Lappeenranta University of Technology
School of Business and Management
Degree Program in Computer Science

Jere Kaplas

Review of Automation and Remote Control Technologies for Forest Industries

Examiners: Associate Professor Jouni Ikonen
D.Sc. (Tech) Ari Happonen

Supervisors: Associate Professor Jouni Ikonen
D.Sc. (Tech) Ari Happonen

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
School of Business and Management
Tietotekniikan koulutusohjelma

Jere Kaplas

Katsaus Automaatio- ja Etäohjausteknologioiden Soveltamisesta Metsäteollisuudessa
Diplomityö

2017

87 sivua, 10 kuvaa, 12 taulukkoa

Työn tarkastajat: Dosentti Jouni Ikonen
TkT. Ari Happonen

Hakusanat: automaatio, etäohjaus, raskaat koneet, materiaalin käsittely, sensoriteknologia, kirjallisuuskatsaus, metsäteollisuus, terminaali
Keywords: automation, remote control, teleoperation, heavy machinery, sensor technology, material handling, review, survey, forest industries, terminal

Tämä työ tarjoaa kirjallisuuskatsauksen automaatio- ja etäohjausteknologioiden soveltamisessa metsäteollisuudessa, tarkastelemalla muiden alojen teollisuuksia. Työssä käsitellään automaatio ja etäohjaus teknologioiden mahdollisuuksia, rajoitteita ja haasteita puuteollisuudessa. Tulokset käsittelevät sensoriteknologioita, etäohjausta, sekä erilaisia valvonta- ja ohjausjärjestelmiä, jotka ovat osa automaatiojärjestelmiä, sekä näiden järjestelmien välistä kommunikointia. Automaatiotehtävien haastavuus riippuu tehtävän vaatimuksista, mutta usein on olemassa monia erilaisia teknologia ja anturi vaihtoehtoja. Useasti toistuvat tehtävät sopivat parhaiten automaatioon. Automaatiohankkeet ovat tavallisesti inkrementaalista kehitystä, osittaisesta automaatiosta täyteen autonomiaan.

ABSTRACT

Lappeenranta University of Technology
School of Business and Management
Degree Program in Computer Science

Jere Kaplas

Review of Automation and Remote Control Technologies for Forest Industries

Master's Thesis

87 pages, 10 figures, 12 tables

Examiners: Associate Professor Jouni Ikonen
D.Sc. (Tech) Ari Happonen

Keywords: automation, remote control, teleoperation, heavy machinery, sensor technology, material handling, review, survey, forest industries, terminal

This work provides a literature review on automation and teleoperation technologies for the forest industries by reviewing the possibilities, challenges and feasibility of automation and teleoperation technologies found in other similar industries. The results deal with sensor technologies, teleoperation, and different control and management sub systems that are a part of automation systems, as well as the communication between those systems. There are many different technologies and sensors to facilitate the automation tasks, depending on the requirements of the tasks. Repetitive tasks are best suited for automation first. Automation projects are usually gradual, incremental development from partial automation to full autonomy.

ACKNOWLEDGEMENTS

I would like to thank first and foremost my employers for enabling me and giving me the chance to do this research. Secondly, I'd like to thank the instructors, Associate Professor Jouni Ikonen and D.Sc. (Tech) Ari Happonen for their invaluable advice, support and expertise during the work. Lastly, I'd like to thank all the participants for taking part in the interviews.

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

bps	-bits per seconds
DGPS	Differential GPS
DoA	Direction of Arrival
EOT	Environment-, Operator-, Task-
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HMD	Head Mounted Display
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IR	Infrared
IT	Information Technology
LIDAR	Light Detection and Ranging
LoS	Line of Sight
LUT	Lappeenranta University of Technology
MEMS	Micro Electro Mechanical Systems
RF	Radio Frequency
RFID	Radio Frequency Identification
RPM	Revolutions per Minute
RSSI	Received Signal Strength Indication
RTK	Real Time Kinematic
SLAM	Simultaneous Localization and Mapping
SLR	Systematic Literature Review
SMS	Systematic Mapping Study
SNA	Social Network Analysis
ToA	Time of Arrival
U.S.	United States
US	Ultrasonic
UWB	Ultra-wide Band
VR	Virtual Reality
WLPS	Wireless Local Positioning System
WOS	Web of Science

1 INTRODUCTION

This chapter will serve as an introduction to the thesis work. First, some background is given to describe the researched field and how this research relates to it, followed by the motivations and reasons behind the work. This chapter also introduces the goals and delimitations of the work, including the main research questions. Finally, some related literature is briefly discussed and the structure of the rest of the thesis is presented.

1.1 Background

Industrial automation is the next step in the industrial revolution, and has a long history, dating back to the 18th century. Sure Controls Inc. defines industrial automation as the use of control systems and information technologies (IT) to replace a human being handling machinery with an automated process. They consider industrial automation as the *"second step beyond mechanization in the scope of industrialization."* (Brei, 2013) In the current era, it might be more apt to talk about digitalization instead of automation, but for our context both terms apply.

The topic being researched is automation and remote control (teleoperation) in a forest industries context. More specifically in an outdoors environment or yard 'terminals'. The research is being done for a company, which processes a lot of raw material in various terminals internationally. The thesis work focuses on the possibilities, challenges and feasibility of automation of the processes used in these terminal operations. The specific goals and delimitations are discussed further in the next subchapter.

In the context of in-yard terminals, material handling is the process of moving raw material to be processed or stored, using different kinds of specialized machinery. The focus of interest is not the entire material processing chain, but rather only the material handling subset, i.e. not the processing of the material once already transported. The process of handling material is not to be confused with a specific machine, referred to as a material handler, instead the processes described here refer to all processes in forest industries context, in which material is handled and can be potentially automated. Material handler is a mobile hydraulic crane, which is usually fixed in place, but can move with tracks or rails, as seen later in figure 3.

Material handling can involve anything between entirely manually operated and fully automated machinery or equipment. Automation is defined as the operation of control systems, machinery, vehicles or equipment with minimal or reduced human interaction. Thus, it is important to note that even though this work researches automation in the context of forest industries, it does not necessarily mean fully autonomous processes.

1.2 Forest industries context

To better understand the processes involved and the potential of automation and teleoperation, the current processes and machinery are briefly described. In the forest industries context, the environment is a wood terminal, which includes areas between and surrounding the mills. This environment differs from terminal to terminal. In the scope of this work, typical operations in these terminals includes reception of material, measurement of the material, unloading the material to storage or directly to the mill process, or transporting the material from storage to the mill. The material is most commonly roundwood (i.e. pulpwood, saw logs, veneer logs) or woodchips. The terminals differ from each other in their layout, transportation methods and volume that they handle. For example, some terminals include port operations (wood deliveries by water). This somewhat dynamic and differing environment means that any automation solutions cannot be designed only for one terminal, but must instead be applicable to the differences between terminals. The three main methods of material being transported into the terminals are on road by trucks, on railways by trains and on water by ships, and each method has differences in how the material is unloaded. It should be specified that material handling, or wood handling in this process generally means the transportation and manipulation of roundwood or woodchips on the terminal yard, and not debarking or chipping processes.

Figure 1 illustrates the typical process of delivering roundwood. The unloading process varies somewhat, depending on the delivery method, but mostly the process is quite similar once unloaded. Depending on whether the mill can take the wood for processing immediately or not, the material can be taken into storage or directly into processing. The context of teleoperation and automation processes discussed in this thesis deal mostly within this area of moving material around.

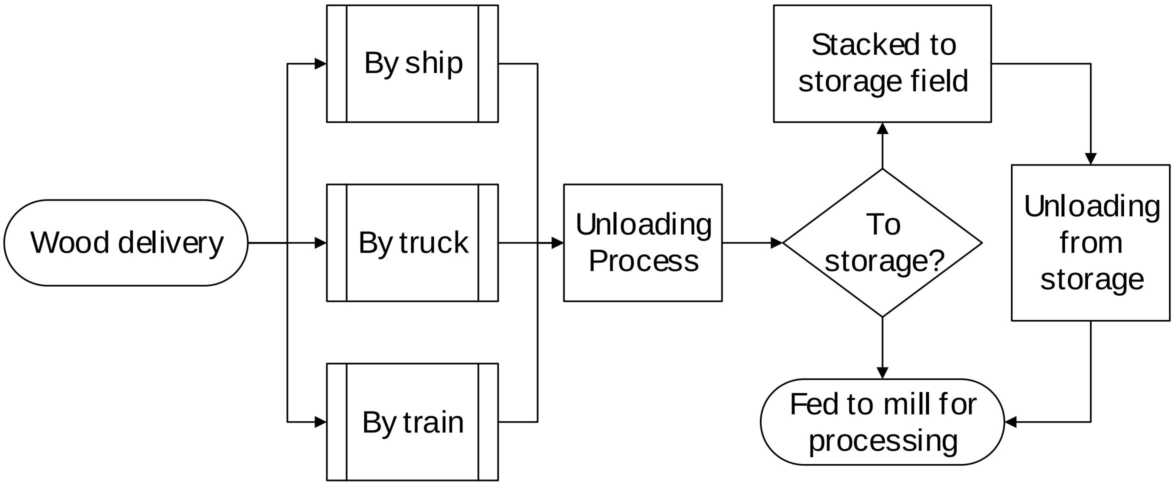

Figure 1. Basic flowchart of a typical wood delivery process.

To give some idea of the scale of these operations, the machinery at the terminals can operate in a range of anywhere between few meters all the way up to several kilometers. This is of course highly dependent on the type of machine and task being performed. The various types of machines and vehicles include log stackers, material handlers, wheel loaders and timber and chip trucks, as well as wood chip trucks for transportation of material internally. Some of these machines are depicted in figures 2-4. Furthermore, a type of machine can differ from another of the same type, as the machines can be of different make and model from different machine manufacturers.

Figure 2. RTD3126 TW Log Stacker, manufactured by SKS Toijala Works Oy, handling roundwood. Copyright 2017 by Stora Enso Oyj. Reprinted with permission.

Figure 3. Mantsinen Material Handler. Reprinted from Stora Enson Kaukopään tehdas - Mantsisen osaamista parhaimmillaan, In *Mantsinen*, n.d., Retrieved August 4, 2017, from http://www.mantsinen.com/fi/tuotteet/referenssit/kaukopaan-tehdas/#ad-image-0. Copyright 2017 by Mantsinen Group Ltd Oy. Reprinted with permission.

Figure 4. Volvo L90E wheel loader shaping a woodchip pile. Copyright 2017 by Stora Enso Oyj. Reprinted with permission.

These different types of machines and vehicles perform different operations, and these operations can and should be further divided into individual tasks, which could be automated. Tasks which are highly repetitive and easy for automated machines are prime candidates for being automated first. Some of the simpler tasks could include automating the navigation and movement of the vehicles. Tasks which could be harder to achieve with automation might be more suitable to be handled by teleoperation. The task of operating the arm and grapple of a log stacker, i.e. grabbing and moving roundwood can be considered significantly more challenging than automated navigation of the vehicles. There are other aspects to consider besides the physical tasks involved in the terminal processes, when talking about the automation of said processes. For instance, resource management, control systems, communication protocols, level of automation, security are all important parts of the whole system.

When it comes to automation, the possibilities are endless, but not everything is feasible. For automation to make sense for a company, it must be cost effective or provide other significant benefits. That is why it is important to prioritize different tasks which could be automated based on their ease of automation compared to the gained benefit. The level of automation must also be considered, as there is a big difference between a fully automated system versus a teleoperated and partly automated one.

The delivery of the material to the terminal is done by third parties, meaning the deliveries are not by employees of the mill. In addition to non-employees in the terminal area, other employees can operate in the same areas with various work machines, making access control within the terminal an important issue when considering possible autonomous operations of the work machines. Furthermore, machinery can be working very close to each other, meaning they need to be aware of each other’s locations and actions. This dynamic nature of the work environment and potential personnel in the area mean security is of utmost importance. Security will be considered from perspectives of the machinery, control systems and possible policy changes. There are machine manufacturers and terminal entrepreneurs on the premise, supplying services, such as machine and factory maintenance, logistics, port operations, et cetera. These third parties must be considered when designing and implementing automation solutions throughout, as they are an integral part of the process, and work closely together on many of the operations in the wood terminals.

Lastly, scalability of the proposed solutions should be factored in, when considering an automation system. Especially in a case like this, where multiple terminals could be automated, and the potential for taking the automation to a global scale exists. In this context scalability means the ability to take the system and solutions implemented for one terminal and use the same system and solutions at another terminal. Without proper scalability, the cost of developing the automation systems might not be feasible. The required sensors and hardware are only a part of the total costs, and even though the amount of required hardware scales with the number of terminals and work machines automated, the cost of designing and developing the required control systems and related software does not. Meaning it might be feasible to develop such systems if the benefit is considered from multiple terminals, instead of just one.

1.3 Goals and delimitations

Industrial automation is an ongoing trend in many industries. Some of the biggest advances in automation can be seen, among many others, in industries such as mining, agriculture and port terminals. The forest industry has not seen a widescale move into automation yet, but certain efforts, for example on machinery manufacturer's level, can be seen. The main potential benefits of automation are cost reduction, productivity and safety. Automation and teleoperation can increase the performance of operating the used machinery, reducing costs such as fuel costs, maintenance, labor costs, and many others. The most important factor to consider is safety. Automation and teleoperation removes humans from potentially dangerous work environments, into more safe and efficient positions. For these reasons, researching the potential of industrial automation is an important task, and should provide value for any future endeavors in automation and teleoperation development.

The goal of this work was to provide a practical view of automation technologies in the forest and similar industries used in the 21st century for heavy machinery. This work can be used as a basis to help determine the possibilities, challenges and feasibility of automation and digitalization efforts in industrial terminals. This goal was achieved through literature review, which purpose was to gather a body of knowledge about the current state of automation and remote control technologies and solutions suitable for the forest industries. The literature review was extended to include articles, marketing and white paper material from automation project implementation cases from other industries. In addition to the literature review, interviews were conducted to gather more relevant information about the specifics of automation cases from other companies in similar industries. Furthermore, interviews with some terminal entrepreneurs and machine manufacturers were conducted to learn more about the processes and the machinery being automated.

Even though the focus of this work was on automation and digitalization of machinery in a forest industries context, the review looks at technologies used for automation in many different fields and areas. The technologies and solutions used in automation cases in different industries could be applied to use-cases outside of their original context. The data collected from the literature review and the interviews was analyzed to find out the possibilities, as well as the challenges in different areas of automation. The purpose of the analysis was to find out what different technologies, sensors, control systems are available, and the limitations of those technologies. These technologies were then considered for their applicability and feasibility.

The processes which could be automated were described earlier, but the exact company, or specific details about the process at hand are not revealed in this research, but the realistic needs and requirements at the wood terminals guide the goals and limitations of this work. The limitations start by restricting the area of automation to technologies and solutions applicable to machinery used in handling material in forest industries' terminals. The working environment is limited to an industrial, in-yard terminal context, which implies a closed off environment where the machinery operates. The possibilities of automation outside of this environment, for example deliveries of raw material on public roads is outside of the scope of this work, but some of those possibilities are speculated on in a later chapter.

Automation and autonomy has many different levels of operation. A process can be fully autonomous, requiring no human interaction, i.e. a fully automated process. On the other hand, only some parts of the process may be automated, and the process can still require human intervention or remote operation. This research does not limit itself to only fully automated or autonomous solutions, as it is unlikely that the most cost-effective solution would be full automation. Rather the currently used machinery process can be retrofitted with automation and remote control equipment. All viable possibilities were taken into consideration.

Lastly this research focuses more on the side of available technologies, sensors and commercial solutions, with a lesser focus on control systems or the system architecture of the automated process. The objective is to find feasible solutions to reduce or minimize human interaction required in the processes used in the wood terminals. In other words, to automate the process in a way that is cost-effective, safe and enables further automation in the future.

1.4 Research questions

This research was done to find out the current state of automation and teleoperation in the context of the forest industries. This thesis tries to answer what are the automation and teleoperation technologies and methods used in literature, as well as in practice, applicable to the automation of heavy machinery used in forest industries, more specifically for use at wood terminals. We can formulate the main research question as such: **What are the current technologies used in industrial automation and teleoperation for forest industries?** This question is specifically restricted to the context of technologies applicable to the forest industries, as the field of industrial automation is so broad. To answer the research question, we must find out firstly, what is the current state of automation and remote control technologies? What are the possibilities and limitations of those technologies? And lastly, how well can those technologies be applied to the requirements in forest industries? To answer these questions, a body of knowledge is acquired through systematic literature review, including papers from scientific sources, as well as from white papers and other material provided by companies working in similar industries. The research also includes interviews with companies working in similar industries, who have used automation or teleoperation in their processes. By similar industries, I'm referring to industries where their automation and teleoperation solutions are likely applicable to the forest industries, hence the phrasing *for* forest industries, rather than *in* forest industries. This is done because the forest industries are not highly automated yet in the way that, for example, the mining industry is.

1.5 Structure of the thesis

The first chapter gives an overview of the research topic, as well as some background to put the work in context. The goals and limitations, as well as the specific research questions this thesis tries to answer were also covered. Chapter two contains the methodology, which is used to answer the research questions defined earlier. Methodology is given for the systematic mapping study, the literature review process, as well as the interviews. The third chapter documents the literature review and research process, explaining the selected search terms, the rationale of how different sources were selected and how the search criteria was refined, making it possible to verify the results of the research. The fourth chapter introduces the results of the research. Results chapter will categorize all the information in a way that makes them easy to ingest. These results are further reviewed in chapter five, where the results from both the literature review, case studies and interviews are analyzed. The fifth chapter provides different views in to the researched information, answering the research questions. The sixth chapter includes the conclusions from the reviewed information and the analysis of it, as well as some discussion about the research and possible future research areas. Lastly, the seventh and final chapter gives a summary of the research and the thesis work.

2 METHODOLOGY

This chapter describes the methodology, i.e. the methods and techniques used in the research procedures. The process of the review and research is documented separately in the next chapter. The main method of research in this thesis is a literature review, and the secondary method is interviews. Combination of these two data sources is used to form a comprehensive view of both possibilities and challenges of automation in a forest industries context.

The systematic literature review (SLR) is a secondary study of literature relevant to industrial automation technologies and systems, which is first complemented by a systematic mapping study to scope the research area. The second method; interviews are done with other companies that have done successful machine automation projects and implementation cases during the 21st century, in other, similar industries with similar processes, as well as manufacturers and operators of the machinery in use.

2.1 Systematic mapping study

A systematic mapping study (SMS) defines a method for building a classification scheme. The process uses research questions to define a review scope, conducts a search on that scope, screen all the results of that search for relevant papers and uses keywording and other methods to build a classification scheme. Finally, data is extracted from the results and mapped to a systematic map. (Petersen et al., 2008).

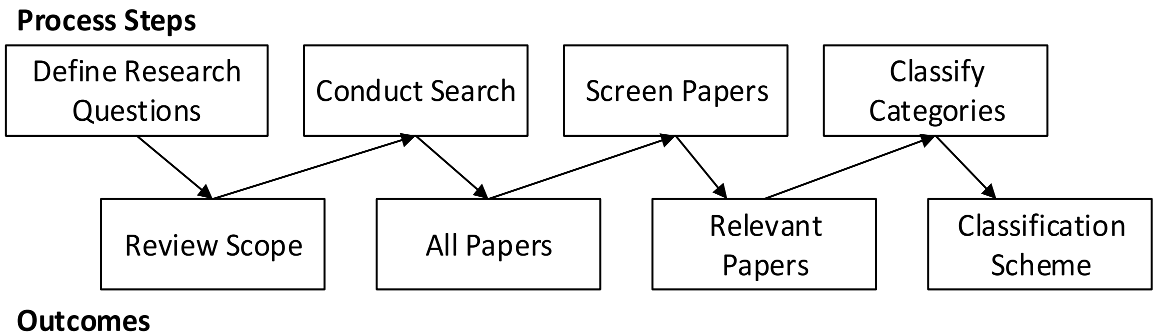

Figure 5 Systematic Mapping Study Process Steps Adapted from (Petersen et al., 2008)

A SMS uses more generic search terms with the objective of classifying and scoping out the field of research, where as a systematic literature review aims to evaluate and analyze the search results and gives a summary on the current state of the researched field. (Kitchenham and Charter, 2017). In this thesis, an adapted version of the mapping study process from Petersen et al. is used. Figure 5 shows the steps and outcomes of each step of the process used. The way the process used in this thesis differs from the original defined by Petersen et al. is that the final outcome is a classification of the main categories of topics covered by the SLR, whereas the original produces a systematic map, by extracting and mapping the data from the classification scheme.

As mentioned, this work uses both SMS and SLR in its methodology. The search terms are more generic than those usually fit for a SLR, but the objective is in line with those of a typical SLR, which is to analyze and give a summary of the results found in literature. The reason for using both methodologies comes from the need to research a field, which has not been well defined and does not have many publicly available publications directly on the subject. Meaning first a wide search of the surrounding fields must be done, i.e. a mapping study, followed by more focused literature review on the classified categories that result from the SMS.

An initial mapping study is first conducted to help determine the search terms, criteria and databases. The point of the preliminary mapping study is to help determine the breadth of the scope and the strategy, with which to conduct the literature review itself. The mapping study is especially helpful in a case such as this, where the researched area is broad and there are no clear limitations with which to narrow the scope of the review yet. The initial trial searches are done using various combinations of keywords, based on the research questions. The mapping study also helps determine the selection criteria, both for which studies to exclude and include. The initial results will also give some indication as to which databases contain most relevant results, which helps define the databases used in the SLR.

The mapping study starts with broad search terms, searching the Web of Science (WoS) Core Collection database, as the WoS results can be analyzed with NAILS. NAILS stands for Network Analysis Interface for Literature Studies. It is a tool for statistical and social network analysis (SNA), which analyses search result data from the exported WoS search results. (Salminen, Knutas, & Hajikhani, 2017). NAILS provides useful information about the most important keywords, citations, authors and papers, which can be used to help narrow or broaden the search, or point out important publications which might be relevant for the research.

From NAILS, important authors will be used to look for other possibly relevant works, as well as discard authors whose work does not appear to be relevant. NAILS provides both most popular authors and publications as well as most cited authors and publications, which makes it easier to find commonly referenced authors and publications, that might not be found within the original search terms. NAILS also lists important keywords, which can help find new relevant keywords to be included in the searches, or irrelevant keywords which should be excluded to narrow down the search. Keywords, authors and publications are the three most valuable and used factors, but data about the publication years is also available. Analyzing the years when most of the publications were done can help narrow the search. Lastly NAILS provides data about topic modeling, which helps with discovering common topics that occur in the datasets. The analysis lists ten most common characteristic words for each topic. Each analysis contains about 4-6 topic groups.

The preliminary mapping study should help define the research area, search terms, databases and criteria to allow for the literature review process to start. The search terms and criteria, even though initially defined, will be further refined as the process progresses and new information is learned.

2.2 Systematic literature review

The literature review follows the guidelines of Kitchenham & Charters (2007). The guidelines were developed for systematic literature reviews (SLR) in software engineering, and even though this literature review is not directly related to software engineering, most of the guidelines and protocols still apply.

The aim of the literature review is to find as many publications relating to the research questions as possible, in an as unbiased approach as possible. The literature review helps summarize the available technologies and possibilities in industrial automation, and provides a background for further research and project activities. A literature review should be unbiased and thorough to have the most scientific value, which is why a systematic approach is ideal (Kitchenham & Charters, 2007). Even though a systematic approach for the literature review is something to be striven for, in our case it can prove to be a difficult task, as there is no one clear subject or topic which is being researched. Therefore, the initial search terms could influence the end result, which is why it is important that the process of the search and review is as transparent as possible. The review process is documented in detail in the next chapter.

Keyword selection is based on the list of initial keywords, derived from the research questions and refined through the preliminary mapping study and the results from NAILS. The primary source of data is from the databases available through the Lappeenranta University of Technology (LUT) library's search service, Finna. This includes 111 potential databases. Finna also has access to an international e-materials search, a service provided by Ex Libris Primo Central in co-operation with providers. The NAILS searches are done using the citation indexes from the WoS Core Collection database, as it allows exporting the data in the format that NAILS requires. In the process of refining the search results, some databases are excluded from to search, the specific databases and search terms are defined in the next chapter.

Databases are selected from the potential list of accessible databases, and narrowed down by a few selection criteria:

- The database's publications should be focused on technology, information technology, engineering or automation. For example, medical, physics, mathematics, chemical, social sciences and humanities are excluded.
- The database must have search functionality to support the kind of search terms used, i.e. Boolean logic, language and year span.
- The publications on the database must be accessible through the LUT Finna's databases.
- The database must have access to full text, not only citations or abstracts.

The criteria for excluding and including publications for a more in-depth review were selected to make sure the articles are relevant to the research. To be included in the review, the publication must:

- Talk about automation, remote control or related technologies applicable to automation processes or machinery,
- talk about autonomous vehicles and the technology or processes used in them or their control,
- be from the 21st century, i.e. between the years 2000 and 2017, With newer publications given more preference,
- have some real-world applicability, i.e. not be purely theoretical or unavailable or unviable technology.

A paper is excluded from the review if it:

- was published before the year 2000, or has become irrelevant considering newer research,
- contains keywords or topics unrelated to this research, even if it contained some of the original search terms, i.e. does not consider the researched topic from the relevant perspective,
- is a duplicate publication or contains exact same or too similar information to previously included publications,
- is published in a language other than English.

Papers that are not directly on the topic of the research, but contain relevant information in some parts can still be included in the review. This way a more complete review can be achieved. Furthermore, to validate and improve the scope of the search, expert opinion is taken into consideration, this means consulting with professors, authors, experts and other important figures in the field. Once the search terms and databases are refined to meet the expected standards the searches are ran and the results are collected. The result set is then cleaned based on the exclusion and inclusion criteria. The results, which are included in the actual review, are sorted and categorized based on their topics. Lastly, the results are documented and analyzed.

The relevancy of a publication is reviewed by first inspecting the abstracts, keywords and conclusions of papers, and if found to be relevant to this research, more data is collected from the relevant chapters of the publication. In this case the data being looked at is more qualitative than quantitative, and as such, there is no intention of any kind of meta-analysis. Since this work is not a pure review of scientific literature, material outside of scientific publication is also gathered and used to help answer the research questions of this work. This outside material includes articles, white papers, marketing material and interviews. Furthermore, the literature review searches are complemented with additional online searches as necessary, if the topics are not covered in great enough detail or they reveal new research areas, which should be taken into consideration.

2.3 Case material and interviews

The main method for researching the field is a literature review, and as a part of that, material from the automation industry is also reviewed. Interviews are conducted to learn more about automation in use-cases involving heavy machinery from other industries. The objective of these interviews is to get information about successful real life automation implementation cases, from industries that have comparable circumstances and machinery. Interviews can also help verify, validate and draw comparisons on the finding from literature. Lastly, being in contact with some of the top professionals from different industries involved in automation can give knowledgeable insight, which might not be available in literature. Potential parties to be interviewed include other companies that have implemented successful automation cases, machine manufacturers of the potentially 'to be automated' machinery at hand, as well as researchers, professors and other professionals in the field. Focus being on the other companies involved with implementing automation projects.

It is important to note that the bulk if the information is gathered from resources provided by the companies, these resources can include online and marketing material, white papers, technical documentation, et cetera. The interviews serve as a means to get further information on what can already be learned by reviewing the mentioned materials first. The interviews allow for getting specific information about a topic or information that would not be otherwise available, and hence improve the quality of the research, instead of being the only source of information.

Interviews as research methods are either qualitative or quantitative, the latter can be called structured interviews or surveys. For our case, qualitative interviews, or less formal interviews are better suited, as each interview can vary widely, depending on the interviewed party. There are no set of questions, that could be easily applied and asked from each party, and the number of interviews is relatively low. As such, it is a better option to tailor each set of questions for each interviewed party, which allows for greater detail in the questions, as well as the answers.

3 RESEARCH PROCESS

This chapter documents the stages from the preliminary review to the final full literature review. The process of the research is documented in this chapter, which includes how the process itself, the search terms, databases and criteria are refined. This chapter should give a better understanding of why papers are included or excluded, what some of the intermediary results are, and how certain decisions were arrived to.

3.1 Preliminary mapping study

By looking at the research question, few possible search terms can be immediately derived. First topic of interest is automation or more specifically industrial automation, second remote control, also known as teleoperation. Heavy machinery in automation is especially considered, and since this machinery is commonly some form of a vehicle we are also interested in autonomous vehicles. The review is focused on the technologies that enable the automation, often these technologies are some type of sensors. As a part of the preliminary mapping study, another point of interest are other potential mapping studies and literature reviews.

The first set of search terms are derived from the research questions, goals and limitations. These terms are searched from the WoS Core Collection: Citation Indexes

- Science Citation Index Expanded (SCI-EXPANDED)
- Conference Proceedings Citation Index- Science (CPCI-S)
- Book Citation Index– Science (BKCI-S)
- Emerging Sources Citation Index (ESCI)

The WoS chemical, social sciences and arts & humanities indexes were excluded from the search, as per the selection criteria of databases.

For the first round of searches, the search terms were used to search for topics, limited to results from between 2000 and 2017. It becomes very apparent after a few searches, that any search terms related to automation, teleoperation and autonomous vehicles are too broad and ambiguous to be searched as topics, as the number of results is far too high to be analyzed and a quick look at the results shows they are mostly unrelated to the type of automation we are interested in. The searches all gave thousands or tens of thousands of results, which is far too many search results to be analyzed with NAILS, let alone to be included in the review. Since these terms are vague and widely used in many different topics, the search strategy needs to be refined. To limit all further queries, future searches will be limited only to the titles, keywords and abstracts of the publications, when available.

Searching based on titles yields much more manageable results. For the first set of results to be analyzed, the main search terms were “automation”, “(remote* AND (control* OR operat*)) OR teleoperat*”, "Autonom* vehicle*". These broader search terms were combined with the Boolean operator AND with more specific search queries. The results of the searches are listed in table 1.

These queries still contain too many unrelated results. The search terms need to be refined, and that is done by going through the results and seeing which searches gave accurate results, and which contained most of the unrelated results. For the final searches, the amount of search terms needs to be lowered, as it is not feasible to run this many searches on multiple databases. To further help with narrowing down the search results and search terms, the results are exported from the WoS site and analyzed using NAILS.

Search Term	Results
automation AND	
industrial	507
technolog*	392
machinery	11
truck OR UAV OR UGV OR excavator OR tractor	18
material* AND handling	8
sensor*	157
driving	173
((remote* AND (control* OR operat*)) OR teleoperat*) AND	
technolog*	109
automation	40
machin*	79
material* AND handling	2
"Autonom* vehicle*" AND	
technolog*	14
sensor*	54
automation	4
Miscellaneous searches	
robot* AND sensor* AND technolog*	32
autonom* AND “material handling”	8
autonom* AND sensor* AND technolog*	17

Table 1 Mapping Study Search Terms by Title from Web of Science database

By looking at the most important keywords in each of the analysis, we can identify keywords which seem irrelevant or unrelated to what we are researching, and thus we can gather a list of keywords NOT to be included in the searches, listed in table 2. These keywords can be excluded from either the search of the title or topic. Furthermore, we can look at important publications and citations from these results and see if these publications are of interest to us, and if so, whether they should be included in the review.

Keyword	Reason for exclusion
factory	Research is limited to outdoors environment, not in factory automation.
manufacturing	Automation is related to material handling processes, as opposed to manufacturing processes.
home	Research is limited to industrial automation, not ‘smart homes’ or home automation.
building	Same as home automation
“smart grid”	Electrical systems are irrelevant

Table 2 Excluded keywords

Lastly, we are looking for other literature reviews, surveys or other secondary studies, which could be used as a basis for this work. Reviews, surveys a were searched for, by including AND (review OR survey OR “secondary study” OR “mapping study”) at the end of each of the previous search terms. The result of searching for previous reviews can be seen at the end of chapter 1.1.

3.2 Literature review

Using the previous list of search terms, criteria and analysis results from NAILS, a second iteration of search terms is derived, which are the search terms to be used in the literature review. These search terms listed in table 3 are derived by combining the most relevant search terms from table 1 into search terms which seemingly gave the most relevant results, whilst excluding the search terms in table 2.

Search term
automation AND ((material* AND handling) OR sensor* OR machinery)
teleoper* AND (sensor* OR technolog* OR machine*)
autonom* AND vehicle* AND (sensor* OR technolog*)

Table 3 Literature review search terms

These search terms are used on the selected databases, with the excluded keywords added NOT to be searched for. After purging irrelevant search results based on the inclusion and exclusion criteria defined earlier, the amount of included and total results can be seen in table 4. The included results were chosen based on the title, keywords and abstract of the publication, and these results are taken for further review, where the inclusion and exclusion criteria are further applied.

Database	Included / Total Results
Emerald Insight	32 / 235
IEEE Xplore Digital Library	38 / 306
ProQuest	10 / 57
ScienceDirect	31 / 566
Web of Science	33 / 395

Table 4 Literature review databases and number of results

In the next step of reviewing the 144 publications chosen previously, the papers are gone through with the intent of further excluding those papers which do not meet the criteria and removing any duplicate entries or papers which include too similar or outdated information. During this process notes are taken down from each selected paper. These notes include sections or chapters in the papers that seem relevant for our analysis, areas that could require further research, as well as other interesting remarks.

Out of the 144 papers, 30 were selected to be included in the literature review. Most common reason for excluding a paper was not being relevant enough for the research area, which could mean either the subject not being applicable or the subject being too specific or single case implementation oriented. For example, a paper focused on underwater automation or aerial vehicles, even though talking about automation and sensors, were not applicable enough to the type of ground vehicles discussed in this paper, and on the other hand papers focusing heavily on mathematics or algorithms, commonly do not provide material that is generally applicable enough to write about. The type of publications that are of interest for this review, are those that look at automation, teleoperation and autonomous technologies, sensors and the application of those technologies and sensors, in areas that can be related to a forest industry context. That is why for example automated vehicles operating underwater were excluded, as the working environment is too different, that the automation applications used in that environment cannot be reasonably expected to be applicable in a ground or wood terminal environment.

From the first impression of the review, three major categories can be classified. These categories are sensor technologies, teleoperation, and control systems & communication. Out of these three categories sensor technologies is the largest one, encompassing technologies and sensors related to positioning & orientation, navigation, environmental perception, tracking & monitoring, as well as safety. Papers on teleoperation focus on control and controller schemes, feedback sensors, visual perception and human interaction or usability. Lastly, control systems and communication are primarily discussed within other papers, and rarely on their own, but the main topics include communication protocols, resource management, and development of the control system software. Out of the three main categories, ‘control systems’ is the least represented one, as papers rarely write on the topic matter on its own, but rather in conjunction with specific technologies or implementation cases of automation systems. Regardless it is an important topic to cover, as it is an integral part of an automation system.

The topics covered in the papers selected for the review matched mostly those found in the preliminary mapping study, but the some gaps were also revealed. Some sensors or technologies were only briefly mentioned, making them into possible inquiries for further research. If a technology, sensor, topic or research area that is of interest is not is detailed extensively enough, it will be directly researched, but the search results will not be reviewed as exhaustively as the original papers. This is done to ensure a complete view of the research area is achieved, even though admittedly it does introduce a level of bias in to the research, as new papers can be introduced in to the review without formal review.

During the screening process, it became apparent some of the topics were covered inadequately for the purposes of this paper, requiring further research. But once all the material from the literature review, subsequent complementary searches and case material was gathered, a reasonably full coverage of the topics classified in the SMS was obtained.

3.3 Case material and interviews

Part of the research process is to gather data on companies, solutions, systems or technologies used in real life automation implementation cases. As mentioned before, these parties can include terminal entrepreneurs, machine manufacturers, and companies from other industries. Part of this data gathering process are interviews. As described in the methodology, these interviews serve to get more in-depth information directly from experts in various fields. In this chapter, the different parties from whom data will be gathered from are shortly introduced, as well as the general areas or industries those parties represent.

Terminal entrepreneurs provide logistics, maintenance, and terminal operation services. Some terminal entrepreneurs that operate in Finland include Fin-Terpuu Oy, Oy Adolf Lahti Yxpila Ab and Mantsinen Group Ltd Oy. Some terminal entrepreneurs are also terminal machinery manufacturers. For example, Mantsinen Group Ltd Oy, provides both machinery and operation services. Other machine manufacturers that develop the type of machinery commonly used in wood terminals include SKS Toijala Works Oy, Svetruck AB, Volvo AB and Terex Fuchs GmbH. These manufacturers provide the same type of machines that were listed in chapter 1.1.1, which included log stackers, material handlers, wheel loaders and trucks for transporting materials. Understanding the products and services of machine manufacturers and terminal entrepreneurs is important, as it is their machinery and operations that are being automated, and their co-operation is required as new automation solutions for the machinery are being developed.

Parties that are not involved with wood terminal operations or the forest industry in general can still be valuable sources of information. Other industries have undertaken development of automation solutions for much longer than the forest industries, and there is great potential to learn from these other industries. Some major industries that have made significant progress in automation are mining, agriculture and port terminals. The main focus of the research on the part of automation implementation cases is on these other industries.

Sandvik AB develops automation, teleoperation and control system solutions for mining operations (Sandvik, 2017). Trimble provides services and solutions for many industries, of which our interest is in their agriculture field solutions (Trimble, 2017). Kalmar, owned by

Cargotec Oyj, mainly provides products and software for port automation (Kalmar, 2017). Kalmar is also the distributer of TW Logstackers, manufactured by SKS Toijala Works Oy. (TW LogStacker, 2017). Volvo Trucks, owned by Volvo AB works, among other things, on truck automation. They have made recent developments in truck automation in the mining and agricultural industries, as well as taking autonomous trucks to public roads. (Volvo Group Trucks, 2017)

4 AUTOMATION AND TELEOPERATION IN LITERATURE

This chapter will introduce the findings of the mapping study, literature review and the material gathered from implementation case studies. The chapter is divided into three subchapters. The three categories are, sensor technologies, teleoperation and control systems. Sensor technologies focuses on all different technologies used in automation and autonomy. Teleoperation deals with telepresence, main usability issues of teleoperation and different control systems for remote control. Lastly, control systems, i.e. the different sub systems involved in automation and teleoperation systems, and the communication between these systems is discussed in this subchapter. The goal of this chapter is to introduce the different results, studies and material found during the research, as well as to somewhat classify them into categories. The results found here will be analyzed for their suitability and usefulness in real life terminal operations in the next chapter.

The first set of searches for the SLR had 1,559 results, out of which 144 were selected for further review. After reviewing the 144 papers 30 were selected for the final review and analysis. Based on the findings from those papers, some further inquiries were required to get a full, comprehensive view of the researched area. The results from the gathered case material and interviews are also presented in this chapter. The interview material will not be introduced separately, but rather as examples along the entire chapter, where most suitable. Some of the case material was already covered in the introduction chapter, mainly the roles and machinery of terminal entrepreneurs and machinery manufacturers involved in the terminal operations. Here technologies, teleoperation and automation solutions and control systems from other similar industries will be covered.

4.1 Sensor technologies

Sensor technologies will describe different sensors for different use cases, outlining what the sensors are used for, what are their limitations, and comparing different sensor technologies that might provide the same use. The sensor technologies covered in this chapter are categorized by use case, rather than by grouping similar technologies together. Some technologies can have multiple uses, creating some overlap between the chapters. The uses cases are classified to navigation, positioning and orientation, environmental perception, and lastly tracking and monitoring.

4.1.1 Navigation

In the context of wood terminals, we can simply define navigation as the process of gathering and using information on how to get from one point to another. In this context navigation applies to the machinery used at the terminals. The navigator can be a person operating the machine, following the navigation instructions, or the machine itself, if it is sufficiently autonomous. In our context, navigation does not refer to manual navigation efforts by people, but the information provided by sensors, unless explicitly stated otherwise.

There are multiple ways to achieve navigation. One of the most common ones is using a global navigation satellite system (GNSS). GNSS can be used to accurately locate a receiver's geographical location anywhere on the globe. There are multiple different GNSSs, the most famous being the Global Positioning System (GPS), which is owned by the United States (U.S.) government. Others include the Russian GLONASS, and the European Galileo positioning system, which is set to reach fully operational capacity in 2019 (European Comission, 2017). Some GNSS receivers can use multiple satellite systems, such as the GPS and GLONASS satellites. Furthermore, the completion of the Galileo satellite system should increase the availability of GNSSs. (Vähä, Heikkilä, Kilpeläinen, Järviluoma, & Gambao, 2013).

GPS does not always provide pinpoint accuracy, and the accuracy can range from anywhere between centimeters to ten meters or more, depending on factors such as satellite geometry, signal blockage, atmospheric conditions and the capabilities of the receiver. Accuracy can be improved by using dual frequency receivers or combining data from multiple satellite systems. (gps.gov, 2017). Accuracy is generally more accurate horizontally, than it is vertically, making GNSS readings in a deep concaved area potentially inaccurate. Accuracy in difficult environments is expected to increase further as more Galileo satellites are launched (European Global Navigation Satellite Systems Agency, 2014).

There are other methods, namely differential GPS and kinematic GPS systems, that can be used to increase the accuracy of GPS data. A GNSS is often referred to as GPS, as GPS is the most used satellite system in the U.S and Europe. As it is referred to as GPS in literature, it will also be referred to as GPS in this thesis, but it is important to note that in this context GPS could also be GLONASS or Galileo or a combination of these.

Differential GPS (DGPS) uses a second stationary receiver as a reference point. By knowing the exact location of the stationary reference point, the known error can be transmitted to the mobile receiver, allowing the mobile receiver to calculate and correct the error in its measurements. (Trimble, 2017). Differential GPS systems can achieve accuracies under a meter (Vähä, Heikkilä, Kilpeläinen, Järviluoma, & Gambao, 2013).

Kinematic GPS or Real Time Kinematic (RTK) navigation is similar to DGPS in that it also requires a static base station receiver to correct for errors. Where it differs is that RTK does not use the codified data transmitted in the GPS signal, but rather the signal itself. RTK measures the phase of the carrier wave in the signal. NovAtel's introduction to GNSS describes the method simply: "*At a very basic conceptual level, the range is calculated by determining the number of carrier cycles between the satellite and the rover station, then multiplying this number by the carrier wavelength.*" (NovAtel, 2017). RTK GPS can achieve accuracies in the centimeter range (Vähä, Heikkilä, Kilpeläinen, Järviluoma, & Gambao, 2013), but in comparison to GPS or DGPS, RTK techniques are complicated and costlier.

The obvious benefit of DGPS or RTK GPS is in the increased accuracy, but neither method can eliminate all errors. Multipath and receiver errors as well as signal loss can cause issues with the stability and reliability of using GPS for navigation. Resolving whether errors are caused by atmospheric effects, multipath errors or noise in the receiver can be practically impossible (NovAtel, 2017).

Practically all modern vehicles have use GPS to provide navigation, and autonomous vehicles, such as Google's self-driving car, use GPS as a part of their navigation systems (Bogue, 2015) (Chakraborty, Laware, Castanon, & Zekavat, 2016). GNSS data can be used with other sensors, to provide supplementary data to improve accuracy and provide navigation when GNSS is not available. Another type of navigation, commonly used together with GNSS, is the Inertial Navigation System (INS).

INS use kinematics, measuring the motion of objects, to determine the current location of an object, based on the previous location of that object. By knowing the speed, acceleration, direction, rotation, etc. of an object, it's location can be calculated, if the previous location was known. This process is called dead reckoning (Reid, Zhang, Noguchi, & Dickson, 2000). Dead reckoning is a part of INS, i.e. INS uses dead reckoning to continuously calculate the position, orientation, speed and direction of an object in motion.

INS use inertial measurement units (IMU) to measure and process position, velocity, heading and attitude (pitch, roll and yaw). IMUs are based on multiple sensors, such as odometers, multi-axis accelerometers, wheel speed sensors, gyroscopes, pressure sensors and magnetometers. Many of these sensors are often based on micro electro mechanical systems technology (MEMS), meaning they can be encapsulated in a relatively small space. (Bogue, 2015) Generally, an IMU consists of at least an accelerometer and gyroscope on three axes that are perpendicular to each other. Both the accelerometer and gyroscope measure acceleration, the gyroscope rotational and accelerometer linear. With these an IMU can measure movement in 3D space. (NovAtel, 2017) Odometers or tachometers are devices that measure the revolutions of a wheel, i.e. a wheel speed sensor. Odometers are another type of sensors that can be used in inertial navigation systems. These types of sensors can provide an independent measurement of displacement and velocity. (NovAtel, 2017)

INS are based on relative navigation, meaning an initial or absolute position must be known first. GNSS can be the source of reference where INS start from. IMU like any sensor contains measurement errors, and since navigation with IMU is based on relative positions, errors in the measurements will accumulate. If this accumulation of errors is left uncorrected, the calculated and assumed location will drift further and further from the true position. GNSS can be one way to try and correct INS, using vision is another. (NovAtel, 2017) The use of cameras, radar and other types of sensors will be covered in more detail under chapter 4.1.3 *Environmental perception*.

A 2010 study on track loader kinematics showed that using a kinematic model for dead reckoning, using track speed sensors and gyroscopes, gave good results compared to a GPS navigation system. (Fredriksson, Andersson, & Hyyppä, 2010). Dead reckoning is method of calculating the position of something based on the current position and using, for example, gyro and odometer measurements, to get the new position.

One company that offers navigation and positioning services featuring many of the technologies covered here is Trimble. They provide solutions and sensors for GNSS correction, as well as in-vehicle navigation and telematics sensors. Their wide range of solutions for both satellite and inertial systems can provide centimeter level accuracies for positioning. Trimble's network RTK scheme, RTX (Real Time eXtended), can provide the accuracy of RTK positioning, without requiring local reference stations, as a network of reference stations is maintained globally by Trimble and delivered through their CENTERPOINT RTX™ service. The system works by collecting data at the reference points, transmitting that data to operation centers at various locations via the internet. Then data processing servers generate precise location data, which is compressed and packed in messages to be transmitted via satellite. Lastly the messages are delivered either via an uplink station or the internet. (Leandro, et al., 2012).

There are various navigation systems and technologies, which operate at different levels. GNSS gives absolute positioning at a global level, whereas INS gives relative position based on a previous known location, and other localization methods generally give a position relative to the tracking infrastructure. Main navigation technologies and their primary methods are listed in table 5, as well as some of their biggest weaknesses and problems. Note: positioning methods will be covered later under chapter 4.1.4 *Tracking and monitoring.*

Navigation System	Localization level	Main technologies	Main concerns
Global Navigation Satellite System	Global	DGPS, RTK GPS	Accuracy, reliability, coverage (in-doors)
Inertial Navigation System	Local	Dead reckoning, IMUs (gyroscopes, accelerometers, wheel encoders)	Accuracy drift, relative positioning
Tracking / Localization	Local / Remote	WLPS, UWB, RFID	Requires infrastructure (base stations, tags)

Table 5. Summary of navigation techniques

4.1.2 Positioning and orientation

Understanding the position and orientation of a remote controlled or autonomous work machine can be important for more use cases than navigation. Although the sensors used in inertial navigation and inertial measurement units are same sensors, namely gyroscopes and accelerometers, used to calculate and measure the position and orientation of things like cranes or arms and grabbles of log stackers, material handlers or wheel loaders.

In addition to accelerometers and gyroscopes, force and pressure sensors may be used to gather information about a state of a machine. This information might be vital for automated systems to make decisions, or important for teleoperators, as they are not present themselves to experience the force feedback from a work machine. Haptic and kinesthetic feedback will be covered in greater detail in chapter 4.1.3. Modern terminal machinery, such as the TW LogStacker RTD12 KURO includes detailed information about the lengths, angles, forces and pressures of the machine, as seen in figure 6.

Figure 6. TW LogStacker RTD12 KURO cabin touchscreen interface. Screen capture from 360 user interface video, In *TW Logstacker*, n.d., Retrieved August 20, 2017, from http://twlogstacker.fi/new-cabin/360/. Copyright 2017 by SKS GROUP. Reprinted with permission.

4.1.3 Environmental perception

Environmental perception deals with sensors that are used to detect roads, lanes, signs and objects in the environment or the general shape and mesh of the environment. Generally, these sensors detect objects like other vehicles or people. These sensors also serve to measure distances to objects and relative speeds of other objects. Environmental perception can be another point of reference for INS, or provide supplementary data when GPS is not available. Navigation usually assumes a known operating environment, but that is not always the case. Operating in unknown environments uses simultaneous localization and mapping (SLAM). Environmental perception plays a big part when trying to navigate or operate in an environment, where paths or obstacles are not known.

The main types of sensors used for environment perception are Light Detection and Ranging (LIDAR) sensors, radars, ultrasonic (US) sensors and cameras. LIDAR, radar and US sensors active sensors, meaning they measure signals transmitted by the sensor itself. These three sensors are all radar based, meaning they send different kinds of wave pulses, and receive it back, one the wave has been reflected by an obstacle and finally measure the total time of flight. (Chakraborty, Laware, Castanon, & Zekavat, 2016).

LIDAR is the most advanced of these types of sensors. LIDAR sensors generally rotate at hundreds of revolutions per minute (RPM), sending multiple pulses of light (laser beams) horizontally in 360 degrees, creating a detailed 3D map of the surrounding area. LIDAR's effective range depends on the surface it is reflecting from. Surfaces with poor reflective material can generally be detected up to 30 meters away, in best case scenarios LIDAR can detect distances up to 100 meters. A laser beam can only detect one point, which why generally multiple beams are used at once, and the sensor rotates very rapidly, as well as having the angles of the lasers vary. One of the downsides of LIDAR is that it cannot accurately determine the speed and distance of other moving objects in real time. Since LIDAR is not effected by adverse lighting conditions, meaning it operates well at night, but it does not do well in adverse weather conditions. (Bogue, 2015) (Chakraborty, Laware, Castanon, & Zekavat, 2016) (Ilas, 2013)

Radar uses a different wave length of electromagnetic radiation and can operate in several frequency bands. Unlike LIDAR it is not affected by weather conditions. Since the emitted beams are much wider than those if LIDAR, but, the signal beam has to be narrowed, to achieve a good angular resolution. The effective range for radar is anywhere between 100 to 250 meters, depending on the implementation. Short-range radars, with effective range of just few meters exist as well. Due to the poor resolution and long operating distances of radar technology, object detection can detect obstacles, but does not necessarily get a clear image of what the obstacle is. The main benefit of radar compared to LIDAR is its ability to determine the relative speed of other objects, which is vital information for autonomous vehicles. (Ilas, 2013)

Good example of radar used in autonomous is Audi's SQ5 equipped with Delphi's self-driving car technology, which used four short-range radars and six long-range radars. The radars were used to derive speed information about other vehicles on the road and distances to other objects in real-time. (Bogue, 2015)

Ultrasonic sensors use, as the name implies, high frequency sound waves to operate in the same manner as radar. US sensors have a very good effective range at 0-1 meters, and operate well at adverse weather and lightning conditions. Autonomous ground vehicles are often equipped with collision avoidance sensors, which are frequently based on US sensors (Bogue, 2015). Commercial self-driving cars or cars with autonomous features most commonly use radar, cameras and LIDARs, which can replace US sensors, which have been around for much longer. Some of the latest developments also include short-range LIDAR. As a whole the trend in environmental perception seems to be combining two or more sensors into one device. (Ilas, 2013)

Ian Stott, David Sanders and Giles Tewkesbury describe low cost ultrasonic sensors for teleoperated vehicles, namely a teleoperated wheelchair in a publication from the year 2000. They found ultrasonic sensors to be cheaper than other alternatives at the time. (Stott, Sanders, & Tewkesbury, 2000). Even though US sensors are being replaced by newer technologies, they can still provide a cheap robust alternative to many different use cases, involving short-range detection and collision avoidance.

Cameras are a big part of environmental perception. They can provide visual information not available from other types of sensors. Camera sensors are based on an array of passive light sensors. Passive, meaning they record light sources not produced by the sensor itself. These light sensors produce values for pixels in an image. A single image is two dimensional, and either in greyscale or color. The higher the resolution, the more information single image contains. The fact that the image is two-dimensional means that complex algorithms are often required for process the image for any useful information. Since cameras are based on light sensors, they are especially sensitive to poor lighting conditions, such as low intensity of light, direct sun light or areas with sharp contrast between bright and dark areas, which is known as dynamic range.

Low light can be improved by amplifying the signal, but this should be done in a way that does not simultaneously amplify the noise as well. Another method for improving vision in dark lighting conditions is to use infra-red (IR) as a part of the captured range. If the sensor in a camera also covers IR or near-IR spectrum, it can detect reflections from objects even at night, capture thermal radiation, and potentially use IR light sources for further illumination. (Ilas, 2013)

One of the main uses of cameras and visual sensors is obstacle detection. Obstacle detection is one of the key components of autonomous driving. One of the most important factors of obstacle detection is depth perception, commonly achieved through stereo vision and other three-dimensional perception sensors, such as LIDAR. (Bernini, Bertozzi, Castangia, Patander, & Sabbatelli, 2014)

CCD cameras can be used to detect the 3D position of objects, generally by detecting certain easily distinguishable features, such as edges, holes or markers. Camera based sensors are relatively low cost, but require good lighting conditions, complex algorithms and can be computationally expensive, requiring sufficient hardware and processing power. (Vähä, Heikkilä, Kilpeläinen, Järviluoma, & Gambao, 2013)

There are two major approaches to vision based obstacle detection, monocular and stereo. Monocular vision relies on detecting features from many images, but lacks depth perception, and thus can greatly benefit from being fused with depth sensors. Stereo vision uses two cameras to achieve depth vision, much in the same way humans do with two eyes. But, as said generating a 3D map with camera based sensors requires complex algorithms with expensive computation costs. One way to reduce the computation cost is to use field programmable gate arrays. (Park, Lee, & Son, 2016)

Obstacle detection can simple detect obstacles of any kind, but in some scenarios, it might be desirable to detect specific types of objects, people for example. This requires training of classification algorithms, so they can identify certain objects. A paper by (Milella & Reina, 2014) introduces some possibilities of self-adaptive learning, meaning the algorithm can teach itself to classify one type of objects from others.

To give a few examples of vision based sensors being used in autonomous vehicles, Bogue describes Google's self-driving car as having a pair of cameras with overlapping fields of view, which track an object in real time and are accurate to about 30 meters. (Bogue, 2015). A paper on ‘High precision localization for autonomous vehicles via multiple sensors, data fusion and novel wireless technologies’ proposes a system, which uses high-resolution cameras on an autonomous vehicle, which can detect lane markings, road and street signs, and other objects. (Chakraborty, Laware, Castanon, & Zekavat, 2016)

A paper from 2007 on ‘Collision avoidance technology: from parking sensors to unmanned aircraft’ features a Honda ASV-3, which “uses cameras and radar to detect obstacles and approaching vehicles. … The cameras also detect infrared and the car uses infrared headlights.” (Connolly, 2007)

A paper on ‘Tracking a moving object with real-time obstacle avoidance’ showcases a robotic platform, which uses a single CCD camera and a laser-based range sensor to track a moving object. (Chen, Cheng, Page, Koschan, & Abidi, 2006). The study is a good example of simple sensor fusion, combining a camera sensor and a depth or range sensor for an effective solution.

Du, Mouse and Sheng describe a robotic system which uses an RGB-D sensor to map the environment in their paper ‘Design and Evaluation of a Teleoperated Robotic 3-D Mapping System using an RGB-D Sensor’. RGB-D sensors use an RGB (three separate CCD sensors to get red, green, blue color data) camera and a depth sensor. They describe RGB-D sensors as a low-cost sensor. (Du, Mouser, & Sheng, 2016) RBG-D sensors aren’t a new type of sensor, but rather a device that uses sensor fusion to combine the two sensors into one application. Perhaps the most famous use of RGB-D sensors is in Microsoft’s Kinetic sensor, a motion sensing input device for Microsoft’s Xbox consoles. In the Kinetic, the depth sensor is a laser time of flight sensor, with an IR light source. (Demerjian, 2013)

LIDAR, Radar, US, Cameras and other sensors all have their advantages and disadvantages in different use scenarios. They are generally used together to solve a problem, by fulfilling different requirements in a problem. The information gathered from the sensors is fused together, in what is commonly referred to as sensor fusion. An overview of the different sensor types can be seen in table 6.

Criteria	LIDAR	Radar	Ultrasonic	Camera
Effective range	1-80 m	1-100+ m	0-1 m	1-30m
Operation in adverse lighting conditions	Good	Good	Good	Poor
Operation in adverse weather conditions	Poor	Very good	Good	Poor
Sensor type	Active	Active	Active	Passive
Main benefits	Accurate 3D measurements, 360 degree FoV	Robust, able to detect speeds	Cheap, precise short range measurements	Various uses, great for sensor fusion

Table 6 Summary of sensors for environment perception

Radar is commonly used for its range and speed detection, LIDAR for its accuracy, cameras for object analysis and ultrasonic for reliable shorter-range detection. One of the major deciding factors in using different kinds of sensors is their cost. Older technology, such as radar and ultrasonic sensors are often considerable cheaper than newer 3D imaging based on LIDAR.

4.1.4 Tracking and monitoring

Tracking and monitoring for this work is defined as sensors or technologies used to keep track of, i.e. monitor, resources. These resources can be vehicles or machinery, people, materials, or any objects for that matter. These types of sensors and technologies are mostly communication and locating or positioning technologies, which have use cases outside of tracking and monitoring, but have been separated into their own chapter, as they do not exactly fit into navigation or positioning applications alone.

One technology for identification uses radio frequencies (RF) to do so, this technology is referred to as Radio Frequency Identification (RFID). RFID uses electromagnetic waves on the radio frequencies to transmit data. RFID tracking requires to parts, a two-way radio transmitter-receiver, a ‘reader’ and a tag, which receives a signal from the reader and emits a response. A passive RFID tag is powered by the radio signals of the reader, an active tag has an external power source, and can operate at hundreds of meters away from the reader. (MHI, 2017).

RFID can be used with ‘received signal strength indication’ (RSSI) to help locate the position, or at the very least the distance, of the tag. RFID for localization requires multiple readers or reference points and positioning algorithms to be effective. (Chakraborty, Laware, Castanon, & Zekavat, 2016).

Wireless Local Positioning System (WLPS) uses Time of Arrival (ToA) and Direction of Arrival (DoA) to create a positioning system. In WLPS, active tracking is based on a dynamic base stations and mobile target units. The base station sends a unique identification code request to every nearby target, which then respond back to the base station. ToA and DoA to estimate the position of the tracked units. The method of communication can vary depending on the implementation, but one possibility is using millimeter wave frequencies. Millimeter waves use the millimeter subpart (30-300 GHz) of the RF band. Millimeter waves require line of sight (LoS), as the propagation of the waves is stopped by solids and diminished by foliage. Thus, techniques using this wavelength are best suited for short range communications, of 20 kilometers or less. Millimeter waves have high bandwidth and can transmit large amounts of data. (Chakraborty, Laware, Castanon, & Zekavat, 2016). Time of Arrival is also called Time of Flight, which has been discussed together with other technologies already. DoA can be based on techniques such angle of arrival, time difference of arrival or frequency difference of arrival.

Localization systems based on radio frequencies can in general be divided into model and map based system. Model based systems use the techniques discussed in WLPS, map based systems use a radio map, which must be constructed a head of time. In a radio map, beacon signal strengths are recorded in known locations. The map is then used and compared to measured data, with algorithms based on various methods.

These kinds if simple systems can be used for Wi-Fi or Bluetooth as well, where distance can be measured using RSSI or ToA methods, and localization accuracy can be increased with DoA methods. With simple systems, the accuracy can be within few meters, although some methods can achieve relatively high accuracy of around 0.5 to 1 meters. One such system is the Ultra-Wide Band (UWB) real time locating system. (Vähä, Heikkilä, Kilpeläinen, Järviluoma, & Gambao, 2013). Ultra-wide band is a RF technology, which uses low energies for short range communication, but has a high bandwidth. The high bandwidth is achieved by using a large spectrum of radio frequencies.

The wide bandwidth of UWB has many advantages. Firstly, high bandwidth increases reliability due to the signal containing many frequency components, as it is more likely that some will reach their target through or around obstacles. Secondly, the higher bandwidth is useful to high resolution radars, which means higher accuracy. Thirdly, higher bandwidth alleviates small-scale fading. Lastly, large bandwidth means the power spectral is spread and less dense, reducing interference of other systems. The high reliability and accuracy are especially useful for wireless positioning. (Gezici, et al., 2015). These localization technologies can be used together with navigation systems, complementing the data from GPS, much like INS. RF based localization can be more accurate and reliable than GPS, but requires the infrastructure and algorithms to support it.

In conclusion, there are various types of sensors for different use cases, and usually alternatives for the same case. Generally, there is no 'best' sensor for everything, but the definition of best depends on the context and task, for which the sensor is required. For industrial use best is usually the one that is the most cost-effective and gets the job done. Navigation often requires the use of inertial or other localization methods in addition to GPS data to be accurate enough for industrial use. Detecting the surrounding environment of automated machines can require cameras, radars or other sensors to capture all the required data for safe operation. In addition, there can be need for other types of sensors, for other uses, such as safety, access control, resource management, etc.

4.2 Teleoperation

This chapter deals with technologies and issues related to teleoperation. The three main subjects related to teleoperation are telepresence, usability issues in teleoperation, and different types of control schemes and controllers for remote control.

The term teleoperation and remote control are used somewhat interchangeably in this context. They both mean to operate a vehicle or a system over a distance. There can be direct teleoperation, where the operators (master) actions are directly reflected in target (slave), and the operator gets real-time feedback, e.g. when controlling a radio controlled car. Another type of remote control is supervisory control, where the operator gives high level commands to the target, which can perform tasks more or less autonomously. (Lichiardopol, 2007). This study is not concerned with the exact type of teleoperation, but rather inspects different possibilities and different levels to autonomy. The real tasks that take place at the wood terminals, would most likely be a mixture of directly remote controlled and partly or fully autonomous tasks. It is important to note that even though this chapter deals with teleoperation and remote control, many of the same sensors, controls, technologies or solutions presented here, could also be used in automation.

4.2.1 Telepresence

Telepresence is the feeling of presence on the teleoperation site, which is created by sensor information, such as vision, sound and force. A step further from telepresence can be called virtual presence, or virtual reality (VR). Virtual presence is the same as telepresence, except the site of teleoperation is virtually generated. Combining real world sensor information with virtual reality can be called augmented presence/reality. The simplest example of telepresence is a camera-monitor combination. A more complex multi-sense telepresence can include vision or stereo-vision, hearing, head or body movement tracking, touch (haptic) feedback, force feedback, and even temperature and pain feedback. (Lichiardopol, 2007). The main categories of telepresence introduced here will be vision, hearing and touch.

Vision is the most dominant sensory information for humans. Humans' eyes are capable of depth perception through stereo vision, and has a very wide field of view. Translating both depth perception and a wide field of view through a camera-monitor system can be hard. Providing the operator with the same amount of information as they would have if they were on site is extremely difficult. That said, in most cases it is not important to build a complex telepresence system. The operator can learn to compensate for the limitations in visual information and delays, but more advanced telepresence systems can help create the illusion of presence, increasing performance and reducing fatigue of the operator. One way to increase telepresence is through depth perception, either through stereo-vision or generating 3D visual information from depth measurements, from a laser for example. The use of stereo-vision will be discussed more thoroughly with virtual and augmented reality. The feeling of visual telepresence can be increased by tracking things like pan, tilt and roll of the operator's head, and reflecting those movements to the camera. Even eye movement can be tracked, making the feeling even more realistic. (Lichiardopol, 2007).

A good example of telepresence via cameras comes from the mining industry. Sandvik's AutoMine system for surface drilling uses a panoramic camera system to provide 360-degree visibility around the machine. The system additionally includes a pan-tilt-zoom camera for various tasks. (Mine Stories, 2017).

Another important factor for telepresence is sound. Hearing is a valuable sensory tool for humans, which can provide information about the environment and events which might not be visible to the eye. When controlling heavy work machinery, the noise often means that the operator has to use hearing protection, but even when the sound is dampened, sounds can still give very valuable information to the operator. That is why it is important to include audio information when creating telepresence. Furthermore, it is possible to adjust the sound levels and filter useless noise away. (Lichiardopol, 2007).

The third major sensory information is touch. Touch can be separated into two feedbacks, tactile and force. Tactical information provides haptic feedback, i.e. the sense of touch or contact with and object. This type of information is felt be pressure on the skin and underlying tissues. The second type, force feedback provided by kinesthetic information, i.e. the sense of position and motion of limbs is felt with sensory receptors around the muscles, joints and tendons. Force feedback is the force that the operator feels, when the operated device or 'manipulator' feeds back force information to the operator's control system. Force feedback is important for good telepresence, when dealing with manipulation tasks. (Lichiardopol, 2007).

4.2.2 Usability issues

Teleoperation has a lot of issues with control and usability, which need to be addressed when designing and building a teleoperation system. The two main issues are with time delays and stability of the communication media, and the lack of visual and sensory information, both on the master and slave side. (Kamezaki, Yang, Iwata, & Sugano, 2016), (Chen, Mu, Du, & Guo, 2013), (Lichiardopol, 2007).

Many studies consider time delay problems to be the most important issue, whereas others consider lack of visual information to be the highest priority. Furthermore, falsified or corrupted information can be even worse than lack of information. Regardless it is safe to say, sufficient amount of sensory information delivered to the operator in a timely and stable manner is the foundation of functional teleoperation.

A study on the effects of time delays on the teleoperation of a mobile robot found that teleoperators can perform better without assisting sensory systems, in more simple environments. Although, with the introduction of time delays, the teleoperators did better with a sensor system assisting them, i.e. when telepresence was increased. (Sanders, 2009). To strengthen telepresence and improve teleoperation, one of the most important things that can be done, is to improve communication quality and reduce the delay (Chen, Mu, Du, & Guo, 2013).

Time delays cannot be completely eliminated, but their effects can be minimized and the problems and risks they cause can be taken into consideration. A study on 'Remote controlled short-cycle loading of bulk material in mining applications' showed that to avoid risks of accidents, as well as unnecessary wear and fatigue on the machine, the operation of the machine can be restricted. This could mean restricting the movement, speed, or power of the machine. These restrictions should make for safer operation, but also need to be balanced between energy efficiency and productivity, without causing risks to the machine. (Bodin, et al., 2015)

Incomplete information is the second major hurdle in teleoperation systems. Usually this means lack of complete visual information or lack of tactile and kinesthetic sensory information. Incomplete visual information can mean unsatisfactory camera angles, obscured vision, inability control, i.e. turn, rotate, move or zoom camera, or poor lighting conditions, etc. Increased information, especially virtual reality, be it visual or otherwise sensory can increase the quality, accuracy and speed of executing teleoperation tasks (Cui, Liu, & Gong, 2006). A good example of missing visual information is a part of the teleoperated machine, e.g. a bucket on a wheel loader, obscuring the vision of the operator in the cabin of the vehicle or the camera used for teleoperation. One study proposes a model where the image from four independent fisheye lensed cameras are combined into one view, covering the entire surrounding of the work machine. (Iwataki, et al., 2015). Another way to increase visual information is using stereovision or laser sensors for depth perception cues, a study found that using three dimensional visual feedback helps mitigate collisions and leads to safer driving than two dimensional feedback. (Livatino, Muscato, Sessa, & Neri, 2010).

The second half of incomplete information deals with everything non-visual, e.g. hearing, touch (haptic, kinesthetic) or virtual and augmented reality. This type of information can be especially useful in scenarios where detailed manipulation is required. A user study on teleoperation for plant inspection found that a head mounted display (HMD), which includes stereovision, audio feedback and motion tracking, was more efficient and advantageous compared to conventional joystick control, but had drawbacks, such as simulator sickness. It may be required to implement assistance systems for teleoperation tasks, to achieve tasks in fast enough time. Teleoperation assistance systems could mean automation of sub-tasks, i.e. the combination of automation and teleoperation to achieve the goal of a task. (Schmidt, Hegenberg, & Cramar, 2014)

Teleoperation brings together many different disciplines of technology, and it combines technologies and information from mechanical, optical, electrical and acoustic systems. The application of multi-sensor fusion technology is required for teleoperation to be able to answer the increasingly difficult challenges. (Chen, Mu, Du, & Guo, 2013). Table 7 summarizes the main types of presence, visual, acoustic and haptic, used for teleoperation, along with the common technologies used to achieve the presence and the main benefits and issues in those areas.

Type of presence	Technologies	Main benefits	Main issues
Vision	Camera / monitor, Panoramic cameras, Stereoscopic cameras, Virtual reality, 3D (motion tracking), Infrared vision	Visualizing around obstacles, depth perception, improved vision in poor lighting conditions	Lack of depth perception, missing visual information, eye fatigue, simulation sickness
Hearing	Stereos, earphones	Extra information about environment, feeling of presence, ability to filter audio data	Requires extra sensors, wearable items can be strenuous
Touch	Haptic and kinetic	Provides sensory information unavailable by vision, assists with object manipulation	Costly, potentially little gained benefit

Table 7. Summary of technologies for different types of presences, with their main benefits and issues.

4.2.3 Control schemes

This chapter deals mostly with different types of interfaces between the teleoperator and the operated machine, i.e. the controllers and control schemes. So far, a few different types of control systems and controllers for teleoperation have come up, but in this chapter control schemes will be introduced in greater detail. Some examples of conventional and less conventional controllers for teleoperation include joysticks, touch screen, motion tracking of arms, hands/gloves, head mounted displays, virtual reality goggles, visual gesture and motion tracking, and many others. The interface between the operator and machine should enable tasks to be performed in an efficient and safe manner. The task can be complex and require managing several degrees of freedom at the same time. This means the teleoperation method should be intuitive.

Most common teleoperation controllers are based on joysticks and keyboards, as well as dedicated buttons for specific functions. Keyboards offer a lot of complexity, but lacks intuitiveness, and can require a great deal of technical training, and still be difficult to master.

For more intuitive controls, the gaming industry can be a great source of innovation. Common gamepads, joysticks or motion game controllers, such as Nintendo Wii Remote or PlayStation Move are good examples of modern sensors for more intuitive control. Motion game controllers, which map human body actions to digital signals are largely based on accelerometers and video capture. Another similar technology is the Myo Armband sensor, which is a motion tracker attached to the wrist. One of the biggest issues with such systems for teleoperation is their accuracy, and may not be viable depending on the accuracy requirement of the task being performed. (Pachana, Trzcionkowski, & Turek, 2016)

The study by Pachana, Trzcionkowski and Turek included a user test for controlling a teleoperated robot with a gripper. The test included three different input devices, a joystick, keyboard and a LeapMotion sensor, a modern gestural sensor with high precision. They found that the use of LeapMotion sensor resulted in increased intuitiveness of controlling the gripper arm with six degrees of freedom, in comparison to the joystick. In conclusion, there are many different types of controllers for teleoperation. Most of the production-ready solutions however are based on keyboards with dedicated function buttons and joysticks. (Pachana, Trzcionkowski, & Turek, 2016)

A more closely related form of teleoperation comes from a study on excavator teleoperation using a human arm. This study describes a system for an excavator controlled by the motion of a human arm, where three sensors are attached. This research aims to solve the high risk of operating heavy machinery and the unintuitive control of joysticks. They found that they were able to effectively operate the excavator by using visual feedback from the operator, i.e. from a camera feedback on the excavator. (Kim, et al., 2009)

Similar to an excavator arm, a paper on ‘A novel data glove using inertial and magnetic sensors for motion capture and robotic arm-hand teleoperation’ describes a motion tracking system, which can capture the motion of the arm and hand, including the fingers, by inertial and magnetic sensors. The findings show that the proposed controller can accurately capture the gestures of the hand and fingers. (Fang, Sun, Liu, & Guo, 2017).

Lastly, a control system from Hiab, called HiVision, uses telepresence, namely virtual reality (3D vision) head mounted-display to be able to control a timber crane, allowing the teleoperator to work from the cabin of the truck. The crane is attached to a truck, loads roundwood into the back of the truck, eliminating the need for a separate crane cabin. The controls are the same as those that would be found in the crane cabin, making the operation of the crane intuitive.

The system features two forward facing cameras for stereoscopic images, which are required for the head mounted-display to have depth vision. To get a full view of the surrounding, the system also includes side view cameras. Image processing algorithms are used to enhance the image quality in adverse lighting conditions. The system also features a heads-up display overlay, giving the teleoperator essential information about the system. (Hiab, 2017).

So far mostly classic control schemes have been covered. These controllers can be significantly improved by incorporating environment-, operator-, or task-specific (EOT) information. Controllers that use this type of online gained information are referred to as EOT-adapted controllers.

A survey on EOT controllers for teleoperation systems found that most important qualities when designing a remote control system, should be robustness, telepresence, performance of tasks, and transparency. These qualities should be optimized, but in a way, that does not destabilize the control system. To achieve these objectives, the type of teleoperation, operator device, used sensors, system limitation, and time delay or packet loss must be considered in the design of the controller. For further improvements, the human operator, remote environment and the task at hand should be taking into consideration.

Environment-related controllers aim to provide a realistic presence of the environment by gaining additional information about the remote environment. Operator-related controllers take the role of the operator, i.e. the human into consideration. These types of controllers aim to take human behavior into consideration, when a task is being executed. Task-related controllers consider the task itself in the design of the controller, when the task is known, with the goal of improving task efficiency and performance.

The survey finds that many of these methods involved the use of additional sensors and models. In comparison to classic control approaches, the EOT-adapted controllers are largely application-dependent, whereas the classic controllers are largely application-independent. The cost of adapting an EOT-controller should be considered, as the cost could be too high compared to the gained benefit. (Passenberg, Peer, & Buss, 2010)

Sandvik mining has recently developed a teleoperation system, AutoMine™ Tele-Remote, for remote loader operations. The system uses operator-adapted or -assisted controls, with features such as automatic steering and wall collision avoidance. The teleoperation system can work in unknown environments, without requiring any sensors in the infrastructure or any definitions of the working environment beforehand. The system is also capable of sharing information with Sandvik's control systems, which will be introduced shortly in chapter 4.3.1. The systems open interfaces also allow it to be integrated easily to other IT systems. (Sandvik, 2017).

In conclusion teleoperation is a complicated subject matter, that must consider different sensory information, controllers, and usability issues, such as ergonomics and time delays. The correct teleoperation system depends on the task which the system is designed for. How advanced the system should be balanced with cost effectiveness of said system. It would make little sense to develop a system that uses advanced virtual reality techniques and intuitive high-tech controls, if there is little benefit to be gained from such systems, in terms of gained performance.

4.3 Control systems

An automation system consists of many different sub systems. This chapter looks at examples of different systems and interaction between those systems found in literature. These can include sub systems such as navigation and path planning, resource management, access control, communication, both between systems and sensors.

The previous chapters have looked rather closely at certain aspects of automation and different sensor technologies. This chapter looks at the bigger picture of automation systems.

Control systems are not to be confused with control schemes or controllers, from the previous chapter.

4.3.1 Control and management

This chapter looks at the higher-level control and management sub systems of automation systems. First, we will inspect how these systems fit in the processes of autonomous and teleoperated machinery, as well as introduce examples found in other industries as well as those developed directly for the forest industry.

If automated or teleoperated machines are being implemented, it can be assumed a control system is also included as a part of the system. A control system can consist of many different sub-systems, which are responsible for tasks such as navigation, path planning, scheduling, fleet management, resource (people, machines, material, etc.) management, and access control, i.e. limiting the access of people and machinery to certain areas.

A study on sensors technologies for autonomous vehicles describes a high-level diagram of a control architecture of an autonomous robot. As can be seen in figure 7, the vehicle contains sensors, which provide the perception data required for planning and control. The control sends commands to the actuators of the vehicle, which ultimately control the vehicle. (Ilas, 2013)

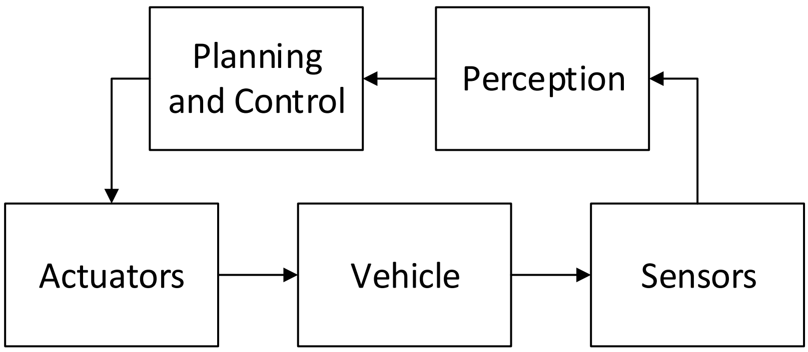

Figure 7. High-level control system architecture diagram of an autonomous vehicle

This simple closed loop is self-sustaining, and allows for autonomous operation of the vehicle. The planning and control system can be on-board the vehicle, making it fully autonomous, or it can be in a remote location, meaning a control system is in charge of the logic of the vehicle, and the vehicle captures and transfers data, as well as executes commands from the planning and control system.

Another study on vehicle automation in agricultural machines provides a more detailed diagram of the navigation system for an automated vehicle. Figure 8, is an adapted and simplified diagram from 'Agricultural automatic guidance research in North America'. The process also includes a stage for planning and navigation. The navigation planner in this process is responsible for path following and obstacle avoidance. This logic may be on-board or off-loaded to a remote operating center. In fact, the paper explores the possibility of separating the processing, resource management and the sensor information to their own respective entities. The processing of the automated vehicle happens in an off-board processing center, which considers information from the resource management system and the sensors on-board the vehicle, and sends commands back to the vehicle. (Reid, Zhang, Noguchi, & Dickson, 2000).

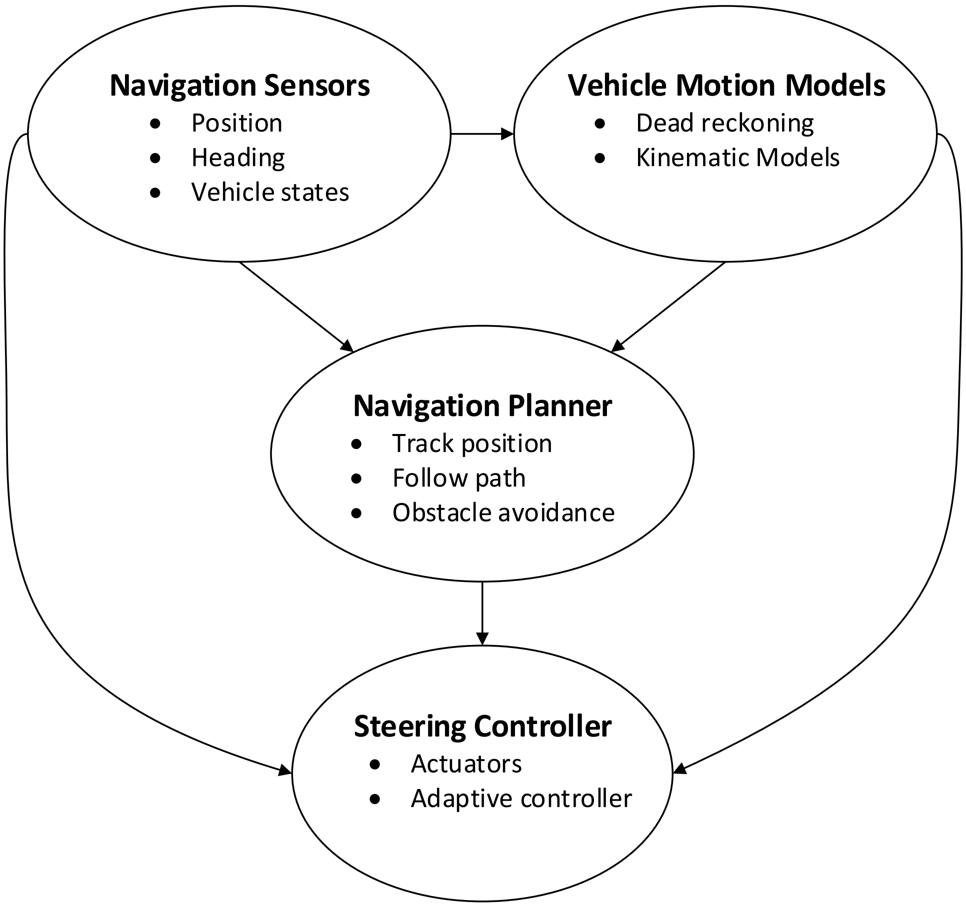

Figure 8. Diagram of navigation automation in vehicle automation.

Practically all autonomous vehicles have some kind of control systems to monitor, control or manage the vehicles to a varying degree. Teleoperation by definition has control systems manipulating machinery. The research of case material from the forest and other industries has many examples of control and management systems used in automation.

Some of the most advanced automation systems are developed and provided by Sandvik. Their automation, teleoperation and information management systems especially are of interest in this study, as the mining industry deals with many of the same challenges as the forest industry. Sandvik provides equipment automation and teleoperation systems for mining operations, such as hauling, loading and drilling, and everything is designed with safety first in mind. Besides generic tasks such as navigation, many of the automated and teleoperated tasks differ from those required in the wood terminals, but their general architecture, or the information management system solution is something that could be learned from. (Sandvik, 2017).

Sandvik's information management system, OptiMine®, is a modular information management solution. The system can include a 3D visualizer of the mine, a drill plan visualizer, location tracking, monitoring, scheduler and task management. The 3D map of the environment is generated automatically from 3D scanned data. The drill plan visualizer is not something that's directly applicable to the forest industries, but similar systems that allow for visualization and preplanning of tasks could be useful in other contexts than mining. The location tracking allows for real time and accurate tracking of all vehicles and equipment in the area, which can be visualized on 2D and 3D models of the environment. The tracking units are based on laser scanners and are stored locally, which means no additional equipment is required for the infrastructure.

Lastly, we have the monitoring system, scheduler and task planner. These are important tools for oversight of the operation and necessary information for teleoperators. The monitoring system gives automatic real time updates on things such as condition of the machinery, maintenance needs, equipment utilization and productive measurements. The scheduler on the other hand allows for creating and planning tasks, as well as for monitoring the progression of those tasks. It’s easy to imagine how such a tool can be vital for a teleoperator managing a fleet of machinery at once. The task management system receives tasks from the scheduler, updates and tracks those tasks, and allows for adapting to any changes in real time. The task management system allows for information to be shared easily between the operators and control rooms. (Sandvik, 2017).

Looking at navigation systems, Navitec Systems Ltd. provides solutions in navigation and controls for autonomous machinery. Navitec also worked together with Sandvik on Sandvik’s navigation systems. Navitec’s systems for positioning and controls for autonomous navigation include Navitrol Navigation, Navitrol Machine Control and Navithor Fleet Control solutions.

Navitrol is a navigation system for Automated Guided Vehicles. The navigation system is based on detecting features of the environment using 2D-laser scanners, as well as wheel encoders for dead reckoning. The system is capable of accuracies of ±1 cm in positioning and ±1 degree in heading. The Navitrol system is used for scanning the environment, tracking positioning, and driving / following routes, with position, speed and steering controls. In addition to the localized positioning system with laser scanners and dead reckoning, the system features external positioning based on GPS or RFID tags. The constant monitoring of the environment allows for detection of collision risks, making the system safe.

The Navitrol system can communicate with a control room supervisory system, Navithor Fleet Control System, via WLAN. Navithor is a fleet controlling software solution for AGVs. The system can control multiple vehicles simultaneously. The system features mapping tools, traffic control, task creation, routing, scheduling, collision avoidance, among other things. (Navitec Systems, 2017)

Some of the latest in modern machinery for wood terminals comes from SKS Toijala Works Oy, with their recently developed TW LogStacker RTD12 KURO. The RTD12 KURO was designed with low operational costs, ease of use and maintenance, and performance in mind. The interesting part from a teleoperation and automation perspective is the use of sensors and displaying the measured data to the user via the machines new interface, as well as possibilities to remotely monitor the condition, maintenance planning, fuel economy, capacity and work cycle planning of the machine via the TW REMOTE remote-control system. The interface includes information about practically every party of the machine: fuel consumption, engine state, transmission, brakes, position, angle and forces of the boom arm, telescope, cylinders, as well as intricate settings for calibrating different parts of the vehicle and a suite of diagnostic tests. (TW LogStacker, 2017). The RTD12 KURO is not a teleoperated or automated machine, but it is easy to see how the use of modern sensors and interfaces lays the ground work for automation and remote operation.

Trucks for transporting roundwood and woodchips are another common type of vehicle used in wood terminals. Volvo Group Trucks has a long-standing history with truck automation, and they have truck automation solutions in agriculture, mining as well as on public roads. Previously their automation endeavors have mostly included partial automation, or automation of certain tasks, but still requiring a human driver. More recently, Volvo has developed and are testing self-driving Volvo FMX trucks, used for mining operations. Using various sensors, such as cameras and radar/laser, the truck can monitor its surrounding environment and detects and avoids stationary and moving obstacles. The trucks also feature an on-board transport system, which gathers data, optimizing the navigated path as well as fuel consumption. The sensors responsible for scanning the environment collect information on every trip, and continuously build and update a map of the route the truck traverses, optimizing the operation constantly. Safety is a top priority for Volvo. Their system in autonomous vehicles is designed in a way, where at least two sensors monitor the same area. If any obstacle is detected, the vehicle stops and a control center is automatically notified. Furthermore, if any fault is detected, the trucks can be remote controlled from the control center. (Volvo Group Trucks, 2017) (Macduff, 2017) (Venter, 2016).

One of the sub systems mentioned was resource management, and one such system for the forestry and transportation side of the process is developed by Fifth Element, a Trimble Forestry company. LogForce™ is a software service for transportations in the forestry industry. The software helps the forestry company handle transport orders, and gives the transporting contractor the tools to plan and manage transport roundwood. Other key functionalities include resource and capacity management, delivery planning and scheduling, stock management, and many others. (LogForce, 2017). Currently the system requires mostly manual input, but the product manager for LogForce at Trimble Forestry Finland sees extending the interfaces and exchanging information via cloud services as a potential direction for automated systems in the future (Peltonen, 2017).

Lastly, we will look at some smart automation systems in port terminals by Kalmar. Although port terminals are a very different environment from wood terminals, monitoring and management systems are an integral part of both, especially when considering automated systems. Kalmar provides many different automation solutions that could be learned from when considering similar solutions for other industries, firstly, SmartTrucks for tracking movement of trucks in real time, secondly, SmartFleet for process automation through remote equipment monitoring and reporting, and lastly Kalmar's Terminal Operating System and equipment control system TLS, which are responsible for managing, coordinating, optimizing and planning cargo and equipment moves at a terminal. The TLS is a shared interface for all Kalmar automated equipment. TLS integrates equipment, process automation, access control, safety and fault monitoring systems. The equipment control system, TLS, executes planning and routing of automated operation orders from the Terminal Operating System. (Kalmar, 2017).

As can be seen, there are many different sub systems in an automation system, and most companies have developed their own systems for their products. With multiple systems, all performing their own tasks, there's usually a need to integrate the different systems and services, under a single suite of control systems, to form an automation system.

4.3.2 Communication

Communication is a part of practically every system involved in an automation process. There is communication between sensors and processing units, communication between equipment, machinery or vehicles and control systems. Communication can happen via internet or intranet, over wired or wireless networks, over local networks or cellular networks. We will consider the different communication methods and structures found in literature. In addition, different communication methods, such as Wi-Fi, mobile (4G, 5G) networks, and other RF based communication mediums are reviewed. Some of the technologies introduced in chapter 4.1.4, namely ultra-wide band (UWB), is originally a communication method, which can be adapted for location tracking purposes. This chapter focuses on more traditional communication methods, starting with common Wi-Fi protocols and moving onto wide area or cellular networks, and finally touching on personal area networks, such as Bluetooth and ZigBee.

Wireless networks are divided into three major categories, Wireless Wide Area Network (WWAN), Wireless Local Area Network (WLAN), and Wireless Personal Area Network (WPAN). WLAN or Wi-Fi as it is more commonly known, is based on 802.11 standard or specification of access for wireless LANs. The latest and most common standards are 802.11n and 802.11ac, **n** is compatible with older standards **a**, **b** and **g**, whereas **ac** is only compatible with the previous **n** standard. Table 8 lists the most common 802.11 wireless standards, including the frequency, bandwidth, data rates and compatibility to previous protocols. The data rates listed are theoretical, and depend on the equipment, environment and the communication medium of the signal. (Moxa, 2016).

Protocol	**Frequency (GHz)**	**Bandwidth (MHz)**	**Data Rate (Mbps)**	**Compatibility**
802.11	2.4	20	1, 2	802.11
802.11b	2.4	20	1, 2, 5.5, 11	802.11b
802.11a	5	20	6 to 54	802.11a
802.11g	2.4	20	6 to 54	802.11b/g
802.11n	2.4 / 5	20 / 40	6.5 to 28.8 13.5 to 600	802.11a/b/g/n
802.11ac	5	20 / 40 / 80 / 160	6.5 to 693.6 13.5 to 1600 29.3 to 3466.4 58.5 to 6933.6	802.11/ac/n

Table 8. Summary of 802.11 standards with theoretical maximum data rates

WWAN or cellular networks are commonly referred to as 3G and 4G networks. Cellular networks in industrial use, such as automation and teleoperation have major concerns regarding bandwidth, latency, IP management and operational costs. Although, as these technologies advance, these concerns are lessened. Cellular standards evolved from 2G (GSM) to 2.XG (GPRS and EDGE) to 3G (W-CDMA, HSPA(+) into 3.XG (LTE) which is commonly referred to as 4G, even though the original LTE standard does not fulfill the technical requirements set by International Telecommunication Union. LTE Advanced (LTE-A) has improved on LTE in various ways, and release 8 of LTE is closer to 4G, but still does not reach the requirements of true 4G. LTE-A release 10 on the other hand does reach the requirements of IMT-Advanced (4G), but is not commercially available yet in most places, if any. LTE-A release 10 could be marketed as 5G, but technically only meets the requirements of 4G. (Moxa, 2016) (Poole, 2017). Table 9 lists some cellular technologies, and their theoretical data rates and latencies. It is important to note that these values area ideal, and real rates can vary highly, depending on distance to base tower, terrain, weather, and especially on other users, as the capacity of wireless towers is commonly shared between the users. A reliable connection could require a dedicated base tower or at the very least using a cellular network that is provided specifically for corporate use. Even then the there would likely be big variance on the quality and reliability of the connection, depending on the location of the operating site, in relation to the cellular tower.

Technology	Upload Rate	Download Rate	Latency
UMTS	64 Kbps	2 Mbps	150 ms
HSPA	5.5 Mbps	14.4 Mbps	100 ms
HSPA+	22 Mbps	42 Mbps	50 ms
LTE	50 Mbps	100 Mbps	10 ms
LTE-A	500 Mbps	1 Gbps	< 5 ms

Table 9. WWAN Technologies with theoretical maximum data rates and typical best-case scenario latencies.

WPAN technologies were developed for short range communication, generally between mobile devices. Technologies such as ZigBee and Bluetooth are categorized as WPAN technologies. ZigBee is a low cost and low power consumption standard, but as a result also features low bandwidth (250 kbps) and range 100m, making it unsuitable for the type of environment discussed in this thesis. Same goes for Bluetooth, which has a data rate of about 1 Mbps and range of 10 to 100 meters depending on the class.

WLAN seems to be the most commonly used communication method. Companies like Navitec use WLAN-based communication for exchanging information with their control systems. Companies that operate in underground mines, such as Boliden or Sandvik also require their own infrastructure for wireless communication, generally Wi-Fi, as remote operation require relatively low latency and high reliability, which generally cannot be achieved with mobile networks or other communication methods, which require line of sight. A study on ‘Mechanisms for collaborative teleoperation with a team of cooperative robots’ also used Wi-Fi networks for communication between robots, as it offered low latency in communication between the robots. (Reinoso, Gil, Payá, & Juliá, 2008), (Bodin, et al., 2015), (Ruokojärvi, 2017).

5 ANALYSIS OF AUTOMATION SYSTEMS

This chapter will give an overview of the process of an automation system, and we will then analyze parts of that process in more detail. We will look at various possible tasks in a wood terminal, and compare which technologies could be applied to those tasks. We will start by giving a high-level overview of an automation system process, and move on by dissecting it from the inside out, i.e. starting from the lower-lever sensor technologies, moving onto teleoperation tasks, into sub-systems and finally into communication. Lastly, we will analyze different safety aspects of the automation process.

5.1 Automation system overview

This chapter gives an overview of an automation system and dissects the different potential automation tasks at wood terminals. Figure 9 describes an automation and teleoperation system at a high level. The diagram encompasses everything from the control system, teleoperation controls, communication methods, all the way to the sensors in a teleoperated or automated vehicle. Although the figure describes remote operation, this could just as easily be oversight of automation, or a combination of both. The figure is a simplification and reality is much more complicated and nuanced, and in this chapter, we will look at some of the possibilities, issues and challenges of such automation systems.

In chapter 1.2 we reviewed some typical operations at a wood terminal, those included reception of material, measurement, unloading either into storage or directly to the mills for processing. These operations can be divided into smaller tasks, for which we can then consider the possibilities, limitations and challenges of automation.

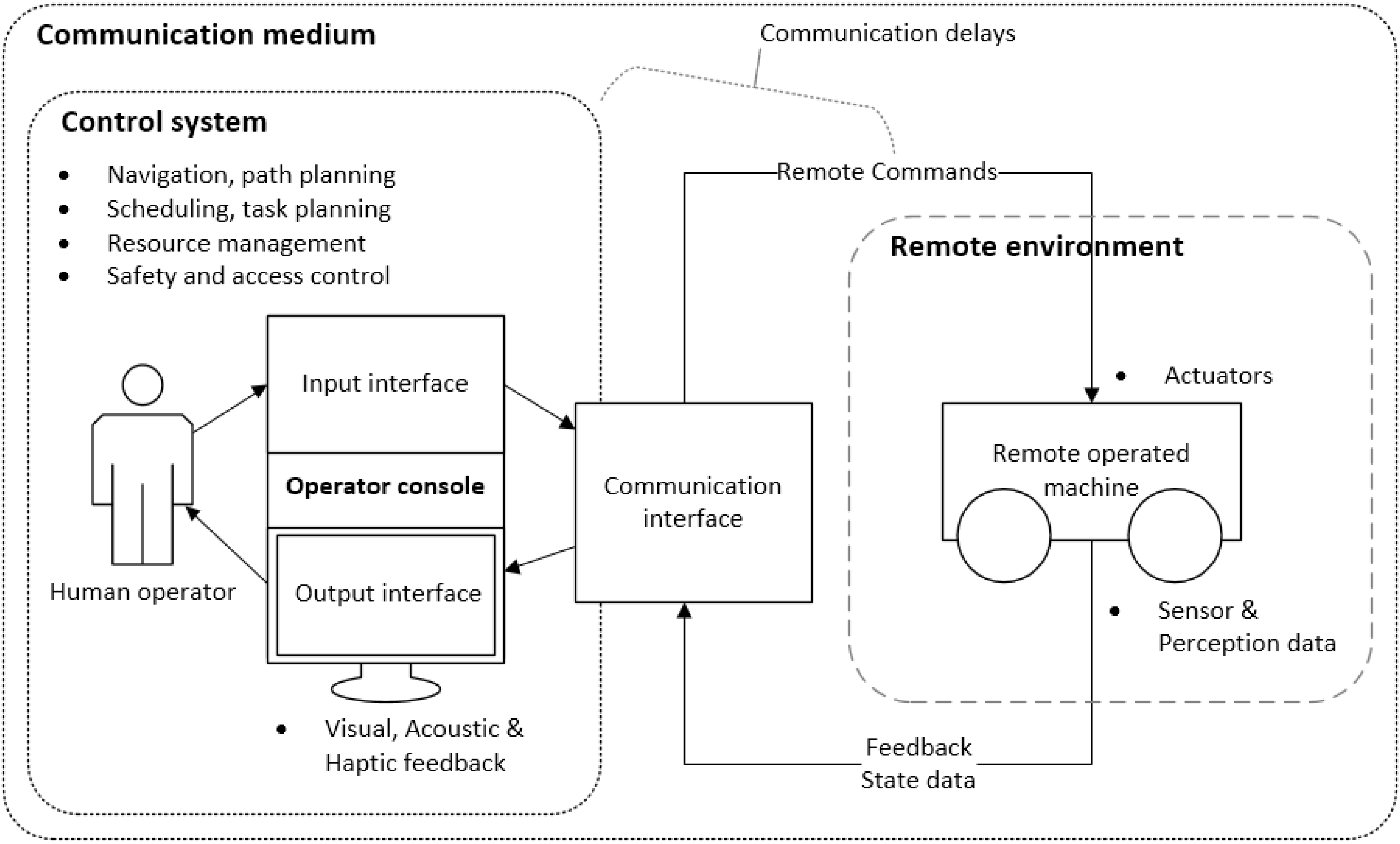

Figure 9. High level diagram of an automation system.

One of the most common tasks is transportation. Practically every machine on the terminal yard is capable of being driven. Vehicles, such as timber and chip trucks, wheel loaders or log stackers all do some kind of transportation and are currently manually driven by human drivers. The task is relatively simple, highly repetitive and thus has great potential for automation. Besides transporting material, material can also be manipulated in other ways, namely by log stackers, wheel loaders and material handlers. There are various tasks involving loading, unloading, storing and feeding the mills with material.

Most tasks revolve around transportation or manipulation of material, as well as the associated control and management tasks. There can also be less obvious tasks involved with other means of transportation, such as trainyard and port operations. Majority of the tasks compiled to a list:

- Transportation
    - Internal material transports via trucks
    - Navigation of terminal yard machinery
- Manipulation of material
    - Moving roundwood with log stackers, wheel loaders and material handlers
    - Managing woodchip piles with wheel loaders
- Control and management tasks
    - Scheduling
    - Management of tasks themselves
    - Resource management
    - Access control
- Tasks in trainyard and port operations

Some of these tasks are easier to automate than others, and some tasks are better suited for teleoperation rather than full automation. The difference in difficulty of automating a task raises the question, which tasks should be automated first? The process of developing and deploying an automation is gradual and requires incremental development. Those tasks which are highly repetitive, easy to automate, increase performance and safety are optimal candidates for automation. The main goals are to cut costs, increase performance and improve safety. When considering a task for automation, it is important to consider if these goals are reached. For example, automating a task that frees the operator does not necessarily increase performance, if the operator does not have other tasks to perform during the time freed up by the automation. On the other hand, if the operator is freed up to perform other tasks, which can be executed simultaneously, for example by operating multiple machines from one remote terminal, then a clear benefit is gained. Increasing performance and lowering costs are obvious goals, but a case could even be made for increasing safety, even if performance is not increased or costs lowered. Safety generally takes priority when considering any task, especially automated ones.

5.2 Automation technologies in use case context

This chapter will look at different automation, teleoperation and communication technologies and analyses which ones are suitable for different use cases in a real-world context, i.e. for use at wood terminals. The chapter starts with a task simple to automate, i.e.

good starting point for automation, and moves onto more challenging aspects of automation. This chapter will also look at some of the costs of automation technologies.

One of the simplest tasks is transportation, and the transportation of trucks is especially tempting as the first candidate for automation, as it the driver is not necessarily required for other tasks, unlike in log stackers for example, where the driver is still required for operating the grapple. The main tasks of sensors in transportation are navigation, localization, and scanning the environment. The context of the working environment is out doors, in closed off terminal areas. The travelling distances within terminals can be kilometers, including both slow- and fast-moving vehicles.

Since the environment is out doors, GPS should be available in most cases, but the terminals contain large buildings which could obscure satellite signals. A GNSS alone is not accurate enough for most terminal operations, meaning other means for improving accuracy are required. One option is to use INS, which can provide supplementary location data, as well as more accurate data about the heading and orientation of the machinery. GNSS can be improved with differential or real time kinematic techniques, but those require added infrastructure (reference stations, receivers, etc.) or other paid correction services, which further increase costs. Other options are localization methods, such as WLPS and UWB, or some other RF based tracking system. The choices come down to the requirements of the tasks, as well as the feasibility or cost of the different solutions.

Another thing to consider with navigation, is the use of mapped data, i.e. pre-planned paths versus operating in unknown environments. “The benefit of planned paths is full autonomy, and potential for optimization, and therefore high-performance level, whereas machines operating in unknown environments can be deployed more quickly” (Ruokojärvi, 2017). For common operations, the use of planned paths seems reasonable, but the potential for operating in unknown environments can also be desirable, as the environment at the wood terminals can be somewhat dynamic, as log stacks and woodchip piles move around.

In addition to navigation or positioning methods, environmental perception, i.e. scanning of the surrounding environment is required, if not for navigation, at the very least for obstacle detection and safety reasons. The most common technologies used in literature were either camera and radar, or LIDAR, although generally speaking vehicles which used LIDAR also use cameras and radar as well. Some popular self-driving vehicles, such as Google's and Toyota's self-driving cars, use LIDAR sensors, but some, Tesla's for example, do not. (Hawkings, 2017) (Hall, 2015). The cost of LIDAR is much higher than that of radars and cameras. Radar sensors combined with cameras are sufficient to facilitate autonomous driving, and furthermore radar has other benefits, such as being able to detect motion and measure speeds, as well as operating better in adverse weather conditions, such as heavy fog, rain or snow. LIDAR and laser scanners have their benefits too, as they are able to capture much more detailed 2D and 3D data about the environment (Example, see figure 10). LIDAR as a sensor is costlier than radar, and in addition it can generate huge amounts of data require more processing power and thus further increasing costs. 3D scanning might be required for dealing with manipulating material. Information about log stacks or woodchip piles might be invaluable when considering automation of tasks related to manipulating those in any way.

There are other sensors for environmental perception, such as ultrasonic sensors, and different types of radar (varying ranges and resolutions for different purposes), and other technologies based on laser scanner and depth perception, such as RGB-D sensors. Different types of sensors give different information, which have their own uses. For example, radar is not disturbed by poor weather conditions, making it more suitable than LiDAR for environmental perception in some scenarios. As with everything, the right solution depends on the use case and its requirements.

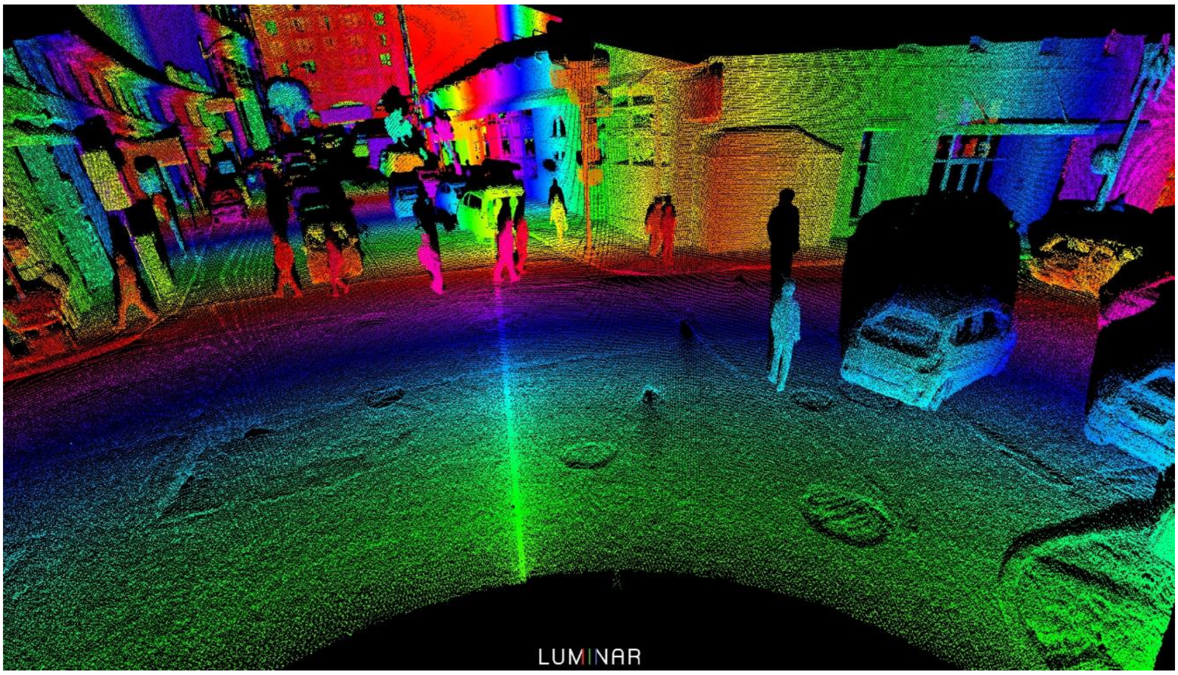

Figure 10. Visualization of data gathered by Luminar's LiDAR, as a high-resolution point cloud. Adapted from Luminar's game-changing LiDAR makes its way to TRI's self-driving car, In *Techcrunch*, n.d., Retrieved September 28, 2017, from https://techcrunch.com/2017/09/27/luminar-lidar-toyota-research-institute/. Copyright 2017 by Luminar.

A 2015 report by the Boston Consulting Group estimated the cost of sensors for autonomous vehicles to be as described in table 10. (Davies, 2015).

Sensor	Cost (USD)
GPS (GNSS)	80 - 6000
LiDAR	90 – 8000
RADAR (Long range / short range)	125 - 150 / 50 - 100
INS (Odometers, tachometers, gyroscopes)	80 - 120
Video cameras (Mono / stereo)	125 – 150 / 150 - 200
Ultrasonic	15 - 20

Table 10. Boston Consulting Group Sensor Cost Estimates

LiDAR is by far the highest cost. Some LiDAR sensors used to cost around $75,000, as the technology was relatively new and not manufactured at mass, but companies such as Google and Velodyne are developing new LiDAR sensors, that cut costs dramatically, down by 90% according to Google. Velodyne reports that their new LiDAR sensors could cost less than

$50 per unit when manufactured at high volumes. (LeVine, 2017) (Ohnsman, 2016). These new sensors will bring the cost of autonomous driving and automation down significantly, and the Boston Consulting Group estimates reflect the more current prices. With all these sensors, the cost of the processing power required to handle all the data has to be considered. The Boston Consulting Group puts the cost of a central computer at roughly 50-200% of the cost of the sensors, making it at the very least a significant portion of the cost. This still does not consider the cost of the necessary control systems, development, integration, etc. Before moving onto control systems, let’s first look at the tasks involving teleoperation.

A task which can be perceived as significantly more challenging than navigation of the vehicles, is manipulating objects or material with them. Operating log stackers, material handlers or wheel loaders for picking up and moving roundwood seems much more suitable for teleoperation, rather than directly going for full automation. Developing a teleoperating systems for the machinery used at the terminals requires working together with machine manufacturers and other automation experts. The first systems should be robust and reliable, and once basic controls have been established, the need for more intuitive controls and teleoperation systems can be evaluated.

Teleoperation systems which embed sensory information, via virtual reality, or use intuitive controls, such as motion tracking may not always be cost effective. The gained benefit from such systems should be studied before implementing, as in worst case scenario a poorly designed system can decrease productivity or introduce side effects, such as simulation sickness. Generally speaking though, most studies have found that virtual reality and audio, haptic and kinesthetic feedback have improved productivity and shortened time to complete tasks, especially when dealing with manipulation of objects.

Some remote operation systems have taken the route of using the controls found in the original machinery, and moving it to a remote operating terminal, making the transition from local to remote operation as intuitive as possible. Obviously, some new equipment, such as cameras and monitors have to be added, but the controls remain largely the same. The possibility of adapting controllers to the environment, operator or task can also improve efficiency of the operator.

A study on 'Human Performance Issues and User Interface Design for Teleoperated Robots' summarizes the factors, effects and suggested solutions to common performance issues in teleoperation, as can be seen in table 11, adapted from (Chen, Haas, & Barnes, 2017).

Factor	Effects	Suggested solution
Field of View	Erroneous speed & distance judgements; peripheral vision loss; degraded remote driving	Increase FOV (caveats: perceived speed increases and motion sickness)
Multiple cameras	Attention switching; change blindness; perception registration	Auditory alerts; multimodal solutions and visual momentum techniques
Camera viewpoint and frame of reference	Egocentric – cognitive tunneling; exocentric – loss of immediacy and true ground view; integration of info from different frames of refence may be challenging; saliency effect	Dual mode and inserts of other views (e.g. sensory ego-sphere); peripheral cues for egocentric
Depth Perception	Underestimating of distance and size; degraded driving and telemanipulation	Stereoscopic displays – improved depth perception, obstacle avoidance, arm manipulation; (Caveats: limited use – benefits mainly for difficult tasks; may induce motion sickness;
Video image / frame rate	Degraded motion perception and spatial orientation; degraded target identification and latency	Minimum frame rate: 10 Hz Augmented reality / Synthetic overlay Stereoscopic displays
Time delays	Task dependent: negative effects from 170 ms to over 1 sec; degraded driving, tracking and telemanipulation; over-actuation when delay is variable; robot-to-operator delay more detrimental than other direction; motion sickness; degraded telepresence	Minimum -170 ms for driving like tasks, others depend on task; predictive displays (e.g. Ecological Display) – navigation faster and more accurate (caveats: disturbances in remote environment may make prediction model unreliable)
Motion	Degradation on accuracy and latency; sometimes severe motion sickness	Multimodal user interfaces; tailor interface to vibratory and motion effects, possible medical remediation

Table 11. Summary of teleoperation performance issues.

In the case of teleoperation in applications for the forest industries, I would imagine the most significant are those that impact accuracy of control, i.e. problems with depth perception as those require more in-depth technology, such as a virtual reality head set or machine assistance.

Teleoperation, depending on the task, can have very demanding time delay (latency) and reliability requirements. Time delay especially has a huge impact on the performance of teleoperators. Time delays come from many different sources, such as network delays, delays from sensors, processing as well as the reaction delay of the operator. (Vozar & Tilbury, 2014). Studies show that people can detect latencies as low as 10 to 20 milliseconds, but major negative side effects become more apparent when delays are above 170 ms. When the latency is over 1 second, the operators begin the control by moving and then waiting, before moving again, as opposed to continuous motion. (Chen, Haas, & Barnes, 2017). Time delays and the subsequent risks caused by them should be considered in the limitations of teleoperated machinery. For example, the movement, speed or power of a machine could be clamped, to decrease the risk of serious damage or injury caused by accidents.

This naturally creates the need for timely and reliable communication methods. In literature, and in most systems, using WLAN was the preferred method of facilitating communication. With the introduction of LTE and LTE-A in the near future, WWAN or cellular networks have improved a lot in the recent years, in terms of data rates and latency. WWAN has the obvious benefit of not required additional infrastructure, but there are still concerns about the reliability of cellular networks, especially in applications, such as teleoperation, which can have strict requirements in order to operate safely. Using cellular networks would likely mean they would be used in all terminals, and it has hard to guarantee the availability of the level of required cellular service at all terminal locations, especially if considering locations globally. The advancement of true 4G might alleviate some of these concerns, but theoretical data rates and latencies are just that, it will remain to be seen if cellular networks can facilitate all networking needs, or if they could be used for less critical applications only. WLAN on the other hand has the benefit of guaranteed high data rates, low latency and high reliability. The major downside is that in a large working environment, WLAN base stations would have to be added to the infrastructure to ensure coverage.

So far, we have discussed the automation of simple tasks and processes, but the other side besides the physical tasks themselves being automated, is the inclusion of control systems. Other companies, such as Sandvik and Kalmar have developed complicated automation systems for their respective industries. These systems are a result of years of research and development, and it is unlikely that the forest industry is any exception. That said, the technologies required for automation are increasingly commercially available, and in many cases, it can be more cost effective to buy ready-made solutions, rather than developing everything yourself. At very least integration of services and sub systems, under a unified control system for the terminals is required, much like what the TLS is for Kalmar.

One thing to note, is that no two terminals are exactly alike, the environment, infrastructure, operations, volume and type of material can differ. Scalability of a desired feature of an automation system, meaning the solutions used to develop automated systems for one terminal, should be applicable to another. Differences in terminals should of course be considered during development. Whether or not it is financially feasible to undertake an automation project like this, may largely depend on how many terminals the automation can be applied to. The cost of development is largely independent of the number of terminals, whereas the benefits, increased performance and cut costs scale directly with the number of terminals. For example, automating one terminal might not be feasible, at least in the short term, but automating multiple terminals could be.

This work has largely focused on the terminal processes and how automation and teleoperation technologies can be applied to those, but it may be valuable to consider changes to the current processes or infrastructure to facilitate automation, rather than think of automation solutions that can adapt to the current processes. A simple change in infrastructure or process can make an automated task much simpler. Changes in infrastructure or processes increase development cost, but this should be weighed against the benefit gained in potentially simplifying the automation process, especially if the automation process yields benefit in the long term. Table 12 summarizes the main tasks, goals, technologies and limitations that have been covered. These tasks can’t be considered on their own, as they are often performed in conjunction with one another. Navigation requires a navigation system, but automated navigation requires more than just GPS for location, it also requires knowledge about the environment. But not all tasks are easily automated, and user assistance in the form of teleoperation is expected to be required for certain more challenging tasks. All of this automation needs to work together seamlessly with the driver/controller. And the whole system needs to be facilitated by a communication system and network, which is both fast and reliable. The table lists various technologies commonly used to achieve these tasks, and a real-life scenario would likely use most of these, with few being true alternatives for each other.

Tasks	Goals	Technologies	Limitations / Challenges
Navigation	Autonomous driving around terminal	GNSS + INS / UWB / WLPS	Loss of GPS signal. Determining min. required accuracy
Scanning environment	Obstacle avoidance Mapping surroundings Object recognition (roundwood, woodchip piles)	Cameras, RADAR, LiDAR, US	Finding most cost-effective solution. Integration / sensor fusion of different sensors. Reliable sensors for adverse weather
Teleoperation (Manipulation)	Facilitate remote operation of machines	Cameras, Stereoscopic displays, VR, bilateral feedback, auditory feedback	Fatigue, simulation / motion sickness. Developing solutions to increase performance.
Communication	Reliable communication for teleoperation, Cost-effective	Wi-Fi, Cellular networks,	Adapting cellular networks to communication. Backwards compatibility. Cost of WLAN network infrastructure.
Monitoring	Tracking devices, people, machinery	RFID, UWB, WLPS, Cameras	Access control, resource management.

Table 12. Summary of automation tasks, goals, potential technologies and their limitations or challenges.

5.3 Safety in automation

One important topic that has not been covered yet is safety. Safety is an integral part of almost every step in an automation process. Safety must be considered at the machine level, communication level, as well as at the system level. In both physical terms and IT security terms, as well as financial safety or risk management. As this work is mostly focused on the technological side of automation systems, we will consider different sensors and methods for achieving safety in the automation processes.

Safety in automation can be divided into three levels, safety in sensors, safety in the infrastructure and safety at the operational level. Firstly, safety in sensors means considering safety in the remote operated or automated machinery. Safe operation of machines can be achieved at a machine level by using obstacle and environment detecting sensors, such as LIDAR, radar or ultrasonic sensors, to ensure the machinery does not cause harm to people, the infrastructure or itself. Sensors should make the final decision whether to stop in a situation which has been detected to be potentially dangerous. Teleoperators should also have the necessary tools to seize activity if they detect any issues or hazardous situations.

Secondly, safety at an infrastructure level means gated off areas for automated machines, access control and use of RFID or other tracking technologies to make sure no personnel or other devices are operating in an area without permission. This entails a system level safety procedures, which can mean access control systems, tracking of personnel and resources, monitoring the conditions of machinery, preventive maintenance, and diagnostic checks.

Lastly, there are also safety measures which can be taken at an organizational level, by changing the working methods and habits of people, to adjust to new processes brought by automation, or at the infrastructure level. Changes in infrastructure does not mean only access control by limiting movement in certain areas, but can also include changes to different mechanisms, for example how roundwood is fed to the processing line.

In conclusion, the process of automating terminal operation is large undertaking, and requires incremental development, moving from easily automated systems and teleoperation towards full automation. There are many alternatives to consider in almost all manner of technologies and sensors, and no right or best solution for all scenarios. The choices have to be based on feasibility of automation and the requirements of different automation tasks and systems. Furthermore, the collaboration of machine manufacturers, terminal entrepreneurs, service providers and management is required, as large projects like these involve many stakeholders. Finally, some advice given by many companies in different industries: managing change is something to prepare for.

6 CONCLUSIONS

This thesis set out to do a literature review on the current state of automation and teleoperation for forest industries, by gathering information from scientific literature and by looking at other similar, but more automated industries, such as those involved in mining, agriculture, cargo ports and autonomous vehicles. The goal of this work was to provide a practical view of automation and teleoperation technologies and used in the 21st century for heavy machinery, such as log stackers, wheel loaders, material handlers and transportation trucks used in forest industries. The objectives were to find the possibilities, limitations and applicability of those automation technologies. The literature review uses material from various databases, online sources, as well as articles, marketing and white paper material from automation project implementation cases from other industries and relevant companies. Interviews with experts and professionals from different industries were conducted to gather more relevant information about the specifics of automation cases.

The main research question was, what are the current technologies used in industrial automation and teleoperation for forest industries? This question is answered by taking a systematic approach for doing a literature review. The methodology in chapter 2 details what approaches were taken to ensure an objective result which meets the goals and limitations set in the introduction. One of the major challenges for this research was defining the scope of the research area. For this reason, a systematic mapping study was conducted first, to help review the scope and define a classification of the major categories that were to be researched in the literature review. Another challenge, which arose during the literature review, was finding enough relevant information from the original papers selected for review. In the end, it was required to expand the searches into additional relevant topics, found from the reviewed papers.

The mapping study identified three major categories for the literature review. Those categories are sensor technologies, teleoperation, and control systems. The topic of sensor technologies focuses on different technologies used in automation and autonomous operations. The topic was further divided into four sub-categories: sensor technologies dealing with navigation, positioning, environmental perception and monitoring. The second category, teleoperation, deals with issues such as telepresence, usability of teleoperation and different forms of control systems for remote control. The last category deals with control systems, which facilitate the integration and communication of various automation and teleoperation systems.

This research identifies many different areas of automation and teleoperation and has introduced them in-depth in the previous chapters. Rather than reiterating those technologies here, I'm going to discuss my views on how applicable those technologies are to the common tasks at wood terminals. Common tasks at wood terminals are those that involve transportation or navigation, manipulation of material, as well control and management tasks related to the automation processes. There are many different sensors or technologies to facilitate these tasks, and the 'correct' choice depends on the requirements of the task and the cost-effectiveness of the solution. It is important to note that these are my views and speculation on the topic, and real feasibility studies and comparison of the different technologies and cost of these solutions would give more definitive answers.

Let's start with sensor technologies. In navigation GPS is a given but improving the accuracy with differential or real time kinematic solutions is debatable. The navigated vehicles would most likely be loaded with an INS, which can already give high precision. Instead of DGPS or RTK GPS, it is likely less expensive to use other localization solutions, such as UWB. The machines can get assistance in navigation from other sensors and systems as well. Environmental perception can help with navigation and make sure the vehicles stay on route, hence centimeter accuracy with GPS may not be required. Environmental perception itself has many different technologies used. The use of cameras and radar, potentially ultrasonic sensors seem to be standard. The real issue is with LiDAR, which I believe would be very useful for mapping and navigating near high log stacks, and managing woodchip piles, but the cost is much higher than the other, older, technologies. That said, the cost of LiDAR has and is coming down rapidly, thus making it potentially feasible and cost-effective in a matter of year(s), if it already isn't.

For teleoperation, it is essential to get robust controls, which are able to handle the complexities of the remotely controlled tasks. Virtual reality, motion controls, and other more complex, but potentially intuitive controls could be added after a steady basis has been achieved. Even then, the benefits should be studied, as improving the controls may not actually improve performance. Virtual reality or more specifically stereoscopic visuals have the most benefit for complex manipulation tasks. Operating log stackers or material handlers could be a task, where the use of stereoscopic goggles could be beneficial. Other companies, such as Hiab with their HiVision system, have successfully implemented this kind of solutions. More important than which specific controller scheme is used for teleoperation, is to consider the usability and performance issues with teleoperation, such as problems with visibility, depth of field, and time delays. The requirements in terms of usability are what are going to determine what kind of control systems are required. Time delay, or latency especially, can have a big impact on the performance of a task. To ensure low latencies, the communication network is important. The operation is wireless and long range, which really leaves two options, wireless local area networks (Wi-Fi) or wireless wide area networks (cellular). Wi-Fi can practically guarantee high reliability and low latencies, but the cost of the infrastructure is something to consider. Latest cellular technology is theoretically powerful enough, but in practice there are many variables to consider. At the very least, the practical potential of using cellular networks for transferring all the data needs to be studied and discussed with the service providers.

Let’s next consider the feasibility of automation at a more generic level. Developing an automation process is no small task and requires a lot of effort as well as investment. It is only reasonable to assume, that the automation should achieve the minimal requirements in the most cost effective way. Sensors and the technology required for automation is becoming increasingly cheaper, but the cost of development, the software, the intelligent systems required to take the data from the sensors and turn it into an automated process or task, are going to be the biggest cost initially. That is why it is important that the automation solutions developed can be scaled to a high number of machines or vehicles, in multiple terminals if possible. Some tasks are easier to automate than others, some tasks require human interaction in the form of teleoperation. Generally, tasks which are repetitive, can help cut costs, increase performance and safety are the ones most likely to be automated first. The process of developing and deploying an automation is gradual, an automation system may start by implementing automation to some tasks and machines, teleoperation to others and gradually increase the level of automation. Besides sensors and different technologies for automation, the control and management systems required for an automation system are also important. An automation project requires both the hardware and the software, as well as integration of the two.

The likely starting point would be automating navigation of vehicles, such as trucks for transportation, as these are the easiest to automate. Automation of trucks makes sense, as it can remove the driver from the trucks, into teleoperation or monitoring duties remotely. Other heavy machinery that even if partially automated, would either still require a human driver in the cabin or a teleoperator operating parts of the machinery remotely, would not be cost effective in the same way. Furthermore, the automation of transportation and navigation of trucks lays the important ground work, in terms of the technology used and the control systems developed, which could likely be transferred into other heavy machinery, when they would be automated in turn.

To summarize the potential process of automating a terminal:

- Research and define the minimum requirements for automating the navigation of trucks or other easily automated machinery.
- Test and implement autonomous driving of trucks or similar machinery with remote control and supervision capabilities.
    - Research the communication requirements and see if cellular networks are capable of meeting those requirements.
    - Start with the minimum requirement of sensors, upgrade as the technology becomes less expensive.
- Develop the necessary control systems (path planning, task planning, supervisory tools, resource management, access control) with automation of other machinery and parts of the processes in mind as well.
- Extend automation to more complex machinery, such as log stackers, wheel loaders and material handlers.
    - Develop more robust remote control systems, with dedicated controls for these types of tasks
- Move towards full automation of remote operated tasks, with the knowledge learned from the previously developed processes.

The important factors are ease of automation and scalability. Cost effectiveness is reached the easiest by meeting the minimum requirements of automating tasks, and upgrading and improving the processes as technology advances and becomes cheaper.

The value of this thesis comes from the general knowledge base it provides, which should help with future endeavors in discussing, researching, designing and implementing automation systems. The research area is wide, and there is a lot of information. My advice would be to focus on the summaries and specific chapters, and dive deeper into the text if necessary, or furthermore in the references if required. The whole area of research is too wide and the entire automation process too complex for there to be any absolute answers in this work, and a lot of future research is required to find specific answers.

Overall this thesis focuses heavily on the technologies and sensors found in literature, not covering other subject matters, such as feasibility, cost analysis and technical specifications in detail. Possible future research directions could include feasibility of actual implementation of an automation system, technical implementation of sensors for automating specific tasks, artificial intelligence and sensor fusion, or more specific studies on limitations of certain sensors, usability issues of teleoperation technologies, or requirements of communication methods.

REFERENCES

Bernini, N., Bertozzi, M., Castangia, L., Patander, M., & Sabbatelli, M. (2014). Real-time obstacle detection using stereo vision for autonomous ground vehicles: A survey. *17th International IEEE Conference on Intelligent Transportation Systems*, (pp. 873-878). Qingdao. doi:10.1109/ITSC.2014.6957799

Bodin, U., Andersson, U., Dadhich, S., Uhlin, E., Marklund, U., & Häggströmff, D. (2015). Remote controlled short-cycle loading of bulk material in mining applications. *IFAC-PapersOnLine, 48*(17), 54-59. doi:10.1016/j.ifacol.2015.10.077

Bogue, R. (2015). Sensors for robotic perception. Part two: positional and environmental awareness. *Industrial Robot: An International Journal, 42*(6), 502-507. doi:10.1108/IR-07-2015-0133

Brei, T. (2013, October 15). *What is Industrial Automation?* Retrieved May 7, 2017, from Sure Controls: http://www.surecontrols.com/what-is-industrial-automation/

Brown, C. (2012, January). Autonomous Vehicle Technology in Mining. *Engineering and Mining Journal, 213*(1), 30-32.

Chakraborty, S., Laware, H., Castanon, D., & Zekavat, S. R. (2016). High precision localization for autonomous vehicles via multiple sensors, data fusion and novel wireless technologies. *2016 IEEE 7th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference*, (pp. 1-9). New York. doi:10.1109/UEMCON.2016.7777799

Chen, C.-H., Cheng, C., Page, D., Koschan, A., & Abidi, M. (2006). Tracking a moving object with real-time obstacle avoidance. *Industrial Robot: An International Journal, 33*(6), 460-468. doi:10.1108/01439910610705635

Chen, J. H., Mu, X. H., Du, F. P., & Guo, H. L. (2013). Key Technologies of Telepresence in Time-Delayed Teleoperation System: Review and Analysis. *Applied Mechanics and Materials;, 328*, 48-55. doi:10.4028/www.scientific.net/AMM.328.48

Chen, J. Y., Haas, E. C., & Barnes, M. J. (2017). Human Performance Issues and User Interface. *IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS—PART C: APPLICATIONS AND REVIEWS, 37*. Retrieved October 5, 2017

Connolly, C. (2007). Collision avoidance technology: from parking sensors to unmanned aircraft. *Sensor Review, 27*(3), 182-188. doi:10.1108/02602280710758101

Cui, Z., Liu, Y., & Gong, Z. (2006). Research on Multi-sensory Virtual Guides based Robotic Teleoperation System. *2006 International Conference on Mechatronics and Automation*, (pp. 1447-1452). Luoyang, Henan. doi:10.1109/ICMA.2006.257842

Davies, A. (2015, April 22). *TURNS OUT THE HARDWARE IN SELF-DRIVING CARS IS PRETTY CHEAP*. Retrieved from Wired: https://www.wired.com/2015/04/cost-of-sensors-autonomous-cars/

Demerjian, C. (2013, October 15). *A long look at Microsoft's XBox One Kinect sensor*. Retrieved from SemiAccurate: https://semiaccurate.com/2013/10/15/long-look-microsofts-xbox-one-kinect-sensor/

Du, J., Mouser, C., & Sheng, W. (2016). Design and Evaluation of a Teleoperated Robotic 3-D Mapping System using an RGB-D Sensor. *IEEE Transactions on Systems, Man, and Cybernetics: Systems, 46*, pp. 718-724. doi:10.1109/TSMC.2015.2461186

European Comission. (2017, 08 20). *Galileo's contribution to the MEOSAR system*. Retrieved 08 13, 2017, from European Comission: http://ec.europa.eu/growth/sectors/space/galileo/sar/meosar-contribution/

European Global Navigation Satellite Systems Agency. (2014, May 27). *The Results are In: Galileo Increases the Accuracy of Location Based Services.* Retrieved August 15, 2017, from GSA Europe: https://www.gsa.europa.eu/news/results-are-galileo-increases-accuracy-location-based-services

Fang, B., Sun, F., Liu, H., & Guo, D. (2017). A novel data glove using inertial and magnetic sensors for motion capture and robotic arm-hand teleoperation. *Industrial Robot: An International Journal, 44*(2), 155-165. doi:10.1108/IR-07-2016-0179

Fin-Terpuu Oy. (2017, August 26). *Fin-Terpuu Oy Logistics*. Retrieved from Fin-Terpuu.fi: http://fin-terpuu.fi/sisainen-logistiikka/

Fredriksson, H., Andersson, U., & Hyyppä, K. (2010). Track Loader Kinematics. *IFAC Proceedings Volumes, 43*(23), 139-142. doi:10.3182/20101005-4-RO-2018.00044

Gezici, S., Tian, Z., Giannakis, G., Kobayashi, H., Molisch, A., Poor, H., & Sahinoglu, Z. (2015, July). Localization via ultra-wideband radios: a look at positioning aspects for future sensor networks. *IEEE Signal Processing Magazine, 22*(4), 70-84. doi:10.1109/MSP.2005.1458289

gps.gov. (2017, August 15). *GPS Accuracy*. Retrieved from gps.gov: http://www.gps.gov/systems/gps/performance/accuracy/

Hall, S. (2015, October 16). *Elon Musk says that the LIDAR Google uses in its self-driving car 'doesn't make sense in a car context'*. Retrieved from 9to5Google: https://9to5google.com/2015/10/16/elon-musk-says-that-the-lidar-google-uses-in-its-self-driving-car-doesnt-make-sense-in-a-car-context/

Hawkings, A. J. (2017, September 27). *Toyota's new self-driving car has two steering wheels to prevent robot joyriding*. Retrieved from The Verge: https://www.theverge.com/2017/9/27/16373058/toyota-research-institute-self-driving-car-luminar

Hiab. (2017, September 3). *HiVision*. Retrieved from Hiab: https://www.hiab.com/en/pages/loglift-jonsered/HiVision/

Ilas, C. (2013). Electronic sensing technologies for autonomous ground vehicles: A review. *2013 8th International Symposium on Advanced Topics in Electrical Engineering* (pp. 1-6). ATEE.

Iwataki, S., Fujii, H., Moro, A., Yamashita, A., Asama, H., & Yoshinada, H. (2015). Visualization of the Surrounding Environment and Operational Part in a 3DCG Model for the Teleoperation of Construction Machines. *2015 IEEE/SICE International Symposium on System Integration*, (pp. 81 - 87). doi:10.1109/SII.2015.7404958

Kalmar. (2017, August 10). *Kalmar Automaatio*. Retrieved from Kalmar: https://www.kalmar.fi/automaatio/

Kalmar. (2017, August 31). *Kalmar Automation*. Retrieved from Kalmar: https://www.kalmarglobal.co.uk/automation/

Kamezaki, M., Yang, J., Iwata, H., & Sugano, S. (2016). Visibility Enhancement using Autonomous Multicamera Controls with Situational Role Assignment for Teleoperated Work Machines. *Journal of Field Robotics, 33*, 802-824. doi:10.1002/rob.21580

Kim, D., Kim, J., Lee, K., Park, C., Song, J., & Kang, D. (2009). Excavator tele-operation system using a human arm. *Automation in Construction*, *18*(2), 173-182. doi:10.1016/j.autcon.2008.07.002

Kitchenham, B., & Charters, S. (2007). *Guidelines for performing Systematic Literature Reviews in Software Engineering.* Keele University and Durham University.

Leandro, R., Landau, H., Nitschke, M., Glocker, M., Seeger, S., & Xiaoming Chen. (2012). *RTX Positioning: The Next Generation of.* Germany: Trimble Terrasat GmbH.

LeVine, S. (2017, March 5). *What it really costs to turn a car into a self-driving vehicle*. Retrieved from Quartz: https://qz.com/924212/what-it-really-costs-to-turn-a-car-into-a-self-driving-vehicle/

Lichiardopol, S. (2007). *A survey on teleoperation.* Technische Universiteit Eindhoven, Eindhoven.

Livatino, S., Muscato, G., Sessa, S., & Neri, V. (2010). Depth-enhanced mobile robot teleguide based on laser images. *Mechatronics, 20*(7), 739-750. doi:10.1016/j.mechatronics.2010.01.011

LogForce. (2017, September 19). *LogForce Service Description*. Retrieved from LogForce: https://www.logforce.fi/description-of-the-service/?lang=en

Macduff, A. (2017, July 7). *The Volvo Truck's view on automation*. Retrieved from Volvo Trucks: http://www.volvotrucks.com/en-en/news/volvo-trucks-magazine/2017/jul/view-on-automation.html

MHI. (2017, August 4). *Automatic Identification and Data Collection (AIDC)*. Retrieved from MHI: http://www.mhi.org/fundamentals/automatic-identification

Milella, A., & Reina, G. (2014). Adaptive Multi-sensor Perception for Driving Automation in Outdoor Contexts. *International Journal of Advanced Robotic Systems, 11*. doi:10.5772/58865

Mine Stories. (2017, September 12). *Mine Stories*. Retrieved from Total control: http://minestories.com/total-control/

Moxa. (2016). *Industrial Wireless Guidebook.* Retrieved from Moxa: http://pages.moxa.com/rs/211-ZWW-883/images/2016_MUS-EN_Industrial%20Wireless%20Guidebook.pdf

Navitec Systems. (2017, August 18). *Autonomous Industrial Machinery & Robotics*. Retrieved from Navitec Systems: http://www.navitecsystems.com/wordpress/autonomous-industrial-machinery-robotics/

NovAtel. (2017, August 19). *Real-Time Kinematic (RTK)*. Retrieved from NovAtel An Introduction to GNSS Chapter 5 Resolving Errors: https://www.novatel.com/an-introduction-to-gnss/

Ohnsman, A. (2016, December 13). *Velodyne Unveils Low-Cost LiDAR In Race For Robo-Car Vision Leadership*. Retrieved from Forbes: https://www.forbes.com/sites/alanohnsman/2016/12/13/velodyne-unveils-lower-cost-lidar-in-race-for-robo-car-vision-leadship/#43d36edb74c4

Oy Adolf Lahti Yxpila. (2017, August 27). *Oy Adolf Lahti Yxpila Ab Services*. Retrieved from Oy Adolf Lahti Yxpila Ab: http://www.adolflahti.fi/oy_adolf_lahti_ab/services

Pachana, T., Trzcionkowski, R., & Turek, W. (2016). Modern Sensors in Mobile Robot Teleoperation. *Advances in Intelligent Systems and Computing, 440*, 501-510. doi:10.1007/978-3-319-29357-8_44

Park, J., Lee, J.-H., & Son, S. H. (2016). A Survey of Obstacle Detection Using Vision Sensor for Autonomous Vehicles. *2016 IEEE 22nd International Conference on Embedded and Real-Time Computing Systems and Applications*, (pp. 264-264). Daegu. doi:10.1109/RTCSA.2016.54

Passenberg, C., Peer, A., & Buss, M. (2010). A survey of environment-, operator-, and task-adapted controllers for teleoperation systems. *Mechatronics, 20*(7), 787-801. doi:10.1016/j.mechatronics.2010.04.005

Peltonen, K. (2017, September 28). Product Manager, Trimble Forestry. (J. Kaplas, Interviewer)

Petersen, K., Feldt, R., Mujtaba, S., & Mattsson, M. (2008). Systematic Mapping Studies in Software Engineering. *12th International Conference on Evaluation and Assessment in Software Engineering*, (pp. 71-80). Bari, Italy.

Poole, I. (2017, September 20). *4G LTE Advanced Tutorial*. Retrieved from Radio-Electronics: http://www.radio-electronics.com/info/cellulartelecomms/lte-long-term-evolution/3gpp-4g-imt-lte-advanced-tutorial.php

Reid, J. F., Zhang, Q., Noguchi, N., & Dickson, M. (2000). Agricultural automatic guidance research in North America. *Computers and Electronics in Agriculture*, *25*(1), 155-167. doi:10.1016/S0168-1699(99)00061-7

Reinoso, O., Gil, A., Payá, L., & Juliá, M. (2008). Mechanisms for collaborative teleoperation with a team of cooperative robots. *Industrial Robot: An International Journal, 35*(1), 27-36. doi:10.1108/01439910810843261

Rovira-Más, F. (2013). Vulnerability of GPS to Provide Vehicle States in Real Time. *IFAC Proceedings Volumes*, *46*(18), 207-212. doi:10.3182/20130828-2-SF-3019.00002

Ruokojärvi, J. (2017, July 12). Product Line Manager, Underground Automation, Sandvik Mining and Rock Technology. (J. Kaplas, Interviewer)

Salminen, J., Knutas, A., & Hajikhani, A. (2017, May 13). *Network Analysis Interface for Literature Studies*. Retrieved from Nails Project: http://nailsproject.net/

Sanders, D. (2009). Analysis of the effects of time delays on the teleoperation of a mobile robot in various modes of operation. *Analysis of the effects of time delays on the teleoperation of a mobile robot in various modes of operation", Industrial Robot: An International Journal, 36*(6), 570-584. doi:10.1108/01439910910994641

Sandvik. (2017). *Mining Products and Equipment - Automation Systems*. Retrieved June 23, 2017, from Sandvik Mining: https://mining.sandvik.com/en/products/equipment/mine-automation-systems

Sandvik. (2017, September 22). *SANDVIK ADDS NEW INTELLIGENT SOLUTION TO ITS INDUSTRY-LEADING AUTOMINE PORTFOLIO*. Retrieved from Sandvik Mining: https://mining.sandvik.com/en/news-media/sandvik-adds-new-intelligent-solution-to-its-industry-leading-autominetm-portfolio

Sandvik AB. (2017, August 29). *Mine Automation Systems*. Retrieved from Sandvik Mining: https://mining.sandvik.com/en/products/equipment/mine-automation-systems

Schmidt, L., Hegenberg, J., & Cramar, L. (2014). User studies on teleoperation of robots for plant inspection. *Industrial Robot: An International Journal, 41*(1), 6-14. doi:10.1108/IR-02-2013-325

Stott, I., Sanders, D., & Tewkesbury, G. (2000). Low cost ultrasonic sensors for tele-operated vehicles. *Sensor Review*(3), 227-235. doi:10.1108/02602280010372377

Trimble. (2017). *Trimble Agriculture*. Retrieved August 2, 2017, from Trimble: http://www.trimble.com/Agriculture/index.aspx

Trimble. (2017). *Trimble GPS Tutorial - How Differential GPS works.* Retrieved August 6, 2017, from Trimble: http://www.trimble.com/gps_tutorial/dgps-how.aspx

TW LogStacker. (2017, September 17). *RTD12 KURO*. Retrieved from TW LogStacker: http://twlogstacker.fi/stackers/rtd12-kuro/

TW LogStacker. (2017). *TW LogStacker*. Retrieved August 7, 2017, from TW LogStacker: http://twlogstacker.fi/

Vähä, P., Heikkilä, T., Kilpeläinen, P., Järviluoma, M., & Gambao, E. (2013, December). Extending automation of building construction — Survey on potential sensor technologies and robotic application. *Automation in Construction*, *36*, pp. 168-178. doi:10.1016/j.autcon.2013.08.002

Venter, I. (2016, September 14). *Volvo places self-driving truck in operation at underground mine*. Retrieved from Mining Weekly: http://www.miningweekly.com/article/volvo-places-self-driving-truck-in-operation-at-underground-mine-2016-09-14

Volvo Group Trucks. (2017). *Driving Automation Is Driving Progress*. Retrieved August 10, 2017, from Volvo Trucks Automation: http://www.volvotrucks.com/en-en/about-us/automation.html

Vozar, S., & Tilbury, D. M. (2014). Driver Modeling for Teleoperation with Time Delay. *The International Federation of Automatic Control.* Cape Town, South Africa.