Nordfjell et al. 2003), soil damage (see Horn et al. 2007), and ergonomic issues for machine operators (see Törnqvist 1998).

Common to the work environment of most forestry machines are the mental and physical stress from machine operation. Too high cognitive work-load can occur when the amount of information that needs to be processed are extreme, or when information needs to be processed rapidly; situations that occur during forest machine operation (Löfgren 2004). In addition to that, forestry machine operators exhibit higher frequencies of musculoskeletal disorders because of their work environment, despite mechanization and more easily maneuverable controls (Eklund and Cederqvist 1998, Attebrant et al. 1998).

Other activities on forestland occur after final felling, including mechanical stump removal (Berg 2014), forest regeneration through site preparation and subsequent manual planting (Sutton 1993) and mechanized tree planting (Rantala et al. 2010).

Forestry operations such as these are needed for proper forest utilization. However, one identified major challenge is ground damage caused by forestry machines (Edlund et al. 2013), preventing these activities to be considered sustainable (see MCPFE 1998). The likelihood of widespread soil deterioration increases with site preparation intensity, use of heavy machinery and shortening of rotation (Worell and Hampson 1997). Thus, different techniques have been introduced to prevent soil rutting and compaction (Alakukku et al. 2003, Chamen et al. 2003). Still, some effects of site preparation on carbon stock have been measured over decennia and there are indications of increased net carbon fixation at the ecosystem scale because of higher establishment and growth of tree seedlings (Mjöfors et al. 2017)

The prevalent view is that intense silvicultural measures for stand establishment are essential to obtain high sustained yields, but the effect of increasing regeneration measures on productivity is not consistently positive. Sometimes it has little or no effect due to high mortality rates of artificially regenerated seedlings and/or abundant natural regeneration. In such cases, an investment in intense

regeneration measures cannot be justified (Hallsby et al. 2015). Other researchers claim that the conventional system might need reevaluating in order to meet a wider range of environmental, economic and socio-cultural needs (Puettmann et al. 2009, Kuuluvainen and Siitonen 2013).

3.2.1 Forest regeneration

In Fennoscandia, forest owners are required by law to ensure that stands are reforested after clearcutting; the most common method is to plant seedlings (Eriksson 2013, Granhus et al. 2015, Juntunen and Herrala-Ylinen 2013). Around 80 % of reforested areas in Sweden are planted with seedlings (Skogsstyrelsen 2016) and the trend is increasing (Eriksson 2013). Other methods of forest regeneration, such as direct seeding or natural regeneration, are not used to a great extent. Prior to planting, machines almost always prepare the soil in order to ensure favourable conditions for the seedling (Forest statistics 2012). A place created by soil preparation, or site preparation, where a seedling (or seed) is to be planted is variously termed planting spot (Berg 1980), a microsite (Sutton 1984) or a planting area (Adelsköld and Örlander 1989).

Mechanized site preparation is considered an efficient method for improving regeneration of boreal forests. Well-done site preparation provides the seedlings with increased nutrient availability (Sutton 1993), as well as reduced *Hylobius abietis* predation (Petersson and Örlander 2003, Nordlander et al. 2011), vegetative competition (Malik and Timmer 1996, Archibold et al. 2000) and frost heaving (Goulet 1995). The procedure typically uses disc trenchers or mounders (Figure 5); the choice of machine depends on terrain properties (Lundmark 2006) and level of difficulty (Berg 1982). Studies have shown that the choice of site preparation methods in southern Sweden is often a function of tradition and available resources rather than aspects pertaining to the stand (Skogforsk 2017).

Figure 5. A Bracke two-row mounder (left) and Bracke two-row disc trencher (right). Photo: Bracke Forest AB.

The disc trenching method of site preparation (Figure 5, right) uses a forwarder machine that typically weighs more than 15 tonnes; arms are mounted on the rear, on which discs turn transverse the driving direction while digging into the ground. This produces a continuous ditch where soil is dug up and turned upside down, creating a row of mineral soil without underlying humus (Löf et al., 2012). Most often, two or three trenches are created in parallel. Afterwards, suitable planting spots are found manually by planters that place the seedlings (preferably) deep in the continuous mound. Disc trenchers are less sensitive to obstacles on the clearcut and are used more frequently on obstacle-rich clearcuts.

Site preparation through mounding (Figure 5, left) typically uses a forwarder. While the machine drives forward continuously, intermittent mounds are created with uniform distances behind the machine, most often two or three rows in parallel using three or four-point mattock wheels (McCarthy et al. 2017). Seedlings are preferably deep planted in the mound with a cap of mineral soil (Örlander et al. 1990). Correctly performed mounding can lead to better early shoot growth of subsequent planting (Örlander et al 1990, Saksa et al. 2005) and is considered more environmentally and economically beneficial (Uotila et al. 2010) than disc trenching. However, mounding execution fails every other time because of obstacles on the clearcut (Larsson 2011), which cause mounding to be more seldom used on obstacle-rich clearcuts. Today, mounders are equipped with hydraulic load-sensing valves and articulated arms so that the wheels are able to find their way around stumps and stones (Saksa et al. 2018). The improvement

Inverting is another, more recent, method of conducting site preparation. This method is either excavator-based or continuous with similar base machines as disc trenching and mounding. The method is considered to be on a par with or better than mounding in terms of seedling growth and survival (Örlander et al. 1998, Hallsby and Örlander 2004, Wallertz et al. 2018), but the method still needs to be improved technically (Hallsby and Örlander 2004) and is not commonly used.

To create a satisfactory number of planting spots during disc trenching, around 50 % of the area needs to be disturbed (Lundmark 1986). An advantage of this procedure is that more planting spots can be found, as opposed to finding spots in intermittent mounds that may or may not have been created at all because of obstacle occurrence. Thus, disc trenching is often chosen instead of mounding on obstacle-rich sites (Lundmark 2006). Mounding disturbs only around 35 % of the clearcut area.

A planting spot with exposed mineral soil of 20 dm^2 (Adelsköld and Örlander 1989) to 25 dm^2 (Söderström et al. 1979) is considered sufficient. Thus, a perfect, circularly created inverted mound of 25 cm in radius is sufficient for one planted seedling. By law, at least 2,300 seedlings are to be located per hectare in certain parts of Sweden some time after final felling (Skogsstyrelsen 2017). To ensure sufficient numbers of surviving seedlings, imagine 2,500 planting spots per hectare,

which optimally would render a minimum soil disturbance of 5 % of the area using this theoretical inverting procedure (also discussed by J. Hajek pers. comm. 2016). Thus, there is still a high potential for less soil disturbance while still ensuring sufficient quantities of seedlings.

Highly automated continuously advancing planting machines already existed in the 1970s – the Swedish Silva Nova and the Finnish Serlachius – regenerating with decent quality (Kaila 1984, Hallonborg et al. 1995). Both projects were ultimately abandoned; the Silva Nova around the turn of the millennium. The reasons that the Silva Nova was not commercialized include (Berg 1985, Hallonborg et al. 1995, Malmberg 1990, von Hofsten 1997, Nilsson et al. 2010):

- a high purchasing cost that could not be offset by an increase in productivity; they were too expensive,
- poor ergonomic conditions for the operators,
- low acceptance from district and private forest owners due to initial problems with low planting quality and the fact that it "stole" the easiest planting grounds and labor otherwise available to local teens,
- lower survival rate than manual planting,
- high administrative, logistical and wage costs,
- shift towards piece-rate pay instead of an hourly wage for manual tree planters, which increased motivation and productivity of the main competitive method.

The current state-of-the-art planting devices are less automated than the continuous machines introduced in past decades (Rantala et al. 2009) and have some advantages, including (Berg 1983, Hallonborg et al. 1997, Ersson and Petersson 2003, Ersson 2010):

- increased robustness because of less complex design,
- flexibility to choose planting spots
- less problematic to work on irregularly shaped stands,
- less soil disturbance,
- qualitative, consistent deep planting, leading to high survival and growth,
- lower investment cost, thus reduced requirements for productivity, utilization, planning and organization.

Nearly all planting machines these days are excavator-based and mechanically perform mounding before a seedling is automatically fed down to the ground to be planted from storage located on the planting head. The Bracke P11 mounds and plants one seedling at a time, while the M-Planter can mound and plant two at a time. The productivity of these machines ranges from 130-260 seedlings/hour for the P11 (von Hofsten 1993, St-Amour 2009) to 150-300 seedlings/hour for the M-Planter (Rantala and Laine 2010, Laine and Rantala 2013). Reforestation

using the Bracke P11 in southern Sweden is approximately 25 % more expensive than combined disc trenching and manual planting (Ersson 2014), while some studies have suggested that mechanized planting with the M-Planter device may be cheaper than combined mechanized mounding and manual tree planting (Rantala et al. 2009) and combined excavator based mounding and manual planting (Strandström et al. 2011). Researchers argue that the demand for mechanized planting will increase since the current manual workforce is due to retire, leaving few who are willing to do manual forest work (Juntunen 2013).

The need to preserve environmental, recreational, and archaeological values is becoming more important, which for site preparation means that disturbed soil surface area should be minimized and natural ground contours preserved (Örlander et al. 1998). Low area disturbance improves the likelihood of advance regeneration, which may be a valuable contribution to the developing stand (Örlander et al. 1998). Other ecosystem services may also benefit from decreased soil disturbance, including reindeer lichen cover that could take 50 years to recover from intensive disc trenching (Roturier 2009); mushroom and berry picking that is a multi-million euro industry in Sweden and Finland (Hansen and Malmaeus 2016), or the fact that lower soil disturbance is aesthetically and recreationally less controversial (Brunson and Shelby 1992, Hallsby and Örlander 2004). High intensity site preparation also causes unwanted effects that degrade soil structures (Ballard 2000), and disturb nutrient and water fluxes (Piiranen et al. 2007). Such effects may lead to unacceptable long-term effects on sustainability (Worell and Hampson 1997). Piiranen et al. (2007) however argues that these effects can be minimized by preparation techniques that leave some of the soil surface intact.

3.2.2 Outlooks in forest regeneration

When forestland is reforested in the future, it is plausible that an increased quantity of slash and stumps will be extracted for energy purposes, which will lead to more forest sites that are suitable for mechanized planting (Saarinen 2006, Rantala et al. 2009). Saarinen et al. (2013) report a planting machine under development that aims to use planting spot detection and tray-wise-loaded automatic feeding of seedlings to increase efficiency and productivity.

When it comes to how the future forest regeneration should be conducted, researchers argue that it should be mechanized and that a machine concept could supersede combined mechanical site preparation and manual planting. To do so, future solutions should:

- be flexible and maneuverable to manage deviations in site selection (Hallonborg et al. 1995) and seedling logistics without being too expensive (Ersson 2014),

- be designed such that jobs are not left unfinished; it should be flexible to allow for added manual planting where mechanized planting has failed (Ersson 2014),
- enable use of band-mounted seedlings, while tray-wise loading is efficient on current crane-mounted devices such as the Bracke Planter and the M-planter (Ersson 2014),
- access the same terrains as current machines and ideally reach the same productivity levels as current scarifiers (Alvehus, pers. comm., as cited by Ersson 2010),
- be cheap enough to allow for seasonal stops and one-shift operation (Ersson 2010),
- work continuously at an adequate speed to enable sufficient productivity (Saarinen et al. 2013),
- utilize planting principles and mechanics of previous planting machines Silva Nova and Serlachius (Saarinen et al. 2013),
- complete site preparation and planting in a single operation and be highly utilized (Rantala et al. 2009),
- as the next step in development, use the mechanization principle of a continuous working method (Rantala et al. 2009).

Calculations (Bäckström 1978) and reports from practical experience (Hallonborg et al. 1997) further corroborate the use of continuous working methods to enable sufficient productivity.

3.3 Forestry Automation

Most forestry machines are manually operated from the machine cab. In other industries, however, manual control has been superseded by remote control, tele-operation or automation (Parker et al. 2016). During the last few decades, technologies for remotely sensed, high resolution data through laser scanning and stereo vision have become a major turning point for many industries. Remote sensing data collected in real time (during operation) or before operation have become the springboard for automation of vehicles both on road (see Levinson et al. 2011) and offroad (see Wooden et al. 2010). Such technology has started to influence the forest industry as well, enabling high resolution spatial and temporal information about forest landscapes and machines (Holopainen et al. 2014). With new sensor and computing technologies, it is possible to obtain information about the surroundings, such as tree diameters, positions and stand density. Such information can be used for decision-support systems for operators, or in off-line forest asset management systems (Öhman et al. 2008).

Research is examining how spatial data from the terrain through exteroceptive, (cf. proximal; Talbot et al. (2017)), sensors can be combined with highly accurate positioning equipment, e.g. global navigation satellite systems (GNSS)

(Zimbelman and Keefe 2018), and proprioceptive sensors to navigate in highly dynamic forest environments (Miettinen et al. 2007, Waslander et al. 2013, Pierzchala et al. 2018) in order to be more sustainable during operation. As data from the surroundings and the machine itself are collected, the route needs to be planned and decided while simultaneously executed, taking resulting wheel ruts (see Salmivaara et al. 2018, Nevalainen et al. 2017) and soil wetness (see Ågren et al. 2014) into consideration. Research on route planning was conducted through the project "Intelligent offroad vehicles", where forestry machine routes were verified in simulated terrain (Ringdahl 2011), and smart control systems for forestry cranes were developed (Shiriaev 2008). In addition, numerous related research efforts regarding terrain navigation have been conducted and applied in practice, for example autonomous legged robots (Wooden et al. 2007, Stelzer et al. 2012, Nishiwaki et al. 2012) or wheeled vehicles (Goldberg et al. 2002, Thrun et al. 2006).

Research connected to forestry machine autonomous navigation has been relatively common, although the operations practiced by forestry machine external equipment have been studied less. Both automation and control within the area of crane movements have been researched (Morales et al. 2014), while few other studies exist for movement control of harvester heads, logging grapples or site preparation arms. Internal control for bucking (Dasa 2018) and data logging has been standard for many years.

Automation is still an unexploited option for productivity improvements in mechanized planting (Rantala et al. 2009). Research has been conducted for subsequent control, including autonomous planting spot detection after mounding intended for autonomous tree planting (Kemppainen and Visala 2013), tree positioning and size determination intended for autonomous harvesting (Jutila et al. 2007), or spruce detection intended for autonomous point cleaning (Hyyti et al. 2014) but needs further attention (Rantala et al. 2009).

3.3.1 Outlooks in forestry automation

There are still a lot of opportunities for utilization of automation in forestry and forest regeneration. Forest operations management need to start understanding and utilizing emerged technologies and knowledge to ensure that the field is continually developed (Talbot et al. 2017). The complex environment of forest terrain requires high ruggedness and robustness of emerging technologies to be accurate and reliable. Researchers believe that exteroceptive sensors may be in an early revolutionary change as data are increasingly collected, stored and interpreted (Talbot et al. 2017). This could serve as an enabler for recognizing appropriate planting spots within sites, along with information and communication technology solutions to improve planning and implementation of mechanized planting (Rantala et al. 2009).

However, researchers claim that it is not the field of how data is collected that will gain interest in the future; it is rather how to use the data, i.e. how to analyse and make effective decisions based on them (Talbot et al. 2017). Important tasks include reliable and accurate positioning solutions in mature and dense forest environments, which would be a step towards automation (Tang et al. 2006).

3.4 Success Criteria

From the as-is review, workshops and interviews with people, the following forest regeneration methodology success criteria were identified:

Criterion 1. Economic impacts

- Machine costs
- Operator costs
- Operating costs
- Efficiency/accuracy of current forest regeneration

Criterion 2. Environmental impacts

- Soil disturbance/advance regeneration considerations
- Machine GHG emissions
- Efficiency/accuracy of current forest regeneration

Criterion 3. Social impacts

- Diversity
- Recreation
- Aesthetics
- Cultural value preservation
- Work environment

To reach sustainability, criteria from all dimensions must be fulfilled simultaneously. Solutions that optimize these criteria should enable optimal ecosystem service provision.

4 TO-BE SCENARIO

The to-be scenario is based mainly on reviewed literature (Section 3). In addition, workshops were conducted initially in this research project with both academics and industry in order to gain an additional outlook of how the field is evolving.

Ideal forest regeneration execution can be translated into a solution leaving minimum soil compaction, disturbance and pollution of GHG. It works fully autonomously, does intermittent inverting (and sometimes mounding) on correct positions, where seedlings are planted deeply into the inverted mound, generating minimum soil disturbance with maximum commitment to several ecosystem services (biomass production, recreational areas, lichen growth etc.). The machine allows for ideal machine and seedling logistics. This to-be scenario is a visualization of a desired future situation used to focus research activities on enabling sub-solutions.

Quality-wise, today's mechanized planting procedure seems to surpass results from manual planting. The main issue, however, seems to be productivity. Forest regeneration with automated operations can enable disruptive changes in productivity and promote sustainability. To address this main issue, this scenario suggests that a solution for forest regeneration work as follows. A mounding/inverting system is attached on a current continuously advancing base machine, where it:

- positions planting spots autonomously using the mounding or inverting procedure, whichever procedure and wherever the position are most suitable from a sustainability perspective,
- accesses the same terrain as current scarifiers and can be run at similar speeds,
- enables planting to be conducted simultaneously.

This solution was created for the purpose of underscoring the studies conducted in this thesis. It was noted that site preparation (almost) always precedes planting. Therefore, the focus is on how to utilize automation in CI procedures, since it is well-established as a sustainable method and has high improvement potential. The system for autonomous creation of planting spots can be separated into sensing and actuation, with the following requirements:

- The sensing system must be able to identify suitable planting spots during continuous advancement based on data collected from the surroundings, preferably taking other ecosystem services into account (Results are presented in Section 5).
- The actuating system must be able to reach the sensed planting spot positions without delaying the base machine's advancement. (Results are presented in Section 6).

The design of planting heads and seedling storage and logistics chains is outside the scope of this thesis. In this scenario, we assume that the planting device is not the bottleneck. However, productivity is addressed in how the mound/inverting position is chosen automatically. Furthermore, technological solutions for how to switch site preparation methods during execution do not exist either. The similarities between mounding and inverting execution make it likely that any positioning method can be conducted by any actuating head in the future. Since inverting heads are commercially unavailable, the mounding procedure is of main focus in the research presented in this thesis.

There is a potential for sensing technology to consider advance regeneration and ecosystem services, such as provision of berries, mushrooms and reindeer lichen when positioning planting spots. However, the efficiency of the mound or inverting execution to become more competitive is a priority; thus, clearcut obstacles that impede execution are of importance. Efficient mound positioning could implicitly address a higher degree of other ecosystem services. Moreover, data collected during forest regeneration may be of interest in other forestry operations, such as high-resolution mapping of ground gradients, machine rutting (see Horn et al. 2007), soil water content or obstacle frequencies.

In total, this to-be scenario requires a methodology for automation, particularly for CI machines, the focus of this thesis.

5 SENSING SYSTEM FOR OBJECT AVOIDANCE OR TARGET IDENTIFICATION

A rule-based approach to the problem of object identification was chosen. An alternative way would, e.g., be to utilize machine learning and enable object identification with training data. This seems to be the approach for many automotive manufacturers working on self-driving cars. However, due to the knowledge base of the research group and the lack of options for collecting many kilometers of training data for supervision from clearcuts, this rule-based approach was chosen for system development.

To enable object identification during silvicultural activities, properties and characteristics of clearcut objects to be used for detection have to be determined. Then, sensing techniques, tools and methods that can be used operationally for such identification are needed. Figure 6 illustrates the flow of information in a proposed computer-aided system, where properties and characteristics of clearcut objects are obtained by sensing tools. Afterwards, information is analysed through algorithms (conducting object recognition, etc., in a 3D cloud) and machine activities are chosen. The specific activities will make the machine target or avoid objects, i.e., perform an actuation activity. Computer-aided systems (flowchart in Figure 6) using this information to avoid obstacles, find stumps, plan routes, etc., will allow for a greater degree of forestry machine automation.

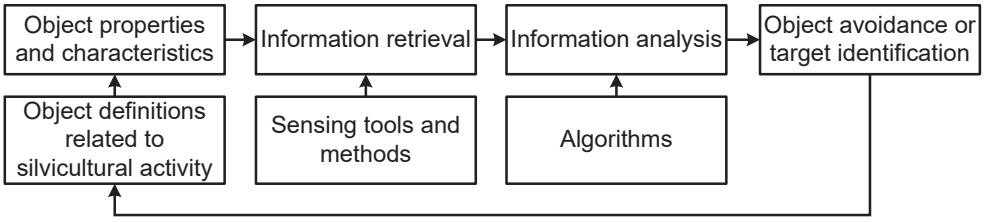

Figure 6. Flowchart of the activities conducted by a computer-aided system using object identification for avoidance or targeting purposes. (Paper A)

5.1 Properties and characteristics of clearcut objects

After clearcutting, machines traffic the clearcut, conducting different silvicultural activities. Many objects on a forest clearcut (stones, stumps, slash residues and roots) disturb site preparation and planting. The following section describes the properties and characteristics of these objects. Identification of these objects is the basic requirement for sensing objects as part of (semi)automation of site preparation, mechanized planting, and stump removal.

To address the definition of objects located on clearcuts, the types of objects that could interact with silvicultural machinery were first identified. Clearcut obstacle properties and characteristics were then quantified and categorized for silvicultural operations. Properties were divided into two main categories, quantitative

properties and qualitative characteristics. A directly quantifiable property has a certain unit and numerical range, while qualitative object characteristics do not have a specific unit. The classification method developed by Campbell and Wynne (2011), based on eight significant characteristics of objects and features, was applied.

First, the objects of interest were defined; previous literature gave information about quantitative properties: a basis for subsequent choice of sensor tools and methods, as well as algorithms. Table 1 shows the identified quantitative clearcut object properties. The objects were found to be (mainly) stones, stumps, slash and roots. The other important object is the soil in which other objects are located, and is thus important to separate.

Data mainly represent the boreal forest zone where silvicultural machines commonly traffic clearcuts. In addition to quantitative properties, qualitative characteristics were associated with each object. An object either has or does not have such qualitative characteristics (Table 1).

Table 1. Quantified obstacle properties, sourced from literature, and obstacle characteristics based on Campbell and Wynne's (2011) classification of objects. If the obstacle possesses the stated characteristic, Y (Yes) is marked. An N (No) indicates that the obstacle does not possess such characteristics.

Characteristic	Stone	Stump	Root	Slash	Soil
Density [kg·m^{-3}]	2500–3200[a]	440–670[b]	301–499[c]	844–883[d]	1400–2050[e]
Tensile modulus [10^9 Pa]	40–68[f]	8.1–16.2[b]	8.1–16.2[b]	8.1–16.2[b]	$4.8 \cdot 10^{-4}$–0.2[g]
Thermal conductivity [W·m^{-1}·K^{-1}]	2.51–3.97[f]	0.12–0.22[f]	0.12–0.22[f]	0.12–0.22[f]	0.17–2.2[f]
Reflectance [%] ($\lambda \in [300m^{-9}\ 2500m^{-9}]$)*	5–80[h]	10–65[i]	-	3–85[i, k]	0–55[h, i]
Moisture content [fresh weight %]	~0	15–64[d, j]	15–55[j]	29–56[d, l]	0–100
Distinguishable tone [m]	Y	Y	N	Y	Y
Distinguishable texture (roughness) [m]	Y	Y	Y	Y	Y
Casts a shadow [m]	Y/N	Y	N	Y/N	N
Forms a distinguishable pattern [m]	N	Y/N	N	N	N
Other objects or features is associated to the obstacle [m]	Y	Y	Y	Y	Y
Distinguishable shape [m]	Y	Y	Y	Y	N
Is found on specific topological sites [m]	N	Y/N	Y	N	N
Can be moved with force exerted during mounding or disc trenching	Y/N	N**	Y/N	Y	Y
Degradation over a forest rotational period	N	Y	Y	Y	N
Exists above ground	Y	Y	Y/N	Y	N
Exists below ground	Y	N	Y	N	Y

[a] Elming (1980); [b] Tsoumis (1991), Doran (1992), Nordling and Österman (2006); [c] Kalliokoski (2008); [d] Kärkkäinen (1976); [e] Parasnis (1971), Parasnis and Dattatrai (1997), Cardarelli (2008); [f] Saarman (1992), Cardarelli (2008); [g] U.S. Army… (1990); [h] Bowker et al. (1985); [i] Lang et al. (2002); [j] Laurila and Lauhanen (2010); [k] Williams (1991); [l] Nurmi (1999); [m] Campbell and Wynne (2011)
* λ = wavelength of radiated light
** Applies for stumps > 100 mm in diameter

In Table 1, the quantitative and qualitative properties and characteristics of clearcut objects are shown. This classification can be viewed as a basis when considering what kind of technology and identification or detection algorithms can be used to better control forest machinery and its external equipment. A special focus was on how machine and equipment move during site preparation; thus the chosen objects had a particular effect on how site preparation are conducted. These objects may also be of interest for identifying or detecting by other forestry operations during harvest or other logging activities.

Furthermore, other ecosystem services such as reduced soil disturbance, reindeer lichen cover, berries growth, were not taken into consideration explicitly. This is however important, as future sustainability should enable a diversity of services. That will put further demands on what are considered objects of importance during site preparation in the future.

5.2 Information retrieval and analysis

Several ways to sense surroundings and analyse collected data were identified. A Time-of-Flight (ToF) camera was chosen as a sensing tool since it showed good potential with its resulting 3D point cloud spatial data. The ToF camera sends electromagnetic energy towards the surroundings and measures the time it takes for it to return after reflection. The distance to points representing the scene is measured without any additional post-processing. Each depth matrix retrieved is 160x120 points with 16 bits depth per pixel. The retrieval of clearcut information was conducted outside Umeå, Sweden on an easy classed clearcut with a snow cover of 1 cm. The ToF camera was mounted in the front of a forwarder and directed at approximately a 45 degree angle such that information was retrieved at a maximum distance of 10 meters from the machine. Camera snapshots were taken at standstill, and physical measurements from the camera to clearly visible obstacles were conducted to compare the ToF camera identification with actual obstacle positions on the clearcut. As the first step, six snapshots were used as basis for data collection and subsequent analysis. 2D planes were placed in the 3D point cloud, fitted as mean planes to the pixels of the corresponding area in order to compensate for ground surface changes (Figure 7). The planes overlapped and the size was adjusted to optimize obstacle identification. Residuals from the corresponding 2D mean plane were analysed and screened; pixels with z values exceeding ~100 mm (above ground and approximately in the normal direction) were saved. Remaining pixels that were clustered with at least 5 pixels and comprising an area in the x-y plane of at least 5,000 mm^2 were saved and considered obstacles.

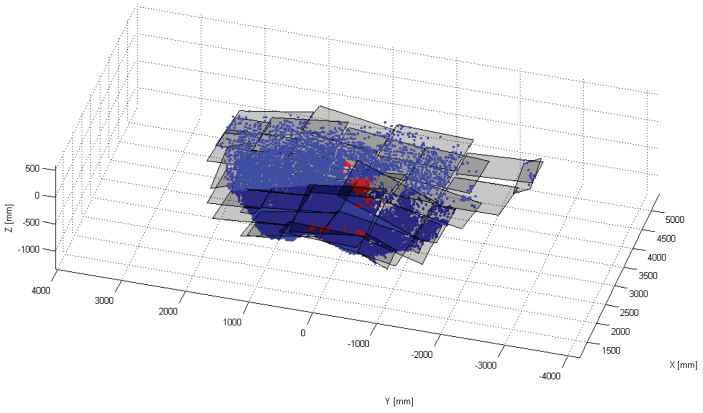

Figure 7. Several overlapping 2D planes (transparent) fitted to the 3D point cloud data (blue and red pixels), and a detected obstacle (red pixels).

In Figure 8, an example of clustered and deviating pixels from the snapshots are depicted next to an RGB image of the same clearcut area. In this area, three stump locations were measured and found (obstacles 1, 2 and 6). Three other objects

were identified, possibly protruding branches from slash piles that were not measured in the field (obstacles 3, 4 and 5).

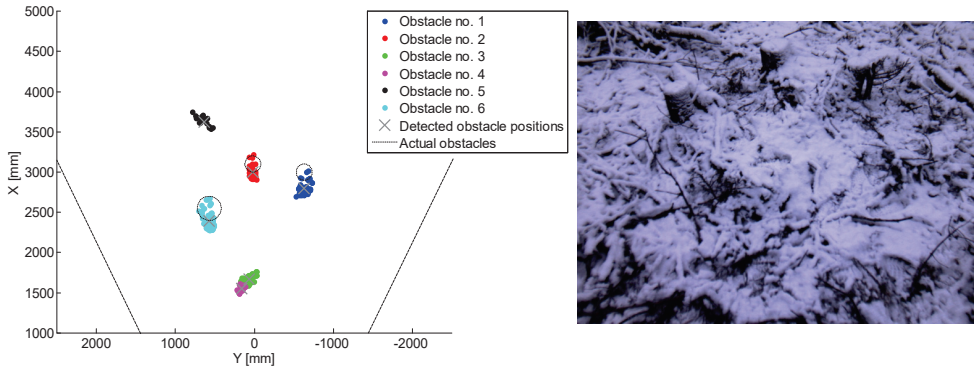

Figure 8. Left: Identified obstacles in color-coded pixels marked with 'X' and actual stumps depicted in dashed circles, viewed normal to the x-y plane. Right: Angled RGB image over the same clearcut area.

The post-processing algorithm uses ~3 seconds on an office laptop @ 2.7 GHz to process each snapshot of around 5x5 meters. This yields a maximum advancement speed of 1.7 m/s, not accounting for time delay of the actions taken by the machine given the identified obstacles, which is sufficient for many existing site preparation machines.

A comparison was made between the obstacle positions identified by the algorithm and the actual obstacle positions on the clearcut. On basis of six snapshots, the accuracy was around 90%. Although these results were promising, additional tests were needed to determine the reliability and accuracy of testing in alternating weather conditions, bright sunlight and darkness, different obstacle frequencies, etc. The results showed that a ToF camera with sub-sequent data processing can be used to identify visible stumps with reasonable accuracy and that other protruding obstacles, such as stones and slash piles, were distinguishable.

Another study followed, paper E, with the goal of developing a system for detecting stumps (as the main obstacle) at clearcuts using a ToF camera. Using an iterative process of implementing, testing different detection techniques and evaluating different algorithms, a detection system strategy was determined, see Figure 9.

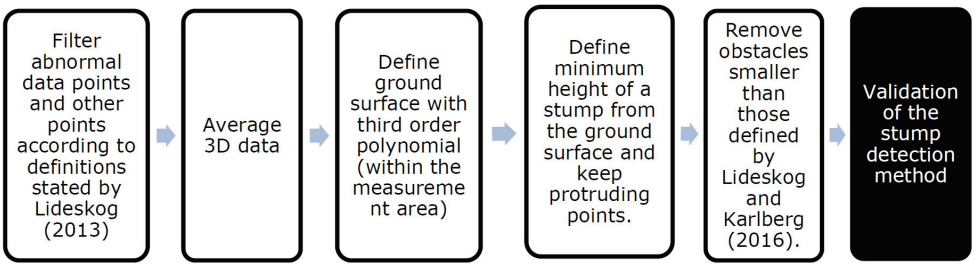

Figure 9. Stump detection system, deterministic method prescribed for use of 3D data and real time analyses.

Corresponding to the steps in Figure 9, the prescribed stump detection system is further explained in points 1-6 below:

1. Initially abnormal data, i.e., outside the measurement's range and zero values, are excluded. In addition, Lideskog (2013) defined the physical volume in which it is necessary to identify obstacles during mounding. This volume was used to exclude data points outside the boundaries. Finally, points floating mid-air by themselves (without proximal neighbors) are removed using sparse outlier removal (Rusu et al. 2008), as well as points outside the possible camera measurement boundaries.
2. The remaining data can then be averaged by several measurements within a range such that measures are assumed to be statical. This requires fast sample times and small increments in space. In our case, no averaging was conducted.
3. A third order polynomial surface is then fitted on the remaining pixel data to mimic the ground surface of the terrain.
4. In the next step, the residuals in the Z (gravitational) direction are analysed. All residuals protruding less than 125 mm above the fitted surface are discarded, and the remaining pixels can be deemed potential stumps.
5. As a stump is not considered an obstacle during site preparation, in our case continuously advancing mounders, if the diameter of the stump falls below 7 cm (Jukka Alakorpi, Bracke Forest AB, pers. comm. in 2013), this step ensured that clusters falling below this limit were disregarded. Clusters had to span at least 70 mm in any direction, and thus we accepted any cluster shape.
6. The positions of detected stumps were determined by deriving the center of gravity of each point cluster. To obtain information about stump size, the area of each detected stump was derived through polygonization of the outermost points of each cluster.

The system was then validated on a delimited clearcut area, showing a stump detection rate of 40 %; see Figure 10 for a snapshot of the resulting stump detection. Supplementary File 1 appended to Paper E further shows stumps (depicted as circles) located on the controlled clearcut area; the results (depicted

as clusters of red-colored points) from the stump detection system are overlaid and viewed orthogonally to the ground plane. The external validity of the results, i.e., how representative the size and choice of the clearcut control area is in relation to what the results are applied to, is greater in this follow-up study, but are possibly not generalizable to a clearcut area with various numbers of obstacles, inclinations etc.

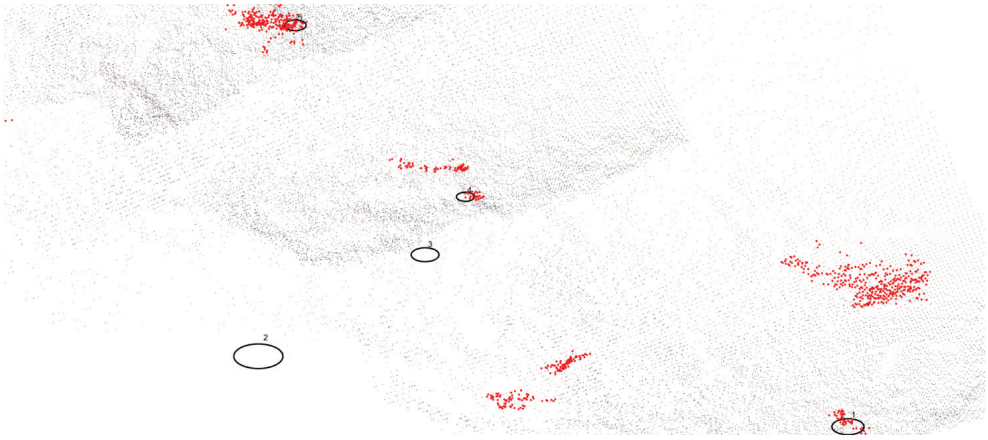

Figure 10. Angled 3D plot of raw data points (RGB color), numbered circles showing actual stump positions, and red points indicating where the detection algorithm has found obstacles. Note differences in point cloud density and false hits.

A complementary study, paper D, was conducted to assess additional sensing tools and methods, as well as new algorithms. In this case, an experimental setup was created to mimic an obstacle in the shape of a speed bump on an otherwise flat road; the goal was to automatically identify the starting point of the speed bump, see Figure 11.

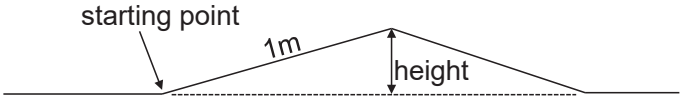

Figure 11. Environment setup for data collection.

An RGB-D camera was used to collect data from static positions at 1.00, 2.00 and 3.00 meters from the starting point. Afterwards, the acquired information was analysed by estimating the normal vector for each point in a 2D depth map. A distinct change in angle indicates the starting point of the speed bump. The trigger points were found by differentiating the data and automatically identifying spikes. The speed bump height was further varied between 0.10 and 0.15 m to assess sensitivity in angle deviation (0.10 m height: Figure 12, 0.15 m height: Figure 13).

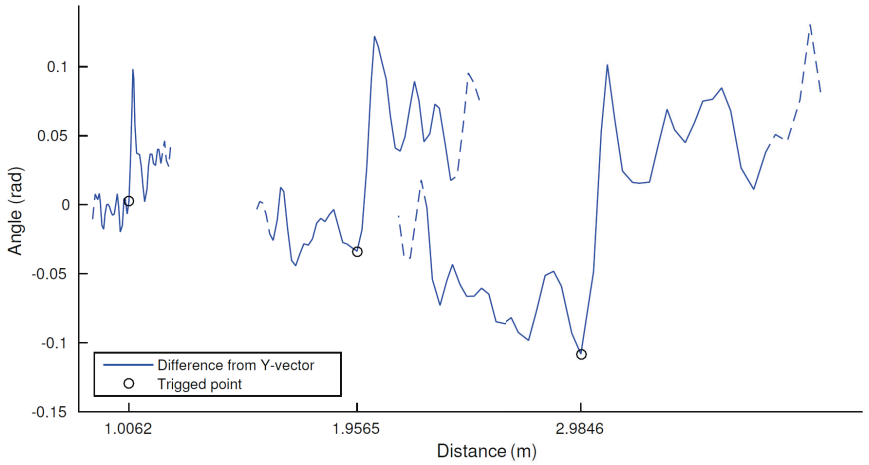

Figure 12. Results of static identification of a 0.10 m high speed bump transversal to the driving direction. Measurements were performed at 1.00, 2.00 and 3.00 meters.

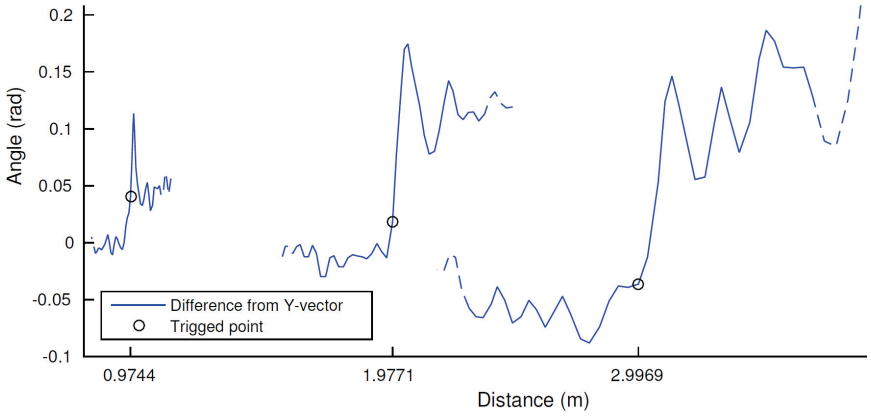

Figure 13. Results of static identification of a 0.15 m high speed bump transversal to the driving direction. Measurements were performed at 1.00, 2.00 and 3.00 meters.

The resulting data from the experiments had sufficient resolution, speed and quality to properly identify obstacles or targets with a maximum error of around 2 %, see Table 2.

Table 2. Results of the identification algorithm that conducted automatic speed bump detection.

Real distance to starting point [m]	Identified distance for speedbump height 0.10 m. [m] (Error %)	Identified distance for speedbump height 0.15 m. [m] (Error %)
1.00	1.01 (0.6)	0.97 (2.5)
2.00	1.96 (1.7)	1.98 (1.1)
3.00	2.98 (0.5)	2.99 (0.1)

Obstacles were measured and identified in less than 20 ms; processing time mainly reflected data transfer from the USB bus. The obstacles found 100 % of the times. In the study, the developed obstacle identification method was intended to be used to actively control vehicle suspension, send feedback to the driver about obstacles ahead or optimize speed and direction for autonomous vehicles. However, the technique has potential for forest regeneration to identify the rapid change in inclination between ground and vertical stump sides.

6 ACTUATION

6.1 Evaluation of object avoidance and target identification in forest regeneration

By utilizing remote sensing methods, new strategies for CI machines can enable efficient mound/inverting working procedures. The potential of sensing combined with appropriate working procedures for forwarder-based continuously advancing mounders was the focus of the following study. The study aimed to quantify the potential of a sensing system that ideally works (full identification of clearcut objects' sizes, positions and types) with future realistic working procedures for forwarder-based continuous mounding.

Three different strategies were studied. One strategy used the fact that the mounder is continuously advancing, allowing the mound to be placed anywhere along the driven path: a longitudinal strategy. The other strategy required a minor mounder redesign (marked as ⋆ in Figure 14, a new hydraulic cylinder enabling transverse movements of the mounder): a transversal strategy. For the third strategy, both the transversal and longitudinal movements were used such that the mound could be created in the entire operating range: an area strategy.

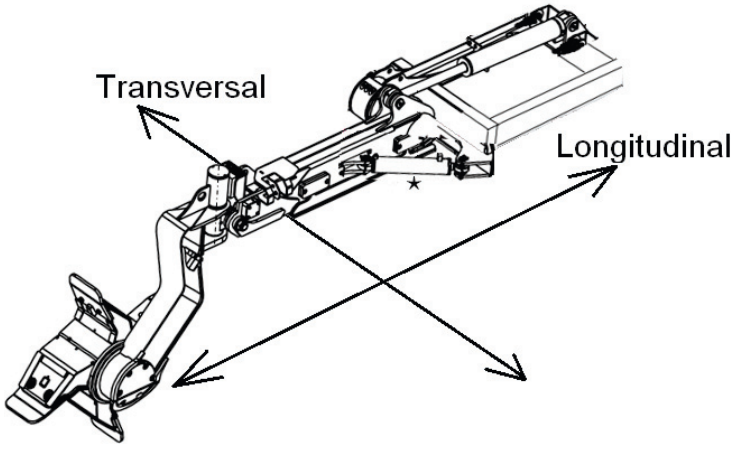

Figure 14. One mounding arm with suggested new strategies for movement, given utilization of sensing. Suggested solution for transversal movements is shown as a ⋆. Rendering and suggested mechanical solution are based on ideas and renderings from Bracke Forest AB.

To evaluate the different work procedures, computer simulations were conducted that modeled the terrain and machine using the results from paper A and the developed working procedures.

By mimicking the system in a computer program, the computer can produce numerous events with help from a random generator, and thus get an idea of the

system's behavior over the long term. The Monte Carlo method generally follows this procedure (Metropolis and Ulam 1949):

1. Define the input parameters and their respective domain.
2. Generate inputs randomly and independently from the domain following a probability density function (PDF).
3. Conduct a deterministic computation on generated inputs.
4. Repeat the procedure until results converge and aggregate.

The most important objects that impede CI machines (mainly mounding) are subterranean and superterranean stones, stumps, slash and roots. Stones, stumps and slash were input using probability distributions for spatial distribution and sizes defined in literature and interviews. Roots were considered in the model as a zone of rapid taper surrounding each stump (see the example in Figure 15). A pseudo-random number generator in MATLAB® R2013a was used to generate inputs from these probability density functions. Afterwards, deterministic computations were conducted on the inputs chosen from the PDFs whereby several runs were conducted with regenerated inputs. When convergence was reached, the results were aggregated.

Clearcut areas were numerically modelled and presented similar to Ersson et al. (2013) who simulated mechanized planting using discrete events on different terrain types. These terrain types were classified as follows, with the same numbering in Figure 16:

0. Typical southern Swedish clearcut
1. Few stumps, few stones, no surface boulders
2. Few stumps, many stones, many surface boulders
3. Many stumps, few stones, no surface boulders
4. Many stumps, many stones, many surface boulders

Several parameters were tested at various levels to ensure they were not affecting results. One was the resolution of the numerical simulations. In Figure 15, a small snapshot of the simulated clearcut is visible in two different resolutions, where dark grey areas illustrate sub-surface stones and white areas with a light grey border illustrates stump and zone of rapid taper. Additional obstacles in the simulation model were slash piles, assumed to be left after final felling but not visible in the figure.

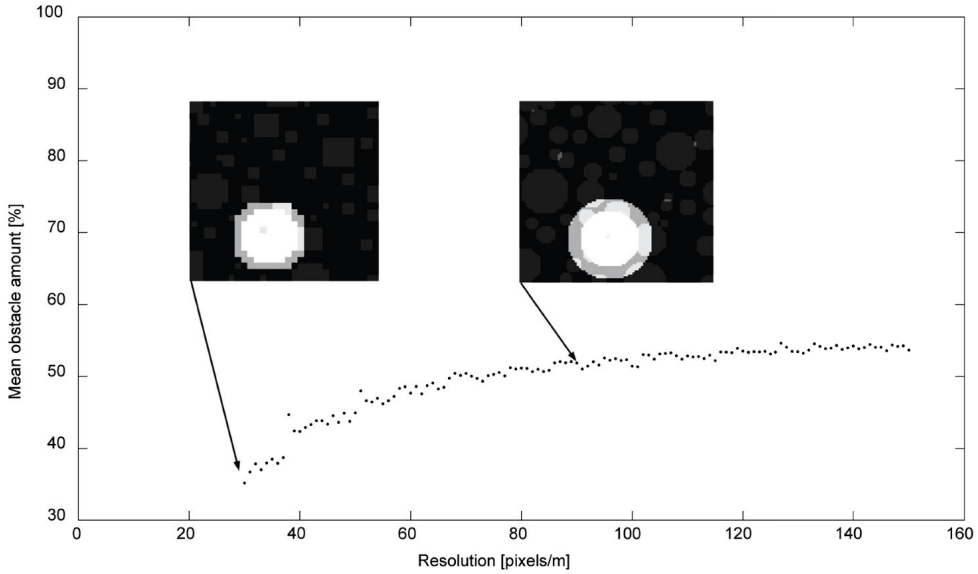

Figure 15. Simulated mean obstacle amount (area percentage) as a function of detection resolution. A visual representation shows the difference between low-resolution and high-resolution clearcuts.

Simulations show that mounding efficiency can be significantly improved with a new mound positioning strategy that utilizes ideal object identification, especially on obstacle-rich clearcuts, see Figure 16.

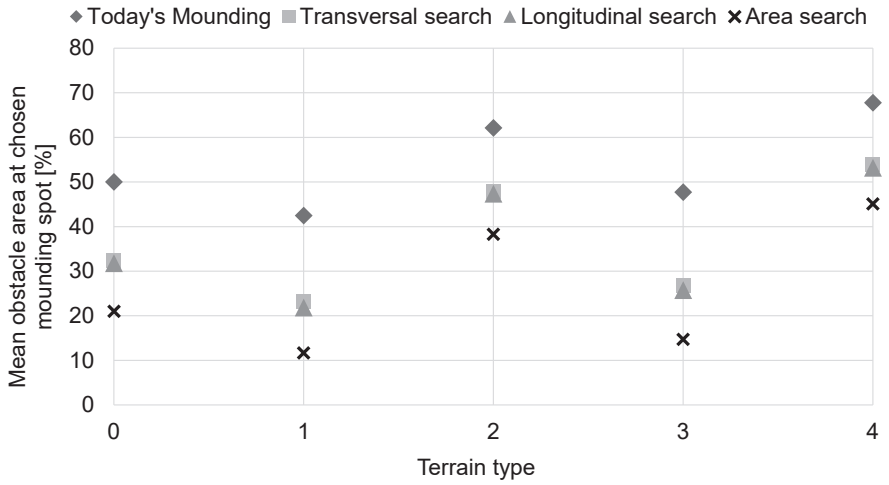

Figure 16. Mean obstacle area at chosen mounding spots on different terrain models using four different strategies in choosing mounds.

In addition to terrain types 0-4, clearcuts with linearly increasing numbers of obstacles were simulated, see Figure 17. To analyse effects on a larger variation of

clearcuts and compare mound positioning strategies, simulations were conducted in which the obstacle quota was incrementally changed. Site preparation was conducted with the four strategies on clearcuts generated in a span from 30 % obstacles (which is a lower obstacle quota than used for terrain configuration 1) up to 70 % obstacles (which is a higher obstacle quota than used for terrain configuration 4). Slash piles were generated the same way for all configurations. In these simulations, the ratio between the different objects was kept constant, which makes a direct comparison between terrain configurations 0–4 difficult.

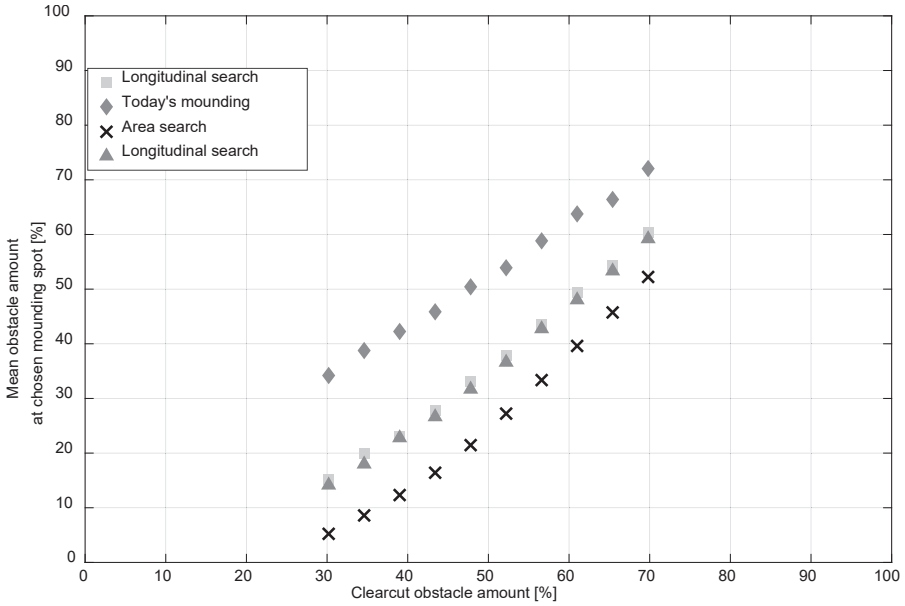

Figure 17. Mean obstacle amount measured at mounding spots created at clearcuts with total obstacle amounts between 30 % and 70 %. Subsurface stones, surface boulders and stumps were linearly changed to range all terrain models 0–4 and more. Slash residue parameters were kept constant throughout the simulations.

The simulation results show that the potential for automation of CI machines is high for any number of obstacles located on the clearcut and have the potential to compete with disc trenching on obstacle-rich clearcuts.

7 OFFROAD VEHICLE PLATFORM FOR VALIDATION

In spite of the high level of mechanization in most forestry operations, there is an ongoing need for improvements in productivity, cost-effectiveness and sustainability. As discussed in Sections 3 and 4, automation of mechanized operations is one possible solution for achieving such improvements. New techniques that can acquire information from the surroundings (using exteroceptive sensors) and make proper analyses to generate streamlined or new working procedures are prerequisites during any forest operation. Purchasers of forest biomaterials often have certain quality wishes. As an addition to automatic working procedures, new technology can be used to obtain information for identification and selection of certain tree assortments with different biomaterial properties in order to expand and improve the assortments of wood products. Solutions for cost-effectiveness, productivity and sustainability must not be sub-optimized. Collaboration has been launched between academia and forestry companies in Sweden; a need has been identified for a dedicated platform for systems and technology development. The objective for the study in paper F was to summarize possible (technical) needs in forestry and to design an experimental offroad vehicle platform for researchers and machine developers to test and validate new solutions that might improve forestry operations. The design development of the research vehicle platform followed Ulrich and Eppinger's (2012) process for product development. Before the start of concept development, customer needs were thoroughly investigated to decide how the product eventually should be designed to meet the needs. In this case, the customers were actors in academia as well as forestry companies. Therefore, people from different disciplines with interest in the experimental terrain vehicle platform were involved in forming customer needs; people from academia with backgrounds in mechanical engineering, forest biomaterials and technology and control systems and robotics, and people from forestry technology companies focused on forestry machines, timber cranes and other forestry equipment and vehicle add-ons.

The outcome from these interviews and workshops were analysed and formed into customer requirements, which, beside information from the benchmarking and related technology phases, resulted in a requirement specification forming the basis for all the demands set on the product. The platform is designed specifically to test and validate various control systems for autonomy and robotics and enable tests and validation of attachments in order to enable better planting procedures or identification of trees with certain properties. Sensors are embedded in the platform to register angles, rotation speed, etc., thus actualizing machine automation as an enabler for automation in forestry operations and performance-based delivery of planting or tree biomaterial assortments.

Figure 18. 2014 offroad vehicle platform (left) and 2018 updated version (right).

The solution in the forest sector may not primarily be to increase the sale of machines, but to increase the quality of the biomaterials extracted from the forests via performance-based contracts. However, such contracts require knowledge of the level of performance. Thus, this platform could also act as an incentive for companies to invest in mechanization and automation technology. For all these reasons, academia and forestry technology companies have decided to collaboratively develop methods, tools and systems with this offroad vehicle. Table 3 shows different tasks that can be performed with the offroad vehicle platform.

Table 3. Verification, validation and testing options for the research vehicle platform in forestry exemplified in a Swedish forest management model. Based on paper F.

Address value chain dependencies during performance-based contracts →					
(Seed and seedling procurement)	Forest regeneration	Forest management	Afforestation	(Transportation from forest)	(Wood processing)
	Site preparation** Planting* Direct seeding**	Pre-commercial thinning* Commercial thinning**	Harvesting** Forwarding** Other machine tasks**		

* = Manual work predominated

** = Machines are mainly used

1. Increase degree of automation
    a. Test algorithms and control systems with existing products and components (including more effective movement of the existing crane or machine)
    b. Test algorithms and control systems with new products and components (such as sensing/machine vision plus new working procedures of streamlined components)
    c. "Superhuman" sensors
2. Increase degree of mechanization
    a. Test new products and components
3. Increase biomaterial quality through automation
    a. "Superhuman" sensors
4. Validate simulations
    a. Go from computer to reality to test control systems, methods and systematic changes

8 DISCUSSION AND CONCLUSIONS

The purpose of the research presented in this thesis was to improve sustainability in forestry through automation. The main objective was to develop a methodology for such automation, CI machines in particular. The developed methodology includes the following list, which are positioned in Figure 19:

(1) a process for how a computer-aided system using object identification for avoidance or targeting purposes could work (Figure 6),
(2) a definition of the properties and characteristics of the most important objects in silvicultural machine context (Table 1),
(3) identified and evaluated tools and methods for information retrieval, including identification of suitable 3D cameras of industrial grade and commercial grade, as well as methods of how to use them in-field,
(4) developed and evaluated several methods and tools for information analysis, including methods (or algorithms) for how to systematically process 3D point cloud data (Section 5.2),
(5) new working procedures for continuously intermittent mounders that utilize the process for object identification to avoid or target objects and the utilization potential (Section 6.1), and
(6) development of a generic and modular experimental offroad vehicle research platform for forestry industry and academia that enables tests of "value chain independent" solutions.

By using the initially developed process (Figure 6), it is possible to update it by inserting all contributions above to a methodology that enables sustainable forestry. The working procedures of CI machines have still not been validated in practice, which is needed to confirm that sustainability has improved.

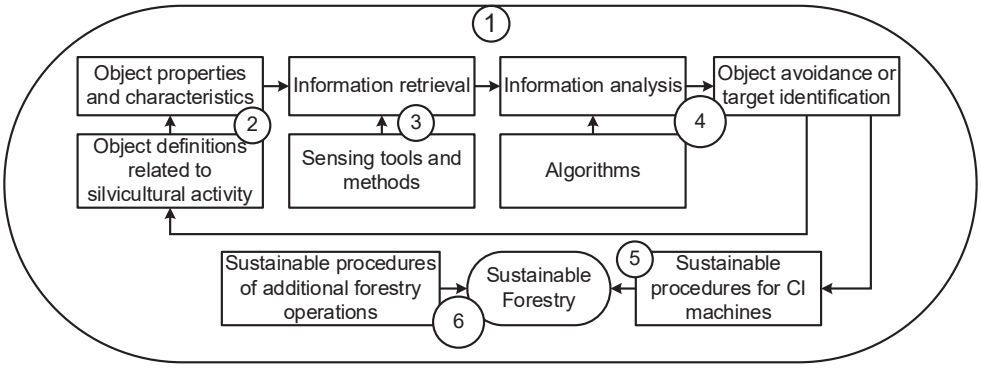

Figure 19. Updated process that comprises the developed methodology along with methods, tools and procedures.

To evaluate whether the methodology developed in this thesis is an improvement on current procedures, the criteria in Section 3.4 was used (Blessing and Chakrabarti 2009).

Economic impacts

The investment cost of a machine is probably not decreased. It is plausible that initial use of sensor technology and software increase the investment cost. However, operating costs will decrease when efficient work procedures are in place to ensure a more accurate job while reducing machine wear-and-tear. The methodology presented in this thesis is a necessary step towards full automation. Together with route planning (Ringdahl 2011), high resolution global navigation satellite systems (Zimbelman and Keefe 2018) and validation of position through 3D data similar to that used in this thesis, the base machine may become completely autonomous in the long run, significantly reducing operator cost.

The efficiency and accuracy of forest regeneration could be improved using obstacle avoidance for CI machines and in the long run for mechanized planting devices that use a base machine that operates continuously while an autonomously directed method of planting is performed. This methodology can be used to position planting spots while seedling positions in the mounds afterwards are chosen if needed according to strategies developed by Kemppainen and Visala (2013). Silva Nova and Serlachius planting machines had several well-functioning solutions in seedling storage, transport and planting when actuating on obstacle-free soil (Adelsköld 1983), and this technology should be reviewed further when site preparation and planting is combined.

Environmental impacts

Soil disturbance and advance regeneration considerations are addressed in this methodology in two ways: First, if mounding is used more frequently on obstacle-rich clearcuts in exchange for disc trenching, soil disturbance and its unsustainable consequences will be reduced. Second, a more accurate planting spot position that considers surrounding objects can reduce creation of unnecessary and low-quality mounds that are disqualified for planting because of obstacles that impede actuation.

Machine GHG emissions may decrease for the same reasons: unnecessary and low-quality mounds could make the operation less harsh for the machine. On the other hand, new working procedures require movement in more directions with precise, rapid control of the machine's mounding device movements, which could lead to an increase in fuel consumption and thus higher GHG emissions. Higher efficiency and accuracy of CI machines can enable better short-term survival and growth of planted seedlings when a larger share of high-quality planting spots is created. In the long run, a potentially larger share of mechanized planting allows a higher degree of continuous, directed planting, which helps avoid negative environmental impacts (Löf et al. 2012). Other ecosystem service preservation has not been addressed explicitly, but less soil disturbance - one possible consequence of employing the developed methodology - allows for less nutrient leaching or continued growth of reindeer lichen, berries and mushrooms. Avoidance of soil

impact in forest regeneration is only one area in which efforts need to be made. If harvesting and forwarding machines irreversibly create unsustainable soil damage, it would not matter that the next operation on the forestland disturbed less. Therefore, solutions are needed that not only work by themselves, but also transcend all operations throughout the forest value chain. Since surrounding information is collected after final felling and removal of trees from the site, it is possible to see how harvesting and forwarding have complied with sustainability targets of certified operations according to Forest Stewardship Council, or the Programme for the Endorsement of Forest Certification.

Social impacts

The probability of diverse ecosystem service choice could increase in the long run if not only objects that are considered obstacles for machine actuation are addressed, but also sensitive grounds that may constitute important ecosystem services regarding provision, regulating and maintenance, or cultural services (Hansen and Malmaeus 2016).

A further positive consequence may be a better workplace: in the short term through a simplified task for the operator who drives the base machine and fewer machine vibrations; in the long term through a workplace located offboard the machine, which could enable a more social, diverse and ergonomic workplace with better safety.

Research questions

The research questions, addressing elements of the proposed methodology, were defined at the beginning as the following three:

1. What surrounding environmental information is needed in order to enable autonomous CI machine operations?
2. How should data from the surrounding environment be captured and transformed into information?
3. How should information about the surrounding environment be used to automate CI machines for increased sustainability?

RQ1 has been addressed in paper A by defining the properties and characteristics of objects (in context of forest regeneration machines). By identifying sensing tools and developing methods for how to retrieve data and analyse information from the surroundings, information for the specific tools and methods was defined and connected to the particular purpose.

RQ2 has been addressed by developing new methods and tools for data capture and transformation in the context of automation in forest regeneration in papers C and E, while paper D shows new methods and tools for obstacle detection using another combination of methods and tools that could be applied to automation in forest regeneration.

RQ3 has been addressed by the development of a methodology for automation in forest regeneration. Moreover, new working procedures of CI mounding were developed and evaluated, showing how to make use of surrounding environmental information for increased sustainability. In paper F, a research offroad vehicle platform was developed to address social needs for research in forestry automation, enabling optimization of solutions for needs that are included in all forest operations.

Generalization

While focusing on the automation of CI machines, it is plausible that many of the results can be generalized for several other purposes within and beyond forest regeneration operations. Offroad vehicles that conduct exploration or material transport could benefit from knowing the whereabouts of protruding objects that could cause discomfort for operators or decrease accessibility of the vehicle, for example in agriculture, military or mining. Knowledge of terrain objects could serve as a basis for improved decision-making, either for automated vehicle systems that require terrain parameters to be constantly updated (see Iagnemma and Dubrovsky 2002) or for the operator to make sound choices.

The developed offroad vehicle platform is modular to allow for system development over the value chain. With this opportunity, it is possible to establish research questions that have an impact on the entire value chain and not sub-optimize solutions. Furthermore, other branches encompassing operations in terrain may take advantage of the utilization strategy of this vehicle.

Conclusion

To summarize, clearcut objects' properties and characteristics have been determined as basis for object identification during forest regeneration. It has been shown that automation have a great potential in improving sustainability in forest regeneration operations; by increasing the efficiency and accuracy of CI machines, the operation will be more economically beneficial, while soil disturbance and machine wear decreases. A methodology comprising algorithms, tools and methods have been developed that can be utilized for CI machine automation. Implemented in a CI machine control system, around 40 % of stumps can be detected and possibly avoided, while the driver focuses on operating the base machine. The methodology further enables the mounding procedure to be used more frequently on obstacle-rich clearcuts and it is plausible that planting can be conducted simultaneously in the short term, using the developed offroad vehicle platform as means for further development.

9 FUTURE RESEARCH

Previous research has not been applied in practice. The next step should be to develop a system that incorporates the methodology into a control system to steer mounding actuators automatically, as visualized in Figure 20. In addition, or in parallel to system development, the obstacle (or stump) detection system needs to be refined in order to fit in the context of the machine, and tuned using more data collection in order to reduce the error between actual stump position and detection, as well as increasing rigor in finding the stumps at all, which is currently around a 40 % success rate. For example, clearcut data may be used to train a classifier using a convolutional neural network, but it will require a large amount of data collection and supervised learning.

Figure 20. Visualization of continuous mounding conducted by the modular forest off road vehicle with attached Bracke Forest mounding arms (left), and visualization of the modular design with holistic options for machine design and testing (right). Photo: Sirius team 2017.

As discussed in Paper F, the machine is modular to allow for system development over the value chain. With this opportunity, it is possible to establish research questions that have an impact on the entire value chain and not sub-optimize solutions.

In the future, it will be even more important to address needs from all dimensions of sustainability to ensure sustainable forestry. Emerging technology in sensing and actuation will enable solutions that could make precise decisions in forest regeneration for a larger plethora of forest ecosystem services, depending on what legislation demands or what the customer requires, whether it be undisturbed reindeer lichen cover, tourism friendly reforestation or avoidance of ancient remains. An improvement in sensing and actuation will in the long-run enable semi- and fully autonomous forestry machines, which for operators' work environment creates big changes in physical and mental work load. This will probably happen progressively, first as operators cognitive load are reduced when less simultaneous maneuvers are required, and later disruptively as they are working offboard the machines.

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APPENDIX 1 (1/2)

Decided at the Third Ministerial Conference on the Protection of Forests in Europe 1998, guidelines below state that forest management planning and practices should:

- make full use of related services such as land-use planning and nature conservation,
- safeguard the quantity and quality of the forest resources in the medium and long-term by balancing harvesting and growth rates, and by preferring techniques that minimise direct or indirect damage to forest, soil or water resources,
- take appropriate silvicultural measures to maintain the growing stock of resources at - or bring to - a level that is economically, ecologically and socially desirable,
- maintain and increase the health and vitality of forest eco-systems and to rehabilitate degraded forest eco-systems, whenever this is possible by silvicultural means,
- periodically monitor health and vitality of forests caused by forest management operations (and other reasons),
- apply appropriate forest management practices such as reforestation and afforestation with tree species and provenances that are suited to the site conditions or the use of tending, harvesting and transport techniques that minimise tree and/or soil damages,
- minimise use of pesticides and herbicides, taking into account appropriate silvicultural alternatives and other biological measures,
- maintain the capability of forests to produce a range of wood and non-wood forest products and services on a sustainable basis,
- carry out regeneration, tending and harvesting operations in time, and in a way that do not reduce the productive capacity of the site,
- prefer natural regeneration, provided that the conditions are adequate to ensure the quantity and quality of the forests resources and that the existing provenance is of sufficient quality for the site,
- prefer origins of native species and local provenances that are well adapted to site conditions for reforestation and afforestation, where appropriate,
- promote a diversity of both horizontal and vertical structures,
- balance the pressure of animal populations and grazing on forest regeneration and growth as well as on biodiversity.

APPENDIX 1 (2/2)

Decided at the Third Ministerial Conference on the Protection of Forests in Europe 1998, guidelines below state that forest management planning and practices further should:

- leave standing and fallen dead wood, hollow trees, old groves and special rare tree species in quantities and distribution necessary to safeguard biological diversity,
- give special care to silvicultural operations such as deep soil tillage and unsuitable machinery on sensitive soils and erosion-prone areas as well as on areas where operations might lead to excessive erosion of soil into watercourses that would influence water quality,
- protect or manage sites with historical, cultural or spiritual significance in a way that takes due regard of the significance of the site,
- take into account all socio-economic functions, especially the recreational function and aesthetic values of forests.

APPENDED PAPERS

A

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Determining boreal clearcut object properties and characteristics for identification purposes

Lideskog H., Ersson B.T., Bergsten U., Karlberg M. (2014). Determining boreal clearcut object properties and characteristics for identification purposes. Silva Fennica vol. 48 no. 3 article id 1136. 7 p.

Highlights

- We define the quantitative properties and qualitative characteristics of stumps, stones, slash, and roots, the most important objects interacting with machine activities after clearcutting.
- We develop a flowchart showing how a computer-aided system using clearcut object identification should be executed.

Abstract

After clearcutting, machines traffic the clearcut conducting different silvicultural activities. Many objects on a forest clearcut (slash residues, stones, stumps and roots) may disturb e.g. site preparation and planting. This paper describes properties and characteristics of these objects. A flowchart was developed that describes a possible computer-aided system that identifies the objects, and ultimately, makes a machine avoid or target them. A system for obstacle identification creates conditions for further technical development and (semi)automation of e.g., site preparation, mechanized planting, and stump removal.

Keywords clearcut obstacles; terrain description; terrain conditions; site properties; forest regeneration; forestry
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1 Introduction

Several machines traffic boreal clearcuts while conducting activities like site preparation, mechanized tree planting, and stump removal. Some objects on the clearcut can become obstacles preventing activities from being optimally conducted, whereas for other activities, some objects are needed to be found and targeted. Stones, stumps, slash and roots impede e.g. site preparation and mechanized planting (Larsson 2011; Luoranen et al. 2011; Ersson et al. 2013) whereas some of these objects need to be located efficiently for other purposes than avoidance, e.g. during slash forwarding and stump removal. Today, identification of objects located on clearcuts is conducted solely by the operator. Because of restrictions in the operator's ability to identify the surroundings, machine performance is affected. Hence, there exists a potential to further increase the productivity through semi-autonomy or autonomy. Required surrounding information can be retrieved remotely and then analysed in a computer-aided system to finally actuate the machine's working procedures. Such remote sensing methods could mimic the human vision, e.g. through computer stereo vision or time-of-flight imaging (Hussman et al. 2008), and even exceed human capabilities via e.g. ground penetrating radar (Annan 2009) or acoustic waves (Sabatier and Xiang 2001). Through such techniques, it is plausible that sub-surface object identification, automatic obstacle-avoidance or guidance during stump removal can be enabled.

To date, however, few efforts have been made to increase the degree of autonomy in silvicultural operations. As suggested by e.g. Kemppainen and Visala (2013), planting subsequent to forwarder-based mounding should be possible to conduct automatically by locating suitable planting spots on created mounds using a stereo vision sensing method. Other researchers have forecasted that autonomous operations will soon be reality during both silvicultural (Nilsson et al. 2010) and harvesting operations (Hellström et al. 2009). There exist many technology challenges in order to enable obstacle avoidance and target identification (Vestlund and Hellström 2006). It is impossible to choose a suitable method for obstacle avoidance or target identification before knowing what to actually measure and within what range. Hence, one critical challenge addressed in this paper regards which clearcut object properties and characteristics that are suitable for identification.

Hence, the objective of this study was to outline relevant properties and characteristics of stones, stumps, roots, slash and surrounding soil. This information should facilitate development of technical solutions for identification of those clearcut objects.

2 Method

To address the definition of objects situated on clearcuts, we first identified which types of objects that could interact with silvicultural machinery. Then, we quantified and categorized the clearcut obstacle properties and characteristics for silvicultural operations through a literature review. The objects' properties were divided into two main categories, quantitative properties and qualitative characteristics. A directly quantifiable property has a certain unit and a certain numerical range while qualitative object characteristics do not have a specific unit. We used the classification method developed by Campbell and Wynne (2011, p. 134–138) which is based on eight significant characteristics of objects and features: tone, texture, shadow, pattern, association, shape, size and site. These characteristics were condensed and adapted to the case of boreal clearcuts. In addition, four other site- and object specific characteristics were included: (1) Can be moved with force exerted during mounding or disc trenching, (2) Degradation over a forest rotational period, (3) Exists above and (4) under ground. These characteristics can be found in Table 1 where each object was classified as either possessing the characteristic (Y), not possessing the characteristic (N), or both (Y/N).

Relevant quantitative properties and qualitative characteristics of objects and features (Table 1) are further explained below. Data mainly represents the boreal forest zone where silvicultural machines commonly traffic clearcuts.

Density – The values for root density include the species *Picea abies* (L.) Karst., *Betula pendula* Roth and *Pinus sylvestris* L. The lowest root density was sampled from *P. sylvestris* at 301 $kg \cdot m^{-3}$, and the highest value from *P. abies* at 499 $kg \cdot m^{-3}$ (Kalliokoski et al. 2008). Maximum slash density was sampled from *P. abies* branches at 883 $kg \cdot m^{-3}$, while *B. pendula* and *P. sylvestris* values were lower at 859 $kg \cdot m^{-3}$ and 844 $kg \cdot m^{-3}$ respectively (Kärkkäinen 1976).

Tensile modulus – For stump, root and slash, the tensile modulus values refer to *Populus tremula* L. ($8.1 \cdot 10^9$ Pa) and *B. pendula* ($16.2 \cdot 10^9$ Pa), where other Fennoscandian species such as *P. abies* and *P. sylvestris* lie in between $9.1 \cdot 10^9$ Pa and $11.8 \cdot 10^9$ Pa respectively. However, it is plausible that the tensile modulus depend on properties that varies within the object e.g. its density or moisture content.

Thermal conductivity – The stone thermal conductivity range refers to that of granite in Table 1. The stump, root and slash values for thermal conductivity is transversally sampled at 12% moisture content where *P. tremula*, and *P. abies*, were lowest at 0.12 $W \cdot m^{-1} \cdot K^{-1}$ and *Betula alleghaniensis* Britt. highest at 0.19 $W \cdot m^{-1} \cdot K^{-1}$. *P. sylvestris* mean value was measured to 0.15 $W \cdot m^{-1} \cdot K^{-1}$ (Saarman 1992; Cardarelli 2008). The thermal conductivity, however, will increase with moisture content and specific gravity (Hoadley 2000), but can be assumed static up to 25% moisture content (Cardarelli 2008).

Reflectance – States the percentage of reflected sunlight. For *P. sylvestris* slash older than six months, values for sunlight reflectance was measured by Lang et al. (2002) to be 3–22% (at 400 m^{-9} and 1300 m^{-9} respectively). Reflectance of green *P. abies* varies from 3–37% (at 680 m^{-9} and 800 m^{-9} respectively) at branch level (Williams 1991). An extreme maximum value for photosyntetically active slash is 85% and occurs at the wavelength 1030 m^{-9} for *Picea rubens* Sarg., whereas minimum value at 3% occurs at wavelengths below 500 m^{-9} for many tree species, e.g. *B. pendula*, *Pinus resinosa* Ait., *Pinus monticola* Dougl. ex D. Don, *P. tremula* etc.

Moisture content – Minimum value of root and stump refers to specimens taken from *P. abies* in the border where the stump ends and root starts, at different stages after harvest (Laurila and Lauhanen 2010). Therefore, we assume that the minimum values are the same for root and stump. Maximum value for stump refers to *P.* abies sampled in sapwood (Tsoumis 1991), exceeding the maximum values stated by Laurila and Lauhanen (2010). The range for slash refers to clearcut slash of *P. abies* (Nurmi 1999). Bark moisture content was measured by Kärkkäinen (1976) whose samples fall within stated maximum and minimum.

Tone variations – denotes the darkness or brightness (or colour intensity) of regions within an image.

Texture – describes the apparent roughness or smoothness of regions in an image. Not necessarily linked to soil texture.

Shadow – an object illuminated from an angle will cast a shadow that could reveal e.g. size and shape characteristics.

Pattern – refers to how individual objects in an image are arranged into distinctive recurring forms.

Association – describes the occurrence of certain objects that, without direct identification, will have certain features bound to it.

Shape – certain shapes are clues for discovering the object's identity.

Size – refers to the size of objects. The absolute measurements of an object, as well as its relative size in relation to other objects, can be utilized during classification.

Site – refers to the topographic location.

Mobility – refers to whether an object is plausible to move by forces originating from silvicultural machinery.

Degradation – concerns objects consisting of biomaterial.

Exists above or below ground – some objects may exist above or below ground or both.

Some of the objects', e.g. stones', criticality depends on the clearance capability of the specific machine used during the silvicultural activity. Likewise, stumps are regarded as non-obstacles during forwarder-based site preparation under a certain minimum stump size and beyond a certain stage of degradation.

3 Results

To enable object identification during silvicultural activities, a necessary first step is to define properties and characteristics of clearcut objects, and then find relevant sensing techniques, tools and methods that could be used operationally for identification (Table 1). Fig. 1 illustrates the flow of information in a suitable computer-aided system where properties and characteristics of clearcut objects are retrieved by the sensing tool. The information is further analysed through algorithms (conducting e.g. object recognition in a 3D-cloud) whereby machine activities are chosen. The specific activities will e.g. make the machine move to the targets or avoid the objects. Irrelevant data are screened out depending on the attribute of the activity.

Table 1. Quantified obstacle properties, sourced from literature, and obstacle characteristics based on Campbell and Wynne's (2011) classification of objects. If the obstacle possesses the stated characteristic, a Y (Yes) is marked. An N (No) marks if the obstacle does not possess such characteristic.

Characteristic	Stone	Stump	Root	Slash	Soil
Density [kg·m^{-3}]	2500–3200[a]	440–670[b]	301–499[c]	844–883[d]	1400–2050[e]
Tensile modulus [10^9 Pa]	40–68[f]	8.1–16.2[b]	8.1–16.2[b]	8.1–16.2[b]	$4.8 \cdot 10^{-4}$–0.2[g]
Thermal conductivity [W·m^{-1}·K^{-1}]	2.51–3.97[f]	0.12–0.22[f]	0.12–0.22[f]	0.12–0.22[f]	0.17–2.2[f]
Reflectance [%] ($\lambda \in [300m^{-9}\ 2500m^{-9}]$)*	5–80[h]	10–65[i]	-	3–85[i, k]	0–55[h, i]
Moisture content [fresh weight %]	~0	15–64[d, j]	15–55[j]	29–56[d, l]	0–100
Distinguishable tone [m]	Y	Y	N	Y	Y
Distinguishable texture (roughness) [m]	Y	Y	Y	Y	Y
Casts a shadow [m]	Y/N	Y	N	Y/N	N
Forms a distinguishable pattern [m]	N	Y/N	N	N	N
Other objects or features is associated to the obstacle [m]	Y	Y	Y	Y	Y
Distinguishable shape [m]	Y	Y	Y	Y	N
Is found on specific topological sites [m]	N	Y/N	Y	N	N
Can be moved with force exerted during mounding or disc trenching	Y/N	N**	Y/N	Y	Y
Degradation over a forest rotational period	N	Y	Y	Y	N
Exists above ground	Y	Y	Y/N	Y	N
Exists below ground	Y	N	Y	N	Y

[a] Elming (1980); [b] Tsoumis (1991), Doran (1992), Nordling and Österman (2006); [c] Kalliokoski (2008); [d] Kärkkäinen (1976); [e] Parasnis (1971), Parasnis and Dattatrai (1997), Cardarelli (2008); [f] Saarman (1992), Cardarelli (2008); [g] U.S. Army… (1990); [h] Bowker et al. (1985); [i] Lang et al. (2002); [j] Laurila and Lauhanen (2010); [k] Williams (1991); [l] Nurmi (1999); [m] Campbell and Wynne (2011)

* λ=wavelength of radiated light

** Applies for stumps > 100 mm in diameter

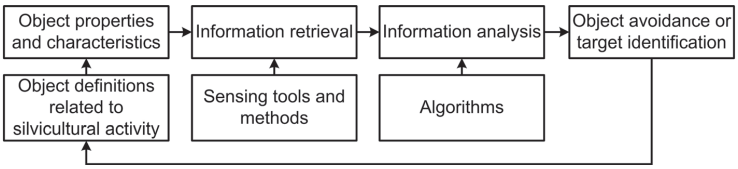

Fig. 1. Flowchart of the activities conducted by a computer-aided system using object identification for avoidance or targeting purposes.

4 Discussion

The information retrieved from an identification procedure could be used in computer-aided systems (Fig. 1). The main advantage of listing properties and characteristics of clearcut objects is that it will enable a requirement specification to be created. With added machine and environmental specific requirements, techniques for object identification can be benchmarked to find techniques that can utilise the listed object properties and characteristics as well as being able to run in specific environments and during specific machine conditions.

As stated by Campbell and Wynne (2011) for process analyses that are "complex and poorly understood", quantitative data are often insufficient. Hence, in addition, qualitative characteristics are often needed to conduct a successful identification. The ability to separate objects from the surroundings is critical. Some objects' property ranges are similar to the values of the surrounding soil, c.f. stump, root and slash densities. Therefore, qualitative characteristics such as object shapes could add information values.

In conclusion, the properties and characteristics derived in this paper can be used to develop solutions for automatic identification of relevant objects on clearcuts (in particular stones, stumps, roots and slash). By combining different properties and characteristics, clearcut objects can be identified by classification of type, position and size. Computer-aided systems using this information to avoid obstacles, find stumps, plan routes, etc. will allow for an increased degree of forestry machine automation and precision.

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Simulated continuous mounding improvements through ideal machine vision and control

Lideskog H., Karlberg M. (2016). Simulated continuous mounding improvements through ideal machine vision and control. Silva Fennica vol. 50 no. 2 article id 1386. 14 p. http://dx.doi.org/10.14214/sf.1386.

Highlights

- Different strategies for how to utilise machine vision to streamline the mounding head movements were developed and evaluated.
- The theoretical minimum rate of encountered obstacles while utilising machine vision in continuous mounding is presented, provided that an optimal continuous mounding has been performed.
- The needed minimum resolution of a machine vision system at work on a clearcut area was found.

Abstract

To promote the growth and survival of regenerated forests, site preparation prior to tree planting on clearcuts is necessary. This is often performed with scarifiers, either through trenching or mounding. Mounding is generally considered better in a plant survival perspective but is inefficient on obstacle-rich clearcuts. By utilising machine vision through e.g. remote sensing methods, new strategies can enable efficient mound positioning. In this paper, three realistic strategies utilizing ideal clearcut object identification through machine vision have been developed that can be used for more efficient mounding. The results show that mounding efficiency can be significantly improved with a new mound positioning strategy that employs ideal object identification, especially on obstacle-rich clearcuts.

Keywords site preparation; silviculture; remote sensing; scarification; mounding simulation; clearcut obstacles; work procedures
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1 Introduction

Successful forest regeneration requires mechanical site preparation, which typically is performed prior to planting of seedlings to increase the survival rate and growth (Örlander et al. 1990; Sutton 1993; Petersson et al. 2005). Often, the site preparation is performed with scarifiers, which are either used to create a continuous trench (trenching) or to create mounds with a specific spatial distribution (forwarder based continuous mounding). To minimize ground disturbance, only the soil closest to where a seedling is to be planted should be prepared, e.g. due to loss of carbon from the soil that increase with increased soil disturbance (Jandl et al. 2007). In fact, disturbing the ground where no seedlings are to be planted is regarded as unnecessary both from a public and ecological perspective, since a paramount wish is both to preserve forest land and minimize unnecessary machine usage. Thus, in this perspective, mounding can be seen as a superior method for site preparation, since areas are created around each planting spot rather than as a continuous trench, as in the case of disc trenching.

Uotila et al. (2010) found that (forwarder based continuous) mounding is more economically and environmentally beneficial compared to disc trenching and, furthermore, mechanized planting with preceding mounding is considered to promote good seedling quality (Luoranen et al. 2011). Saksa et al. (2005) and Örlander et al. (1990) also added that mounding rendered a better early shoot growth of planted seedlings compared to seedlings planted on disc trenched areas.

However, the method of mounding presents problems on obstacle-rich clearcuts where stones and stumps are numerous. In fact, the mounding head could even actuate over top of obstacles, resulting in areas that lack prepared soil. Satisfactorily conducted mounding therefore requires execution on ground with few obstacles, and consequently, obstacle-rich clearcuts are almost exclusively disc trenched since more potential planting points are created.

The retrieval of needed data about a clearcut area to operate a continuously advancing mounder effectively is today conducted solely by the operator, who also perform an analysis of retrieved data and steers the machine accordingly. Lideskog et al. (2014) listed objects located on clearcuts which they defined in terms of their physical properties and qualitative characteristics to be used for identification via e.g. machine vision. If such data exists for the clearcut it can be used to analyse how activities conducted on the clearcut should be performed without (or with less) operator involvement. Similar mapping has been used to distribute objects in a virtual environment for use in different simulations related to possible concepts for mechanized planting (Ersson et al. 2012; Ersson et al. 2013; Ersson et al. 2014) and to simulate the work process of mechanized planters (Andersson et al. 1977).

Recent technology advances in remote sensing methods for retrieval of spatial data or other physical properties have shown that information about the surrounding terrain can be retrieved (e.g. Sabatier and Xiang 2001; Manduchi et al. 2005; Metje et al. 2007; Hussman et al. 2008). Afterwards, computers via algorithms can analyse that information and e.g. target locations for planting (Kemppainen and Visala 2013) or identify clearcut obstacles (Lideskog and Karlberg 2014).

Subsequent use of such identification can be utilised for machine vision to make adjustments of current machine working procedures. However, the actual potential of machine vision combined with appropriate working procedures for forwarder based continuously advancing mounders remains to be explored. Therefore, this study aims to quantify the potential of a machine vision system working ideally (full identification of clearcut objects' sizes, positions and types) together with various working procedures for forwarder based continuous mounding.

2 Materials and methods

A literature review was conducted on the topic of simulations related to forest machines and clearcuts. The literature review was conducted to retrieve input data needed for the simulations, e.g. boulder and stump quota and machine specific data, see Annex 1, available at http://dx.doi.org/10.14214/sf.1386. This input is validated by comparing today's actual boulder quota with the simulations by using Berg's (1982) standardized test for obstacle quota measurements on the simulated clearcut areas.

In addition, semi-structured interviews (Patton 1990) were conducted with a leading manufacturer of forestry equipment for scarification to retrieve knowledge about how forwarder based mounding heads are able to actuate today, as well as an insight in how it would be developed in the future, if efficient remote sensing methods were to be utilised (i.e. find future work procedures for forwarder based continuous mounding). The output from these interviews, as well as the literature review input data was simplified and used in the machine simulation model. Andersson et al. (1977) claimed that tree planting machine simulations need to contain terrain-, machine- and simulation models. A similar approach has been deployed in this study.

The numerical simulations were conducted in MATLAB® R2013a. The efficiencies of different working procedures for how mounds are positioned at the clearcut were calculated numerically using a Monte Carlo approach (Metropolis and Ulam 1949). Analyses were performed on stochastic clearcut models and deterministic machine models where several runs were conducted with the same input data to quantitatively determine the success of site preparation for a number of mound positioning strategies.

2.1 Simulation model

By mimicking the system in a computer program, the computer can produce numerous events with help from a random generator, and thus get an idea of the system's behaviour over the long term. The Monte Carlo method generally follows this procedure (Metropolis and Ulam 1949):

1. Define the input parameters and their respective domain.
2. Generate inputs randomly and independently from the domain following a probability density function (PDF).
3. Conduct a deterministic computation on generated inputs.
4. Repeat the procedure until results converge and aggregate.

The chosen simulation strategy in this study was to follow the Monte Carlo method (Metropolis and Ulam 1949) and use Andersson's (1977) division between terrain, machine and the simulation itself. Input parameters and distributions for terrain and machine models were found in literature and via interviews (defining the input variables and their respective domain). These are explained further in forthcoming sections.

A pseudo-random number generator in MATLAB® R2013a was used to generate inputs from the probability density functions (PDFs) stated in literature and interviews. The MATLAB pseudo-random generator has a very long period ($2^{19937}-1$), and passes diehard tests. The input data needed to execute the simulations are given in Annex 1.

Afterwards, deterministic computations were conducted on the inputs chosen from the PDFs whereby several runs were conducted with regenerated inputs. When convergence was reached, the results were aggregated. Fig. 1 shows the flow of events during a simulation run.

Additionally, in order to get information about steady-state conditions that was sought in the simulations, convergence analyses were conducted with respect to some parameters showing

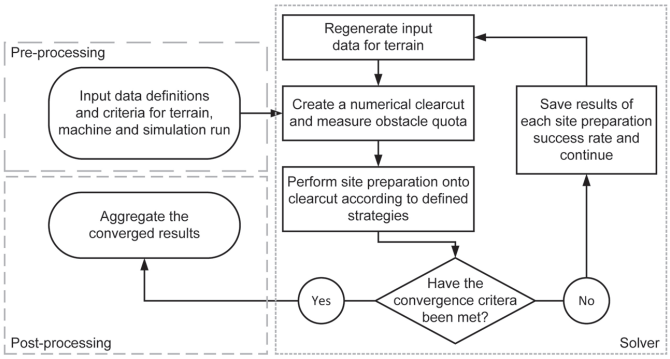

Fig. 1. Flow chart of the conducted simulation following the Monte Carlo method.

significant influence on simulation quality and simulation time. When convergence was found, the parameter could be set accordingly.

2.2 Terrain model

Larsson (2011) acknowledged that failed mounding was caused by subsurface stone and surface boulder occurrence (48%), stump occurrence (34%), slash occurrence (11%) at the mounding site, and other reasons (7%). Lundmark (2006) identified stones, stumps and slash as the critical obstacles during site preparation, while Rantala et al. (2010) emphasized that stones are crucial obstacles that affect mounding efficiency. On that basis stones (both surface and subsurface), stumps and slash were included in the terrain model presented in this paper. Other causes of mounding failure, such as roots interfering with the procedure or lack of mineral soil on the created microsite, were excluded.

2.2.1 Stones and surface boulders

In the terrain model, stones are divided into surface boulders which are visible stones, and subsurface stones. Berg (1982) standardized the technique for measuring the amount of visible stones and stones positioned at a maximum depth of 0.2 m. He divided the amount of surface boulders and subsurface stones into three segments: 25%, 50% and 75% boulder quota. The boulder quota can be estimated by recording the number of times a probe encounters a stone related to the total amount of attempts. The tested terrain model configurations described further in Table 1 have all been tested through Berg's (1982) boulder quota measuring method in the simulations. Stendahl et al. (2009) showed a correlation between the amount of subsurface stones and surface boulders for moraine soils where a boulder quota of 75% corresponded roughly to 4000 surface boulders per hectare and a 25% boulder quota derived practically no surface boulders at all. Ersson et al. 2014 used a number of 1800 boulders·ha^{-1} at 55% boulder quota, which was used in our terrain model as well, although transformed into an area percentage number (Table 1) and validated manually.

The size distribution of surface boulders was thoroughly investigated in a study by MarkInfo (2007), which found that a normal distribution of boulder diameters with mean value 0.4901 m and standard deviation of 0.1233 m is a suitable approximation. The normal distribution span was limited to exceed 0.2 m, since smaller diameters were not regarded as surface boulders (MarkInfo 2007). A large common base machine for mounding, Komatsu 865 (Komatsu Forest 2015), has

Table 1. Five different terrain model configurations based on Ersson et al. (2013) and Berg (1982). Slash residues is further added on these terrain models.

Terrain model config. number	Description	Surface boulder amount [Area %]	Stone amount [Area %]	Stump amount [Area %]	Boulder quota
0	Typical southern Swedish clearcut	3	41	4	~55%
1	Few stumps, few stones, no surface boulders.	0	35	4	~25%
2	Few stumps, many stones, many surface boulders	5	51	4	~70%
3	Many stumps, few stones, no surface boulders	0	35	10	~25%
4	Many stumps, many stones, many surface boulders	5	51	10	~75%

a ground clearance of ~0.7 m. If a surface boulder is assumed to be spherical and its centre is at ground level, the machine operator then needs to avoid boulders with diameter larger than 1.4 m. Therefore, a maximum surface boulder diameter limit of 1.4 m was assumed and the normal distribution span was truncated accordingly.

The subsurface stone sizes followed an exponential distribution (Ersson et al. 2013) with lambda value at 0.05 m, meaning large amounts of small stones and small amounts of rocks larger in size, again assuming a maximum diameter of 1.4 m (i.e. the same as for surface boulders). Andersson et al. (1977) simulated the work operation of mechanized planting units, where stones were included in the terrain model. Here, the minimum size of a cubical stone was set to 50 mm; otherwise, it was not regarded an obstacle. The same conclusions were drawn by Ersson et al. (2013), although a stone was modelled as a sphere with a minimum diameter of 56 mm. In the terrain model used in this study, stones are therefore modelled as circles with a minimum diameter of 56 mm.

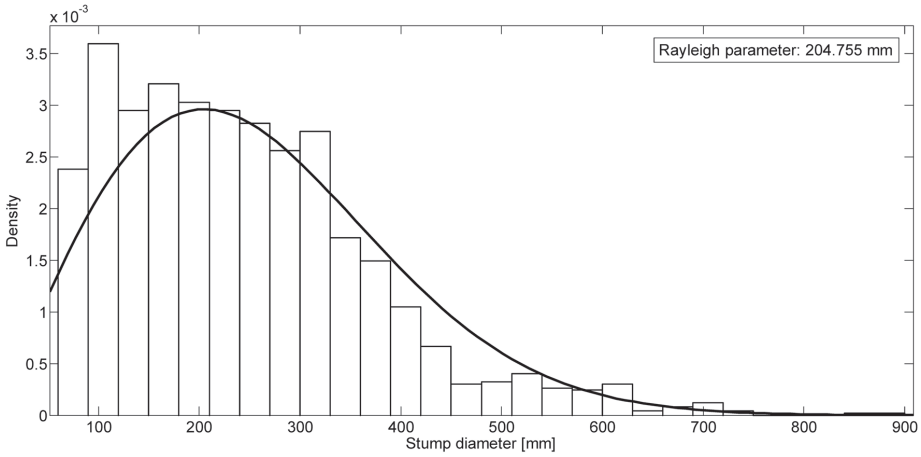

Fig. 2. Stump diameters of 12 stands ready for felling based on Herlitz (1975). The curve represents a Rayleigh distribution with a Rayleigh parameter set to 204.755 mm. The Rayleigh distribution was used to enable the (pseudo)random generator to choose from a continuous domain of values.

2.2.2 Stumps

Herlitz (1975) provided data from 12 stands ready for final felling. In this study, to be able to use a continuous PDF rather than a discrete one for stumps sizes, Herlitz's (1975) data was approximated by a Rayleigh distribution with Rayleigh parameter 204.755 mm (see Fig. 2). A stump is always surrounded by a root plate; a zone of rapid taper (ZRT), where there is a transition of roots going from the ground which connect to the stump (Wilson 1975). Within this zone, any attempts at mounding usually fail, and this is therefore taken into consideration in the terrain model. Kalliokoski et al. (2008) showed for Fennoscandian species (*Betula pendula* Roth., *Picea abies* (L.) Karst. and *Pinus sylvestris* L.) that the ZRT plus the stump itself (root plate) seldom exceed a diametric plate of 1 m and, furthermore, no significant differences between species could be determined. Therefore, the ZRT was modelled as a constant sized ring outside the stump with a radial size of 0.16 m. The ZRT size was derived from the measure of a ZRT for a mean sized stump (Kalliokoski 2008), where the ZRT size is assumed to be the same for any stump size.

2.2.3 Slash

In Sweden, slash is commonly piled and extracted from clearcuts after harvesting (Pettersson and Nordfjell 2007). However, after extraction, remains from such piles form obstacles for subsequent mounding. Pettersson and Nordfjell (2007) measured 552 slash piles where a Swedish, 130-year-old naturally regenerated stand had been clearcut. A layer of 0.2–0.3 m slash remained at such slash pile sites whose size were normally distributed with an average size of 4.06 m^2 and 1.4 m standard deviation. In the terrain model, it is assumed that slash only occurs on the clearcut at positions where there are remains from slash piles. Table 2 shows the slash input data for the terrain model. The slash piles were assumed to have a rectangular shape, where we altered the piles length-wise with a fixed width, making the area following a normal probability density function (PDF). The average width-to-length ratio were set to 2:1. The spatial distribution on the clearcut were based on measures from clearcuts of previous spruce stands in southern Sweden where between 200–305 $m^3sub \cdot ha^{-1}$ were harvested (Lars Eliasson, Skogforsk, pers. comm. 2013). The number of slash piles per 100 m strip road were measured, as well as the distance between strip roads (Table 2). We assumed that all terrain model configurations that are used in the simulations have the same slash input data to generate the slash piles.

2.2.4 Terrain model configurations

Ersson et al. (2013) proposed different terrain model configurations that are valid for typical Swedish clearcuts. These are used in our simulations (Table 1). Terrain model configuration 0 is related to a typical southern Swedish clearcut (Stendahl et al. 2009; Skogsdata 2012), and terrain models 1–4 are chosen in accordance with Ersson et al. (2013) to be able to assess the mounding efficiency for different scenarios.

Table 2. Slash input data for the terrain model based on Pettersson and Nordfjell (2007) and measures from clearcuts of previous spruce stands in southern Sweden with additional material from Lars Eliasson (Lars Eliasson, Skogforsk, pers. comm. 2013).

	Distribution type	Mean value	Standard deviation	High limit	Lower limit
Average basal area [m^2]	Normal (truncated)	4.06	1.4	5.7	2.0
Piles per 100 m strip road [-]	Uniform	8.5	-	4	13
Distance between strip roads [m]	Uniform	13.45	-	12.5	14.4

In addition to the terrain model configurations, slash were determined as described in section 2.2.3, using the same slash input data for all configurations. Berg (1982) suggested a procedure for measuring obstacle occurrence on clearcuts. To retrieve relevant terrain models, this procedure was conducted on clearcuts and iterated until an appropriate boulder quota was found for each terrain model configuration, whereby the area percentage for each object amount was set.

2.2.5 Generating the terrain

All objects in terrain span a 3D space. However, to simplify simulations the objects in the terrain model were projected on a 2D-plane at ground level, i.e. described as pixels in a 2D matrix. Furthermore, the 2D plane does not comprise any height shifts. Thus, some information regarding object size that was described as volumes needed to be transformed into 2D. The value of each element in the 2D matrix was adopted to show the property of it (height, type of object etc.). One parameter states the resolution of the clearcut. For example, a boulder constitutes a circular area on the terrain. That area are built from pixels where a higher resolution allows for a better representation of the sought rounded shape. Thus, a higher resolution (amount of elements in the matrix) give a better representation of the objects, but increase computation time.

An empty terrain model is created onto which objects will be randomly distributed. In addition, each object have specific rules to follow when distributing them in the terrain, e.g. a minimum distance between stumps, no surface boulders lying on top of stumps etc., see Table 3. The amount of each object dispersed onto the terrain is determined by the chosen terrain model configuration (Ersson et al. 2013). It was further assumed that the machine operator is able to avoid objects that could harm the machine or impede accessibility. Therefore, the terrain model excluded any objects that would force the machine to deviate from the route to simplify machine movements.

The procedure for distributing objects into the terrain model is depicted in Table 3. If the prescribed demands are not met, a new, randomized position is generated for the same object and an identical procedure takes place.

First, surface boulders are randomly distributed, one by one, following a uniform distribution. They can not lie on top of each other. The size of boulders followed a normal distribution (Markinfo 2007).

Second, stumps are distributed on the terrain, one by one. Here, the ZRT of each stump was allowed to be placed over top of boulders and each stump was allowed no closer than one metre to another stump already placed. Stump and ZRT size follow the measurements from Herlitz (1975)

Table 3. Object positioning procedure and interrelations between the objects for the creation of the terrain model.

Object type (Order of placement)	Boulder (1)	Stump (2)	Stone (3)	Slash (4)
Boulder (1)	Can not be placed over top of each other.	Doesn't exist during boulder placement.	Doesn't exist during boulder placement.	Doesn't exist during boulder placement.
Stump (2)	ZRT can be placed over top of boulders, not stump.	Can not be inserted closer than 1 metre to another stump (Centre-to-Centre).	Doesn't exist during stump placement.	Doesn't exist during stump placement.
Stone (3)	Can not be placed under top of boulders.	Can not be placed under the stump centre point	Can not be placed over top of each other.	Doesn't exist during stone placement.
Slash (4)	Can be placed over top of stones.	Can be placed over top of boulders.	Can be placed over top of stumps.	Slash piles never exist in same location.

(with the size described with a continuous Rayleigh PDF as depicted in Fig. 2) and Kalliokoski et al. (2008) respectively.

Third, sub-surface stones are placed on the terrain, one by one. They are not allowed to be placed under boulders or under the centre point of a stump. In addition, they are not allowed to be placed on top of each other. The size PDF follow an exponential distribution as suggested by Ersson et al. (2013).

Lastly, slash is placed onto the terrain, all piles simultaneously. Here, we chose to simplify the shape of one pile as a rectangle with a width-to-height ratio of 2:1. The scattering of piles and the piles themselves follow Table 2. The angle of the slash piles in relation to the direction of travel of the scarifier is randomly chosen between 0 and 90 degrees following a uniform distribution. All piles have the same angle in relation to each other.

2.3 Machine model and terrain relations

It is realistic, even on existing machines, to enable transversal movement (X) and/or enable longitudinal movement of the mounder to somewhat change the mounding site in the direction of travel (Y) (Jukka Alakorpi, Bracke Forest AB, pers. comm. in 2013). Therefore, depending on the movement of the base machine, sites can be chosen in a maximum area of X·Y metres (area mounding). A longitudinal positioning strategy allows the square area to be chosen anywhere along Y at the mid line, while transversal positioning strategy allows the square area to be chosen anywhere along X at the mid line. With a combined longitudinal and transversal positioning strategy the mounding square area can be chosen anywhere within the X·Y surface, whereas today's mounding strategy forces the mound to be created at the midpoint.

To be able to compare transversal and longitudinal movement with each other, X and Y were both chosen at one metre in the simulations. Furthermore, the area X·Y, representing one microsite, never overlapped another microsite created before or after.

When the terrain has been created, the simulation execution continues with the mounding procedure on the created terrain. The machine travels in a straight line where mounds are conducted with a standard distance length-wise (in all our runs 2 metres) and with 2 metres between each row, in accordance with the specifications of a Bracke M26 mounder. An optimally conducted scarification would these cases result in a mound density of 2500 mounds·ha^{-1}. Mounds are then positioned on the chosen terrain model, where the possibility to change the mound position from the nominal position depends on the positioning strategy. In every mound position the amount of encountered obstacles are measured as the quota of pixels considered obstacles on the intended mound area divided by the number of pixels that compose the entire mound area, while a mean value is derived for the clearcut using quotas from all mounds.

2.4 Simulation quality analysis

Furthermore, to parallelize the simulation code to decrease the total computational time, the mounding was divided into several clearcuts having the same input data. To validate that the results for several runs coincide with results from one long simulation, a test was conducted. Fig. 3 shows the results from one of these runs, where all input data were held constant. A compilation of 5 runs, 75 metres each, were put after each other and compared with one long run of 350 metres. The simulations converged towards the same mean value meaning that it was possible to divide the clearcuts into smaller sections (several short runs compared to one long). Furthermore, as expected when mounding at evenly distributed positions, the cumulative mean value of obstacle amounts within the mounds converged towards the mean value for the entire clearcut terrain model.

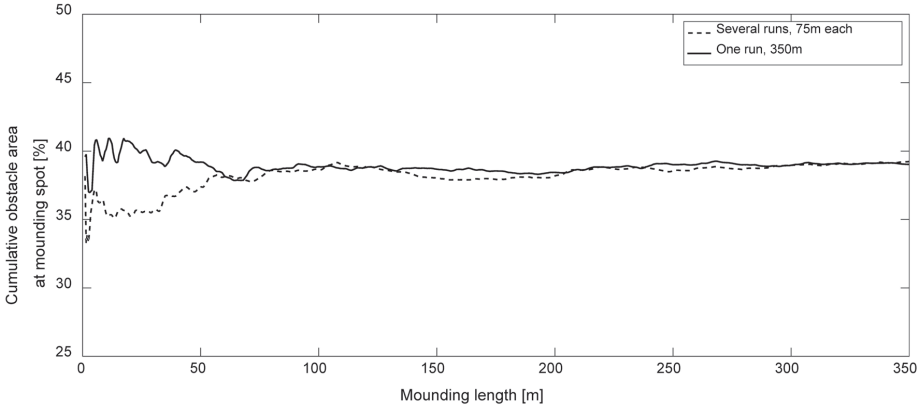

Fig. 3. Graph depicting two runs, one where 5 simulations were run 75 m each and put after one other (dashed line), and one simulation run 350 m (solid line). The simulations converged towards the same cumulative obstacle area at the mounding spots, which occur after around 250 metres.

In order to get information about steady-state conditions, convergence analyses were conducted with respect to clearcut length (fixed width) and clearcut detection resolution, which are two parameters that show significant influence on simulation quality and simulation time. Fig. 3 shows the cumulative mean amount of encountered obstacles at a mound as a function of mounding length (and thus the mounding attempts) with a value of 90 pixels·m^{-1} on detection resolution and scarified with one mounding strategy throughout the simulation. From this analysis

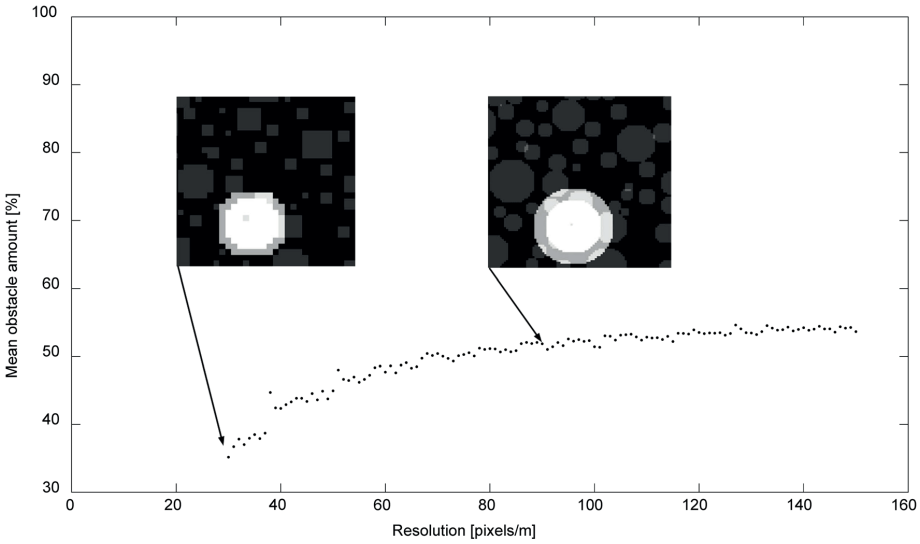

Fig. 4. Simulated mean obstacle amount (area percentage) as a function of detection resolution. A visual representation shows the difference between low-resoluted and high-resoluted clearcuts.

a minimum 300 m clearcut length was chosen for all simulations in the results section. The detection resolution is also important for the simulation quality and can further be related to needed resolution of any object detection system that could represent a clearcut numerically. Fig. 4 shows the mean obstacle amount as a function of detection resolution with the clearcut length set to 90 m (all other variables are also fixed). From this analysis a resolution of 90 pixels·m^{-1} (i.e. ~8100 pixels·m^{-2}) was chosen for all subsequent simulations.

3 Results

Initially, simulations were conducted for each of the three mound positioning strategies (section 2.3) and today's mounding strategy, applied in each of the five terrain model configurations described in Table 1. To get statistical significance, the clearcuts were each run 75 metres and 10 times (750 metres in total) for every combination of terrain model configuration and positioning strategy. For every re-run, new randomized positions and sizes for objects were used (where the input data for the specific terrain model configuration were fixed). In Fig. 5 the mean obstacle area at the mounding spots are presented for all terrain models 0–4 and for all developed mounding strategies (a low amount of encountered obstacles could imply a better mounding success).

To be able to analyse effects on a larger variation of clearcuts and in this context compare the mound positioning strategies, simulations were conducted where the obstacle quota was changed incrementally (Fig. 6). Mounding was conducted with the four positioning strategies on clearcuts generated in a span from 30% obstacles (which is a lower obstacle quota than used for terrain configuration 1) up to 70% obstacles (which is a higher obstacle quota than used for terrain configuration 4). The obstacle quota was linearly increased from 30% to 70%. In these simulations, the ratio between the different objects was kept constant and could therefore not be entirely compared with the ratios of terrain configurations 0–4.

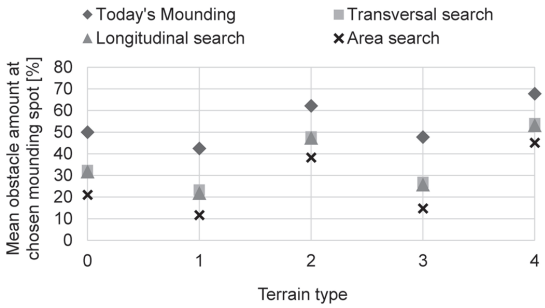

Fig. 5. Mean obstacle area at chosen mounding spots at different terrain models using four different strategies in choosing mounds.

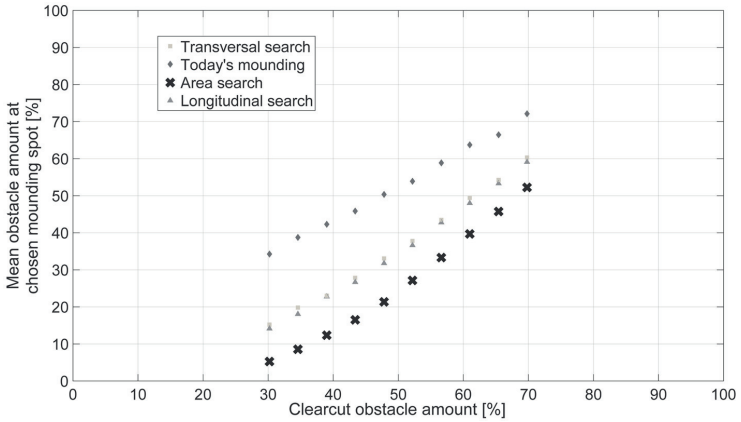

Fig. 6. Mean obstacle amount measured at mounding spots created at clearcuts with total obstacle amounts between 30% and 70%. The obstacles subsurface stones, surface boulders and stumps were linearly changed to range all terrain models 0–4 and more. Slash residue parameters were kept at the same rate throughout the simulations.

4 Discussion

The amount of encountered obstacles using the four compared positioning strategies differs significantly for terrain model configurations 0–4. Today's strategy encountered on average the same amount as at the clearcut as a whole, longitudinal second-lowest, transversal second-highest and area mounding highest (i.e. the order between the different mounding strategies remains constant, regardless of terrain model). The transversal mounding strategy showed a lower amount of encountered obstacles on average than the longitudinal, possibly since the mounds are modelled as rectangles with the longer side in the longitudinal direction (i.e. requires more space). Hence, since the possibility for transversal and longitudinal movements for the corresponding mounding strategies were set at the same value, it is more likely that successful mounding positions will be found in the transversal direction.

Already at small obstacle quotas, as illustrated in Fig. 5 for terrain model configuration 1, the difference between today's mounding strategy and the three other suggested mound positioning strategies are significant (around 70% decrease in encountered obstacles). The most notable difference for all mound positioning strategies is caused by a change in subsurface stones (and surface boulders), where the difference between high and low stump quotas is insignificant in comparison to a change in subsurface stones and surface boulders. The difference between today's mounding procedure and the other suggested procedures is largest at clearcuts with obstacle quotas around 30–50% (where clearcuts having under 30% is unrealistic to encounter). This difference shows that an efficiency improvement potential can be realized by first addressing the need for machine vision, and then the need for new mound positioning strategies that utilise machine vision efficiently.

Today, during operational manual tree planting, trees are typically planted in each mound created by the mounder. If it is assumed that seedlings are planted regardless to whether the created mound was acceptable or not, the seedling survival and growth will be directly related to the result in this paper, showing how mounds created in spots with less amount of obstacles can enable higher seedling survival. In addition, mounding is only used on clearcuts with few obstacles. This

result thus shows that on clearcuts with high obstacle quotas, such as terrain configuration 2 and 4 (where mounding is typically not used), mounding can be used since mounds found with better strategies is comparable with mounds found by today's mounding strategy at much easier clearcuts. Using mounding on more grounds would therefore result in better seedling survival compared to planting on disc-trenched clearcuts (Örlander et al. 1990; Saksa et al. 2005; Uotila et al. 2010). In addition, using more efficient mounding on more clearcut areas in general will render less ground obstruction, possibly lower fuel consumption of the base machine and less wear on the machinery. In fact, some performed site preparations today are of such poor quality that they need to be redone. Therefore, through more efficient mounding procedure, the need to redo the site preparation can be significantly reduced.

The needed resolution of the terrain model described in section 2.4 could be related to the need for a clearcut identification technique to recognize and identify clearcut obstacles, although the resolution need to be interpreted into a 3D representation. The convergence limit of 8100 points·m^{-2} chosen for this study can be compared with the Nyquist rate, meaning that at least twice the sampling rate is needed to find the original signal (Nyquist 1928), i.e. a resolution of 8100 points·m^{-2} is enough to adequately represent the actual clearcut environment for this purpose, which could be interesting in machine vision aspects to assess the needed quality of the hardware.

Possible limitations in the simulation accuracy can be due to necessary assumptions, e.g. the conversion of some objects' measurements from 3D to 2D, or the fact that slash was inserted in the same way on all clearcut terrain configurations (although at randomized angles compared to the direction of travel), etc.

Enabling object identification in combination with a mound positioning strategy can significantly improve the mounding success rate and thereby improve subsequent seedling survival while decreasing the environmental impact of site preparation. The potential for machine vision to increase mounding productivity is theoretically high, and we conclude that in this case, it is well worth it to implement remote sensing technologies in silviculture and possibly in forestry as a whole.

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Supplementary files

Annex 1. *Input data for the mounding simulations*, available at http://dx.doi.org/10.14214/sf.1386.

C

Automatic clearcut obstacle identification using a time-of-flight camera

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Abstract
Site preparation by mounding or disc trenching preceding tree planting has in one form or another been practiced for centuries, mainly to increase seedling survival. Mounding is by many authors considered more economically and environmentally beneficial compared to disc trenching. However, mounding is particularly sensitive to clearcut obstacles since actuation can be performed over top of obstacles, resulting in poor quality or ineffectual site preparation. Hence, mounding efficiency is strongly dependent of the obstacle frequency and is inferior to disc trenching efficiency on clearcuts with high obstacle frequencies. One way to increase mounding efficiency (and mechanized planting productivity) is to automatically identify obstacles and thereby avoid them. Studies have shown that over 30% of failed mounding attempts are caused by encountered stumps. Thus, the objective of this paper was to develop and test a system for obstacle identification during mounding with focus on stump identification to enable obstacle avoidance. A time-of-flight camera was mounted in front of a forwarder to record information from a clearcut during operation, creating a virtual 3D point cloud scene. By post-processing this information, it was found that the distinct shapes of stumps (and to some extent also stones and slash) can be found automatically and be used for obstacle avoidance. Further research is needed to streamline the post-processing algorithms and to incorporate retrieval of clearcut data, post-processing and obstacle avoidance activities into a fully operational system.

Keywords: Detection, recognition, clearcut objects, remote sensing, automation, silviculture

Introduction
Site preparation preceding planting has been practiced for centuries, driven by the needs to drain the soil, increase nutrition availability, decrease competition from surrounding vegetation, reduce frost heaving, and to prevent predation by *Hylobius abietis* (Örlander et al. 1990, Sutton 1993, Petersson et al. 2005). Mounding as site preparation technique is considered more economically and environmentally beneficial compared to disc trenching (Uotila et al. 2010). Mounding, however, is particularly sensitive to clearcut obstacles since the procedure can be performed over top of e.g. stones and stumps several mounds in a row, resulting in poor site preparation. Similarly is the productivity of mechanical planting devices strongly dependent on obstacle frequency (Ersson et al. 2013). Hence, one way to increase productivity of mechanical planting devices and mounders is to automatically identify where obstacles are located on the clearcuts and avoid them. Stones, stumps and slash are particularly problematic for mounders and trenchers (Rantala et al. 2010, Larsson 2011). In Sweden, around 50% of all mounding attempts on easy to normal clearcuts fail because of encountered obstacles, and over 30% of failed attempts are caused by stumps (Larsson 2011). Thus, the main objective of this paper was to find and evaluate suitable sensing methods for obstacle identification during mounding with focus on stump identification, and a secondary objective was to find an approach to how post-processing of retrieved clearcut information could be carried out.

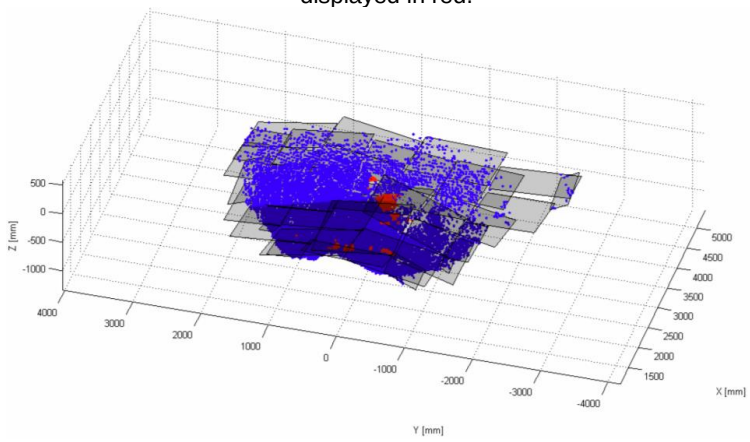
Materials and Methods
Apart from quantifiable properties such as density or moisture content that could be measured, the three dimensional (3D) shape of a stump is possible to distinguish by eyesight. Stumps usually consist of a flat rounded top with vertical sides, while no other similar object exists on clearcuts. This paper focus on identification of stumps because of their characteristic shape compared to slash and stones. Different techniques to retrieve information for stump identification was reviewed after which a time-of-flight (ToF) camera (Fotonic TOF-E70P RGBZ) for mapping the surroundings in 3D remotely was chosen. The

ToF camera sends electromagnetic energy toward the surroundings and measures the time it takes for it to return after reflection. The distance to points representing the scene is measured without any additional post-processing. The size of each depth matrix retrieved is 160x120 points with 16 bits depth per pixel.

The retrieval of clearcut information was conducted outside Umeå, Sweden on an easy classed clearcut with a snow cover of 1 cm at around 0ºC. The ToF camera was mounted in the front of a forwarder and directed at approximately a 45 degree angle so that information was retrieved at a maximum distance of 10 metres from the machine. Camera snapshots were taken at standstill and physical measurements from the camera to clearly visible obstacles were conducted to be able to compare the ToF camera identification with actual obstacle positions on the clearcut.

The raw data from the camera was represented by a 3D point cloud with x, y and z coordinates. 2D planes was placed into the 3D point cloud, fitted as mean planes to the pixels of the corresponding area, in order to compensate for ground surface changes, see Figure 1. The planes overlapped and the size was adjusted to optimize the obstacle identification. Residuals from the corresponding 2D mean plane was analysed and screened, where pixels with z values exceeding ~100 mm (above ground) was saved. Then, remaining pixels that was clustered with at least 5 pixels and comprising an area in the x-y plane of at least 5000 mm^2 were saved.

Figure 1. Point cloud with mean planes fitted in subsections. Deviating, clustered pixels are displayed in red.

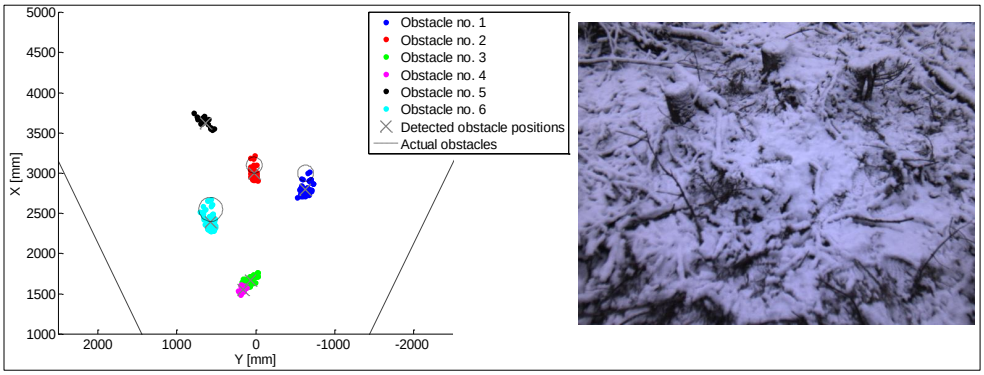


These remaining pixel clusters were considered as obstacles whereby the centre coordinate of the cluster was marked. A comparison with real measurements was conducted, and the accuracy was calculated.

Results and Conclusions

In Figure 2 an example of clustered and deviating pixels from the snapshots are depicted next to an RGB image of the same clearcut area. In this depicted area, three stump locations was measured and also found (obstacles 1, 2 and 6). In Figure 2 three other objects were identified, possibly protruding branches from slash piles which was not measured in the field (obstacles 3, 4 and 5).

Figure 2. Left: Identified obstacles in colour-coded pixels marked with 'X' and actual stumps depicted in dashed circles, seen normal to the x-y plane. Right: Angled RGB image over the same clearcut area.



The post-processing algorithm uses ~3 seconds on an office laptop @ 2.7 GHz to process each snapshot of around 5x5 metres. This gives a maximum advancement speed of 1.7 m/s, (not accounting for time delay of the actions taken by the machine given the identified obstacles) which is sufficient for many existing machines.

A comparison was made between the positions where the post-processing algorithm had found obstacles with the actual obstacle positions on the clearcut. On basis of six snapshots, the accuracy was around 90%. In order to have a reliable accuracy measure further data is needed e.g. from operation usage, alternating weather conditions, bright sunlight and darkness, different obstacle frequencies, etc. The results, nevertheless, showed that a ToF camera with sub-sequent post-processing can identify visible stumps with reasonable accuracy and that other protruding obstacles such as stones and slash piles can be found.

Further research is needed to streamline post-processing algorithms and to incorporate retrieval of clearcut data, post-processing and obstacle avoidance activities into a total system. If this setup is successfully applied on a mounder, failed mounds can be lowered by around 30%, assuming that 94% of all identified stumps can be avoided. Additional research is required to reduce failures caused by surface stones and slash. This further implies that mechanized planting directly subsequent to mounding is one step closer to realization.

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LULEÅ UNIVERSITY OF TECHNOLOGY

Automatic obstacle identification using a time-of-flight camera

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1. Background and objectives

Mounding conducted forwarder based or during mechanized planting is particularly sensitive to clearcut obstacles since the procedure can be performed over top of e.g. stones and stumps. In Sweden, around 50% of all mounding attempts on easy to normal clearcuts fail because of encountered obstacles[1], exemplified in Fig. 1. One way to increase productivity is to automatically identify obstacles (size, type and position) on the clearcuts and avoid them. A Time-of-Flight (ToF) camera has previously shown good potential in identifying objects.

Objective:
Develop a method for automatic obstacle identification using a Time-of-Flight camera

Fig. 1. A clearcut with a high obstacle quota.

2. Experimental Setup

The ToF camera was mounted as in Fig. 2. Snapshots were taken at standstill and physical measurements from the camera to clearly visible obstacles were conducted to be able to compare the ToF camera identification with actual obstacle positions on the clearcut. The data from the camera was represented by a 3D point cloud with x, y and z coordinates.

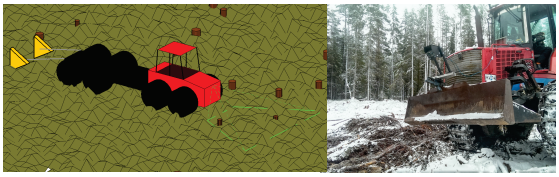

Fig. 2. Left: Simulated field of view for hood mounted ToF camera.
Right: Fotonic TOF-E70P TGBZ mounted on a harvester.

3. Obstacle identification algorithm

The raw data from the camera was represented by a 3D point cloud with x, y and z coordinates, see Fig. 3 (blue pixels). 2D planes was fitted as mean planes to the pixels of the corresponding area. Residuals from the corresponding 2D mean plane was analysed and screened, where pixels with high z values from the 2D plane were saved. These pixels are depicted in red in Fig. 4. Then, remaining pixels that was piled in clusters were considered obstacles.

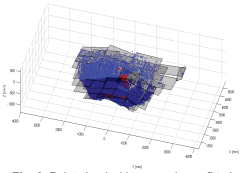

Fig. 3. Point cloud with mean planes fitted in subsections. Deviating, clustered pixels are displayed in red.

Acknowledgements
This project was partially funded by the Kempe Foundations. Thanks also to the students working in the 2013 SLU SIRIUS project.

4. Post-processing

Fig. 4. shows the obstacle identification conducted on the neighbouring depicted clearcut site. Some obstacle were measured by hand on the clearcut and are rendered as circles in the graphs. Identified obstacles are depicted as X-marks.

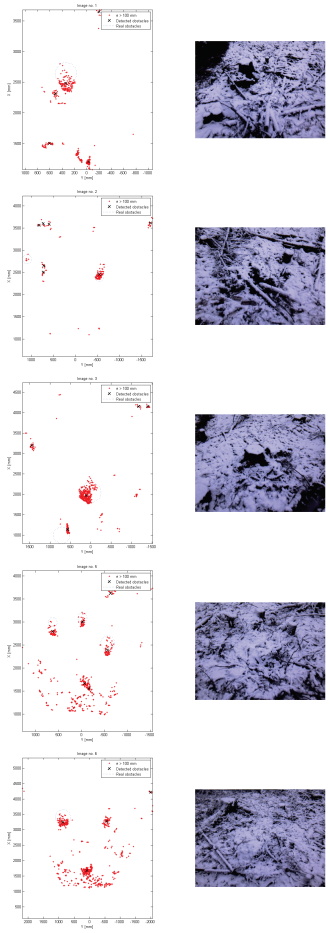

Fig. 4. The obstacle identification algorithm tested at different clearcut sites.

5. Conclusions

The camera raw data showed potential to assist in identifying obstacles located above ground. In addition to finding stumps, stones clearly protruding the mean ground surface were also possible to discern.
The algorithm for finding above ground obstacles showed potential to be directly utilized during site preparation where the main concern is the integration between camera, algorithm software and the site preparatory equipment.

[1] Larsson, A. (2011). *Selection of soil scarification method in northern Sweden within Sveaskog AB domains.* Department of Forest Ecology and Management, SLU. Examensarbeten 2011:9.

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OBSTACLE IDENTIFICATION THROUGH FAST VECTOR ANALYSIS

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ABSTRACT

During road travel, obstacles can impede productivity or durability for many different vehicles and render discomfort or injuries for the people within. Using remote sensing techniques, information from the surroundings can be acquired and analysed to identify obstacles ahead. The subsequent analysis can create a decision support for how the vehicle or driver should act upon encountered obstacles, through either autonomous control, guidance to the driver or a combination of both. In this paper, an experimental setup was created to mimic an obstacle in the shape of a speed bump on a flat road. An RGB-D camera was used to acquire information while travelling towards the speed bump. Afterwards, the acquired information was analysed by an estimation of the normal vector for each point in a 2D depth map. The resulting data from the experiments had sufficient resolution, speed and quality to retrieve proper identify obstacles or targets indoors with an accuracy of 2%. Obstacles were measured and identified in less than 20 ms where processing time mainly comprised data transfer from the USB-bus. The obstacle identification can be used to e.g. actively control the vehicle suspension, send feedback to the driver about obstacles ahead or optimise speed and direction for autonomous vehicles.

NOMENCLATURE

N	Normal vector
Z_c	Camera height from ground level
Z_h	Speed bump height from ground level
D	Depth map
P_z	Depth pixel in position Z
S_z	Slope pixel in position Z
α_c	Angle between the horizontal plane and the camera horizontal plane

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α_h Angle between the horizontal plane and the speed bump plane
$\frac{\delta X_Z}{\delta Z}$ Rate of change for X in the Z-direction
$N_{(Y,Z)}$ Normal vector in (Y,Z)
X_{1p} Normalized X_1 vector
X_{2p} Normalized X_2 vector

INTRODUCTION

Vehicles travelling on roads encounter obstacles constantly. These obstacles, whether they are pedestrians crossing the road, speed bumps or traffic cones, force the driver to make adjustments in steering angle or velocity to manage it properly. Other adjustments to the vehicle might be desirable, but are not possible to do fast while driving, or are desired as to relieve the driver, e.g. suspension adjustments, seat belt tension, lane keepers, emergency systems and driver assistance [1]. Identifying these obstacles is crucial for vehicles driving autonomously.

Therefore, remote sensing technologies might be utilised to automate (or semi-automate) some of these adjustments in order to increase the vehicles' efficiency. There exist various technologies for how to gain spatial 3D information from our surroundings in real time. Utilising the data acquired from the principles of e.g. time-of-flight [2], passive triangulation [3], active triangulation [4] or optical interferometry [5], some obstacles can be identified with algorithms that analyse the encountered scene. Subsequently, signals can be sent to the vehicle which alter the parameters to streamline how the vehicle act upon encountered obstacles.

In recent years the automotive industry have developed various methods to identify the surroundings. There are three technologies that are frequently used: Radar, Lidar[1] and computer vision [6,7]. Those three all have their strengths and weaknesses. Radar and Lidar both have a narrow field-of-view and are therefore mainly used for adaptive cruise control and/or emergency braking systems [7]. Computer vision systems relies solely on the ambient lighting of the road which render in performance issues at night or when large objects cast shadows on the road [6]. The field of view is, however, superior to Radar and Lidar. Another downside of computer vision is that compared to Radar and Lidar the computational effort is greater [7].

Utilising these technologies, it is possible to identify objects that may be encountered during road drive. Using the fact that some road speed bumps are painted in stripes, RGB data can be used in collaboration with transformed 3D data using Inverse Perspective Mapping (ISP) to detect speed bumps [8, 9]. RGB data alone can also be utilised to find road bumps using horizontal information variation and local neighborhood information in the retrieved data [10]. Ganesan et al. [11] found road obstacles with an IR monocular camera using an edge detection approach effectively by minimising false results with a method that could compensate for shadows. By using an elevated and downwards looking LIDAR sensor, Han et al. [12] allowed for obstacle detection that through line segmentation could distinguish between road, obstacles and road boundaries.

One key limiting factor for systems identifying the surroundings is that velocities when travelling on a road are notably high, demanding high sampling frequency in order to not pass the obstacle before the sensor measurement system delivers the information. In addition, the information needs to be analysed and action has to be taken before the obstacle is reached. The requirement on depth resolution is also high since even quite small bumps can decrease the vehicle's performance in many regards. Therefore it is of interest to assess whether software processing of retrieved data from surroundings could provide vehicle control systems with a better decision support in time, and secondly, to examine whether a low cost commercial hardware can reach these demands.

Scope and objective

The objective of this paper is to investigate whether developed algorithms can automatically find obstacles in a simplified experimental setup, simulating an encountered obstacle in the shape of a speed bump. An (RGB-D) camera will be used to automatically perform data collection during the experiment. The identification should be embodied by algorithms that automatically find the correct length between the camera and the obstacle.

METHOD

Today, inexpensive hardware that can be used to acquire spatial 3D information exist, such as the "Kinect" for Xbox or the "Asus Xtion Pro Live" (AXPL) for PC. They fall under the term RGB-D cameras which produce both colour (RGB) information and a correlated depth (D) map.

The coordinate system used in this work is a standard vehicle coordinate system. The coordinate system and the important entities are defined in Figure 1.

Data processing

After data is captured to the sensor the algorithm have two forks, one for the Z-direction and one for the Y-direction. The first step in each fork is to calculate the slope for each measured point. The slope map is then used for detection and the X-distance to the detected obstacles is calculated.

The data-flow is shown in Figure 2. The Y-direction fork is not used in the obstacle identification since only the angle in the Z-X plane is of interest, meaning that the core columns of each map can be averaged to reduce noise. The data processing is explained in-depth below.

[1] Light detection and ranging

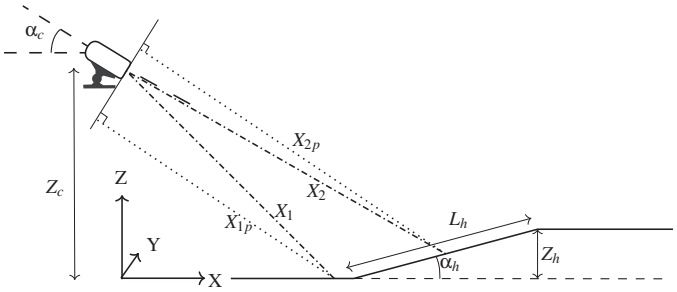

Figure 1. DEFINITIONS OF EXPERIMENT PARAMETERS.

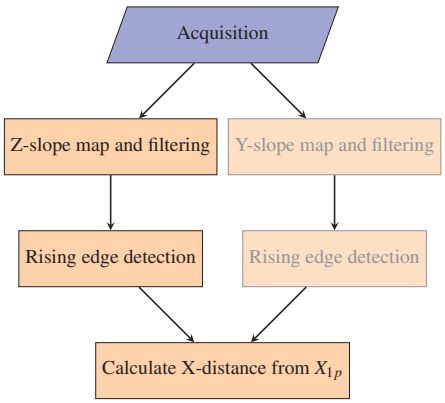

Figure 2. ALGORITHM DATA FLOW.

To numerically find the local slope of a curve in a depth map, the depth difference between two points is divided by the distance between them. This will, for a noisy depth-map, yield a noisy representation of the slopes in the map. In order to smooth out noise, the slope can be calculated from a neighbourhood of pixels, which however decreases the accuracy for determining the edges between different slopes when the neighbourhood of pixels increases in size.

For a pixel P_Z in a one-dimensional depth-map, two slopes can be found: one from the pixel before and one towards the next. The estimated slope over the pixel is the mean value of these combined. By simplifying

$$\frac{\delta X_Z}{\delta Z} = \frac{\frac{P_{Z-1}-P_Z}{\delta Z} + \frac{P_Z - P_{Z+1}}{\delta Z}}{2} \rightarrow \frac{\delta X_Z}{\delta Z} = \frac{P_{Z-1} - P_{Z+1}}{2 \cdot \delta Z}, \quad (1)$$

where P_{Z-1} is the distance to the previous point and P_{Z+1} is the distance to the next, Equation (1) can be used to find a linear operator that through a convolution operation can find the slope-map of the depth map. The distance in Z is 1, δZ is eliminated, hence

$$\frac{\delta X}{\delta Z} = [D] * \left[\tfrac{1}{2} \; 0 \; \tfrac{-1}{2} \right] \quad (2)$$

follows, where $[D]$ is the depth-map. By convolution with the operator $[\frac{1}{2} \; 0 \; \frac{-1}{2}]$ and the transposed operator to a two-dimensional depth-map, a two-dimensional slope-map can be created. In Figure 3 the process of transforming the depth-map to a slope-map is visualised. The figure shows the calculation of the slope in position Z and which elements if the depth-map used for transformation.

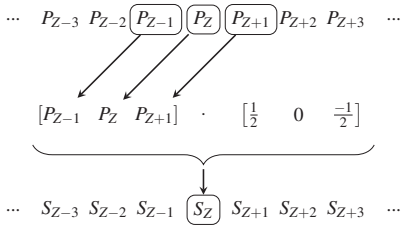

Figure 3. TRANSFORMATION FROM DEPTH TO SLOPE IN ONE DIRECTION.

The operator can be extended to smooth noisy data while calculating the slope map. The extension of the operator also takes the slopes between $P_{Z-2} - P_Z$ and $P_Z - P_{Z+2}$ into account,

however since they span a the double amount of pixels they get the values $\frac{1}{4}$ and $\frac{-1}{4}$. Larger operators will be less affected by noise but also be less sensitive.

By analysing the depth data there is no visible difference in distance on the last pixel of the ground and the first pixel of the obstacle, thus the start of the obstacle can not be found with only a depth map representation. Since the map consists of depth-data, and therefore represents a 3D-space; for each measured point it is possible to create a plane using surrounding pixels. If the normal vector of that plane can be found it will be oriented differently on a protruding obstacle compared to the ground.

The normal vector of each point

$$N_{(Y,Z)} = \begin{bmatrix} \delta Y \\ 0 \\ \frac{\delta X}{\delta Y} \end{bmatrix} \times \begin{bmatrix} 0 \\ \delta Z \\ \frac{\delta X}{\delta Z} \end{bmatrix} \tag{3}$$

can be numerically determined by the cross product of the two gradients in the point. These two in turn consist of δZ which is the distance over which $\frac{\delta X}{\delta Z}$ is calculated. $\frac{\delta X}{\delta Y}$ is defined in the same manner but for the Y-direction.

By utilising the normal vectors of each pixel in the depth image, obstacles can be distinguished from the ground, as shown by Holz et al. [13] where local surface normals were used to create plane segments in order to distinguish between obstacles, ground and graspable objects. However, for the rapidly changing conditions of e.g. road- or terrain-travel, the distinction of graspable items and obstacles is not necessary.

By studying the normal vectors angle against the Z axis in the Z-X-plane small deviations in height at the start of a slope translates into a larger deviation in angle. Thus, even a slight slope can be detected. To detect the start of the slopes, and thus the obstacle, a rising edge detection was used. In order to assess the effectiveness of the algorithm with real data, the experimental case study was conducted using an inexpensive, user-friendly RGB-D camera (named Asus Xtion Pro Live, AXPL).

Experimental Setup

The RGB-D camera used in the experiments rely on the technique developed by Primesense LTD [14]. The camera projects a speckle of IR dots and detect them using a CMOS image sensor with an IR filter. The speckle changes based upon the illuminated objects reflecting the light. The dots change size and position based on the distance from the camera. Integrated software identifies the dots and translates their state into a depth value at maximum 60 frames/s. The field of vision is a rectangular cone, 58 (H) by 45 (V) degrees. At 2 m, the depth resolution is around 10 mm while the horizontal and vertical resolution is 3 mm at the same distance from the camera. The software also project the measured depth in each pixel from the magnitude length to the camera's normal, as shown in Figure 1. The camera works best when not exposed to direct sunlight that would outcompete the IR light sent from the camera. Therefore, an indoor scene is best suited to assess obstacle identification performance.

The AXPL camera is arranged on a wheeled pushcart with weights to reduce high frequency vibrations. The camera is connected to a laptop through the USB-port, as in Figure 4. The laptop is provided with an OpenNI software that allows the user to import data from the AXPL camera. Then the AXPL camera and laptop setup is tested in various situations, such as when the pushcart is moving or at standstill. This allows for calculation of identification accuracy and speed.

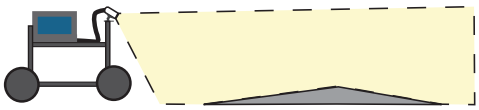

Figure 4. THE EXPERIMENTAL SETUP.

The depth measurements were performed with a 320x240 pixel resolution, at a sampling rate of 60 images/second. The experiments were conducted in an indoor environment, ensuring that no external factor could inhibit the experimental results. The pushcart was placed in different distances in X from the speed bump: 1.00, 2.00 and 3.00 m away. For each distance, data was acquired for two values of Z_h: 0.10 m and 0.15 m. L_h and α_c were always constant at 1.0 m and 20^o respectively. In total, 6 data acquisitions were conducted at standstill. In addition to these, data was retrieved with a constant speed of the pushcart: $\dot{X}$ = 3 m/s. These measurement was conducted in order to assess blurring due to camera movements.

Filtering and correction

Since the data from the camera contains quite a lot of noise, the algorithm was applied using an operator with 5 elements in order to estimate the normal vector of each position in the depth map. Furthermore, since only the angle in the Z-X plane was of interest, the core columns of each map was averaged to further reduce noise.

The camera had a systematic error that was assessed by measuring the distance to a flat surface when the actual distance was known. Results from these measurements was used as basis for a polynomial to correct the distance readings. The resulting polynomial is plotted in Figure 5 for the interval where the algorithm was tested.

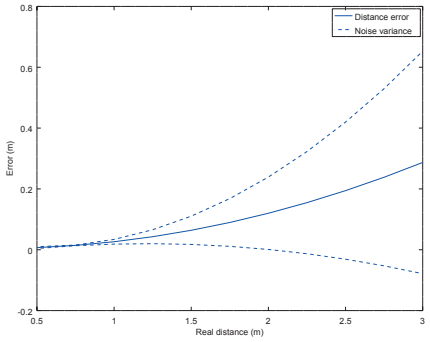

Figure 5. SECOND-ORDER POLYNOMIAL TO COMPENSATE FOR AN ENCOUNTERED SYSTEMATIC ERROR. THE DASHED LINES SHOW THE NOISE VARIANCE.

RESULTS

The results from the experiments will be presented in the following section.

Obstacle identification

Static measurements were conducted with the pushcart in well-defined distances from the speed-bump. Table 1 shows the results from the measurements. The identified distance is calculated along the X-axis and is corrected for systematic errors in the sensor.

Table 1. RESULTS FROM THE IDENTIFICATION ALGORITHM.

Real dist.	Identified distance at Z_h = 0.10 m (Error %)	Identified distance at Z_h = 0.15 m (Error %)
1.00	1.01 (0.6)	0.97 (2.5)
2.00	1.96 (1.7)	1.98 (1.1)
3.00	2.98 (0.5)	2.99 (0.1)

First, the depth image raw data was transformed by producing the normal vectors of each pixel and assess the conformity of the normal vector to the actual y-vector (horizontal plane normal). Figure 6 and Figure 7 shows the mean signal of 40 vertical lines of the normal vector transform map at three distances from the speed bump. The actual distances in these cases were 1.00, 2.00 and 3.00 metres, where measured values are seen in the X-axis of the figures. The Y-axes in Figures 6 and 7 show the normal angle from a horizontal plane. A fast value change indicates where the normal angle changes rapidly. The trigger points were therefore found by differentiating the data and searching for spikes.

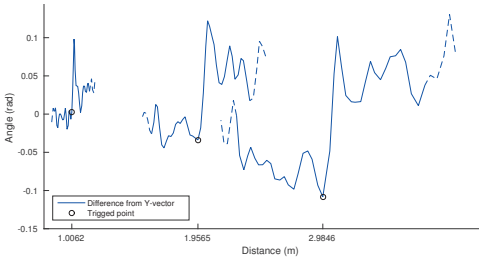

Figure 6. RESULTS FROM THE STATIC IDENTIFICATION OF A 0.10 M HIGH SPEED BUMP (I.E. Z_h = 0.10 M). MEASUREMENTS WERE CONDUCTED AT 1.00, 2.00 AND 3.00 METRES.

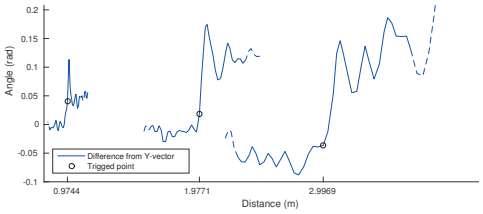

Figure 7. RESULTS FROM THE STATIC IDENTIFICATION OF A 0.15 M HIGH SPEED BUMP (I.E. Z_h = 0.15 M). MEASUREMENTS WERE CONDUCTED AT 1.00, 2.00 AND 3.00 METRES.

Execution times

The measurements of the algorithm execution time was conducted in several steps. One step for data acquistion and one for data processing. In order to stress the performance of the algorithm this step was performed on the higher resolution of the camera, i.e 640x480 pixels. This timing was performed on a standard laptop computer with an intel Core i7 CPU.

The obstacle identification algorithm was timed in a large series of runs. The average algorithm run time was 2.1 ms and the longest time measured was 3.0 ms. Since the camera was connected with USB 2.0 to the host computer, the transfer of data, however, was significantly slower than the algorithm execution.

The acquired depth map was 640x480 pixels, where each pixel had 16 bits of information. In an ideal set up this yield transfer times of 12 ms.

In summation, all steps of the obstacle identification was performed in less than 20 ms for the larger resolution. Since the algorithm's execution time is linearly dependent on the number of pixels in the depth map, the execution time of the lower resolution was averaged to 0.5 ms and had a maximum measured time of 0.6 ms.

DISCUSSION

The identification of speed bumps from depth information was performed by applying a normal vector transform on each pixel, whereby it was easier to discern sudden differences in plane normals on the road ahead. Within the camera performance range, the speed bumps were possible to be identified, within an accuracy of around 2 % and at maximum 4 metres from the camera. For each depth map image an RGB image is also sampled on the same measuring area. If it is possible to procure information of sought objects regarding their colour or intensity (data from the RGB image), this can be mapped to possibly be utilised in the future for increased accuracy of object identification and as a confirmation that objects are in fact found. The methods used by Danti et al. [10] to distinguish bumps using only RGB data could be used as confirmation or as an enhancer in our case since each depth map is accompanied by an RGB image. In addition, RGB data may be possible to use to identify speed bumps if they are marked in discernible colours which is common in many countries [8, 9]. However, in countries with differentiating weather conditions (snow, heavy rain etc.) this may prove problematic as the speed bump could be covered and render the RGB pixel intensity levels indiscernible from each other. Therefore, a robust algorithm should rely not only on RGB data, but also (or mainly) utilise 3D depth data.

The depth images often contain areas where no reading has been performed, i.e. holes. This is due to factors that impedes the IR-light to bounce back e.g. a low angle or material properties of the scanned objects which could render a bad scattered signal for the receiver. Other reasons for ineffectual readings can be coupled to restrictions in the hardware. In addition, the resolution decreases (pixel size increases) with the distance between objects and the camera, rendering in bad resolution at larger distances. With a longer distance between the camera and an obstacle, all these cumulative faults decrease the camera performance to such extent that depth images with more than around 4 metres in depth is too low in quality. The tests to check for blurred depth maps during continuous velocity towards the obstacles rendered no difference in image quality. However, the speed during these tests did not exceed 3 m/s. Thus, it would be wise to test the camera in higher speeds. Having the camera operate outdoors would probably decrease the camera performance even further. Therefore, measures need to be taken to be able to implement the obstacle identification algorithm on outdoor working vehicles.

The results indicate that this have been a successful method in detecting objects in the tested environments at the measuring range of the AXPL and at the speed in which the experiments were performed. Despite camera constraints, we mean that this or similar cameras can be modified cheaply to increase its usability in outdoor environments, by changing the wavelength of the built-in IR light and sensor or changing to e.g. a time-of-flight camera suited for outdoor use, whilst embedding the same algorithms. Mertz et al. [15] for example, developed a structured light sensor that was able to perform well under direct sunlight, and Gupta et al. [16] found an approach to compensate the scanning speed of a laser scanner to the intensity of ambient sunlight. The function of identifying encountered obstacles integrated in the vehicle's general system could hence allow for several different actions to be made for vehicle optimisation.

Although the algorithm has shown to be sensitive to small changes of the surface normal, even in noisy data, there are still limiting factors. For obstacles in close proximity to the sensor, the sensitivity actually decreases. This can be seen in Figures 6 and 7 where the angle difference is significantly lower when the obstacle is only 1.00 meter from the sensor. Even though identification was successful in the noisy data tested, noise makes the identification algorithm accuracy to deteriorate. The built in filtering should be kept to a minimum as it will lower the sensitivity and increase calculation time.

CONCLUSION

The proposed method of finding obstacles in 3D data from road travel show good results to identify where the normal of the measured surface changes. The change in normal vector was successfully used to identify speed bumps located up to 3 metres from the acquiring device. The limiting factor, however, in the performed measurements was the acquiring device as the noise level was high and the range limited.

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E

Clearcut stump detection using a time-of-flight camera

Håkan Lideskog & Magnus Karlberg

Highlights

- A system for automatic stump detection to be used during continuous mounding was developed
- The stump detection system finds around 40 % of encountered stumps when it is run on a clearcut area

Abstract

To ensure proper reforestation, site preparation is usually conducted using disc trenching or mounding. During execution however, obstacles impede the performance, especially during mounding which makes the method unsuitable on obstacle-rich clearcuts although mounding is desirable with regard to environment and economy. Obstacle avoidance is therefore needed in order to increase the mounding productivity and enable mounding usage on obstacle-richer clearcuts. Therefore, the aim for this paper was to develop a system for how to detect stumps (as the main obstacle) at clearcuts using a Time-of-Flight camera. Using an iterative process of implementing, testing different position determination techniques, and evaluation of different algorithms, a detection system was developed. The system was then validated on a delimited clearcut area showing a stump detection rate of 40 %. A fully implemented detection system could therefore allow for a significantly better mounding productivity and less machine wear.

Keywords

obstacle detection; continuous mounding; remote sensing; site preparation; silviculture; scarification

1 Introduction

Reforestation is legally required in many countries in order to safeguard the existing forest cover. For companies owning forest land, it is further important to ensure that the standing volumes of their ownership are maintained. One common procedure to ensure our future forests is to plant forest seedlings on afforested areas. An important step to provide high survival and growth of new forest seedlings is to perform site preparation before tree planting (Örlander et al. 1990; Sutton 1993; Petersson et al. 2005), which is usually done mechanically by mounding or disc trenching equipment (Forest statistics 2012; Luke 2016). During site preparation, large quantities of clearcut obstacles are encountered which impede the performance, sometimes resulting in poor or ineffectual site preparation. The mounding procedure especially is sensitive to clearcut obstacles (Larsson 2011), but can render a better early shoot growth (Saksa et al. 2005; Örlander et al 1990) and is considered more environmentally and economically beneficial (Uotila et al. 2010). This procedure is also used in combination with mechanized planting, especially in Finland (Laine et al. 2016). Mechanized planting devices, however, are not competitive to the combination of mechanical site preparation and operational manual tree planting (Ersson 2010). Nevertheless, experienced tree planters are expected to become fewer in the future (Strandström et al. 2009) and the cost for site preparation alone has nearly doubled in Sweden the last decade (Skogsstyrelsen 2016), indicating that an increased mechanization degree of reforestation is needed to prevent costs from increasing within the forestry sector (Bäckström 1978; Malmberg 1990; Hallonborg et al. 1997).

Accordingly, automatic detection of obstacles could reduce the number of unsuccessful mounding attempts thereby significantly increasing planting machine productivity (Ersson et al. 2013; Lideskog et al. 2016). To identify objects, their specific position, type and size need to be detected (Campbell and Wynne 2011). If such information is available for obstacle objects and utilized to streamline operation, site preparation effectiveness, can be significantly improved (Andersson and Brunberg 1989) which in turn would improve the forest regeneration. Today's mounders lack capabilities to automatically avoid clearcut obstacles and suffer from low efficiency (Larsson 2011). To enable such capabilities, solutions are needed for identification of clearcut obstacles.

Sensors suitable for data collection outdoors on moving vehicles have gained interest in research and the public in recent years as car manufacturers and private companies continue to strive towards, and closing in on, the self-driving car (Benenson et al. 2008, Furgale et al. 2013), which is forecasted to make its entrance on the market featuring full autonomy in 2018-2025 (Ross 2017).

Utilization of sensors in R&D intensive industries such as the automotive industry, hence drives the development of smart systems which can be used also in other, less R&D intensive, industries as forestry technology, see Talbot et al (2017). Lideskog and Karlberg (2016) determined that identification of obstacles during site preparation can (along with proper machine movements) improve the mounding efficiency and also enable mounding to be carried out even at clearcuts with high amounts of stone (> 50% area coverage). To assess how sensors could be used in order to streamline operations conducted on clearcut areas, Lideskog et al. (2014) determined and quantified clearcut obstacle properties (density, moisture content, shape etc.) which hence can be used for obstacle identification procedures. Moreover, people have the capability to automatically identify and position a stump using previous knowledge of e.g. stumps (relative size, colour, texture, shadows etc.) and our depth perception. In the same way, thanks to stumps' characteristic shape, it is plausible that machines could imitate this way of cognitive recognition. Lideskog and Karlberg (2014) tested a stump identification procedure by use of a Time-of-Flight (ToF) to map the surroundings in 3D and subsequent analyses to identify obstacles on clearcuts and their respective location. This study indicated that such procedures can be successful but requires more research specially in terms of algorithms for data analyses. Therefore, the objective of this paper was to develop and validate a complete system (method, algorithm, hardware etc.) for how to, based on ToF 3D sensor data, detect stumps at clearcuts.

2 Materials and methods

The research approach in this paper is based on the Design Research Method (DRM) proposed by Blessing and Chakrabarti (2009). This approach starts with a research clarification, followed by iterations of descriptive and prescriptive studies until convergence. The research is clarified in the introduction of this paper, which was finalized by stating the goals and connected measurable criteria. The first descriptive study that we base our paper on was conducted by Lideskog et al. (2014) that clarified what kind of information that is needed from the clearcut terrain in order to know what to be identified (i.e. "what should be identified?"). In that study requirements for obstacle identification during mounding were derived. The potential of using remote sensing during site preparation (mounding) was shown using Monte Carlo simulations (Lideskog and Karlberg, 2016), ensuring that it is feasible to continue the work (that the procedure can be sufficiently streamlined), and to find suitable sensing tools connected to effective machine movement patterns.

In this paper, both a prescriptive study and descriptive study are reported. In the prescriptive study a methodology for how to collect, transform and analyse data to detect stumps on clearcuts is proposed. A ToF camera was used for data collection and data transformation since previous studies with such techniques had showed good potential in this particular application. The analysis part of the methodology was based on existing research gathered through literature reviews. Through an iterative process of implementing, testing different position determination techniques, and evaluation of different algorithms, one suitable analysis approach including a stump positioning technique was chosen.

In the second descriptive study phase of DRM the proposed stump detection methodology was validated. This was conducted through a controlled field test carried out in four steps:

1. Definition of control area
2. Measurement of actual stump positions
3. Stump detection (definition according to Campbell and Wynne (2011)) through the prescibed methodology
4. Comparison of detected and actual stumps

Results from these steps are reported under each respective section below.

2.1 Definition of the control area

A recently afforested, but not scarified, clearcut was chosen in the outskirts of Luleå, Sweden (65°40'16.095"N 22°13'20.380"E), see Fig. 1. Here, a rectangular control area 4 metres wide and 30 metres long was marked with wooden sticks with one stick acting as reference point in space (origin of coordinate system). This control area had easily discernible (by eye-sight) stumps, while other objects such as slash debris, water puddles, ruts or large stones occurred only in minor amounts. To assess the resilience against sunlight, the area was directed in such a way that direct sunlight would hit the camera lens to some degree during the later measurements.

Figure 1. Studied field, or control area. The wooden sticks delimits the area.

2.2 Measure actual stump positions

The actual stump positions were measured using a high precision laser scanner called Faro Focus^{3D}S having a ranging error of ±2 mm at 10-25 metres. Several point clouds were created and merged to capture the entire control area. In that cloud, a point of origin was set as the corner of one of the short sides to allow for measurements of the stump positions in the measurement area. The vectors for X and Y were also defined parallel to the control area, see Fig. 2.

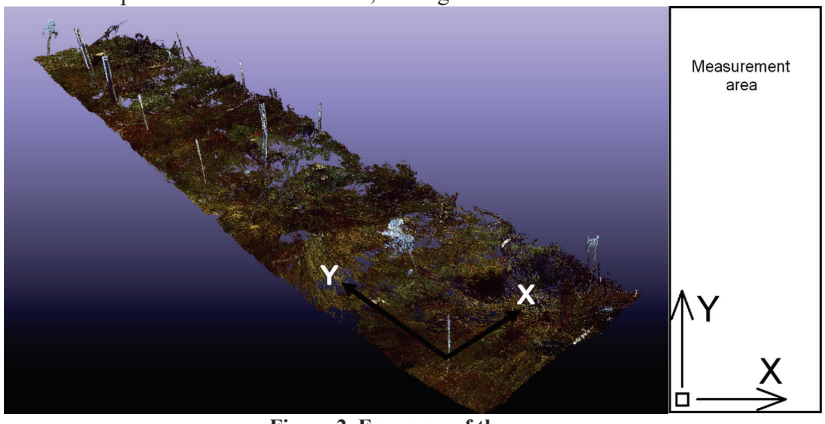

Figure 2. Faro scan of the area.

Stump positions and sizes were measured using the Faro scanner in order to validate the subsequently conducted stump detection. The Faro scanner was positioned in places enabling the entire control area to be measured. From the 3D point cloud data, all stumps' coordinates and diameters were manually determined in the data. The determined positions and diameters were also compared to manual measures done in situ using measuring tapes. In addition, a manual control was made whether to regard or disregard the stump given its decomposition degree. The lower limit was set at 70 mm in diameter.

2.3 Stump detection

The proposed stump detection system was tested through a simulated machine "run over". With a camera using the Time-of-Flight (ToF) principle (Lange and Seitz 2001) as remote sensor (see Supplementary file 2 for sensor specifications), data was collected from the control area.

Through embedded data transformation, this ToF camera measures simultaneous 3d depth in X′, Y′ and Z′ (where ′ referes to a coordinate system fixed with the ToF), as well as RGB. Fig. 3 shows an example of raw data plotted in 3d.

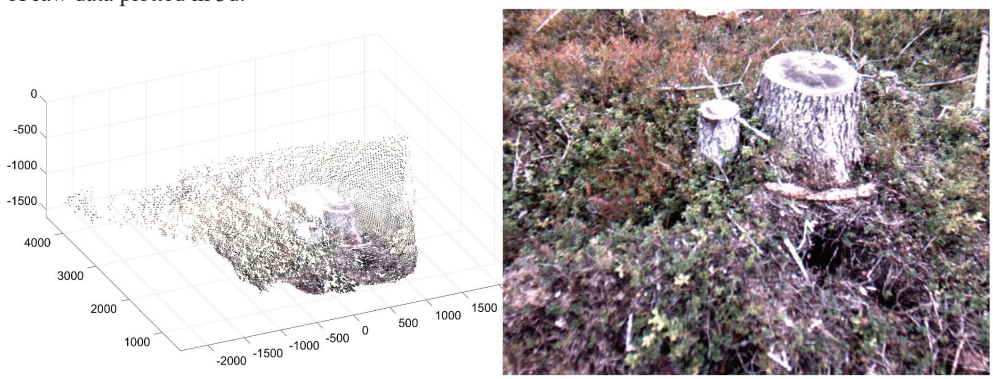

Figure 3. Raw data from the Fotonic T-o-F camera.

2.3.1 Information retrieval method

To imitate a machine run over, the ToF camera was positioned stationary, as seen in Fig. 4, at a certain position where data was collected. Then the camera was moved 2 meters ahead to a new stationary position where new data was captured. This process was repeated until the detection range reached the boundary of the control area (Fig. 5). By this procedure and due to the triangular detection shape of the ToF camera the total detected area consisted of both gaps (transversal to the direction of travel) and overlaps which needs to be accounted for.

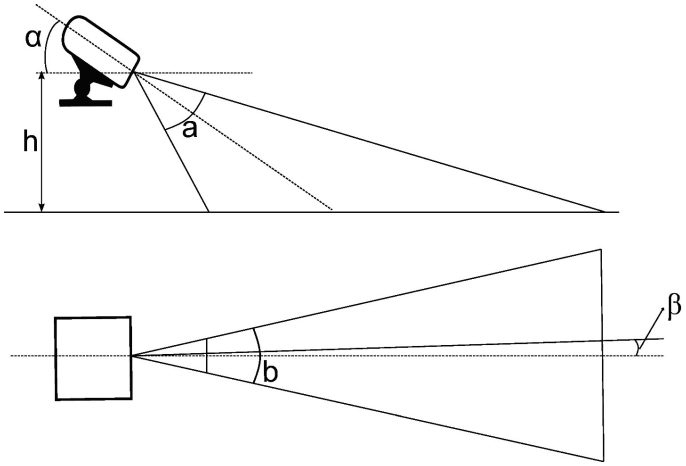

Figure 4. Camera positioning at the control area. Parameters h, α and β are maintained the same throughout the measures.

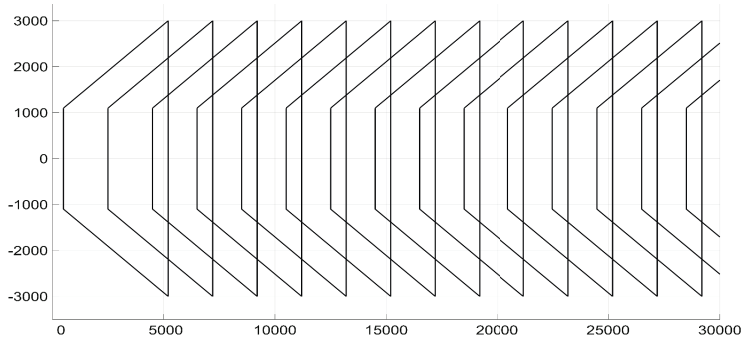

Figure 5. Data collection using the ToF camera. Data was collected every 2 metres. The black lines shows to where each data collection was conducted. Note also the compressed x-axis.

In each position, the camera was faced towards the area with a predetermined angle towards the ground to ensure that the area of measurement lies in length approximately between 0.5 metres and up to 4 metres. Parameters h, α, and β (as defined Fig. 4) were maintained as stationary as possible throughout the data captures. The main reason to have this area of measurement is the actual application where stump detection is needed. Continuous site preparation is conducted at speeds usually under 1 ms^{-1}, and the data collected is used to actuate the equipment located at the back of the forwarder. With that logic, it is possible to make data collection close to the front of the forwarder and still have time for actuation. The most time consuming mounding operation is when the mounding head is lifted to inactive state (~7 seconds, Lideskog (2013)). Since the area of measurement is located in front of the machine, there is about 10 metres at 1 ms^{-1}, i.e. 10 seconds, until the measured area reaches the actuator situated at the back of the machine. Therefore, the area of measurement can be kept close to the camera to increase the point density, however still maintaining the needed width to ensure the machine width are covered. This allows for analysis and actuation times around 10 seconds for a given measured area.

The camera resolution was 19200 coordinates (160x120 pixels in X′, Y′ and Z′) for each measurement carried out at a 30 Hz frame rate. Since the speed of the machine maximally is around 3kmh^{-1} (or 0.8 ms^{-1}), the sequence of measurements could be conducted stationary. To be able to compare with the actual stump locations the measured point cloud was transformed to the horisontal X-Y plane.

2.4 Comparison of detected and actual stumps

The comparison between detected and actual stumps' size and positions is made as the last step to validate the detection system precision. The resulting stump detection was manually overlayed onto the control area including the actual stump layout, by using the position of the camera relative to the actual orgin and the raw data point cloud. To compare positions, the euclidean distance between the actual stump centres and the point cluster centre of gravity. In addition, the position deviations are analysed by comparing the intersection between the actual stump areas and the point cluster areas. As a measure of size deviations, the point cluster area are further compared to the actual stump basal area.

3 Results

3.1 Prescribed stump detection system

Fig. 6 illustrates the stump detection process prescribed in this paper. The last step is the validation of the prescribed method.

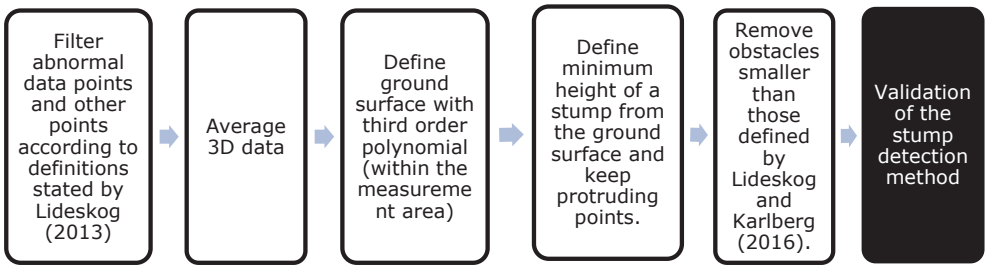

Figure 6. Stump detection system used in paper.

1. Initially abnormal data i.e. outside the measurements range and zero values are excluded. In addition, Lideskog (2013) defined the physical volume in which it is necessary to identify obstacles during mounding. This volume was used to exclude data points outside the boundaries. Finally, points floating mid-air by themselves (without proximal neighbours) are removed using sparse outlier removal (Rusu et al. 2008), as well as points outside the possible camera measurement boundaries.
2. The remaining data can then be averaged by use of several measurements within such range that measures is assumed statical. This requires fast sample times and small increments in space. In our case, no averaging was conducted.
3. Then, a third order polynomial surface was fitted on the remaining pixel data to mimic the ground surface of the terrain.
4. In the next step, the residuals in the Z (gravitational) direction were analysed. All residuals protruding less than 125 mm above the fitted surface were discarded, whereby the remaining pixels were deemed potential stumps.
5. As a stump is not considered an obstacle during site preparation, in our case continuously advancing mounders, if the diameter of the stump falls below 7 cm (Jukka Alakorpi, Bracke Forest AB, pers. comm. in 2013), this step ensured that clusters falling below this limit were disregarded. I.e., clusters further had to span at least 70mm in any direction, and thus we accepted any cluster shape.
6. The position of detected stumps where determined by deriving the center of gravity of each point cluster (See red marker in Fig. 7). In addition, to get information about the stump size, the area of each detected stump was derived through polygonisation of the outermost points of each cluster, see Fig 7.

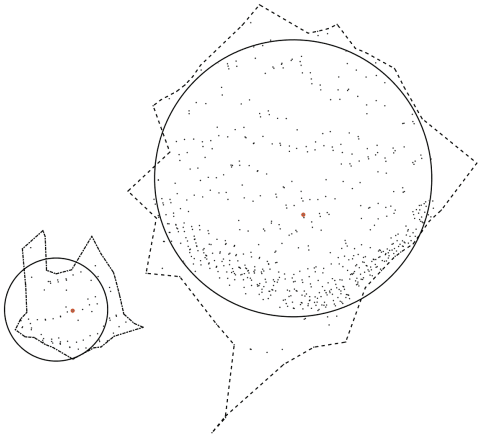

Figure 7. Identified obstacle enclosed to the right but with no overlapping area with an actual obstacle.

3.2 Validation of the stump detection system

Validation of the prescribed stump detection method was carried out as described in Section 3.1.

Fig. 8 shows one section in 3D of the control area where raw data (dark cloud points) have been overlayed with red point clusters representing possible stumps derived through the prescribed detection method. In addition, in Fig. 8 manually identified actual stumps are shown as circles labeled with numbers for identification reasons. Supplementary file 1 depicts all the stumps within the area that is deemed obstacles during site preparation (named actual stumps). The results from remaining sections of the entire control area can be found overlayed actual stumps in Supplementary file 1.

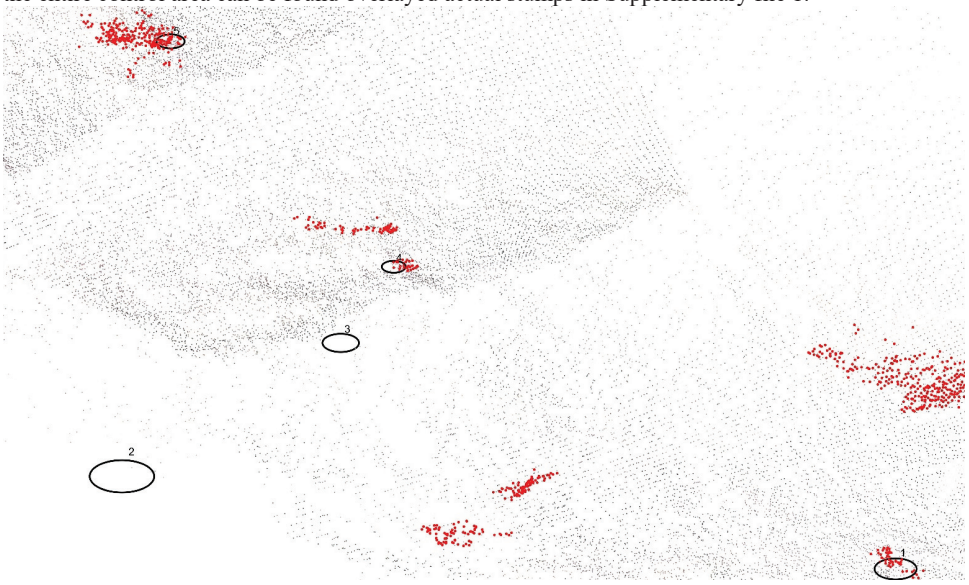

Figure 8. 3D plot of raw data points (RGB colour), numbered circles showing actual stump positions, and red points indicating where the detection algorithm has found obstacles.

In Table 1, statistics about the detection are presented in terms of stump position and area (both actual and detected). In addition, statistics about eucledian distance between actual and detected stumps centre of gravity are given as well as the ratio between number of cluster points intersecting the actual stump area and total abount of cluster points (for each detection hit). Finally, statistics about the ratio between intersection area and detection area (Fig. 7) are given where >100% means that the complete actual stump area is within the detected area.

Table 1. Comparison between actual stump positions (measured by a Faro laser scanner and manual validation) and positions derived from stump detection. Obstacle centres are calculated as the centre of mass of the point cluster that is the obstacle. Missing data is due to unsuccessful stump detection.

No.	Detected obstacle (DO) centre [mm]		DO Area [mm^2]	Actual stump (AS) centre [mm]		AS Area [mm^2]	Area difference [mm^2]	Euclidean distance [mm]	Points within stump area [%]	AS ∩ DO [%]
	X	Y		X	Y					
1	2058	615	10367	2026	555	17671	-7304	68	42	30
2	-	-	-	238	2758	41548		-	-	-
3	-	-	-	1435	3036	13273		-	-	-
4	1957	3333	3155	1915	3351	5675	-2520	45	34	22
5	2185	5199	91077	2260	5108	7854	83223	118	16	97
6	3072	5531	61432	3129	5613	11310	50122	100	7	64
7	-	-	-	2595	6194	5027		-	-	-
8	3195	6006	37012	3226	6030	6362	30650	39	24	100
9	1236	7939	26657	1244	7971	15394	11263	33	42	83
10	2750	8911	15853	2768	8981	31416	-15563	72	48	34
11	3037	9340	41103	2978	9624	101788	-60684	290	1	0
12	-	-	-	2733	10124	3848		-	-	-
13	1343	9894	27867	1231	9825	9503	18363	132	3	17
14	-	-	-	1081	10447	31416		-	-	-
15	2580	11201	63408	2618	11115	13273	50135	94	28	82
16	2191	12460	152764	2166	12460	85530	67235	25	37	81
17	2615	11551	108161	2550	11800	85530	22631	257	9	3
18	-	-	-	1308	13019	25447		-	-	-
19	-	-	-	2922	15662	45239		-	-	-
20	625	14948	73299	578	15021	49087	24211	87	23	44
21	-	-	-	3095	16001	13273		-	-	-
22	-	-	-	3985	16127	20106		-	-	-
23	-	-	-	27	19856	41548		-	-	-
24	1219	19838	21327	1193	19839	20106	1221	26	65	75
25	1575	19990	182962	1559	20046	145220	37742	59	87	98
26	-	-	-	212	21933	25447		-	-	-
27	-4	22791	21243	31	22700	7854	13389	97	10	31
28	-	-	-	2129	20994	13273		-	-	-
29	-	-	-	3268	21611	20106		-	-	-
30	2742	22755	52951	2744	22608	53093	-142	147	42	25
31	1796	23760	24083	1833	23700	1963	22119	71	1	1
32	1402	26024	145847	1381	26075	125664	20184	56	79	90
33	-	-	-	213	27695	11310		-	-	-
34	1228	27862	70371	1322	27922	7854	62517	111	7	98
35	1720	29707	296942	1784	29678	138544	158398	71	54	85
					Average:		50900 (RMS)	95	31	55

3.3 Detection method accuracy

The statistics of correctly detected stumps have been assessed and are given in Table 1. Incorrectly detected obstacle clusters were not included, but are discussed in coming sections. Errors in detection can be categorized as “misses” when an actual stump exists at a location, but no stump was detected. The other category is false detection, where the algorithm has detected an imaginary stump.

3.3.1 Analysis of detection misses

Due to the camera inclination and angle, the point cloud density are not the same on different distances from the camera. As an example, circle no. 2 in Fig. 8 encompasses only a few data points resulting in missed target. Moreover, the Fig. 8 shows the stump no. 3 is also being missed because of low point density near the boundary between two different data acquisition sequences.

As the distance between camera and measured ground increase, the precision of the camera decreases. Simultaneously, the point density gets lower. This is a major reason for detection errors. Moreover, the detection algorithm does not distinguish between shrubbery and protruding branches that together constitute a delimited space (or cluster) from actual stumps.

Another encountered issue resulting in detection errors is the vegetation that sometimes blend into surrounding data points, making it difficult to distinguish from the ground itself, as depicted in the red circle in Fig. 9. The point cloud is constituted by the top most points since vegetation obstructs the IR light to scatter on the underlying ground surface. Hence, part of the vegetation will affect the fitted surface representing the ground level in an incorrect way. In extreme cases, vegetation raises the fitted surface and negates the difference between stump and vegetation, thereby limiting the detection.

Figure 9. Stump surrounded by protruding vegetation that inhibits the detection to work properly.

3.3.2 Analysis of false detection

The algorithm sometimes detects imaginary stumps (constituting a number of clustered pixels) i.e. false detection. Reasons for this include camera noise that increases further away from the camera when data is sparse, increasing the amount of protruding pixels as the variance in Z direction increases. In addition, branches or weeds may prevent IR light to find its way to the actual ground surface, causing pixels to appear higher than they really are. If this event occurs at distances far from the camera, the risk of false hit increases due to the increase in noise.

Some of the false detection refers to obstacles other than stumps. In one case a protruding boulder was detected, however fully overgrown by shrubs, see Fig. 10. In another case a false hit constituted a small pile of slash. Both of these false detection can however be viewed as positive false hits, since such obstacles also should be avoided during continuous mounding (or different actions should be taken). However, these positive false hits were not included in Table 1.

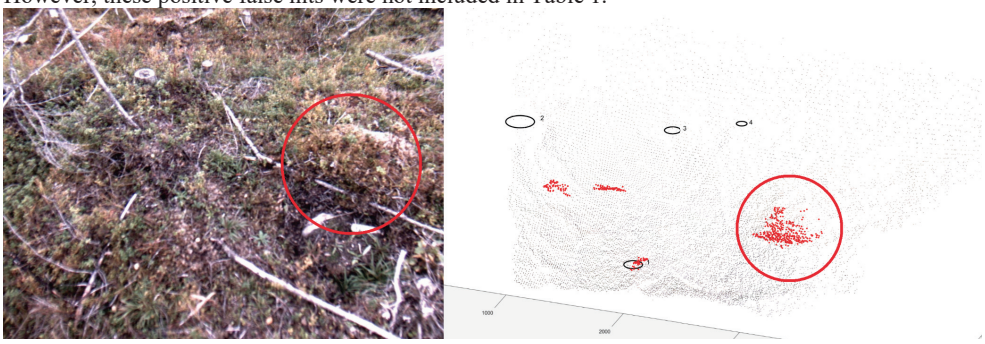

Figure 10. False hit (red circle) where the hit constitutes a protruding stone, fully overgrown by vegetation.

4 Discussion and conclusions

In this paper, a novel system for stump detection have been proposed and validated. The results show that 42 % of all stumps in the control area were correctly detected. In addition, 23 nonexisting stumps were erroneously detected (sometimes still representing obstacles though). The average distance between the actual stump centre position and the detected clustre mass centre was 95 mm (min 26 mm, max 290 mm). Hence, the actual stump centre may be located within a circular area of radius 95 mm centred at the detection centre. An other measure of the detection position accuracy is the intersection between the point clusters and the actual stump areas. The results show that in average 31 % of the cluster poins intersect or 55 % if the cluster area is considered. The system performance further depends on stump detection size. In average, the presented stump detection system deviated with 50900 mm^2 (RMS) compared to the actual area.

If a detected cluster area is large relative to the actual stump area, the probability of an intersection increase. The shape of the cluster may also be skewed which further affects the intersection. Therefore, the quality of the detection depends not only on position and size but also on shape.

There exist several sources of errors in the validation process of the stump detection method including:

1. Manual mapping was conducted to position detected clusters to the actual coordinate system correctly. This positioning may have been inaccurate when
2. Naturally, the control area was not entirely planar, meaning that some deviation occurred when the positions were projected onto a 2D plane at Z=0.
3. The Faro scanner had an built in accuracy of ±2 mm, which in this context is acceptable. (Appointing a mound position would probably need a ±100 mm accuracy). The points encompassing the stumps' planar tops were used to approximate a circle where the circle centre was set as the stump centre position; this method added to the error with approximately ±10 mm.

4. Clustering of the points that encompass the detected stump, as well as deciding which cluster pertained to what actual stump position, were conducted manually thereby plossibly introducing some subjectivity.
5. Points pertaining to a detected cluster for a certain stump has a point density that is reduced with distance from the camera. Therefore, the centre of mass derived from the locations of all points in the cluster have a slight skew towards the front of the stump.

When performing continuous autonomous mounding, which is the primary target for the proposed system, knowledge about position and size is critical causing the machine to hit the stump or generate a bad mound. By taking the known errors of position and size into account, an allowed area can be generated in which the mounder can operate. The accuracy demands hence increases with amount of obstacles on the clearcut (i.e. to have a sufficient mounding area left). It can be concluded that the system has the potential to detect stumps at clearcuts, although more research is needed to increase the hit ratio and decrease the errors. Furthermore, if the system is implemented while mounding continuously, the mounding productivity could increase significantly, but further research is needed to derive the best way to actuate the machine given the new circumstances.

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Supplementary File 1

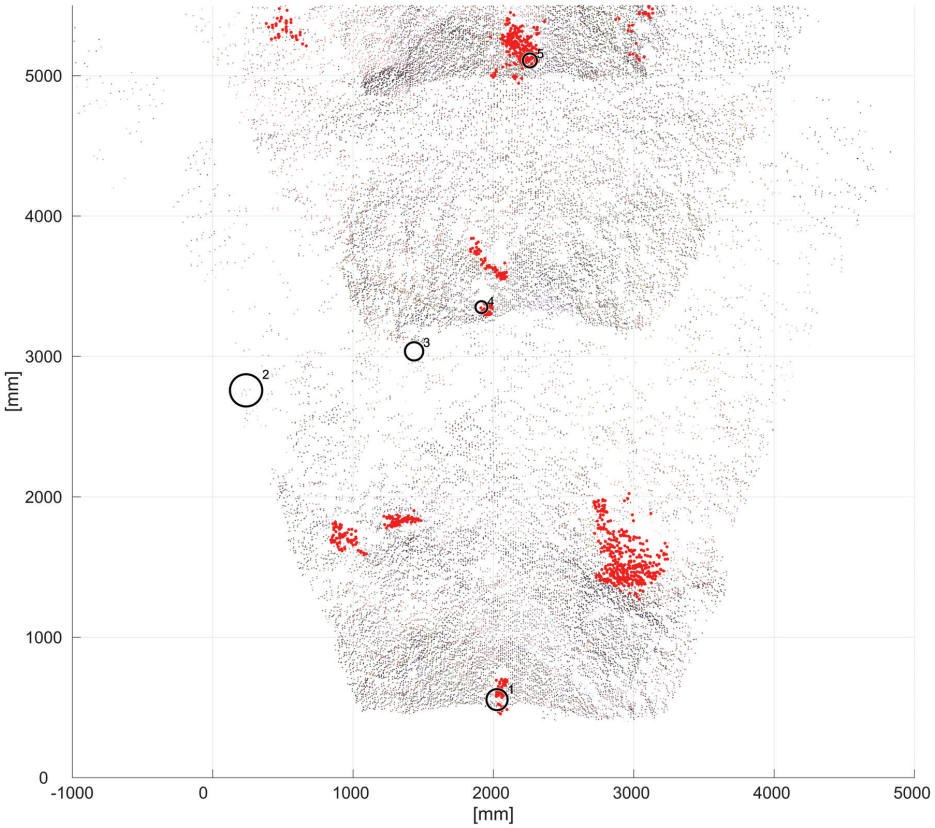

Figure 1. Section of control area from 0 - 5500 mm where raw data (dark cloud points) have been overlayed with red point clusters representing possible stumps derived through the prescribed detection method. Manually identified actual stumps are shown as black circles labeled with numbers.

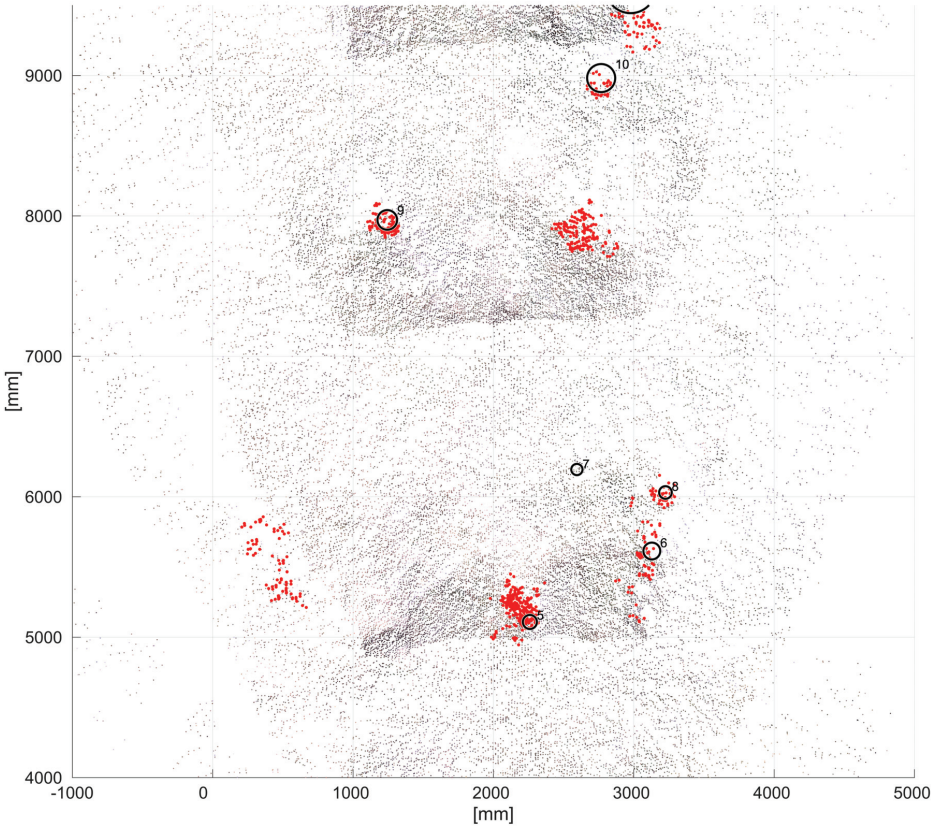

Figure 2. Section of control area from 4000 - 9500 mm where raw data (dark cloud points) have been overlayed with red point clusters representing possible stumps derived through the prescribed detection method. Manually identified actual stumps are shown as black circles labeled with numbers.

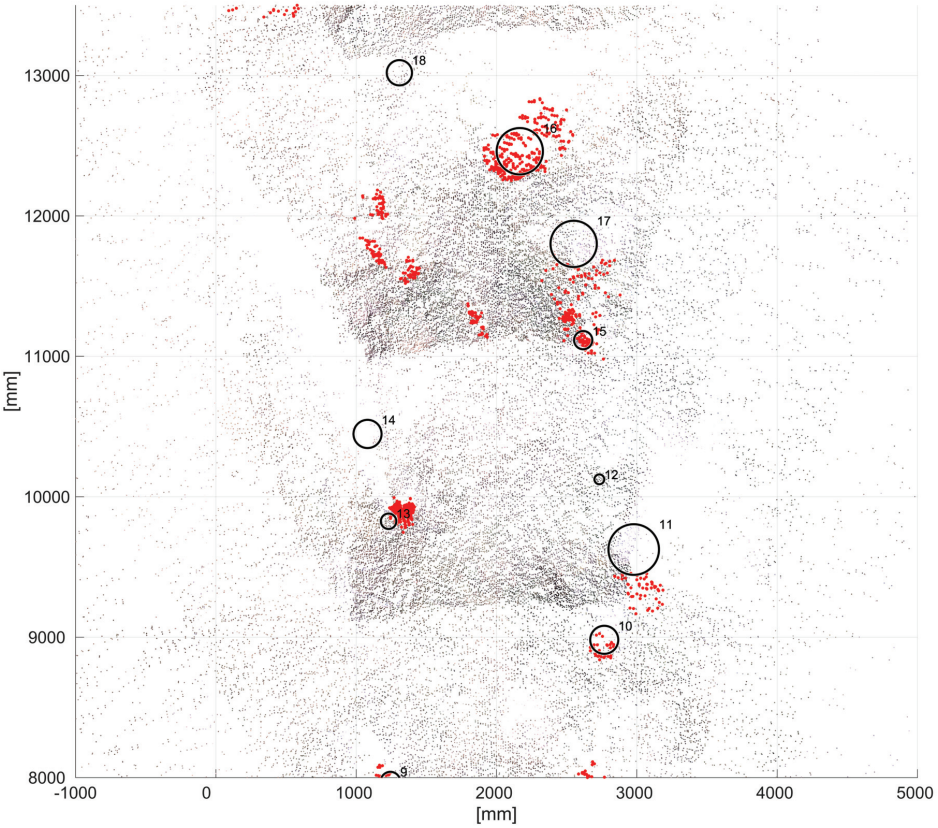

Figure 3. Section of control area from 8000 - 13500 mm where raw data (dark cloud points) have been overlayed with red point clusters representing possible stumps derived through the prescribed detection method. Manually identified actual stumps are shown as black circles labeled with numbers.

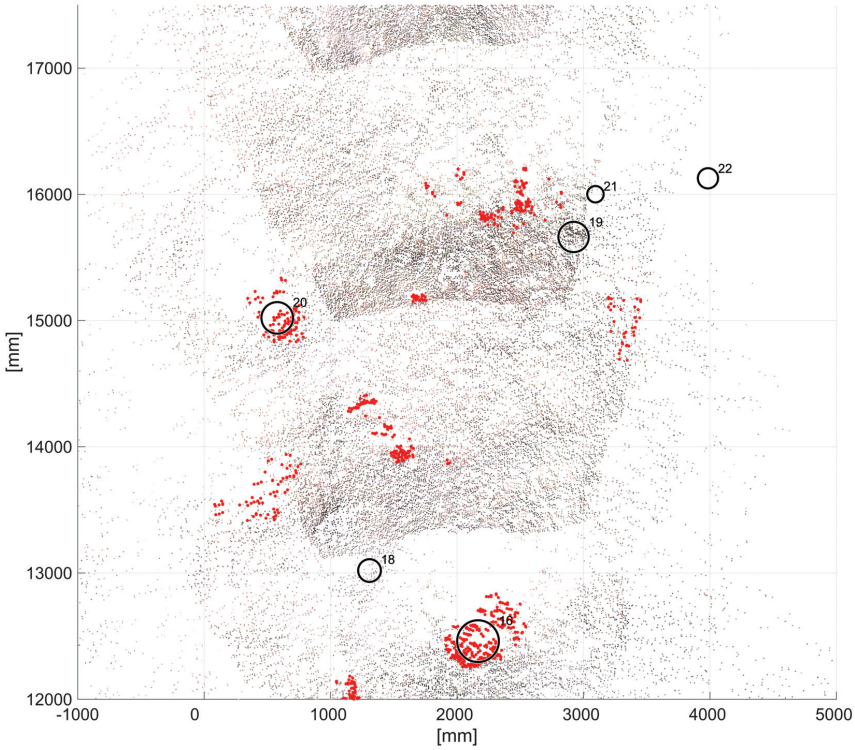

Figure 4. Section of control area from 12000 - 17500 mm where raw data (dark cloud points) have been overlayed with red point clusters representing possible stumps derived through the prescribed detection method. Manually identified actual stumps are shown as black circles labeled with numbers.

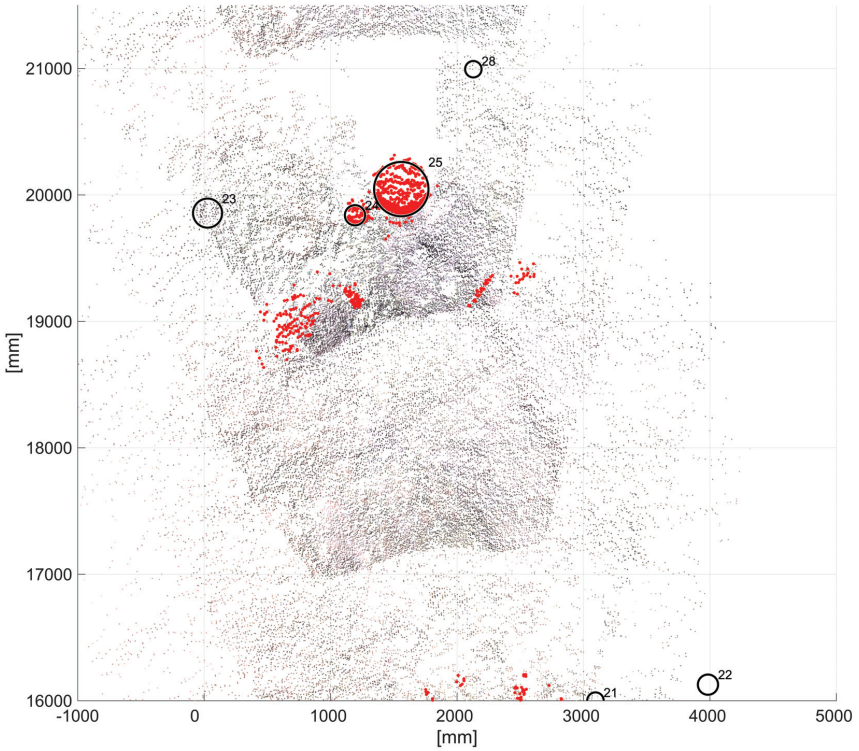

Figure 5. Section of control area from 16000 - 21500 mm where raw data (dark cloud points) have been overlayed with red point clusters representing possible stumps derived through the prescribed detection method. Manually identified actual stumps are shown as black circles labeled with numbers.

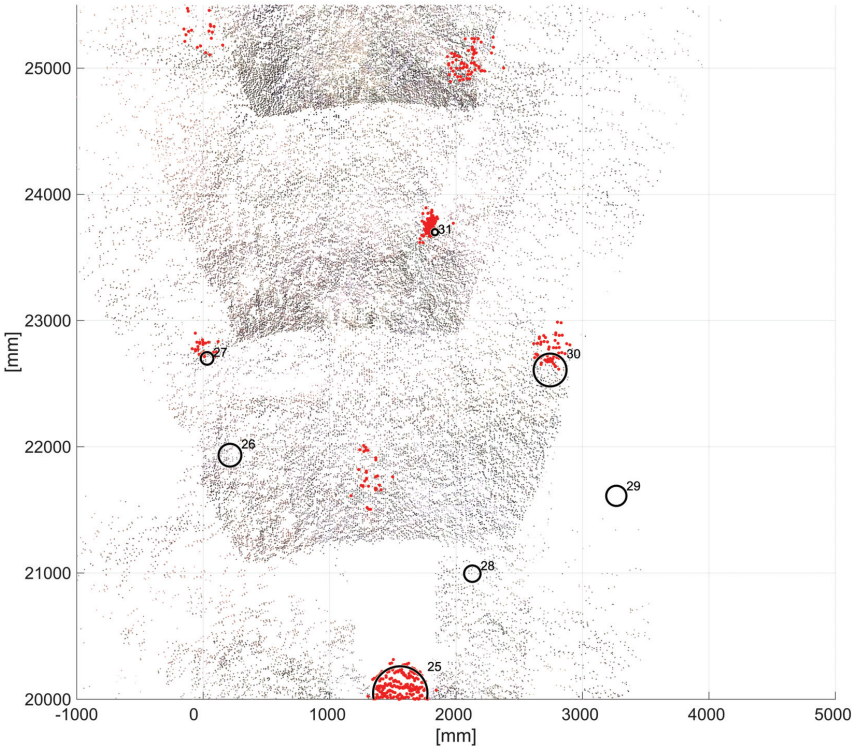

Figure 6. Section of control area from 20000 - 25500 mm where raw data (dark cloud points) have been overlayed with red point clusters representing possible stumps derived through the prescribed detection method. Manually identified actual stumps are shown as black circles labeled with numbers.

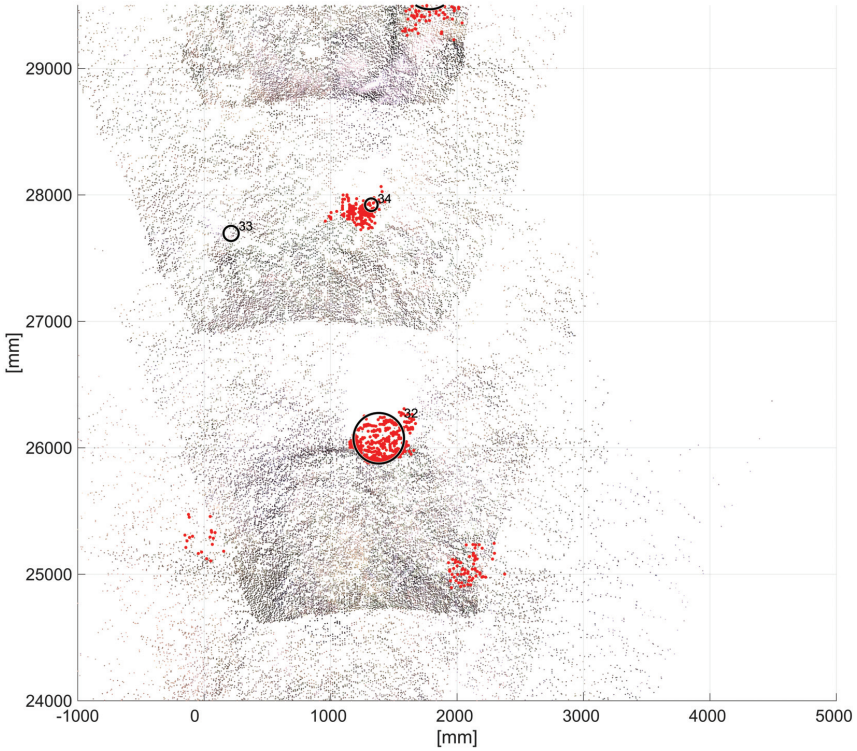

Figure 7. Section of control area from 24000 - 29500 mm where raw data (dark cloud points) have been overlayed with red point clusters representing possible stumps derived through the prescribed detection method. Manually identified actual stumps are shown as black circles labeled with numbers.

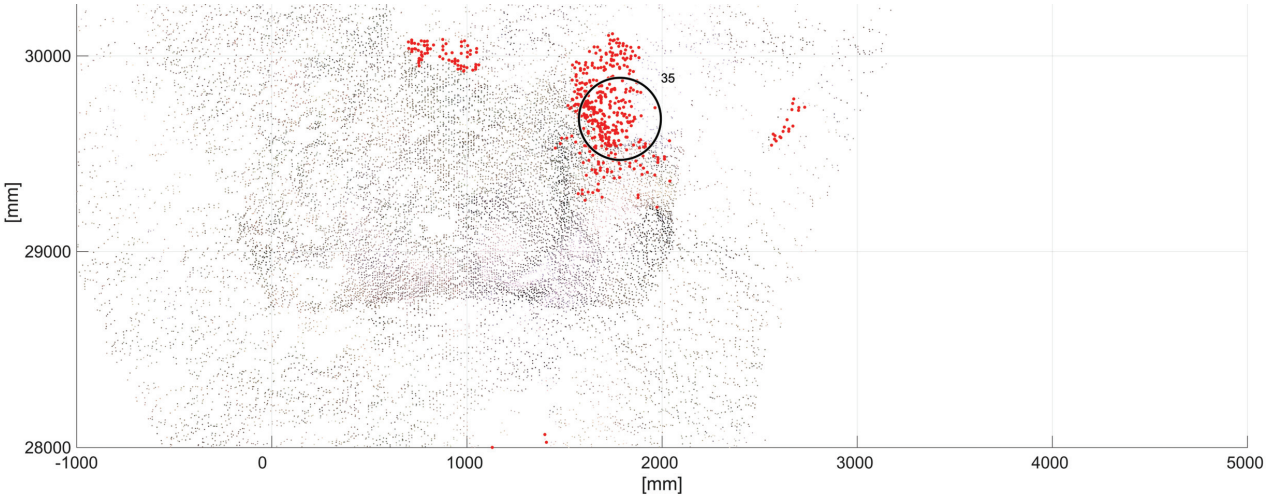

Figure 8. Section of control area from 28000-30500 mm where raw data (dark cloud points) have been overlayed with red point clusters representing possible stumps derived through the prescribed detection method. Manually identified actual stumps are shown as black circles labeled with numbers.

Supplementary File 2

Data sheet for Time-of-Flight camera Fotonic E70p. Source: www.fotonic.com

Parameters	Values	Parameters	Values
Sensor		**Absolute accuracy**	
Type of sensor	CCD	0.3 - 2 m	+/- 10 mm
Maximum frame rate	58 fps	2 - 3 m	+/- 20 mm
Total capture time	Approx. 7 ms	3 - 7 m	+/- 30 mm
Pixel array size	160 (h) x 120 (v)		
External light disturbance	Up to 100 kLux	**Repeatability (1σ)**	
		0.3 - 2 m	7 mm
Illumination		2 - 3 m	10 mm
Power out	16W	3 - 5 m	20 mm
Wavelength	850nm	5 - 7 m	30 mm
Modulation frequency	15 MHz		
		Relative accuracy at 0.4 m	+/- 10 mm
Optics			
Field of view (h) x (v)	70° x 53°	Drift with temperature, T	
Measurement range	0.5 - 10 m	20°C ≤ T ≤ 30°C	≤ 0.5 mm/°C (max)
		10°C ≤ T ≤ 50°C	≤ 1.5 mm/°C (max)
Hardware			
CPU	1.5 GHz Dualcore ARM Cortex-A9	**Data output**	
Memory	512 MB 400 MHz LPDDR2	Distance data resolution	16 bit / pixel
OS	Linux	Signal amplitude resolution	10 bit / pixel
Storage	1500 MB		

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Development of a research vehicle platform to improve productivity and value-extraction in forestry

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Abstract

In spite of the high level of mechanization in most forestry operations there is a continued need for improvements in productivity and cost effectiveness. Automation of mechanised operations is one possible solution to achieve such improvements but new techniques that can acquire information from the surroundings and make proper analyses rendering in streamlined or new work procedures are prerequisites. Furthermore, product producers buying forest biomaterials often have certain quality wishes. As an addition to automatic work procedures, new technology can further be used to retrieve information for identification and selection of certain tree assortments with different biomaterial properties. In this way, performance-based delivery of tree biomaterial extracted with highly automated work procedures has the possibility to be an enabler to continue the productivity development progress in the forest sector. The objective for this paper is therefore to summarize possible technical needs for and to design an experimental terrain vehicle platform for researchers and machine developers to test and validate new solutions that could improve cost effectiveness in forestry. The platform is designed specifically to test and validate various control systems for autonomy and robotics and also to enable tests and validation of attachments, e.g. to enable better planting procedures or identification of trees with certain properties. Sensors are embedded in the platform to register angles, rotation speed, etc., thus actualising machine automation as an enabler for performance-based delivery of planting or of tree biomaterial assortments.

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Keywords: autonomy; automation; forestry; performance-based contract; Functional Products

1. Introduction

The development of forestry machines in Sweden in the middle of the 1950s gradually replaced most of the previous manual work force. During the years machines have increased the productivity through different breakthroughs in technology development; a never-ending struggle to overcome the difficulties caused by unstructured, harsh terrain and unreliable weather conditions. Today, however, the productivity increase of forestry machinery has halted, resulting in needs for new solutions. The reasons for this productivity stall depend mainly on factors described in the following sections.

1.1. Needed increase of automated and mechanical processes

Different machine types traffic forest terrain for various purposes. Forwarders and harvesters conduct commercial thinning and final felling while utilising mechanical processes. Other activities on forest land occur after final felling, including mechanical stump removal [1], site preparation for subsequent manual planting [2] and mechanized tree planting [3]. One challenging problem regards the ground damage caused by forestry machines [4]. For this reason, different techniques have been introduced to prevent soil rutting and compaction [5, 6]. In addition to terrain accessibility issues, some objects, e.g. stones, stumps and slash residues, can become obstacles preventing machine activities from being optimally conducted, whereas for other activities, objects are needed to be found and

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targeted, e.g. standing trees or stumps. Solutions for object identification are yet to be utilised in forestry. In fact, Vestlund and Hellström [7] identified obstacle avoidance and target identification as the most difficult problems to address when autonomous operations in forestry are concerned.

Rantala et al. [8] claim that innovations in communication and sensor technology could offer solutions in mechanized planting that would increase the degree of automation, although requiring more investments that would lead to higher prices and operating costs. One way of keeping the investment costs down when innovations are developed, is to utilise existing technology. In silviculture the field of automation has been poorly explored [9]. Still, Kemppainen and Visala [10] found that stereo vision to some extent could be utilised to automatically find tree planting spots after forwarder based continuous mounding, while Lideskog et al. [11] presented a technique for obstacle identification during mounding with focus on stump identification. As a step towards obstacle identification, research in the area of efficient timber procurement started in Sweden 2002 where a long-term vision was to develop an unmanned vehicle that could transport timber from the felling area to the roadside while actively locating and avoiding obstacles in its path [12]. Research is ongoing, but have not shown any major breakthroughs yet regarding economic, social and ecological advantages.

1.2. Whole value-chain efficiency

Tree biomass is very heterogeneous in properties; some trees or some tree parts have certain properties that are more advantageous in some industries than others. During paper manufacturing, for example, wood fibre properties are important, while high E-modulus and density are decisive when making some solid wood products and high content of extractives could be very important if chemicals are to be utilised [13-15]. Therefore, the biomaterial assortments in our forests could be sorted early in the value-chain to be used as cost-efficiently as possible with high valorisation. In addition, if certain tree biomaterial assortments are sought for, the forest regeneration can be deliberately steered towards creating such assortments. With this in mind, performance-based contracts could be utilized to address a higher-level customer need. Such contracts will hence enable customers and providers to co-create values [16]. Usually the contracts are used for lease of high tech, complex hardware that delivers a function to its customers [17]. Lideskog et al. [18] stated challenges and opportunities for a kind of performance-based concept before it could be implemented in forestry. They highlighted e.g. the need for a higher degree of mechanisation to allow for an easier risk calculation, as well as various possible scenarios that need to be processed in the contract.

1.3. Lack of technology development incentives

A problem in the forest sector is the lack of incentives for technology development. A few thousands of harvesters and forwarders are sold globally each year, while e.g. the car industry sells millions. Therefore, companies usually lack the funding to start and finalize large endeavours such as automating some of the now manually operated functions of a forest machine, or mechanisation of manual work. Companies rather rely on old, well-recognised technology which may be ineffectual and hence unnecessarily costly, although being robust.

1.4. Objective

The solution in forest sector of stated issues may not primarily be to increase the sale of machines, but to increase the quality of the biomaterials extracted from the forests via performance-based contracts. To sell a performance-based contract, it is imperative that you know the level of performance. Thus, this platform would act as an incentive for companies to invest in mechanisation and automation technology. For these stated reasons, academia and forestry technology companies have decided to collaboratively find a way to develop methods, tools and systems to overcome the stated challenges. Collaboration between academia and forestry companies in Sweden is already initiated [11], where the need for an optimized platform for systems and technology development have been identified.

Hence, the objective for this paper is to present the design development of an experimental terrain vehicle platform and to show possible test applications for which it subsequently can be used. The vehicle should act as a mobile platform for researchers and machine developers to come together to test, validate and verify new forestry equipment designs (for tree planting, harvesting etc.) and control systems in vivo as a mechanisation and automation enabler.

2. Method and Materials

The design development of the research vehicle platform followed Ulrich and Eppinger's [19] process for product development.

Before the start of concept development, customer needs were thoroughly investigated to decide how the product eventually should be designed to meet the needs. In this case, the customers were actors in academia as well as forestry companies. Therefore, workshops and separate interviews were conducted with people from different disciplines with interest in the experimental terrain vehicle platform. The involved people were:

- six people from academia with backgrounds in mechanical engineering, forest biomaterials and technology and control systems and robotics, and
- four people from forestry technology companies focused on forestry machines, timber cranes and other forestry equipment and vehicle add-ons.

The outcome from these interviews and workshops were analysed and formed into customer requirements which, beside information from the benchmarking and related technology phases, resulted in a requirement specification forming the basis for all the demands set on the product. When the basis of the product's specifics had been generated, the next phase involved development of concepts. Through an iterative

process basic sub-functions of the experimental terrain vehicle's constituent parts were developed, followed by more specific design parameters: The iterative process involved concept generation, where many different concepts were developed, who all satisfied the requirement specification.

Afterwards, various sorts of evaluations were conducted on some plausible concepts to e.g. test and improve strength and durability, traction power, movement speed and accuracy, weight, etc. When main geometric descriptions existed, the most promising design (fulfilling the requirement specification) proceeded to the detail design where in-depth investigations were conducted on the design and ending with finalized drawings and computer models describing the geometry and manufacturing of each component. The manufacturing of the experimental terrain vehicle developed during this project is yet to be finalized, which means that the testing and refinement phase from Ulrich and Eppinger [19] remains. In addition, the phase involving production ramp-up is excluded since the vehicle will not serve as a commercial product.

3. Results

3.1. Requirement specification

As an output from the investigations of needs, related technology and benchmarking, a requirement specification was created. A summarised version is presented in Table 1. The requirement specification summarises the needs from the stakeholders, and was used as basis during concept development. An important observation from the needfinding was the difficulty to identify which tests that will be performed on the experimental terrain vehicle. Therefore, the requirement specification was composed to secure a robust design, which enabled a lot of test opportunities in several different areas of forestry, where the machines are located at terrain sites.

Table 1. Excerpt from the requirement specification.

Category	Requirement description	Target Value	Priority
Transporting	Able to be transported on public roads	2,6 m wide	Demand
		24 m long	
	Able to be transported on trucks hook lift	2.6 m wide, 6 m lon	Desire
Capacity	Maximum operating cost	900 SEK/h	Desire
	Minimum driving speed while planting	1 km/h	Desire
		0.6 km/h	Demand
	Able to level the chassis while planting in normal conditions	Within 5°	Desire
		Within 10°	Demand
	Able to level the chassis while planting in extreme conditions	Within 15°	Desire
		Within 20°	Demand
	Minimum fuel capacity	8 hours of operation	Demand
		10 hours of operation	Desire
	Lowest top speed at base road transportation	5 km/h	Desire
Other equipment	Designed to allow room for enough plants.	1800 plants	Demand
		3600 plants	Desire
	Compatible interface for external devices	-	Demand
	Designed for three planting arms	-	Demand
	Compatible interface for controller	CAN-bus	Demand
	Withstand loads from external equipment	20 kN	Demand
Terrain	Ground condition	Class 4	Demand
		Class 5	Desire
	Surface structure height class	Class 3	Demand
		Class 4	Desire
	Slope	Class 3	Demand
		Class 5	Desire

3.2. Research vehicle platform design

After the requirement specification was finalized, the process continued to the concept generation phase, in which numerous concepts were developed. Concepts are descriptions of solutions that plausibly meet the requirement specification (and thereby satisfies the customer needs), usually expressed as sketches or a rough 3D models [19]. After this phase, some concepts were chosen for virtual testing aiming at selection of, among the concepts, the most suitable solution. This final solution, a fully functional machine made for various research evaluations, is shown in Fig. 1. Through the iterative development process, the research vehicle platform shown in Fig. 1 was developed. The final assembly of the experimental terrain vehicle included a rear platform for mounting external equipment with the engine and hydraulics in the front section. The pendulum arms are here positioned at a medium height which means that the machine can be both lowered and raised. The machine is powered by a diesel engine which in turn drives hydraulic pumps and motors. Four pendulum arms (Fig. 2) with radial wheels at the ends and separate hydraulic drives on each wheel constitute the solution for forward drive, maximizing the machine's terrain accessibility.

Each pendulum arm can be controlled individually, and the radial wheel can be replaced with other concepts to evaluate different solutions for the machine's forward drive. The vehicle have an articulated joint for better terrain accessibility and agility. The articulated joint now utilises one degree of freedom (dof), but one more can be added if needed in the future by replacing rigid beams with hydraulic ones (while adding further control).

An important design to allow for imitation of different vehicles and good terrain accessibility is the pendulum arms (Fig. 2). The hydraulic motor (1) is bolted to the arm where covers (2) exist to allow for access to the inside of the arm. A protection plate (3) is mounted to avoid external forces to damage the hydraulic brake line underneath. The pin (4) for the hydraulic cylinder in inserted into the bushings of the cylinder mount and the pin is locked into place on the other side of the arm. Bronze plain bearings (5) are used to decrease the wear and simplify mounting of the pendulum arm to the chassis.

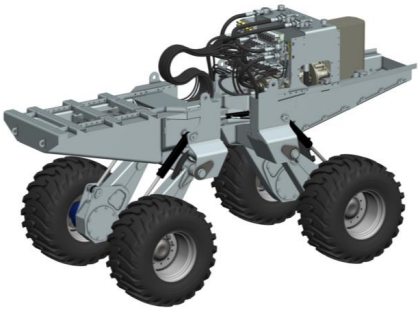

Fig. 1. The final research vehicle platform.

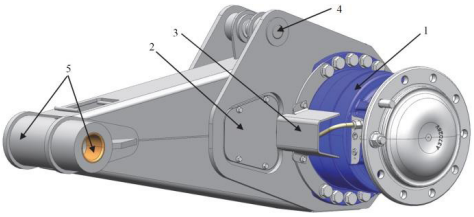

Fig. 2. Pendulum arm of the research vehicle platform.

The drivetrain of the research vehicle platform (Fig. 3) constitute a 129 kW diesel engine (1) which drives three hydraulic pumps in series (2), (5) and (6). The first (2) is the primary pump for driving the four hydraulic hub motors (4) with individual control from the hydraulic valves (3). The second hydraulic pump (5) drives the movement of the pendulum arms (individually) and the articulated joint, as well as any external equipment. The third hydraulic pump (6) is in a smaller with the purpose of moving oil to the cooler. All pumps are coupled in series. The properties of the research vehicle platform (Table 2) was derived from each component performance, such as engine power, dynamics investigations, inertia in the hydraulics, etc. To enable machine automation, sensors are needed to keep track of certain variables. For this research vehicle platform, the following variables are measured:

- The angle of the articulated joint (1 dof).
- Each pendulum arm angle to a horizontal reference (1 dof x4).
- The 3D position and velocity of the mounting platform for external equipment in relation to the gravitational vector (roll, pitch and yaw at 400 Hz sampling rate).
- GPS position.
- The pressure exerted on the primary hydraulics from the wheel in contact with the ground (for each wheel).
- Rotational speed and direction of each individual hub motor (3600 pulses/revolution).
- Hydraulic brakes on or off.

Gear in position 1 or 2 (low speeds in terrain or high speeds for road travel).

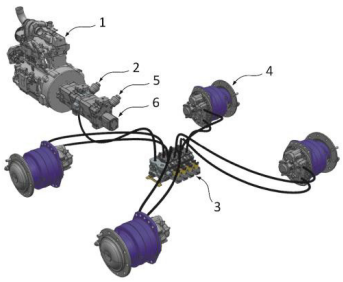

Fig. 3. Drivetrain of the research vehicle platform.

Table 2. Performance of the research vehicle platform (a selection).

Property	Value
Ground Clearance [mm]	188 - 1253
Width x Length [mm]	2343 x 5115
Platform Height Max - Min [mm]	1025 - 2090
Primary / Secondary Hydraulics Performance [bar]	330 / 250
Space For External Equipment [mm]	1022 x 2001
Traction force per wheel [kN]	0 - 16.5
Power [kW]	129
Speed [m/s]	0 - 3.9
Dry weight [kg]	5000

The properties of the research vehicle platform (Table 2) was derived from each component performance, such as engine power, dynamics investigations, inertia in the hydraulics, etc.

The vehicle enables possibilities for many validation, verification and testing activities. It is highly modular at a sub-function level to enable easy switch between e.g. different suspension solutions, regular or hybrid drivelines, or different amounts of planting arms. The main focus of the resulting terrain vehicle is its performance in-field in accurate terrain situations that today's forestry machines encounter. The vehicle could be used in several context to assess the applicability of systems, methods and tools within e.g. forest regeneration, forest management and afforestation as shown in Table 3.

4. Discussion & Conclusions

The resulting design of the research vehicle platform will provide possibilities for testing, verification and validation of different solutions, e.g. contact organs, control systems, methods, ideas etc. The research vehicle platform design allows for components to be exchanged. For example, the diesel engine mounted today is now chosen for the usage as an experimental vehicle, rather than as a commercialised one. Therefore, if this vehicle is to be commercialised, other drive systems may be considered to allow for e.g. better fuel efficiency and a lower environmental impact. As another example, the rubber wheels mounted on hydraulic motors can be removed and replaced with other more advanced contact organs to test terrain characteristics of different solutions. Too many hydraulically actuated of driven components will only result in overly complicated control systems. This might also include power limitations from the engine if the contact organs and other components become unnecessarily advanced.

Successfully developed systems, methods or tools that enable some of the listed areas in Table 3 will enable feedback to be sent between the different areas in the value-chain, both backwards and forwards since the value-chain actually are circular. For example, harvested trees can be given a coordinate whereby such information can be used for tree stump removal or obstacle avoidance during mechanized planting or site preparation in later stages.

In terms of the biomaterial performance, several properties could be measured and the information be used to sort the biomaterial early and to send it to correct facilities, for example by measuring e.g. moisture content, density, knots presence or mechanical capacity and use as decision support [20]. Better sorting in the first step of refinement may further add value to subsequent residues from e.g. paper pulp processes where sludge can be used to create nanocellulose [21]. The performance of the biomaterial can be measured by using several different techniques. It is however the end-customers that know what add value (performance) to the delivered goods, whether it is low amounts of knots, high density or high mechanical capacity. Thus, it is the customers that know what the machine should be capable of measure to sort out the correct biomaterial performance. Therefore, the customers need to assist in the decision making when designing a commercialized vehicle that have the capability to perform autonomous tasks and enhanced sorting i.e. value co-creation. In future steps, customers working with wood refining should therefore be aiding in co-constructing the machine design and the complex design of a performance based contract [16]. Lideskog et al. [18] suggest Functional Products as a suitable business model in forestry where the complexity of supplier-customer business relations are addressed [22]. Lindström et al. [22] stress the importance of trust between the involved parties, the involvement and commitment of the customer in the service provision.

In conclusion, Table 3 exemplifies some of the areas in forestry in which the research vehicle platform can be used as means to verify (meets design specifications?), validate (meets stakeholder needs?) and test (evaluate) various tools, methods and systems. These solutions will be enablers for sustainable development through performance-based contracts having less environmental impact and higher social acceptance. All value-chain phases in Table 3 need to be addressed when providing performance of the biomaterial as the end product, since the phases are circularly dependent of each other.

Table 3. Verification, validation and testing possibilities for the research vehicle platform in forestry (as exemplified in a Swedish forest management model).

Address value-chain dependencies during performance-based contracts →					
(Seed and seedling procurement)	Forest regeneration	Forest management	Afforestation	(Transportation from forest)	(Wood processing)
	Site preparation* Planting* Direct seeding**	Pre-commercial thinning* Commercial thinning**	Harvesting** Forwarding** Other machine tasks**		

* = Manual work is dominating
** = Machines are mainly used

1. Increase automation degree
   a. Test algorithms and control systems with existing products and components (e.g. more effective movement of existing crane or machine)
   b. Test algorithms and control systems with new products and components (e.g. machine vision + new work procedures of streamlined components)
   c. "Superhuman" sensors, beyond human sensing
2. Increase mechanisation degree
   a. Test new products and components
3. Increase biomaterial quality through automation
   a. "Superhuman" sensors, beyond human sensing
4. Validate simulations
   a. Go from computer to reality to test control systems, methods and systematic changes

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