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READINESS ASSESSMENT OF ENGINEERING PRACTICES FOR DESIGNING AUTONOMOUS INDUSTRIAL MOBILE MACHINERY

Faculty of Engineering and
Natural Sciences
Master of Science Thesis
September 2019

ABSTRACT

Valtteri Vuorimaa: Readiness Assessment of Engineering Practices for Designing Autonomous Industrial Mobile Machinery
Master of Science Thesis, 74 pages
Tampere University
Master's Degree Programme in Mechanical Engineering and Industrial Systems
September 2019

Autonomous industrial mobile machines have emerged as proof-of-concept demonstrations in various industries in the past years and commercialized in some industries as well. Advances in automation engineering has developed to a stage where the automated machines are called as autonomous machines with varying degrees of autonomy from semi-automated functions to full autonomy. Advances in maturity of technologies providing autonomous functions have enabled new developments in designing autonomous mobile machines. In addition to the advances in technologies providing autonomous functions, advances in maturity of engineering practices has enabled development in the autonomous technologies.

This thesis aims to assess readiness factors of engineering practices for designing autonomous industrial mobile machinery. The readiness factors consider elements that are required of engineering practices to design autonomous mobile machinery. Such assessment includes presenting focal challenges in autonomous systems design, solutions and methods for overcoming those challenges and important considerations for design. The research objectives are based on a hypothesis that the new technologies which provide autonomous functions result in new design requirements for engineering practices. The research objective is to discover what does the increasing autonomy produce for the design of the machine. The methods include a literature research, which presents design considerations found from varying fields of autonomous systems development (aerial, maritime, road vehicle and mobile machines), and an interview research, which presents an anonymized interpretation of eight thematic interviews findings. Interviews were conducted with mobile machine original equipment manufacturers and system integrator companies interested in the development of autonomous mobile machines.

Based on the literature and interview researches, a set of readiness elements and factors are assessed as a summary. It can be concluded, that the engineering practices should consider a new operational principle of an autonomous system that must include clear benefits compared to the operation principle of a regular machine. The benefits can be gained from varying levels of autonomy. Readiness factors include considerations for a new set of competences, managing an interdisciplinary design process, importance of partnerships and ecosystems with longevity, and advanced use of digital design practices and physical test environments that complement each other and the design process of autonomous functions.

Keywords: autonomy, industrial machines, machine design, readiness

TIIVISTELMÄ

Valtteri Vuorimaa: Teollisuuden autonomisten liikkuvien työkoneiden suunnittelumenetelmien valmiusarviointi
Diplomityö, 74 sivua
Tampereen yliopisto
Konetekniikan diplomi-insinöörin tutkinto-ohjelma
September 2019

Teollisten autonomisten liikkuvien työkoneiden toteuttamiskelpoisuus on osoitettu eri teollisuuden aloilla menneinä vuosina ja joillakin aloilla autonomisia työkoneita on jo kaupallistettu. Automaatioteknologian kehitys on edennyt siihen pisteeseen, missä automaattisesti toimivia työkoneita kutsutaan autonomisiksi ja eri autonomian tasoja ilmenee puoliautonomisista toiminnoista täysautonomiseen toimintaan. Kehitys autonomisten toimintojen mahdollistavien teknologioiden kypsyydessä on mahdollistanut uusia kehityksiä autonomisten liikkuvien työkoneiden suunnittelussa. Autonomisten toimintojen kehityksen lisäksi, suunnittelumenetelmissä on tapahtunut edistystä, mikä mahdollistaa uuden kehityksen.

Tämä diplomityö pyrkii arvioimaan teollisten autonomisten liikkuvien työkoneiden suunnittelumenetelmien valmiuksia. Valmiustekijöitä käsitellään vaatimuksina, eli mitä autonomisten liikkuvien työkoneiden suunnittelulta vaaditaan. Arvioinnissa esitetään keskeisiä autonomisen systeemin suunnitteluhaasteita, haasteiden ratkaisussa käytettyjä menetelmiä sekä suunnittelussa huomioitavia tärkeitä tekijöitä. Tutkimustavoitteet perustuvat hypoteesille missä oletetaan, että uudet autonomisten toimintojen mahdollistavat teknologiat tuottavat suunnittelulle uusia vaatimuksia. Tavoitteena on tutkia minkälaisia vaatimuksia autonomia tuottaa koneen suunnittelulle. Menetelmät sisältävät kirjallisuustutkimuksen, jossa esitetään näkökulmia eri alojen autonomisten systeemien kehityksestä (ilmailu, meriliikenne, maantieajoneuvo ja liikkuva työkone), sekä haastattelututkimuksen, jossa esitetään anonyymisoitu tulkinta kahdeksasta teemahaastattelusta. Haastateltavina oli autonomisten systeemien kehityksestä kiinnostuneita liikkuvien työkoneiden valmistajia, sekä järjestelmä- ja ohjelmistotoimittajia.

Kirjallisuuteen ja haastattelututkimukseen perustuen joukko valmiuselementtejä ja tekijöitä on arvioitu yhteenvetona. Johtopäätelmänä voi sanoa, että suunnittelumenetelmien tulisi ottaa huomioon autonomisen systeemin uudenlainen toimintaperiaate, jossa on oltava selkeitä hyötyjä perinteisen koneen toimintaperiaatteeseen verrattuna. Eri autonomian tasot voivat tuoda riittäviä hyötyjä. Valmiustekijät sisältävät mm. pohdintaa uusista kompetensseista, monialaisen suunnitteluprosessin hallinnasta, yhteistyökumppanien ja ekosysteemien pitkäjänteisyyden tärkeydestä ja digitaalisten suunnittelumenetelmien ja fyysisten testiympäristöjen toisiaan ja suunnitteluprosessia täydentävästä edistyksellisestä käytöstä.

Avainsanat: Autonomia, teolliset koneet, koneensuunnittelu, valmius

PREFACE

This thesis was part of a research and development project at VTT Technical Research Centre of Finland Ltd. I would like to thank my VTT's supervisors Eetu Heikkilä and Päivi Kivikytö-Reponen on providing me an interesting topic for research in my thesis, my colleagues for showing examples of enthusiastic work culture and thinking beyond the obvious and my supervisors from Tampere University. I also present thanks to my girlfriend Laura for providing support for a research trainee wondering in a world of challenges.

Special thanks are presented to the project manager Eetu Heikkilä, who gave valuable comments throughout the writing process and efforts towards aiding me to finish this thesis, and special thanks are presented to the interviewees who gave their precious time and opinions for the interviews.

Tampere 30th September 2019

Valtteri Vuorimaa

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AI	Artificial intelligence
AM	Autonomous machine
AMS	Autonomous machine system
ARE	Autonomy requirements engineering
AS	Autonomous system
ATRA	Autonomy technology readiness assessment
AVRI	Autonomous vehicles readiness index
CE	Concurrent engineering
CV	Computer vision
Data AMA	Data acquisition, management and analysis
DDE	Digital design environment
EMS	Equipment monitoring system
ERP	Enterprise resource planning
FMEA	Failure modes and effects analysis
FTA	Fault tree analysis
GAR	Generic autonomy requirements model
GORE	Goal-oriented requirements engineering
GPS	Global positioning system
HMI	Human-machine interaction
HMIf	Human-machine interface
IMU	Internal measurement unit
LIDAR	Light detection and ranging sensor technology
LoA	Level of autonomy
ML	Machine learning
OEM	Original equipment manufacturer
Radar	Object detection technology using radio waves
R&D	Research and development
RRL	Risk reduction level
SIL	Safety integrity level
TLS	Terminal logistics system
TRL	Technology readiness level
UGV	Unmanned ground vehicle
V&V	Verification and validation

1. INTRODUCTION

The purpose of technology is to serve people by improving wellbeing. Humankind faces interesting challenges and opportunities as the level of automation rises globally. Removing unnecessary work required to keep the society functional has been an ongoing process, leading us towards a day, where autonomous machine systems (AMS) are equipped with human-like abilities such as sensing, thinking and acting. But an increasingly autonomous machine performing better than a human is a challenge to design. This is the hypothesis that the thesis is based on. The increased autonomy makes the design process difficult. Thus, new approaches and methods to design such product are required.

This thesis focuses on presenting challenges and solutions that selected companies developing autonomous products will face, particularly autonomous industrial mobile machinery, such as underground mining equipment, agricultural machinery and container handling equipment. A literature review on the state-of-art of AMS design is presented. The opinions of original equipment manufacturers (OEM) and system integrators developing AMS's on AMS design challenges were studied within thematic interviews. The readiness of engineering practices is assessed as a summary, where important elements of AMS design are presented. In addition to discussing the findings of autonomous industrial mobile machinery, the advances in automotive, maritime and aerial vehicle development are inspected to assess similarities in technology and design, which complement the mobile machinery design.

Autonomous systems are not a new concept. There have been autonomously operating systems for a long time, especially in constrained environments that are forbidden from other operators than autonomous machines. The advances in technologies that enable autonomy are slowly providing better readiness to develop AMS's. In practice, this means that the machine system is less dependent of human interaction. Human operator and a machine together can form an intelligent working unit. Human cognition, a mental process of acquiring knowledge through senses and generating new knowledge through reasoning, is being replaced by technological functionalities in an AMS, as the human operator is no longer solely responsible of the machine's actions. Delegating the responsibility of human cognitive actions to technological functions could ideally provide a safer machine with better work efficiency. However, such sought benefits come to reality only, if difficult design challenges are solved. Not only does the complexity of the AMS design come from technology design, but also from designing a product as if it were to operate better, safer and more efficient than a human.

Artificial intelligence (AI) and machine learning (ML) are hot conversation topics in society and engineering community currently. The word “autonomous” is easily linked with

AI, since self-governing and deciding is an autonomous act requiring intelligence. The conversation about autonomous vehicles revolves around AI and ML models, often not giving attention to other important challenges in autonomous system design (Sifakis, 2019). Some important questions arise as well, such as: How to evaluate system autonomy? What technologies are providing autonomy? What risks and benefits come from autonomy? What new requirements does the autonomy produce?

1.1 Thesis background

This thesis is part of a research and development project on AMS's design at VTT Technical Research Centre of Finland Ltd. The project takes measures towards integrating the existing knowledge of AMS's and providing an overview of tools and resources required for designing and a public vision on the future of AMS's. AMS's need a robust design approach and ways to certify the machine safety and reliability. Integrating the different design processes of technologies required for autonomy into the AMS design is a challenging task: New requirements to design such as AI, 5G connectivity, cyber security and human factor issues are key elements to consider as well. The project context is focusing on industrial systems utilizing autonomous machinery and vehicles.

1.2 Research objectives and methods

The research is based on a hypothesis: New challenges arise in the design of an autonomous mobile machine, which requires new kind of readiness for design. The term readiness means being prepared or ready for something. The readiness aspect is considered as means for finding the focal challenges in designing autonomous machines, finding solutions for the challenges and evaluating how the solutions solve those challenges. If a design challenge has been solved, then the readiness to design is achieved. If a design challenge has no solution, then the readiness is not there. Evaluation of a possible solution may show us a partial readiness, which means that the solution may solve the challenge partially. The research objectives seek to find what the readiness factors are. The question in this case is, to what extent do the current engineering practices enable to design autonomous industrial mobile machinery. In general, the thesis seeks answers to the following questions:

- What are the challenges and practices in design and validation of autonomous systems?
- What new requirements does the increased autonomy produce?
- What kind of readiness factors should be considered when designing an autonomous system?

The research methods include a literature review of autonomous machine state-of-art design and interviews with mobile machinery companies on their design approaches towards an autonomous machine. The literature review presents key technological aspects in autonomous mobile machine design such as definition of an autonomous system, technological requirements for autonomous operation and state-of-art design challenges and methods for solving such challenges. In addition, an example of an actual autonomous mobile machine is presented. The example demonstration presents drivers, enablers and benefits of autonomous machine operation. Operation profile and technologies providing autonomous operation are also presented.

The focus of the interviews was on original equipment manufacturers and system integrator companies' challenges for designing AMS's. A set of thematic (semi-structured) interviews were conducted, where the topics for the interviews were designed based on major challenges found from literature. The interview research as whole was based on the framework provided by Hirsjärvi and Hurme (2011) as shown in figure 1.

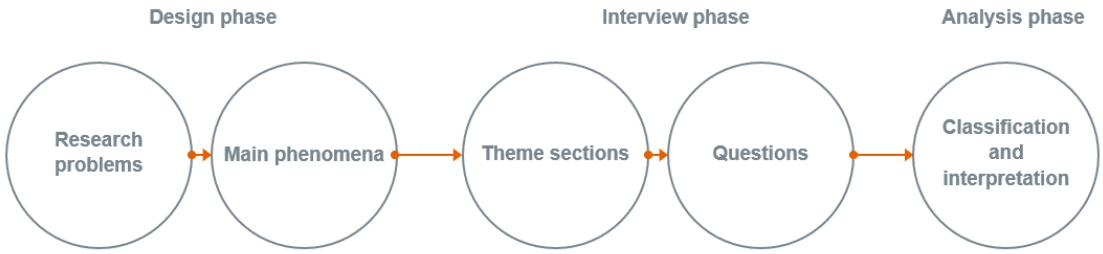

Figure 1.*Phases of interview research adopted from Hirsjärvi and Hurme (2011).*

Interviewees consisted of selected company representatives (e.g. chief technology officer, technology manager, engineering manager, R&D director), with a good general view on their company's direction towards increased autonomy, as well as the overall developments in industry. A semi-structured interview was based on the research prior to the interviews. The research problems and main phenomena were classified to build an interview framework. The purpose of the interview framework was to structure the interview topics, and possibly aid the interviewer to deepen an interesting subject provided by the interviewee. However, the theme sections were only a structure for the interview, merely a basic theory, giving the interviewee freedom to represent their personal opinion on the subjects given.

A qualitative research method called thematic analysis (Hirsjärvi and Hurme, 2011) was chosen as a form to represent the interview research results. Since the interviews consisted of varying points of views and versatile discussion about the topics with common features, and they couldn't be accurately evaluated with a quantitative method, a thematic analysis was chosen to provide a suitable method for interpretation of interviews. Thematic analysis identifies and categorizes the themes, in order to enable a more detailed exploration. In addition to thematic analysis, the research results are anonymized: Interviewees names, represented companies and industries are not presented so that one cannot deduce the source of presented results.

The research questions are discussed as part of research outcome. The research outcome is based on the results of the literature and interview researches. The outcome is presented as readiness elements and factors, which is based on the readiness assessment methodologies presented in literature. These methodologies are more closely inspected in chapter 2.10. Considerations based on literature and interview researches are discussed as part of identifying readiness factors for designing autonomous industrial mobile machinery.

1.3 Scope and limitations

The scope of the thesis is on mobile machinery, in this case meaning heavy equipment and machinery, for example machines used for port and mining operations, forest harvesting and unmanned ground vehicles. The predefined scope mostly affects the interviewee selection, but in the literature review more space is left for studying AMS's from other fields of engineering. The focus is particularly on the design of individual autonomous machine instead of a fleet of machines. Practically this means that on-board systems are included, and machine-to-world connectivity related systems are excluded within the literature study.

The autonomous system development has seen advances in many fields, and the research from different areas provide useful information on design processes and challenges. Although the scope of the thesis is mobile machinery, autonomous automotive, robotics, aerial and maritime technologies were researched in literature in order to provide a comprehensive idea of the technologies used for autonomous system design. For example, autonomous mobile machinery and autonomous vehicles (AV) include technological similarities such as sensors, methods for navigation and planning and systems for safety, thus providing complementing cross sectorial ideas for design of autonomous mobile machine. However, differences exist, for example safety requirements, between mobile machinery and AV's. AI and ML are viewed from the overall machine control perspective excluding algorithm studies. In addition, discussion related to the ethics and acceptance of an AMS is not included in this thesis.

1.4 Structure of the thesis

The thesis consists of a literature review in chapter two, in which the state-of-art of autonomous systems design is presented. The literature review aims to provide a general view on the large field of challenges and design approaches that have been researched and presented in literature.

Chapter three presents the anonymized interpretation of interview research on mobile machine OEM's and system integrators about the state-of-art of AMS design. The presented results are anonymized, and the presentation is an interpretation with an aim to reflect the outcome from multiple interviews. The chapter represents the results of thematic analysis: The qualitative research analysis method "thematic analysis" includes classifying the research under often occurring themes and subthemes.

The research summary and critique are presented in chapter four. The outcome includes identifying readiness factors, which are based on the analysis of interview research. A preliminary method for readiness evaluation is presented, which represents a summary of the research. Conclusions on thesis are presented in chapter five.

2. LITERATURE RESEARCH

The literature research presents important topics to consider from the engineering practices point of view for designing AMS. The state-of-art of AMS design is presented, with discussion on what are the challenges, solutions and considerations in AMS design. The search terms of presented literature on autonomous machine design was based on the original project background information mentioned in chapter 1.1. This chapter presents a definition of the autonomous mobile machine, concept of level of autonomy, technological requirements for autonomous machine, challenges and practices of autonomous machine design found from literature. In addition, a demonstration of a real autonomous machine and important considerations related to its operation are presented. Readiness methodologies from literature are presented as a reference method for assessing readiness factors for engineering practices in chapter four.

2.1 Definition of an autonomous mobile machine

The terms adaptive, intelligent, smart, unmanned, uncrewed or highly automated are used often within the context of autonomy in technology. According to NASAs report Autonomous Systems Taxonomy (Fong *et al.*, 2018), autonomy is the system's ability to achieve goals with operation independent of external control, and autonomy is not AI nor automation, but it may use both for reaching goals. System autonomy can be described as a self-directed and self-sufficient and it can have humans operating with the system (Fong *et al.*, 2018). Autonomy includes understanding about what actions to take according to the data gathered and how to deal with uncertainty (Fong, 2018). Often in literature, the following capabilities for autonomous machines occur: ability to sense surroundings, plan further actions according to the situational awareness, decide further actions and act (Pendleton *et al.,* 2017*;* Kendoul, 2013).

Autonomy is moving to all sorts of domains including mobile machinery, and the main driving forces behind autonomy are environment, efficiency and safety aspects (Behere *et al.*, 2016). Mining, construction, logistics, forest harvesting, field crops, ports, municipal machinery and airports all use mobile machines that have potential to perform functions autonomously. According to the European Commission (European Commission, n.d.) defines mobile machinery as follows:
Mobile machinery includes a wide range of machinery designed to perform specific operations in off-road environments, such as:

- *Agricultural machinery (e.g. sprayers, combined harvesters, forestry equipment)*
- *Construction machinery (e.g. lifting and handling equipment, earthmoving machinery, mobile cranes, industrial trucks)*
- *Gardening machinery (e.g. lawnmowers)*
- *Municipal machinery (e.g. for street cleaning or snow removal)*

Mobile machines operate in various environments with many purposes, making the use of autonomous functions different in each area. According to Tirkkonen (2018), the automation in mobile machinery means fully- or semi-automated control of the machine, remote surveillance and support, autonomous (unmanned) machines and autonomous machine systems. In this view, the autonomous machines are seen as part of automation in mobile machinery in general.

The technological maturity of autonomous technologies varies in each field of mobile machinery industry. Table 1 provides an overview of where selected autonomous mobile machines operate and what kind of autonomous functions and challenges occur in each field. It is to be noted, that the autonomous functions presented in table 1 are still mostly in developmental phases and some of the challenges presented are similar between different mobile machines.

Table 1.*Selected autonomous functions and challenges in mobile machine domains presented in literature.*

Mobile machine industry	Autonomous function	Autonomy challenges
Underground mining operations	**Loading and haulage operations** Human health and safety issues are primary driver for autonomy in underground operations. Secondary drivers are operational effectiveness, increased fleet utilization and production and smoother machine operation (Paraszczak, 2014).	**Localization** is difficult in constantly evolving underground environment without GPS utilization. To solve this issue dead reckoning methods are utilized. (Gustafson, 2011) A challenge is to **improve maintenance**, so that unplanned breakdowns don't happen in difficult locations. (Paraszczak, 2014)
Construction	**Excavation, loading and hauling operations** Repetitive excavator operation can be a future autonomous function (Mevea, n.d.). Load carriers transport material between locations to provide worksite efficiency (Raczon, 2018).	**Complex driving routes and evolving operating environments** provide a challenge for **path planning**. **Communication and positioning** of a machine use Wi-Fi and satellites, but LTE networks are emerging in order to improve performance, security, availability, seamless mobility and service supportability. (Komatsu, 2019)
Agriculture	**Autonomous farming operations** Greater profits are sought through autonomous agricultural field operations: Operations can be done when weather conditions are favorable, outside operator working hours. Smaller than regular machines can be utilized for more accuracy and chemical, fertilizer and fuel use efficiency. Lesser soil compaction and better crop quality and yields are possible due to autonomous farming. (Shockley, Dillon and Shearer, 2019)	**Profitability** of autonomous operation should be considered, as the investment for intelligent controls of an autonomous machine is high (Shockley, Dillon and Shearer, 2019). Autonomous operations can replace repetitive operations in large scale field crops. However, small and medium scale fields have environmental and economic constraints, and too complex tasks to implement autonomous operation. For example, harvesting fruit from trees requires more maturity from sensor and algorithm development. (Vasconez, Kantor and Cheein, 2019)
Forest harvesting	**Felling, extracting and processing of harvested trees** Autonomous extraction systems may have a commercial opportunity in the near future. Long-term opportunities include felling of trees. Ability to remote operate an autonomous machine is a required function. (Visser, 2018)	Tree selection is difficult due to **lacking sensing accuracy** of correct trees. **Safety considerations** when felling trees are required to avoid human and animal hazards. **Forest is a complex environment** to operate in, thus making the autonomous operation difficult. (Visser, 2018) **Localization, navigation and mapping** in deep forests is a complex task, since GPS or satellite connection is not constant. (Kukko *et al.*, 2017)

Cargo handling solutions to ports, terminals, and distribution centers.	**Autonomous container handling** utilizes straddle carriers and stacking cranes. In the future, logistic chains may include various autonomous operations between automated terminals. (Hämäläinen, Yli-Paunu and Peussa, 2018)	**No specific standards** for autonomous container terminal automation, so existing regulations are interpreted to assist design. **Improving the reliability and performance** of load handling and **smooth collaboration** between machines, other vehicles and people are main challenges. (Hämäläinen, Yli-Paunu and Peussa, 2018).
Unmanned Ground Vehicles (UGV's)	**Autonomous operation** for exploring and investigating volcanoes, planets, orchards, forests and battlefields (Kobayashi *et al.*, 2018). **Autonomous following** of an agent or **autonomous navigation** through environment using waypoints. (Rakkatec, n.d.)	**Accurate map of the environment is not guaranteed,** so methods such as Simultaneous Localization and Mapping (SLAM) are required (Kobayashi *et al.*, 2018). **Navigation in unstructured environments** is difficult due to correctly detecting and classifying dense vegetation from non-navigable solid obstacles (Goodin *et al.*, 2018).

Unmanned machines find their usefulness in areas that are restricted from other operating agents than machines. For example, difficult and dangerous for areas for humans, such as underground mines where the extreme environmental conditions take a toll on machine components and possibly on operators, make use of unmanned autonomous machines. Removing the human from the work process and replacing it with autonomous machine in such environments provides a solution for worker safety and work efficiency. Unmanned loading- and hauling machines are used in underground operations. Underground areas make it difficult for the machine to navigate, but solutions for the navigation issue have been developed to a point where the mining automation, with unmanned machines, is commercialized (Tirkkonen, 2018).

Each sector of mobile machinery has their own challenges due to varying use cases and environments. However, most of the challenges are similar: the lack of specific standards for autonomy, reliability and performance, localization, navigation, mapping, environmental sensing and communications are all common challenges. A common challenge among all autonomous mobile machines is ensuring safety. Although, specific standards such as *Earth-moving machinery and mining. Autonomous and semi-autonomous machine system safety* (ISO 17757:2017) and *Agricultural machinery and tractors – Safety of highly automated agricultural machines – Principles for design* (ISO/FDIS 18794:2018) provide some specific safety requirements for autonomous machines in mining and agriculture environments.

2.2 Different levels of autonomy

For a machine to be called as autonomous, it might not require complete independence from human interaction, or to be fully autonomous. This indicates that there are some operating scenarios or modes that are less autonomous, while still including some autonomy. These lower levels of autonomy are for example driving assistance, remote control or conditional automation. The following modified categorization is a widely referenced way to represent different levels of autonomy in the automotive sector. It is based on the report by Society of Automotive Engineers (SAE-J3016). The vehicle system has six descriptive levels of driving automation:

· Level 0: No automation. Driver is solely responsible of the driving task.
· Level 1: Driver assistance. System assists the driver with driving modes, leaving the driver responsible of steering and acceleration.
· Level 2: Partial Automation. System is capable of steering and acceleration by using environmental information, but driver is responsible of monitoring environment.
· Level 3: Conditional Automation. System executes the driving task, but driver is responsible of intervening appropriately when required.
· Level 4: High Automation. System is capable of executing the driving task, without requiring appropriate human intervention.
· Level 5: Full Automation. System has full autonomy and is capable of executing the same driving tasks in as a human driver in all conditions.

The SAE-J3016 description is tied to the autonomous driving task, but the level of autonomy (LoA) concept describes the degree of autonomy of a machine without being bound to a certain task as the SAE-J3016 description. A fully autonomous state means that the machine has complete decision-making and executing capabilities over its functions without the need of human intervention. A machine operated by a human or a machine operating in a fully autonomous state are both at the opposite ends of the LoA spectrum. Defining the LoA is part of defining the autonomous functions and understanding the functional requirements of the machine, which is why understanding LoA is important. LoA and human independency are equivalent means of description (Kendoul, 2013). Defining the LoA in mobile machinery in general is challenging, since the use cases of mobile machinery vary greatly. It has been shown that it is possible for a mobile machine to reach fully autonomous actions with modern technologies and equipment (Huhtala, 2018). However, every use case requires a specific evaluation for LoA. The case specific evaluation results in an understanding of different states of autonomy in between the non-autonomous and fully autonomous state (Durst and Gray, 2014). The system lifecycle may also include varying states of autonomy.

A method for evaluating LoA was presented by Huang *et al.* (2005). The autonomy levels for unmanned systems (ALFUS) framework uses a detailed model autonomy level tool to accurately assess the autonomy level with three adjustable metrics: The type of task performed, type of working environment and the amount of human interaction all together define the LoA. The tool calculates a LoA value from the metrics values given (Huang *et al.*, 2005). It is important to mention, that the theory and practices of autonomy metrics and taxonomies have improved since the creation of ALFUS (Kendoul, 2013). An overview of the different aspects to defining the level of autonomy is shown in figure 2.

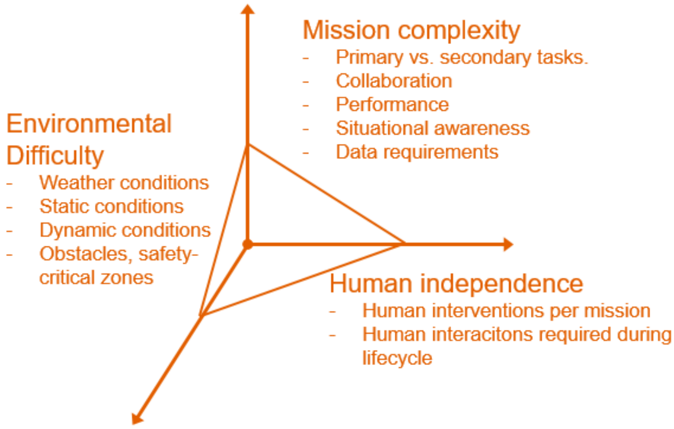

Figure 2. *Environmental difficulty, mission complexity and human independence factors define the level of autonomy. Figure modified from Huang et al. (2005).*

The detailed model shown in figure 2 gives us an idea of type of properties to be considered when defining the challenges of autonomy and LoA. Task complexity, adaptation to environment, human collaboration, different types of interaction and performance factors are key concepts of the ALFUS model (Huang *et al.,* 2005). The factors shown in figure 2 can be requirements set for the autonomous system making the metrics usable in testing of the AS. In general, the LoA describes how advanced the system is and to what degree the machine is dependent on human interaction.

In addition to defining the LoA of an AMS, assessing the readiness to develop autonomous mobile machinery can benefit from further understanding of its LoA and the technology readiness level (TRL) of each LoA defined. The Autonomy and Technology Readiness Assessment (ATRA) framework proposed by Kendoul (2013) presents guidelines to assess the ATRA of an AS in general. It provides a comprehensive picture of the system capabilities and its suitability for a particular application, such as unmanned aerial system. It is based on the autonomy providing subsystems (e.g. guidance, navigation and control), for which the LoA and technology readiness level (TRL) are defined. The LoA itself does not explain the maturity of autonomous enabling technology at the component and system level, which is why both the TRL and LoA of the AS are measured (Kendoul, 2013).

The ATRA framework presents factors to consider within the design process of an AMS. The functions, metrics and approaches in ATRA framework could be adjusted to a design process of an autonomous mobile machine. The highest LoA may not be required to fulfill functional or other type of requirements for the autonomous product but defining the LoA according to important recognized metrics and functional capabilities is part of assessing what improvements are required to reach the desired LoA. For some autonomous functions, a lower LoA may be enough, but acknowledging this through a formal framework like ATRA can help in design and to provide a visual presentation of the autonomous mobile machine design.

2.3 Technological requirements for autonomous functions

AMS's are developed towards the ability to sense, think and act. In the mobile machinery context, this means the AMS must have perception of its surroundings, ability plan further actions and control the machine to act accordingly. In past years, the interest in autonomous systems has increased due to technological advances in computing power effectiveness and reduced cost of components required for autonomous operation, such as sensors and processors (Pendleton *et al.*, 2017). A key research field in autonomous machines and machines assisting the operator is situational awareness. Furthermore, control strategies, sensors and algorithms for autonomous operation of mobile machines are essential research topics (Huhtala, 2018).

AMS's include subsystems for perception, planning and navigation and the interaction of these subsystems with the environment determines system performance (Young *et al.*, 2017). The subsystems of an AMS can also be called as navigation, guidance and control (Kendoul, 2013) or perception, planning and control (Pendleton *et al.*, 2017), but varying types of taxonomies exist for the AMS's and its subsystems. A generalized AMS overview shown in figure 3 divides the system into hardware, software and cloud. Figure 3 is modified from (Pendleton *et al.*, 2017), which divides the autonomous vehicle system into hardware, software and core competencies within them.

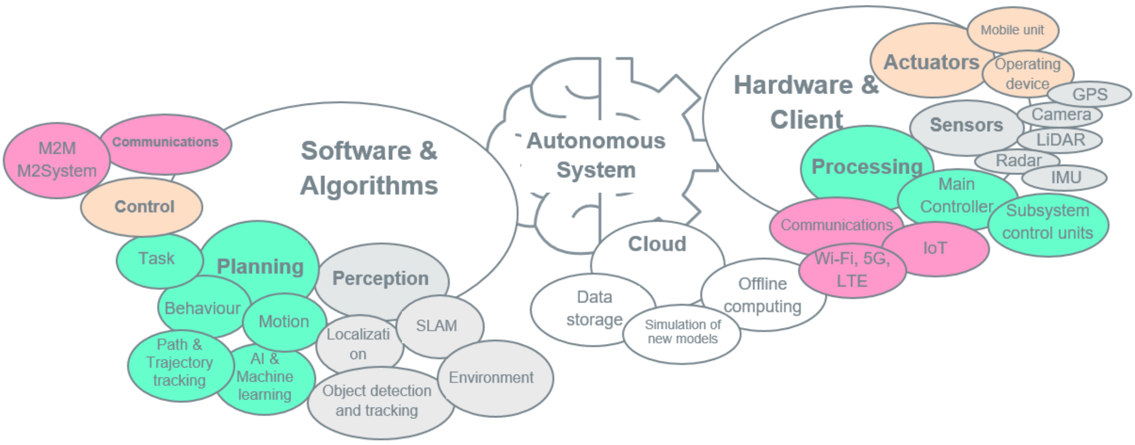

Figure 3.*A generalized overview of AS technologies and functionalities modified from Pendleton et al. (2017).*

The hardware includes sensors for environmental sensing, communication systems for connecting with other machines and systems, processing units for software to work with and vehicle actuators for movement control. The software for AMS consists of communications systems, perception, planning and control competencies. As defined by (Pendleton *et al.*, 2017), perception is the ability of the AS to gather information from the environment, whereas environmental perception refers to knowledge of the environment, objects and their locations, detecting traffic signs, and categorizing information in varying ways. Sensors such as camera, laser ranging sensors (LIDAR), ultrasonic, radar, GPS and IMU are utilized to gather information for environment model and vehicle position and orientation. Localization is the capability of the system to define its position within the environment (Pendleton *et al.,* 2017). The perception of environment can be a result of combined sensor data and algorithms (Pendleton *et al.,* 2017*)*. According to Behere *et al.* (2016), ensuring that the data provided by sensors leads to reliable perception of environment under all potential operating scenarios is a challenge.

For an AMS to achieve its goals, it is required to make decisions, which requires planning. A typical example of the planning competency is to plan the operation to navigate the vehicle from starting location to the desired location without colliding with obstacles and with utilizing an optimized route design. The control competency is the ability of the system to execute the previously planned actions by high-level processes. (Pendleton *et al.*, 2017)

The ability to plan and make decisions can benefit from the use of AI and specifically ML to aid in more complex decision-making. Research efforts from Young *et al.* (2017) discussed, that for a machine to operate in higher levels of autonomy the ability to adapt and learn is important instead of the behavior relying on predetermined code. To achieve a goal in its operating environment, the adaptable AMS can use ML techniques *such as imitation learning, probabilistic planning, model learning, learning from demonstration and reinforcement learning* as defined by Young *et al.* (2017). For example, ML models take sensory data as input and transform the data to an abstract form to characterize environment. This information can be used for reinforcement learning purposes, which provide a way to learn a specified task with the data (Zhang *et al.*, 2017). Autonomous navigation algorithms has seen developments due to ML techniques in the past years, particularly in on-road environments (Goodin *et al.*, 2018). Learning models can also be built to recognize objects, and the training data can be shared among machines for better performance. Systems utilizing ML approaches improve system robustness and overcome brittleness better than hand-tuned parameters in order to achieve desired results in new environments (Young *et al.,* 2017).

The sensors autonomous vehicles use for perception are relatively advanced, and the development of sensor technology in automotive industry provides means for better development of industrial applications. Autonomous vehicles use varying sensor solutions for sensor fusion, in which the data collected from multiple sensors is combined. A large amount of this data generated by solutions is used with ML models to enable autonomous solutions. (Hämäläinen *et al., 2018)*

Extra-functional properties such as reliability, maintainability and safety are affected by autonomy. Since the point of autonomy is to increase human independency, design towards greater robustness is required. Robustness through redundancy, or adding sensors and other hardware, is challenging due to cost and geometry constraints (no space for new hardware). Therefore, new redundancy methods, such as dynamically reconfigurable embedded systems, are needed. For example, a safety-critical function run on a particular failing hardware could be migrated to another hardware unit instead of being run by a replicated system built for redundancy reasons. (Behere *et al.*, 2016)

Autonomous mobile machines have been commercialized in operations, where the restriction of environment has enabled safe autonomous operation. Not only is the environment restricted, but also it is built for autonomous machine operations and implemented with autonomy-supporting technologies. Thus, the autonomous operation design should consider the importance of design for environment.

Tan *et al.* (2016) proposed a framework that considers the importance of co-designing the operating environment and autonomous robot. For the robot to perform a task, a compromise between the task requirements, cost and the robot capabilities may be necessary. A solution for the trade-off may be to co-design the environment, thus allowing a relatively low-cost solution to solve the trade-off issue. The co-design framework by Tan *et al.* (2016) includes three aspects; *robot inclusiveness, taxonomy of robot-environment interaction and design criteria*. Robot inclusiveness is a metric evaluation for how much the environment design considers the robot therein. Taxonomy for robot-environment interaction provides graphical descriptions for the relationships between environment and robots as agents. The five design criteria presented by Tan *et al.* (2016) are observability, accessibility, manipulability, activity and safety. For each criterion, a set of guidelines were proposed, such as the following criteria for observability: maximize perception through selection of surface materials and textures, maximize sensory signal strength such as light, sound etc. and reduce robot sensor interference with environmental mechanisms. The research by Tan *et al.* (2016) seeks to bridge the gap between robot and environment design by considering a co-design of both options.

2.4 Safety and security considerations

In order to assess readiness for designing AMS's, methods for assuring safety should be considered. Safety considerations of AMS are important, since autonomous mobile machinery are lacking standardization (excluding ISO 18497 and ISO 17757). The existing standards are followed, but the lack of autonomy specific standardization may result in creating new methods for assuring safety.

Current standardizations of safety requirements for autonomous machines presented in figure 4 were inspected by Tiusanen *et al.* (2019). The standardizations categorize the safety concepts into three approaches:

- On-board sensor and safety system for a machine that works among humans and other machines but is restricted to indoor applications.
- An isolated autonomous machine works in a separated working area, mostly an intensive outdoor environment where other machines or humans are monitored.
- An operator is responsible for reacting to a hazardous situation encountered by the autonomous machine when being provided with enough time between alert and transferring responsibility.

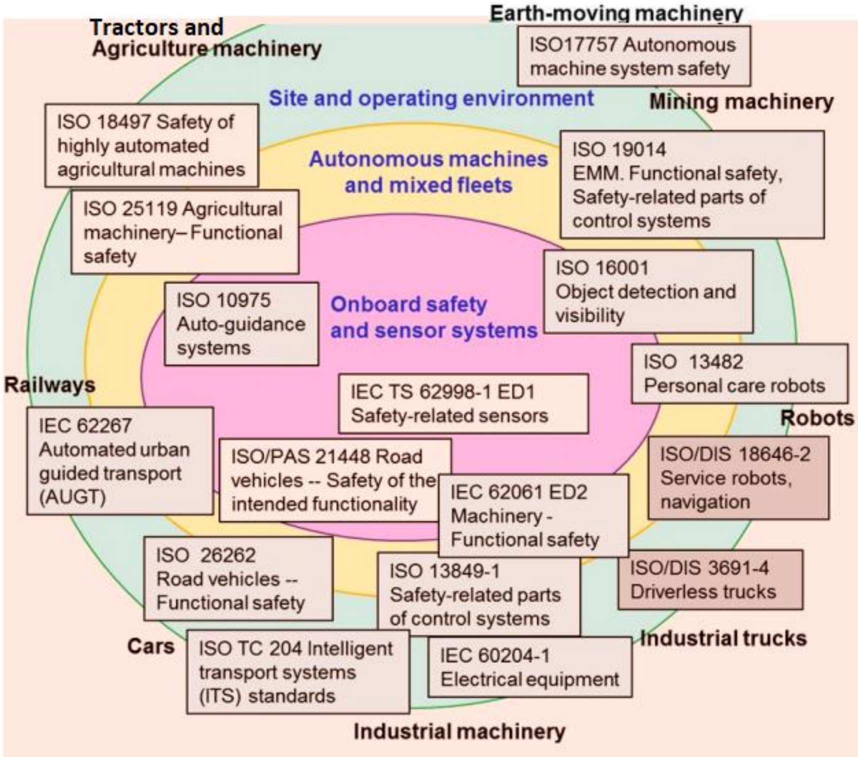

Figure 4.*An overview of existing standards affecting autonomous machinery. (Tiusanen et al. 2019)*

Standardization is difficult to be abided by current autonomous machine designs, since the standards require a fully functioning system. In addition, difficulties arise for worksite operators and owners to integrate the machine, since the standardization excludes such factors. New standards regarding AMS are being developed, and the existing ones are being upgraded as more is learned about autonomous systems. (Tiusanen *et al.*, 2019)

Safety standards such as IEC 61508: *Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related System* or ISO 13849-1: *Safety of machinery – Safety-related parts of control systems* cannot be straightforwardly applied to AMS's (Behere *et al.*, 2016). Standard IEC 61508 includes requirements for design and development of a product for safety-related control systems. The requirements are based on the criticality of the product or evaluating Risk Reduction Levels (RRL). The performance of the functional safety is evaluated with safety integrity levels (SIL), ranging between SIL1 and SIL4, with SIL1 having the lowest requirements for safety and SIL4 having the highest safety requirements. ISO 13849-1 is applicable to machinery, in which the risk reduction is evaluated with Performance Levels (PL) from PL A to PL E which are based on the RRLs. (IEC 61508, ISO 13849-1)

The reason why the abovementioned standards are not straightforwardly applicable to AMS's, is because the methods used for RRL estimation rely on human interaction. However, the intelligence of an AMS could provide support for the safety functions, but new considerations for safety standards are required where the machine intelligence takes responsibility for previously human overseen functions. In addition, the current standards do not consider a dynamic system architecture, whereas a static specification is usually considered. An ASM could benefit from a dynamic system architecture, where adaptations can occur during operation. (Behere *et al.*, 2016)

The safety-engineering issues arising with autonomous machines can be addressed with knowledge learned from safety-engineering design cases for automated machinery. Some methods for assessing safety related issues with automated mobile machinery design were discussed by Tiusanen (2014): The safety-engineering issues arising with automated mobile machinery design can be solved with utilizing a system-safety approach and risk analysis and evaluation processes, such as process- and operating hazard analyses and hazard and operability studies (Tiusanen, 2014). Also, a method for assessing machine control system functional safety risks (KoToTu) was developed by Hietikko *et al.* (2009), which provides tools for assessing performance levels according to ISO 13849-1 mentioned previously.

Though specific subsystems or components can be regulated by performance standards, they don't apply the same way to an AMS. Alternative ways to regulate autonomous systems were suggested by Danks and London (2017), where constraining the human independency or restricting the operating environment were considered. However, these methods were seen to limit the benefits of autonomy, when the AMS becomes more dependent on human interaction. A more attractive and feasible alternative was presented: A regulatory framework analogous to approving process for pharmaceuticals. Similarly, the use of AMS's should be limited to specially informed and trained group of people, who oversee AMS behavior and over time generate information for further developmental phases, eventually leading to a safe and reliable product. (Danks and London, 2017)

Since AMS's are computing and digital systems with connections in to and out of the machine they tend to become fragile towards cyber-attacks and software and hardware failures. In a research report from Malm *et al.* (2018) cyber security and safety related risks were discussed: The cyber-security risks in an automated system are *usually related to safety integrity, availability or response time of the safety-related control system and human and software access to the system.* It was discussed that the viewpoint of cyber security risks is different than safety risks, since the safety risks often occur randomly and cyber security risks happen due to malicious intent, but assessing the risks happen in a similar way. Security risk assessments were suggested to be done separately from safety analysis. (Malm *et al.*, 2018)

In a study by Yağdereli *et al.* (2015) AS's cyber-security vulnerabilities were researched and guidelines for development and a strategy for mitigation were discussed. For example, the cybersecurity requirements should be included in the requirements analysis phase as defined by the IEEE 830-1998 Recommended Practice for Software Requirements Specifications, in addition to other guidelines. Confidentiality, data integrity, authentication, availability and non-repudiation are key concepts to follow in defining requirements. The use of reliable distributed programming techniques and multi-agent system architecture help in mitigating the potential damage done by a cyberattack. A suggested method to counter this issue was the use of encryption methods and using certificates such as used for securing internet transactions (Yağdereli *et al.,* 2015). For instance, many autonomous systems use Robot Operating System (ROS) as a message-passing distributed system, which was lacking security means according to Balsa-Comerón et al. (2018). They applied Advanced Encryption Standard (AES) for encrypting messages as a first approach for security. The second approach includes means for both security and safety: Semantic rules for controlling messages for specific behaviors such as navigation abilities and interaction mechanisms.

2.5 Autonomous system conceptual modeling and requirements management

The uncertainty of situations that the AMS's may face makes it difficult to assure the system. An abstraction or a semantic framework of the autonomous systems goals, operations and structure can be a solution utilized during the design process for assessing requirements. The conceptual ontological models can be intended to be part of a model-based systems engineering strategy (Bermejo-Alonso *et al.*, 2010). The idea of these models is to help the engineers build the system, but also for the autonomous system to operate using the same models. Conceptual modeling can be used as part of requirements management, describing the system architecture or in general help the AMS engineers to understand their common design goals.

Handling autonomy-related requirements of a system are seen challenging, due to the nature of AS's behavior being driven by self-monitoring and self-awareness capabilities (Vassev and Hinchey, 2013). Autonomy requirements engineering (ARE) approach presented by Vassev and Hinchey (2013) aims to merge goal-oriented requirements engineering (GORE) with generic autonomy requirements model (GAR). The GORE approach defines system goals, whereas GAR model defines secondary goals that the system could face when pursuing the original goals defined by GORE. A similar requirements management approach where system level and specific task level goals are defined was also discussed by Magnusson *et al.* (2018).

Magnusson *et al.* (2018) presented a modeling approach to define requirements for AS's. According to Magnusson *et al.* (2018), the requirements for AS's describe the behavior of the AS with the existence of uncertainty that cannot be engineered away. Modeling the requirements helps in managing complexity, demonstrating complicated ideas, leaving out unnecessary details and visually presenting relationships between operating agents, thus providing insights to the uncertainty and expected behavior of the system. The modeling process uses four modeling methods: GAR, Goal decomposition model (GDM), Agent Interaction Model (AIM) and Agent Decision Model (ADM). The modeling methods specify goals and their relationships between actions and information. (Magnusson *et al.,* 2018)

Bermejo-Alonso *et al.* (2010) presented an engineering methodology using conceptual modeling as part of an AS research programme. The methodology is based on an AS's domain ontology that can be used on a wide range of AS's with common features and elements. The concepts, relationships and axioms are described in a Unified Modeling Language (UML) based tool. Systems engineering methods are used to construct a cognitive AS model in two phases: Identifying AS requirements and analyzing the AS's structure, behavior and function. The overall approach of requirements modelling presented by Bermejo-Alonso *et al.*, (2010) can be applied to engineering of varying AS's, since it describes the system structure and function in a general way allowing use between different applications developers. The aim of their presented modelling approach is to be used for any AS as part of a model-based systems engineering strategy. (Bermejo-Alonso *et al.*, 2010)

Conceptual modeling can be used to better understand AMS operation and requirements. It also seems to support model-based systems engineering approaches. A part of AS operation is interacting with humans. This brings us closer to understanding the Human-Machine Interaction problem. The operational requirements of an AM have an effect on the technological and system architectural design and on Human-Machine-Interfaces (HMIf) (Czarnowski *et al.*, 2018).

2.6 Human-machine interaction

Human-machine interaction (HMI) is an important theme for AMS's. In literature, terms such as human-robot interaction (HRI) or human-machine cooperation are also used. Even if the autonomous machines work in an isolated area without active human cooperation, they must interact with humans at some point in their lifecycle. Some autonomous machines work in environments, where they act among humans and for those situations, an HMI design aspect is important to ensure trust between cooperative agents (human and machine).

According to Debernard *et al.* (2016), HMI involves several disciplines: the description and understanding of psychological mechanisms in underlying cooperative activities, and tools for supporting these cooperative activities such as Human-Machine Interface (HMIf). According to Schaefer *et al.* (2019), the HRI interactions between humans and systems are including the user interface and processes that produce the interactions. The HMIf in AMS is important for the human overseer to establish accurate situational awareness. A challenge of the HMIf in autonomous operation is to present the human operator correct amount of information about machine operations (Debernard *et al.,* 2016). Higher levels of autonomy include understanding higher-level objectives, rules of engagement for the AMS and operational constraints, thus making it a challenge to choose what to display for operator responsible. The difficult part in HMI design is choosing what information, how and when to display to the user (Debernard *et al.,* 2016), when the operation itself is autonomous.

When operating in uncertain conditions, the transparency of operations between human and AMS is crucial to effective interactions (Lyons, 2013; Behere *et al., 2016*). According to Lyons, the operator responsible should thoroughly know the autonomous systems functionalities: the operator should know the levels of autonomy, what the AMS can perform under each situation, what the current mode (level of autonomy) is and how to migrate between modes. A principle extracted by Debernand *et al.* (2016), from Lyons (2013), provides an insight of what the driver should know: "*In the autonomous mode, the driver must be able to perceive the intention of the system, why, how, and when this maneuver will be carried out.*"

The aim of the work by Czarnowski *et al.* (2018) shows the effect of UGVs operational requirements on HMIf's. The trend in robotics are towards a standardized, modular and open architectural system, which leads towards designing a system that allows the control of different standardized robots. Derived from the analysis of operational requirements, a universal HMIf includes three important aspects: remote operation and advanced perception, AS's oversight and tactical awareness. These and multiple other subaspects were considered as part of HMIf's technological needs. The conclusion is that the cross-influences between HMIf design, autonomous operation technology and operational requirements should be studied as together, instead of separately. (Czarnowski *et al.*, 2018)

The discussion of user interaction problems by Behere *et al.* (2016) brought out that autonomy is intended to enhance human capabilities, but it often degrades them. If an AMS is in an undesired state, and the operator is lacking skills to provide a way towards a desired state, then it is a design problem. Thus, it becomes important to design a flexible architecture with varying user interaction paradigms, maximum transparency and ways to handle erroneous situations with HMI related strategies. (Behere *et al.*, 2016)

The discussion on important aspects of HMIf in this chapter brings up the fact that HMIf for autonomous mobile machinery is an important research topic and should be considered carefully in order for the operator responsible for autonomous operation, especially if the operator is responsible for overseeing multiple autonomous machines from a common interface. The principles discussed above work as a foundation to different methods for choosing displayable information. In mobile machinery context, the AM is likely working with other AM's and regular machines operated by humans. Understanding the transparency principles and relationships between agents is part of understanding the work process of an AMS and creating trust between agents. In addition, the HMI seems to be an important viewpoint for defining requirements for the AMS.

2.7 Verification and validation

AMS's are complex due to multiple subsystems and communications between them. The complex system may result in a complex system architecture. According to Behere *et al.* (2016), an architecture for AS may become complex with many utilities. In addition, the system becomes more complex due to numerous, possibly conflicting, goals. Thus, great complexity affects test cases and verification and validation (V&V) of AMS in a negative way (Behere *et al.*, 2016). It is challenging for the designers to foresee all possible hazards an AMS may face, especially those systems that can learn, but they can limit the number of possible hazards by defining the operating environment and LoA. There is a need for methodologies, feasible test environments, metrics and standards for V&V of AMS's.

Challenges and methods for V&V of adaptive flight control of complex AS's were identified by Nguyen (2018). A set of metrics should be defined for certification (e.g. stability, performance and robustness). The existing proven methods for V&V should be utilized to the greatest extent possible and the V&V design should be simplified, where sources of non-deterministic events are minimized. V&V methods such as safety case and other formal and analytic methods should be considered. In addition, systems utilizing learning algorithms cause problems due to incorrect learning and trust issues, and such algorithms are difficult to V&V. (Nguyen, 2018)

An established V&V method safety case, also called safety assurance case or assurance case (Denney and Pai, 2017) is a structured method for explaining why the system is expected to be safe in its operating context. The structure of safety case comes from requirement, argument and evidence, where the safety requirement is proven with evidence (e.g. fault tree analysis (FTA) and failure modes and effects analysis (FMEA) tables) and the argument explains how the requirement is proven with its corresponding evidence (Zeng *et al.,* 2012). Alexander *et al.* (2009) proposed that within a safety case for AS's the operational scenarios and context should be well defined, such as mission, environment, interactions with peer AS's. From those scenarios a set of safety-critical capabilities should be identified, and hazard analysis based on those capabilities should be performed.

According to Koopman and Wagner (2016) the standard's ISO 26262 *Road vehicles – Functional safety* V-model sets a process for validating AV's requirements and system, component and program specification. However, testing AV's according to V-model has great challenges: Driver is not in control, validity of complex requirements, non-deterministic and inductive learning algorithms and fail-operational systems. Promising solutions include a phased deployment, where operation and scenarios are limited to a degree where autonomous operation is still possible. To validate autonomous features, performing fault injection (e.g. invalid data within maps) helps to bring out weak spots that would appear in unforeseen situations. Fault injection can be useful in all "layers" or phases in the V process. (Koopman and Wagner, 2016)

A V&V methodology from Halterman and Scrapper (2017) presented set of data-collection and analysis tools and methods for automated testing experimentation for autonomous unmanned vehicles. They emphasize on repeatable testing procedures starting from component level and moving on through subsystem and system level testing progressively. The component and subsystem testing (e.g. elemental perception and planning and relative localization accuracy tests) involves tools for gathering data and analyzing the data error, in order to determine the maturity of the autonomy providing technology. For the developed technologies to be integrated into the baseline system, system level integration tests can be performed. For example, a nominal autonomy test is used to assess overall performance of the system by sending the UGV to a mission, and then analyzing how much human intervention is required during the mission in a challenging off-road environment. A physical test environment can be used to expose weaknesses of the UGV's autonomy providing functions during the mission with obstacles such as blocked and constrained paths, emplaced obstacles and reverse initialization. (Halterman and Scrapper, 2017)

Though these aforementioned V&V challenges and methods were identified in the context of aerial systems, AV's and UGV's, they provide important considerations towards the V&V of autonomous mobile machinery as well. Structured methods, such as safety case, provide means for certification of safety-critical systems. Establishing test scenarios where non-deterministic events are minimized and the autonomy providing functionalities are challenged seem to be important for R&D purposes and system level V&V of an AMS. Software testing utilizing methods such as fault injection may provide solutions for autonomous functionalities testing during all design phases.

2.8 Digital design practices

Digital transformation is a growing trend in mobile machinery design. The growing system complexity and an interdisciplinary design process can be supported with a digital design environment (DDE), which includes digital design tools for varying design purposes. An important tool for developing an AMS in digital form, such as a digital twin (Mevea, N.d.) can be used for simulating the behavior of a real product. A digital twin term is often used and understood in many ways. A definition of a digital twin ideal for AS development is described by Mevea (n.d.) as a physics-based digital twin being able to analyze and predict a behavior of a real-life machine in real time, by modelling a machine, its environment and work process comprehensively and accurately. In addition to a product related digital twin, digital twins created by large global companies exist for other domains such as power plant (GE Power, 2016), manufacturing and production (Taylor, 2017) and operations (Ansys, N.d.).

A digital twin can utilize and generate data related to real machine operation and the behavior of an actual product can be predicted with a digital twin model in varying stages of the product lifecycle (Nortio, 2019). Autonomous machine development can benefit from digital twin and AI by the use of subtask automation development, generation of training data and testing solutions and field data augmentation, according to a handful of global machine manufacturers (Mevea, n.d.). According to Nortio (2019), a digital twin existing along the machine can assist the machine control system or operator to better understand the state of the machine and how it can be optimized. In such scenario, the digital twin aids to complement the sensor data of a machine and estimate its state. Autonomous machines make use of this technique already (Nortio, 2019). The point of digital twin and other simulators is to enable the development of autonomous functionalities in a digital form before any physical prototype R&D.

2.8.1 Simulators

A simulator for autonomous system development, such as a digital twin used for engineering simulation, consists of 3D-models of the product with solid bodies, environment and object models and simulation tools. Physics models used in simulation come from simulation programs, such as Ansys, and component data is gathered from different Enterprise Resource Planning systems (Nortio, 2019). Open source simulation platforms such as Gazebo allows to simulate a physical rigid body and various sensors in an off-road environment (GPS, IMU, LIDAR and Camera) (Meltz and Guterman, 2019).

There are several types of simulators available and Goodin *et al.* (2018) divided them into three broad categories. First category of simulators referred as “Robotic Development Environments”, such as Gazebo, which are intended for early design phase with due to the simplicity of use and integration into the design process. Their intended use is to simulate fast for quick system design and debugging. The environment and physics are not described in detail in order to enable the intended use.

Second category of simulators are referred as “Robotic Test Environments”. They are used for evaluating the performance of an autonomous system in a focused operational setting. This means, that the simulation includes more accuracy in physics, but with trade-offs in other simulator properties depending on what is being tested: For instance, simulator called Virtual Autonomous Navigation Environment has great interaction physics for LIDAR-environment but does not run in real-time. (Goodin *et al.*, 2018)

Third category of simulators are referred by Goodin *et al.* (2018) as empirical or semi-empirical simulators, make use of both real and simulated data collected from previous experiments. Project already including extensive field testing, can make use of such simulators for predicting the performance of an autonomous system (Goodin *et al.*, 2018). Simulation in digital design environment can use real data gathered from real situations. This data group can be fused with generated data, to develop the simulation process to a level where it tests the requirements set for the product. Simulating a product in digital design environment such as digital twin, where real world data is used, can speed up the R&D process significantly (Nortio, 2019).

The off-road autonomous navigation is a challenge for autonomous ground vehicles, which often rely on the LIDARs ability to classify the environment. Goodin *et al.* (2018) presented the design of a physics-based real-time LIDAR simulator to address the issue of developing LIDAR processing algorithms, which spot the difference between navigable vegetation and unnavigable obstacles. The simulator software is suitable to be integrated into a hardware or human-in-the-loop testing for challenging outdoor environments. The benefit of their developed simulator is that the real-time property does not include a trade-off in an autonomous system specific development, such as LIDAR processing algorithm. Dust, snow, rain, fog and retro-reflective surfaces have adverse effects on LIDAR performance, and the interaction of these elements will be brought to the simulator in future work. (Goodin *et al.*, 2018)

2.8.2 Autonomous capabilities development in a digital environment

Development of autonomous functions is likely to happen in a digital environment eventually leading to real-world operation. The computer vision (CV) design, as part of autonomous machine perception and planning capability, benefits from the photo-realism of modern game engines such as Unreal Engine (Müller *et al.*, 2018). Müller *et al*. (2018) presented a photo-realistic simulator Sim4CV with cars based on realistic physics, unmanned aerial vehicles (UAVs) and animated humans within 3D environments. The use of SIM4CV is diverse, for instance, UAV tracking moving objects and unmanned driving utilizing supervised learning can be developed within the simulator. Common CV applications are presented in figure 5 that can be developed with a simulator tool such as SIM4CV.

Figure 5.*The color palette under a described CV application represents types of data that are often a necessity and can be used optionally for the capability utilizing CV (e.g. camera localization is a necessity / video is optional, for 3D reconstruction). (Müller et al., 2018)*

The high cost of collecting and using manually collected data is avoided with the generation of synthetic data. Not only does the simulator generate synthetic data, but also it provides tools for creating and evaluating new environments and tasks that are hard to replicate in real-life. (Müller *et al.*, 2018)

Development of ML models that provide autonomous behavior of a subtask or a machine can benefit from synthetic data generated in simulator environments. The data needs to be result of a highly accurate physics-based operation simulation, in which the real-life product and its environment is simulated in real time. Generated data from machine dynamics and validated mathematically modeled sensors can be used for training assistance and safety systems. The test scenario repeatability enables to train ML models for various tasks using industry standardized interfaces such as Robot Operating System (ROS) and Unity 3D-environment. (Mevea, N.d.)

2.8.3 Digital V&V

Some system-level requirements are simpler to test than others but finding out what are the most critical test scenarios can be difficult. Meltz and Guterman (2019) presented a methodology based on simulation tests, which aims to perform a system-level verification to an algorithm according to ISO 26262 requirements. The methodology provides safety-related functionality tests in a simulated virtual environment and gathers statistical performance data. The gathered data is used for predicting safety performance of a UGV with high accuracy in real life. The methodology is described figure 6, adopted from Meltz and Guterman (2019).

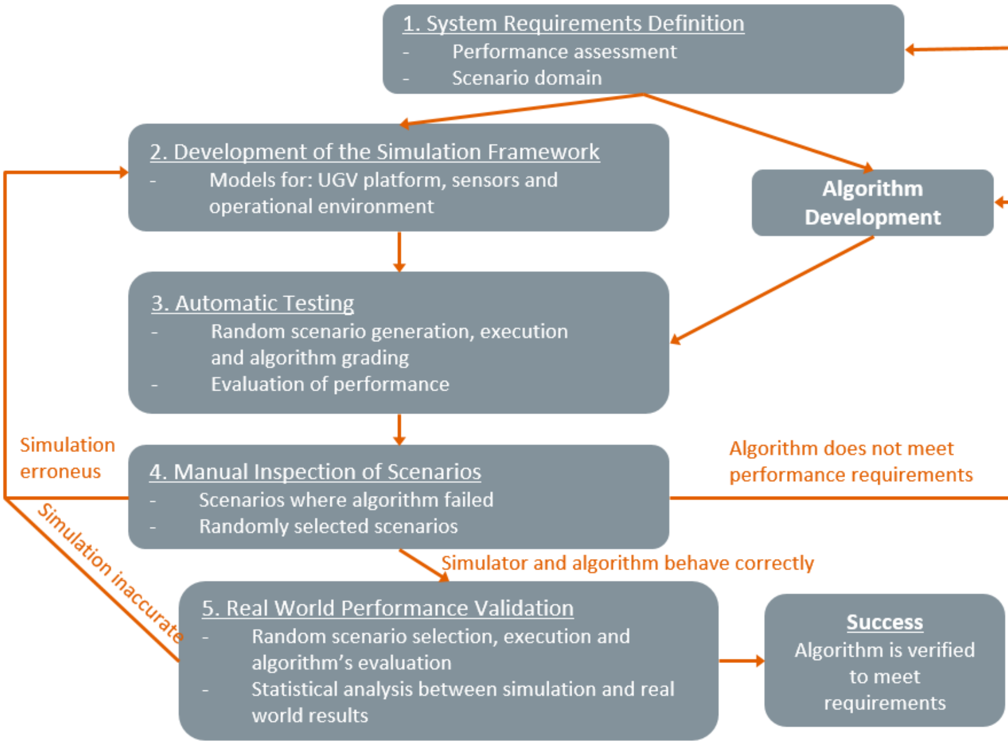

Figure 6.*Simulation framework modified from Meltz and Guterman (2019) where autonomy providing algorithm development is done within scenario simulations leading to a real-world scenario V&V. © 2019 IEEE.*

This simulation framework presented in figure 6 was applied to a RobIL UGV presented in figure 7. The operational environment and RobIL UGV was modeled with an open source physical rigid body simulator Gazebo. It was found, that the simulation models would have accurate and the performance of their applied test case had a failure propability of 1% per scenario, which does not satisfy the requirements of safety standards. However, their simulation methodology is feasible for producing statistical results for V&V purposes. Further research is still required to address the difficulty of defining a scenario domain with all possible UGV operational scenarios and to properly random sample the scenario domain. (Meltz and Guterman, 2019)

Figure 7.*On the left a view from Gazebo simulation environment; on the right RobIL UGV avoids an obstacle autonomously. (Meltz and Guterman, 2019) © 2019 IEEE.*

Worm and van der Made (2019) presented a V&V methodology for AV design as part of a commercial design solution for automotive industry. It is a similar digital and physical V&V methodology as presented by Meltz and Guterman (2019). Where requirements define the simulation properties for vehicle and environment, and they are tested in the closed model-in-loop simulation. As the model-in-loop simulation runs in real time, digital components can be replaced by hardware and software within the loop during the development process. The development process shifts from fully virtual V&V to mixed reality V&V, and eventually leads to confirmation by physical testing. Model-based systems engineering methods were suggested to be broadly implemented into the development process among digital twin for further optimization of designs and factors such as energy efficiency and safety (Worm and van der Made, 2019).

2.8.4 Summary on digital design practices

AMS development gets various benefits from digital design practices:

- The generation of synthetic data for autonomy enabling algorithm development (such as autonomous navigation).
- CV applications development utilizing synthetic data from digital environments.
- Development of ML models utilizing synthetic data.
- Simulations can provide statistical results that can be used as a benchmark for evaluating performance.
- Autonomous machine development can benefit from digital twin and AI using subtask automation development, generation of training data and testing solutions and field data augmentation.
- Varying types of simulations: Ease of use simulations for quick design and debugging, detailed operational setting simulations for evaluating AMS performance and developing specific capabilities, and semi-empirical simulations with data utilized from real-life scenarios.

Digital design practices, where a digital design and V&V loop enables the autonomous functionalities development, seem to be a valuable design asset. Utilizing varying types of simulations and digital twins next to model-based systems engineering methods seem to provide means to reduce time used on engineering and excessive physical testing. However, the simulation model accuracies and methods for simulating harsh conditions make it difficult to fully develop autonomous functionalities to a level where physical V&V is only needed to prove the successful design a single time. Solutions, such as importing sensor data from harsh condition scenarios to digital model simulations may provide design methods for further developing autonomous capabilities in DDE's. Thus, digital design practices and physical testing seem to be equally important things to consider in autonomous functions development, since the data generated in both can be used to complement each other and the AMS design.

2.9 Example of an autonomous mobile machine: Automated straddle carrier

The point of this chapter is to demonstrate a real-life example of an autonomous mobile machine and what is considered in the machine design. The operation principle is shown, technological requirements for autonomous operation are presented and considerations towards skillsets and important factors related to the autonomous machine are presented.

Autonomous machines for port operations include unmanned container handling machines. Part of increasing productivity in a terminal is through automating a part of the operation. A part of operation includes picking containers from seaside, transporting containers through operation area and stacking them on top of each other. An automated straddle carrier can perform this task without human intervention, but still relying on human surveillance. Automation by automated shuttle carriers minimizes human error and improves safety. Unexpected interruptions that impact productivity and profitability can be avoided with automation. Other benefits include savings in terminal operating expenses, improving efficiency, better availability and site security and longer equipment lifetime. The operation is optimized so that it reduces fuel consumption. For instance, engine stops during equipment idle time and driving patterns are optimized through calculation. A view from above automated straddle carrier operation is presented in figure 8. (Kalmar, 2014; Alho *et al.*, 2015)

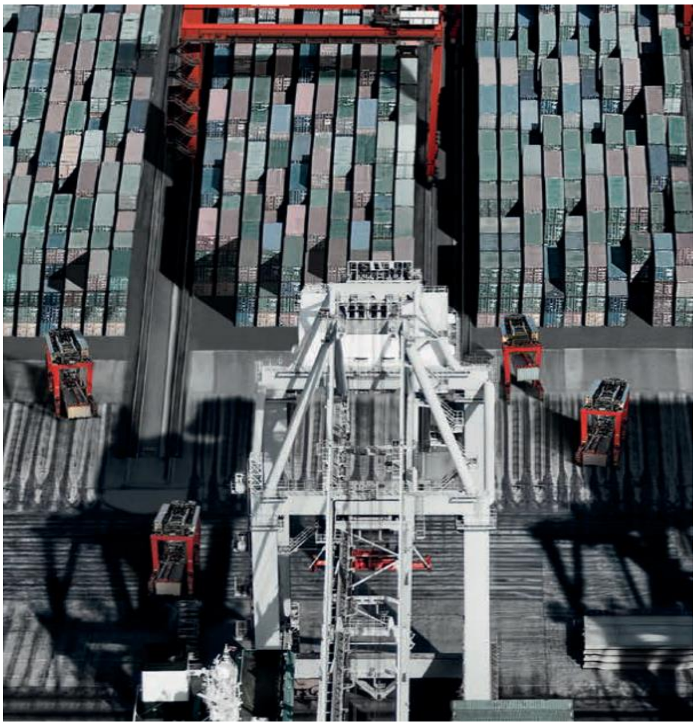

Figure 8.*Four red Kalmar automated straddle carriers pick up containers from shore and transport them to zones ready to be stacked. (Kalmar, 2014) © Cargotec 2014.*

An example of a terminal operation is presented in figure 8 where a ship-to-shore crane moves cargo containers from the ship to shore for the automated straddle carriers to pick up. Four automated straddle carriers move containers from seaside to a buffering zone. From the buffering zone, a larger container handling equipment picks up the container and places it on top of the container stack. The straddle carriers automatically adapt to changes in terminal throughput: If the machine is not required now, it will park away, but in case of need more equipment can be added on demand. (Alho *et al.,* 2015)

The automated straddle carrier navigational capability is considered as autonomous. The vehicle navigation is based on virtual routes with an accuracy of few centimeters. This is achieved with two methods, magnet and radar navigation. Magnet navigation uses sensors on the bottom of the straddle carrier to detect magnets embedded in the pavement of the operation area. The benefit of this method is low cost investment on each straddle carrier, but downside is a large one-time infrastructure investment when installing the magnets. Radar navigation uses typically between 100 and 200 beacons installed on the operation site and the machine has to be in line of sight of at least three radar beacons. A radar-based system requires a lower investment on infrastructure, since the radar beacons are inexpensive and easily installed. Figure 9 presents a Kalmar straddle carrier and its technologies providing autonomous functions. (Alho *et al.,* 2015)

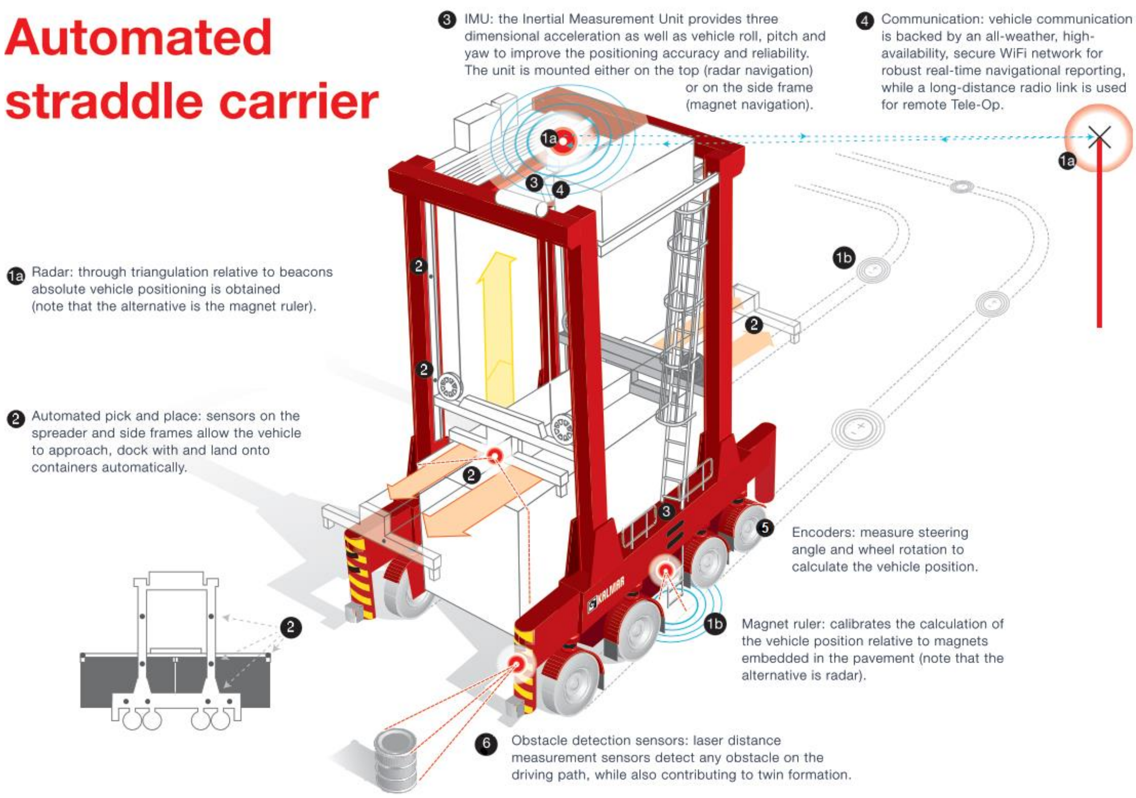

Figure 9.*Kalmar Automated straddle carrier and some of its autonomy providing technologies (1a Radar, 1b Magnet ruler, 2 and 6 sensors for automated picking, placing and detecting obstacles, 3 IMU for improving positioning, 4 communications for navigation reporting in real time and 5 encoders for calculating vehicle position). Modified from Alho et al. (2015) © Cargotec 2015.*

Awareness of environment and objects is provided by obstacle detection sensors and sensors on the side frames and spreader to pick and place containers with high reliability and accuracy. The automation of operation is not only enabled by the technologies onboard the machine. An infrastructure to support automation is required. The terminal layout requires change in order to enable automated operation. To support autonomous navigation of straddle carriers, radar beacons must be installed around the site and/or magnetic markers must be embedded in the pavement. A wireless network for communication with the straddle carriers must be included, by installing radio frequency links that provide emergency stop and remote-control functions. To ensure safety, the operation area must be restricted with fencing, safety infrastructure and access control. In addition to the installations, instrumentations such as sensors and programmable logic controllers may have to be installed to the infrastructure in order to interface with straddle carriers. (Alho *et al.,* 2015)

Adding automation by automated straddle carriers requires careful planning and exercising, and integrating new systems are to be considered in addition to new technical implementation. Systems such as Terminal Logistic System (TLS) and other systems are part of supporting the automated straddle carrier operation. TLS is responsible for conducting and optimizing planning, routing and execution of automated operations (Kalmar, 2014). Thus, the planning and decision making is done outside the automated straddle carrier, making the operation dependent on a whole system, instead of a single machine.

The design of a system using automated straddle carriers includes software integration of all levels of operation, from yard equipment to process automation, which have to be implemented according to clearly specified roles and interfaces between subsystems and business processes. This is ensured by testing and simulation: Laboratory environments are used to confirm the execution of business processes, where all the subsystems are verified in end-to-end scenarios. Various software versions and complex deployments can be simulated in a virtual environment with an authentic TLS and vehicles. (Alho *et al.,* 2015)

Maintenance of an automated straddle carrier is crucial: A manually operated straddle carrier can operate with some minor deficiencies, but automated version of such machine must be in perfect condition to deliver its full potential. Frequent preventive maintenance operations take place at planned intervals. Intelligent systems are used to provide information on machine fleet condition and performance. System such as Equipment Monitoring System (EMS) (Kalmar, 2011) is used to provide information about machine status and fault diagnostics. The result of preventive maintenance is reduction of the total cost of maintenance, reduction of downtime and better equipment availability. (Alho *et al.,* 2015)

New skillsets are required to perform such maintenance operations. A maintenance engineer with appropriate skills is required to enable the maintenance of automated equipment. Maintenance should be based on data, facts and analysis instead of operators reporting faults, reactive maintenance. Proper maintenance of an automated straddle carrier requires data mining and understanding the operation of automated systems and sensor technologies. (Alho *et al.,* 2015)

The automated straddle carrier shows an example of important topics to consider in the design of an autonomous mobile machine:

- Implementing the overall system and technologies requires careful planning and executing.
- Software integration from machine onboard to operational system levels is important.
- Maintenance requires a new type of skillset and methods based on data acquisition, management and analysis.
- Supporting environment for machine navigation with wireless communications.
- Supporting infrastructure for machine operations (e.g. TLS and EMS).
- Methods for ensuring safety such as restriction of zones and local training of employees.
- Simulations in virtual environments enable to verify the design of operations.

2.10 Readiness assessment methodologies

Assessing readiness of engineering practices for designing autonomous industrial mobile machinery is part of this thesis. Since the engineering practices need to consider a wide variety of design challenges for AM's, a method for assessing factors affecting the readiness is required. This type of readiness assessment related to autonomous system design practices is new in a way that it has not been done before according to the literature reviewed for this thesis. Readiness assessment methodologies from the literature are inspected in this chapter for further use in chapter 4.

Karandikar *et al.* (1993) presented an assessment procedure model for concurrent engineering (CE) readiness, which provides an understanding of a company's current readiness to implement CE practices. In their framework, a series of critical elements required for CE are defined, and each critical element is described with a set of key criteria. The elements and criteria are varying qualitative factors that are identified from interactions with companies, literature, case studies, survey results, conferences and seminars. In figure 10 section A is the readiness assessment method from Karandikar *et al.* (1993), in which the results are divided in technology, and process and practices. Each sector represents a critical element, and the score of each element is based on a set of questions that represent the key criteria. (Karandikar *et al.*, 1993)

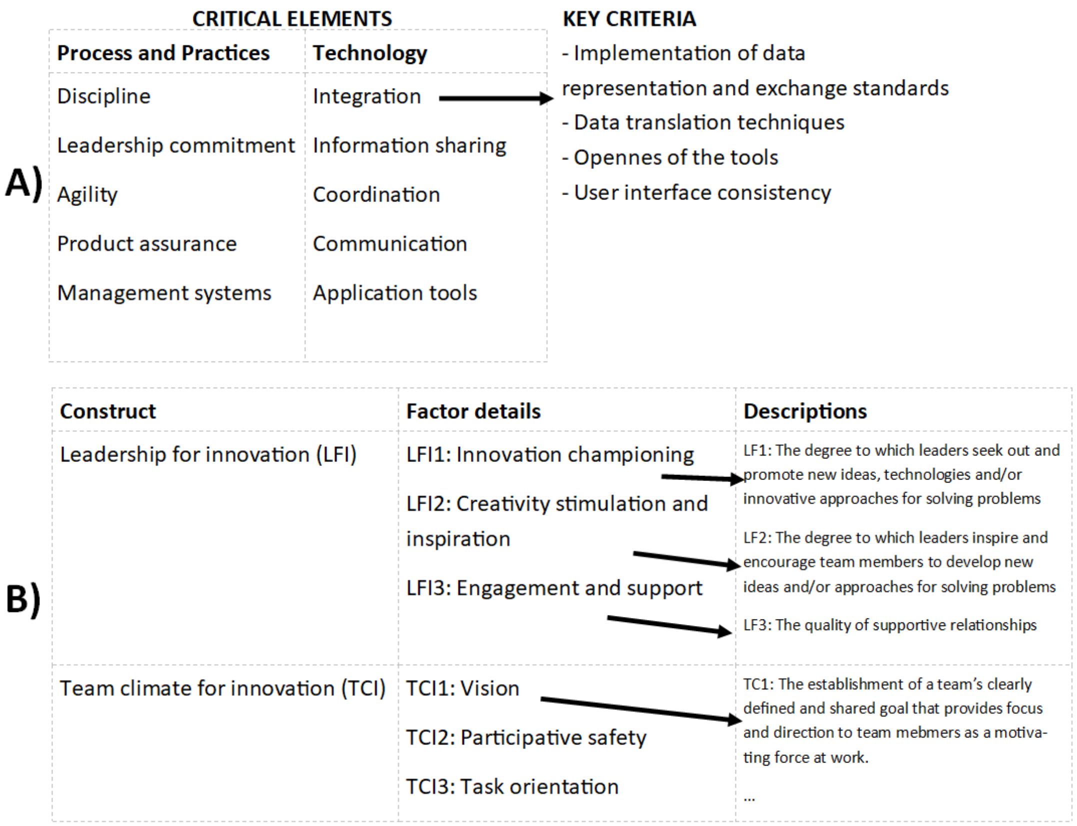

Figure 10.*Readiness assessment A) presents important considerations for readiness as elements and key criteria (Karandikar et al., 1993) and B) presents readiness model as constructs, factor details and their descriptions (Panuwatwanich and Stewart, 2012).*

Organizational readiness for innovation diffusion was discussed by Panuwatwanich and Stewart, (2012). In a similar way to the method presented by Karandikar *et al.*, (1993), where elements and criteria were defined, qualitative constructs, factors and their descriptions affecting innovation diffusion readiness were defined by Panuwatwanich and Stewart, (2012) based on a survey of literature and previous studies. A part of the constructs, factors and descriptions is presented in figure 10 section B.

A readiness assessment for 25 countries preparedness' for autonomous vehicles was performed by KPMG (2019). Their developed readiness assessment tool The Autonomous Vehicles Readiness Index (AVRI) is a score-based tool where scores for four segments are defined: Policy and legislation, technology and innovation, infrastructure and consumer acceptance. The four segments are scored based on publicly available information, media reports, press releases and other material, such as surveys carried on each countries and existing research performed. In a similar way to the aforementioned readiness assessment methodologies, the four segments of AVRI are further divided to smaller descriptions.

The aforementioned readiness assessment methodologies all have common factors: The critical elements, factors or measurements are qualitative units that were chosen as important aspects to consider, and they were also divided into smaller qualitative descriptions that represent the main element. The chosen elements were based the researcher's interpretation of surveys, studies, interviews, case studies and many other qualitative research methods. This methodology of assessing critical elements for readiness and further assessing key criteria for each element is utilized when assessing engineering practices readiness in chapter 4.

2.11 Conclusions on literature research

The studied literature gives ideas for what is required from engineering practices to design AMS's. The readiness could consider whether there is experience on the challenges mentioned in the literature research and experience on the solutions, such as digital design practices where autonomous functions can be developed. Experience and development on those domains could represent positive readiness, whereas inexperience represents no readiness. First, the definition of autonomous machine can be considered by defining the LoA, which in practice means understanding the technological solution, difficulty of operation, complexity of environment and human independency of the AMS. In addition, increasing requirements arise from important topics such as safety, security and HMI. Managing and defining a large field of requirements seem to be a topic for development in AMS design. The example of an AMM presented demonstrates the importance of considering simulations, supporting infrastructure, software integration and new skillsets for data utilization and maintenance as part of AMS design. The arising design challenges seem to be requiring solutions from digital design practices and physical testing environments as well. These topics presented in the literature research became topics of interest for interview research.

3. INTERVIEW RESEARCH

This chapter presents the interview results on mobile machinery original equipment manufacturers and system integrator companies. As mentioned previously in chapter 1.2 selected company representatives (e.g. chief technology officer, technology-, engineering and R&D manager) with a good general view on their company's direction towards increased autonomy as well as the overall developments in industry were interviewed. An interview framework, presented in figure 11, was created as a guideline for the interview. The interview framework is based on the studied literature summarized in the end of chapter 2.11 and the original project background information for the thesis mentioned in chapter 1.1. The focus of the interview was on topics mentioned during interviews by the interviewee, but the following originally planned topics were discussed: Company's interest in autonomous systems, needs and requirements, design approaches and tools, verification and validation, safety, cyber-security, AI and HMI.

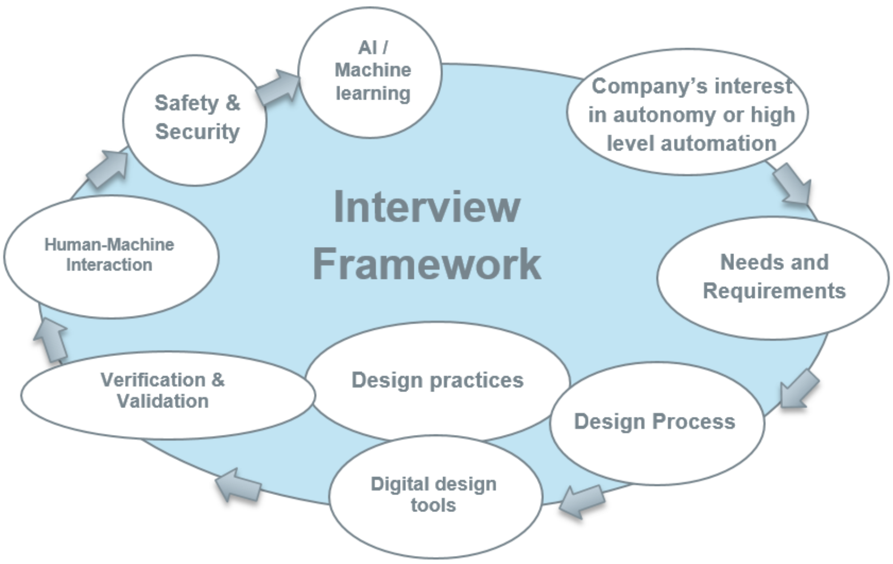

Figure 11.*Interview framework includes these predetermined topics for discussion.*

3.1 Interview and analysis methods

The interviews were thematic interviews (semi-structured), which in practice means that they were not an open discussion neither very constrained. The presented literature research works as an orientation for the researcher to perform a set of thematic interviews. The interviews begun with an introduction to the research objectives discussed in chapter 1.2. A single interview lasted about 1 ½ to 2 hours. The interviews continued with an open question on the company's interest in autonomous machines, and the following questions were deducted on the topics that were brought up. Most of the topics that were brought up matched with the original interview framework topics, but new aspect and new topics arose as well, and those topics were focused on. The key idea was not to pressure the interviewee to give an answer to a predetermined and constrained view based on the literature research, but to freely express their personal views on challenges and solutions that arise in designing autonomous machines. Guidance for conducting a thematic interview were utilized from Hirsjärvi and Hurme (2011).

Interviews were recorded and transcribed. A qualitative research analysis method *thematic analysis* was selected, in which the transcription was categorized into various constantly occurring themes (Hirsjärvi and Hurme, 2011). As presented by Hirsjärvi and Hurme (2011), often occurring features that are common among interviews are categorized and further inspected in thematic analysis. The occurring main themes were selected by the researcher as they represent the interview material in a general way. The main themes of this thematic analysis are:

- Visions, definitions and interest in autonomy in general
- Design considerations
- Human-machine interaction
- Data acquisition, management and analysis
- Safety
- Cyber security
- Digital design practices
- Partnerships and ecosystems

Each main theme has subthemes and they are presented in chapters 3.2-3.9 with an *italic type* on top of paragraphs. The subthemes include findings from various interviews that support the subtheme. Analysis (conclusions and further interpretation based on interviews and literature) on the subthemes is presented after paragraphs under *Analysis*. It is to be mentioned that the dividing of topics and subtopics (themes and subthemes) according to thematic analysis procedure is part of the researcher's analysis and the conclusions presented under *Analysis* is further interpretation of the themes presented.

All the results presented are anonymized, which means one can't deduce the interviewee and the company presented by the interviewee from the results. However, without braking the anonymization the interviewees can be divided into three groups that provide some traceability and quantitative assessment for the main findings presented.

- First group (1st) includes two interviewees who represent different OEM's with little efforts towards autonomous products but they have an interest in autonomy.
- Second group (2nd) includes four interviewees who represent different OEM's with great efforts towards autonomous products.
- Third group (3rd) are the two interviewees who represent different system integrators working with several mobile machinery OEM's.

The 2nd and 3rd groups brought up most of the findings presented in the interview research, whereas the group with little efforts mostly had the autonomous development as a vision. Thus, the group with great efforts provides important insight for many developmental aspects presented in the chapter 3 related to autonomous products. System integrators provided valuable views towards autonomous machine development through their work experience with varying mobile machinery OEM's. The following subchapters present findings from eight interviews under constantly occurring themes.

3.2 Visions, definitions and interest in autonomy in general

Industry overall

It was discussed by the system integrators that *mobile machinery OEM's have not been active to develop autonomous machines*. Proof-of-concept level demonstrations have been done, but to create a disruptive technology, which would bring serious cost benefits is still a vision. However, there are exceptions with companies whose machine operates in a restricted environment. This is where autonomous mobile machine development has happened so far. It was said by an interviewee from 2nd group that with such environment *there is a problem with it being rather stiff and expensive, when flexibility of operation is required in future operations*. The restriction of environment is done to ensure safety, but with the cost of losing some flexibility of the working area and the process within.

Driving forces behind autonomy

It was discussed with all the groups that two main drivers behind autonomy are cost reduction and safety. The cost reduction is seen to come from the reduction of operator costs, designing the machine geometry for greater production of goods and increasing operational efficiency. Reduction of operator costs, by removing the operator from the work process, and a more productively designed machine geometry require a remote operated, unmanned and autonomous machine. Unmanned autonomous machines are still a vision except in restricted environments. It was discussed with two interviewees from 2nd group, that the use of infrastructure of the isolated and restricted operating area has enabled autonomous operation of a mobile machine. In addition, it was discussed with all groups that operational efficiency can be achieved through bringing more intelligence to a work process by developing semi-autonomous functions. Semi-autonomous functions mean that the same technologies, that would provide fully autonomous operation, are being used to improve a function with human still responsible for action.

Two paths, full autonomy and semi-autonomous functions

It can be summarized based on the discussion with all groups, that the road to an autonomous machine is seen to go in two paths: With progressive development of semi-autonomous functions or with developing a fully autonomous machine from the start. Interviewee from 3rd group said that *in practice, autonomy will be increasing in single functions,* and this view was also mentioned by the other system integrator. It was discussed with an interviewee from 2nd group that a path with progressively developing semi-autonomous functions as implementations on an existing machine has a benefit of creating trust between the operator and new technology. As the trust is gained on the existing technology, a new implementation towards eventually fully autonomous machine can be brought to be trusted. For example, it was discussed with the same interviewee from 2nd group commenting on the trust subject, that adding situational awareness to assist operator, semi-autonomous functions to operation, autonomous navigation, connectivity and remote operations as a step-by-step approach could provide the road towards fully autonomous operation. Another interviewee from 2nd group discussed that a semi-autonomous function can provide clear benefits to the existing operation, and also, that *having the operator replaced with fully autonomous system is difficult to leap into.* An interviewee from 2nd group discussed that an important factor in commercializing autonomous products is that there must be trust in the technology. Such trust is gained as the autonomy-providing technology has matured. Trust gained from previous intelligent technologies or machine automation enables further development towards autonomous systems.

Lack of operator skill can be compensated with autonomy

It was discussed with system integrators and two interviewees from 2nd group that providing operator assistance systems or semi-autonomous functions bring a solution to a commonly known problem in with mobile machinery: The negative results of an unskilled operator can be mitigated and possibly removed by providing a semi-autonomous function that compensates for the lack of operator skill. For example, an interviewee from the 2nd group said that *the operator assistance system can increase productivity by letting the operator know about other machines location, help in reducing fuel consumption, help to avoid collisions and help in decision-making of a manual operation*. It was said by a systems integrator that the *semi-autonomous operation providing algorithms can be further developed to ensure uniform quality of work*. The benefits of semi-autonomous functions are lesser faults, faster operation and better quality of work done. A semi-autonomous function could be either autonomous driving or autonomous operation of a subtask. However, even with providing such functions the human interaction is still needed to a degree, where operator costs are not removed. It was said by an interviewee from 2nd group that *the availability of skilled operators depends on the overall local educational level and work culture.*

Vision of a future machine

The following was discussed with interviewees from the 1st group. A vision of a future autonomous machine is that the system supporting the machine and the machine itself is designed to be fully autonomous from the start. A lack of resources to design such a system exists now. To do this with feasible costs, it must be done in a smart way. A new machine geometry provides an efficient production of goods. It was discussed with interviewees from 1st group that a future vision does not only contain a single autonomous machine, but a greater system with a fleet of machines and supporting systems. It was discussed by two interviewees from 2nd group that an autonomous machine fleet probably includes various type of autonomous machines and to know the difference between each machine is important.

High component costs

An interviewee from 1st group said that *most of the technologies and components providing autonomous operation exist, but not with feasible costs.* However, the same interviewee discussed that R&D on autonomous technologies is important even before the component costs enable an autonomous machine commercialization. Two interviewees from 2nd group discussed that automotive technology suppliers provide promising solutions towards cheaper components as the cost of components for autonomous systems reduce. It was discussed with an interviewee from 2nd group that the cost issues with developing operator assistance functions with new components arise: Developing the operator assistance functions is expensive and may not provide clear cost benefits for the end user.

Market demands

An interviewee from 1st group discussed, that the market for their machine is not uniform: An autonomous machine could be a solution for great size operations, but for small size operations autonomous machine may not be feasible. An interviewee from 1st group questioned that *is there really a market demand for such a wild vision? Is it worth to put efforts into autonomous machine development?* It was discussed with all groups, that there are market demands for machines with better efficiency. The efficiency is being provided with varying ways such as adding intelligence to a product and providing means for data collection and analysis but it is not demanded as in forms of autonomous machines. An interviewee from 2nd group said that *we are not exactly in a mass product market, and the autonomous products are business-to-business and project type of work.* However, an interviewee from 2nd group discussed that for the existing autonomous systems in restricted operating environments, there is a customer segment, which demands productivity gains from the highest technological advances in automation and data-analytics. In addition, a customer segment demanding a regular product exists as well. Thus, it may become difficult to serve both customer segments with limited resources.

Analysis

Based on the interviews, it can be concluded the main driving forces behind autonomy are reducing costs and improving safety, however, the market for mobile machinery is not directly demanding these properties as in forms of AM's. AM's in unrestricted operating areas are probably a part of the future, but for now, demonstrations and prototypes are waited for – the so called "first movers" are waited to present their innovations in the future. It can be concluded that the industry is waiting for, and advancing towards a product with greater technological maturity and better performance in productivity and safety than an existing regular machine with a human operator, since there are already advanced technologies available that support autonomous mobile machine development and technologies making the operation efficient. But when does the operation principle of a regular machine becomes unmanned and autonomous still remains a question. It can be concluded, that there are exceptions with autonomous machines that operate in restricted environments and especially with large scale investments, but the challenge in that environment is to further develop the autonomous machines and regular machines both for different customer segments with different demands.

It can be interpreted that varying levels of autonomy can bring significant benefits to a regular machine operation. The semi-autonomous functions represent the varying levels of autonomy (e.g. remote-control, semi-autonomous operation of a device, operator assistance functions). The problem with semi-autonomous functions is that if they require expensive technologies and do not bring enough value compared to the development costs and the investment cost, they are not feasible to develop. For example, an operator assistance system should be built with cost efficient components in order to have market interest. When the cost-efficient technologies are used for semi-autonomous functions, the trust towards new technologies assisting the existing operation is increased. New upgrades and additions are created to make the existing regular machine operation more efficient, which provides a path towards more autonomous products by increasing trust on new technologies progressively. There seem to be a need for this kind of step-by-step approach in order for the customers to accommodate and adapt their own knowhow towards an autonomous system.

3.3 Design considerations

Most of the themes presented in the following chapters were mainly discussed with the 2nd and 3rd groups.

Sector and domain knowledge
An interviewee from the 2nd group discussed that the views of the customers are required to gain knowledge of the processes in order to provide added benefits. Second interviewee from the 2nd group that automation has to fulfill a need of the customer but to understand the customers process in a way that the OEM can fulfill the need with automation may prove difficult. Third interviewee from 2nd group discussed, that *the customers need be understood in a comprehensive way, and especially how the customer makes business and where the value comes from.* In addition, feasibility studies are required, but when performed on an autonomous system, the large field of problems is difficult to reveal within the time limit of a feasibility study – a need for learning the end process of a customer within a long period is crucial and it takes time to learn the key information.

Design of infrastructure
It was discussed by the first interviewee from 2nd group that *the use of the infrastructure supporting the machine enables to develop autonomous machines.* Part of this is due to being able to ensure safety, but also to implement technologies into the environment and existing infrastructure that make the autonomous operation possible. An interviewee from the 1st group discussed that it is a future challenge to design the infrastructure systems supporting the autonomous machine operation in addition to designing the machine itself. Another interviewee from 2nd group said that *the existing machines are efficient in their operation already but there is more to develop within the whole process and infrastructure that supports the operation.* For example, knowledge about supply of operational resources, state of machines and systems among autonomous machines are of interest for the end customer.

Analysis
Based on the interviews to understand the sector and domain knowledge of the end customer is important to identify how autonomy can bring benefits. With existing autonomous systems, improved productivity is a driver for autonomous machines, but it is also a driver to develop the system and infrastructure around the autonomous machine. To consider the co-design of infrastructure and machine is important for autonomous operation. The co-design of infrastructure and machine was also discussed in literature by Tan *et al.* (2016) as a method to increase machine operating capabilities and to enable

a low-cost solution. It can be concluded based on the interviews that cost efficiency is a challenge with autonomy providing components, furthermore, it can be concluded that the co-design of infrastructure and machine may provide a solution for this challenge.

Building a business case

It was discussed by an interviewee from 2nd group that as it is understood how the customers operation provides benefits, a business idea that allows the customer to increase value can be proposed. Another interviewee from the 2nd group discussed that the types of business models around autonomous systems are being studied, and it is believed that autonomy will come with new business approaches. For instance, the operation may include autonomous system or a remote-controlled system. The “remote operation” business model is was not found as attractive as “autonomy” business model nor as feasible in some circumstances. Creating a business case was seen challenging with autonomous systems from a third interviewee from 2nd group and it requires careful analysis on reasonable level of costs – a level where all stakeholders can benefit from autonomy. It was discussed with interviews from 2nd group that example business cases could include to sell a project, machine capacity against annual fee, and responsibility for operation and maintenance. For instance, the role of the customer might only be to use the product, but maintenance and other important roles could be provided by the manufacturer within the business model.

Two interviewees from 2nd group discussed that the data generated in autonomous operation is being studied for R&D purposes, but also for possible business opportunities. Updates and upgrades are seen as business opportunities during the autonomous product life cycle. In addition, it was discussed by another interviewee from 2nd group that the autonomous operation principle may provide the OEM a chance to provide many of the supporting elements (e.g. infrastructure and systems, cybersecurity, data management and maintenance) of autonomous operation, thus, the roles of the customer and supplier are being studied for future operations.

It was found from two interviews from 2nd group that the existing autonomous systems built for restricted environments are large scale investments and business-to-business projects in nature. The large-scale investments have a high rate of customization which adds into the already high cost of the autonomous product. In addition, the cost of customization is known, and the rate of customization is controlled in order to make profits. Cost of components has not been the issue so far in the large-scale investments.

Cost of components

Based on two interviews from the 2nd group, the existing autonomous systems are relatively expensive, and it was seen by the first interviewee to be necessary for the cost of components to come down for further development of medium and high-volume autonomous products. It was discussed that the suppliers for automotive industry who develop components and systems for autonomous vehicles seem to give a solution to the cost issue in future, but to successfully exploit the automotive components in mobile machinery environment requires further testing and research. New possibilities emerge such as sensor fusion (laser and camera), open source software libraries and licensed software.

Testing towards using automotive components has already been done, but the testing and research consumes unnecessary resources. Spending resources on component testing is seen unwanted, thus ready-built sensors and hardware for autonomous systems sought-after. It was discussed that the existing autonomous systems have been tailored from different components and the maturity of new hardware is waited for further development and low-cost solutions.

Analysis

As for creating a business case, it can be concluded that challenges and opportunities come from determining what type of operation principle the business model should consider but also what roles of the operation are fulfilled by the OEM, customer and other stakeholder. For instance, the maintenance needs of the autonomous system may be vastly different than the maintenance of a regular machine operation, thus there is an opportunity for the OEM to provide such services. Automotive suppliers may provide cost efficient solutions for medium and high volume autonomous mobile machine production, as the cost of autonomy providing components comes down within the automotive market. However, the use of those components in mobile machinery operation requires case specific research.

Defining requirements

Interviewee from 2nd group discussed that the complexity of operation and environment makes it difficult to define requirements for the autonomous product – the source of requirements for autonomous operation is so large, that it makes defining requirements, specifically safety requirements, a great challenge. Defining requirements was discussed by a second interviewee from 2nd group - plenty of time and resources are used for defining requirements, by the means of organizing workshops, demonstration projects. Researchers have spent time to study human dependent operations with a goal to find critical information for autonomy. For example, task analysis type of work has been done, where human dependent tasks are broken down into detailed descriptions of manual and mental activities. The idea of such research is to find information that is not well defined in documentations.

A third interviewee from 2nd group brought up that to define requirements, the machine operation is simulated in early design phases for visualization purposes. The simulation helps varying stakeholders to give feedback on the product. It was discussed by a fourth interviewee from 2nd group that defining requirements of a system with increasing degrees of autonomy, is beneficial with a well-managed and systematic requirements management system. Reviewing requirements and operational descriptions is being participated by increasing types of stakeholders, also from outside the design team. Feedback is gained from field operations and taken in consideration in the requirements management system. However, it was seen that in the future the documentation and the ways to review documents throughout the project lifecycle should be even more systematic.

Analysis

Defining requirements for an autonomous system was discussed to be a challenge by Vassev & Hinchey (2013) and Magnusson *et al.* (2018) due to the nature of AS's behavior and having to deal with uncertainty in operation. Based on the interviews and literature research it can be concluded that the uncertainty and nondeterministic nature of operation results as a challenge to define a complete set of requirements for the autonomous system. It can be summarized that methods for comprehensive requirements management seem to include simulations in early stage design phases, workshops and methods involving varying types of stakeholders (e.g. customers, operational domain experts and interdisciplinary design teams), task analysis and improving the methods for systematic requirements management. In theory, it seems that varying points of views from multiple stakeholders to bring in more requirements for the system and systematic requirements management methods become important in order to define as complete set of requirements as possible.

Integration of disciplines

It was discussed in interviews with 2nd group that autonomous machine development requires knowledge from various fields of engineering. There is no previous knowledge for "autonomy engineering", thus it was seen that skills from various industries have their place in a design team for an autonomous product. It was discussed by an interviewee from 2nd group that there is no exact knowledge for autonomy engineering, thus, they have built a cross-skilled team in which the competences support each other and each member of the team have enhanced their personal knowledge towards an autonomous system designer. For example, an interdisciplinary team can include software designers, operational domain experts and industrial design competences. Second interviewee from 2nd group discussed that the use of cross-functional team is a traditional method for design. A knowhow towards designing a system as whole, not only as partial functions, is required. It was told by an interviewee from 2nd group that *it must be understood how the design process advances and the type of interfaces between different engineering disciplines.*

Design process, systems engineering

It was discussed by an interviewee from 2nd group that various creative methods have been applied to manage a design process, but it was found important to have a person to ensure synchronization of design tasks – for example, a system engineer manager with vision based on background and experience. The systems engineer manager's role is to guide the design towards right direction and to require and organize tasks. This role was found difficult. Thus, a smart and skilled engineer is required to direct the design. It was found that the design process needs to be adaptable and some creativity is required. In practice, the process becomes complex with a heavy network of tools, which require smooth integration between the tools and the design process. To synchronize such a network of tools and design processes (e.g. mechanical, electrical and software engineering) is critical. Synchronization means to prioritize tasks and organize design phases in an efficient way.

Another interviewee from 2nd group discussed that a critical task assigned to a person is to ensure architecture-integration. It is critical for the different systems to interact with each other with clear interfaces, and it is responsibility of a skilled person to ensure this. For example, it was mentioned that the role of a system designer is to ensure that the *functional requirements of the machine are met by electrics, hydraulics, software, whole layout and mechanics.* It was seen by a systems integrator that companies with highly developed automation design processes already have a good basis for autonomous system design process.

Agile design approaches

It was discussed by a systems integrator that autonomous product design is heavily software-oriented design towards a highly sophisticated and complex system. For instance, it was discussed by an interviewee from 2nd group that design approach such as SAFe (Scaled Agile Framework) utilizes cross-functional teams where the knowledge of design is shared between disciplines. Design approaches similar to agile software development were utilized by companies creating AS's based on two interviews from 2nd group. It was seen that a benefit of such approach is that the knowhow and information exchanges between products and projects, when the designers of varying competences are working on varying projects for a certain time instead of working on one project for a very long time. Another interviewee from 2nd group discussed, that *we are quite well utilizing methods adopted from scrum, but not pure scrum exactly.*

Modular design

A system integrator discussed, that modular design principles become important part of AS design in order to manage the complexity of the system. It was seen that modular design helps in defining safety classifications and in testing against requirements of the standards. It was discussed by an interviewee from 2nd group that *we must be able to create modular solutions that are easy to integrate.* It was discussed with all interviews from 2nd group that having clear interfaces between systems is important. For instance, a second interviewee from 2nd group discussed that the systems should have clearly defined interfaces, so it is clearly understood what is being sent and received between systems. An interviewee from 2nd group discussed, that they are aiming to simplify the system design, since there is an issue of adding automation on top of automation which complicates to understand the interactions between systems. It should be simple to understand how the system operates and how the interactions between subsystems work. It was discussed by a systems integrator that in future, when neural network components become applicable, the integration of those components is viable to a modular software system with well-defined interfaces. In addition, at some point, the threshold of not being able to manage the system design with human brain will come and it was seen necessary to be able to assess the complex system into smaller pieces.

Analysis

Based on the interviews, autonomous product design process is a well-guided process of interdisciplinary competences. The well guided stands for having the design tasks organized, prioritized and executed by the correct competences for a chosen amount of time. Competence for systems engineering seems to have a place in organizing a multitask design. Agile design principles seem to be useful in design by providing means for utilizing the existing competences to a great degree. Interdisciplinary competences stand for a cross-skilled team with each individual having a common goal to enhance their skills towards an autonomous system designer.

Autonomous functionalities including perception, planning and control, as defined by Pendleton *et al.* (2017), are defined as capabilities performed by software. As part of designing software for autonomous capabilities, companies developing autonomous systems utilize agile and modular design principles. The use of such methods seems important for complexity management and having clearly defined interfaces between systems and modules. Thus, agile and modular software methods are an important competence to be utilized for autonomous system development. In addition, it was identified by Czarnowski *et al.* (2018) that the trend in robotics are towards a modular and open architectural system, where the control of different standardized robots is possible. Thus, it can be concluded based on literature and interviews that the agile and modular design principles become important in AMS design.

Perception of environment

A common discussion topic among interviews was that a great challenge with autonomous machines is perception of environment. For example, it was discussed by an interviewee from 2nd group that to find sensors that operate reliably, when the state of environment varies greatly, is a challenge. It was seen that perception of environment probably provides data for ML related safety-functions in the future, and it is a key function in verification and validation. But it was mentioned by a systems integrator that technological maturity is waited for to provide reliable environmental perception. It was discussed by an interviewee from 2nd group that there are many ways to obtain a perception of environment, for instance, using laser scanners to form a point cloud-based environment for further use, but the use of machine vision with ML and CV applications are being actively researched to be part of perception of environment.

The competence for perception of environment by image recognition has been developed with partners and recruiting researchers from universities. An interviewee from 1st group mentioned that they are researching the use of image recognition with a partner company. A second interviewee from 1st group also mentioned that the use of machine vision application has been thought of as a future project. Interviewee from 2nd group discussed that their computer vision competence has been built by recruiting researches from universities and by cooperation within the ecosystem. The computer vision applications rely on ML, and to teach a ML model to operate with required reliability, it was seen that comprehensive learning data is required. An interviewee from 2nd group emphasized that such data is being gathered from actual environments and it was seen that synthetic data is not enough for teaching the ML models to a reliable level.

Analysis

Perception of environment with image recognition and computer vision applications be is an important research topic for AM developers. The competence around image recognition and ML models utilizing it is a new type of competence that is sought for autonomous capabilities in some environments. It should be mentioned, that autonomous operation can occur without image recognition, but it seems that for future purposes the use of such methods (ML, CV, image and object recognition) are being researched. Autonomous operation relying on perception of environment still awaits maturity in challenging conditions, but the maturing process is ongoing as means to first provide the perception of environment to enable remote operation.

A possible solution for developing a CV application providing autonomous functions can utilize methods presented by Müller *et al.* (2018), where the objects and environment are modeled into a SIM4CV simulator and they provide synthetic data for ML and CV purposes. However, to what technological readiness level such functionality can be developed utilizing synthetic data seem to depend on the use case conditions: Indoor applications may utilize ML and CV more efficiently than outdoor applications with varying conditions. In addition, there is a contradiction with Müller *et al.* (2018) and an interviewee from 2nd group, with utilizing synthetic data for ML and CV purposes, when synthetic data was not seen to be comprehensive enough for reliable ML use for CV applications, though being suggested for CV development.

Accuracy in operation

Accuracy in autonomous operation is found important in various situations. It was discussed by the interviewees from the 1st group that to obtain a sufficient accuracy within autonomous operation is a challenge. This was also discussed by an interviewee from the 2nd group that in order to move on with the system development, you must develop an accurate localization method for navigation purposes and to do that in varying conditions is a challenge. Whether it is the localization of the machine or operation of a device, methods for providing reliable and consistent accuracy are found important. It was discussed by a second interviewee from the 2nd group that there are tough requirements for the accuracy of automated operation of a device, however, the accurate operation is enabled by automation and it is a clear benefit when compared to the regular operating principle.

Connectivity, latency and onboard functions

It was discussed by a system integrator that remote control operations are dependent on a reliable connectivity. In case of bad connection autonomous functions should be developed to be executed on board the machine. Low onboard latency was found important to provide safe operation in current mobile machinery, and it is seen that when the operation becomes autonomous, low latency becomes even more critical. It was discussed that if latency issues are nondeterministic and conflicting, the autonomous operation could become unsynchronized, thus, becoming a safety risk. An interviewee from 2nd group discussed that within their operation, the onboard functions should be able to handle a situation where the machine has to act by itself for safety reasons. A second interviewee from 2nd group also discussed that the safety is ensured by providing the safety functions on board the machine.

Analysis

It can be concluded that autonomous operation should include the onboard development to a level where the safety of operation is ensured with onboard processing. This supports the view, of being able to provide safe operation even in the case of disconnection. Thus, developing onboard autonomous functions is important due to safety and connectivity challenges. In addition, first developing semi-autonomous functions that are processed onboard the machine can provide a path towards developing a fully autonomous machine. Technologies with low latency connection capabilities seem to become important in the design of autonomy providing components, or modules, especially in operations that affect the physical control of a machine or implement and require fast reaction to changes in machine state or environment.

Physical V&V environments

It was discussed with interviewees from the 2nd group that physical V&V environments are utilized for R&D purposes of autonomous functions and for validating the product. An interviewee from 2nd group discussed, that the use of autonomy providing hardware provided by automotive suppliers is being researched in their testing environments, and excessive testing is required to research the feasibility of those components in their operational environment. In addition, the use of components that are feasible but not certified for their specific use need to be researched in physical testing environments. A challenge with physical testing is that it takes excessive amounts of money and time, but it is required to understand how to provide reliable operation. It was discussed by a second interviewee from 2nd group that there are many environmental variables that take place in physical testing. The physical testing environment is required since not all the possible circumstances can be tested in soft- and hardware simulations. The physical environments are utilized for component, subsystem and vehicle level testing. A third interviewee from 2nd group discussed that they perform physical testing in their own laboratory for sensors in many ways. In addition, they have sensors implemented on test vehicles in outdoor environments, from where they gather data for image recognition purposes and they study the behavior of sensors in varying conditions. It was seen by a systems integrator that before AI components are added to the system, the methods utilized currently in software and hardware V&V will most likely be sufficient.

Analysis

Physical V&V environments are being utilized for component and system level and functional testing of an autonomous machine. For instance, test scenarios including varying temperatures, difficult weather conditions such as smog or over illumination can be utilized to test the of components and systems. To understand the actual limits of components and systems, it is required to generate a lot of testing data from various scenarios. The data generated in physical testing environments is as a necessity for teaching ML models, instead of using synthetic data. For example, reliable ML models for object recognition are dependent on data generated in real environments. Such data from real environments can be imported to complement algorithm development in digital design environments. Physical testing is something that is necessary but it takes excessive resources. Though the physical testing is necessary to some degree, it seems that the further one can develop a product in a digital form the more resources (money and time) are saved.

In literature, Halterman and Scrapper (2017) discussed on component and subsystem testing and testing of autonomous functionalities in physical test environments, where the subsystems providing autonomous capabilities are exposed to weaknesses and similarly, according to the interviews, physical test scenarios with challenging conditions are utilized for component and subsystem testing in addition to system level testing. It can be concluded that physical test methods providing test scenarios unfeasible for digital design environments should be identified and efficiently utilized for R&D purposes.

3.4 Human-machine interaction

Research efforts
The interaction between human and machine was often understood in interviews as interaction through the user interface in remote operation. User interfaces as part of remote operation, and HMI in general, were seen as an important research and development subject among interviewees. For now, the user interface in remote operation is mostly provided with 2D displays, but according to a system integrator, research efforts are made among mobile machinery companies towards providing the operator a more intuitive feel of the machine and environment. Such efforts include improving the interface input with lower latency, better environment awareness through various senses and mixed reality view and improved remote operation accuracy.

Research on user interfaces
It was discussed by an interviewee from 2nd group that research has been made on how to design a remote operation system so that it functions with human cognition in a smooth way. Research on cognition gives feedback to important questions on remote operated autonomous systems: What should the system be like, in order to switch between different kinds of remote operated machines and environments? What should the operator be aware of, to enter situations and take control without overwhelming stress? The research includes hired experts from the operational domain and collaboration with operational domain educators. It was seen that well designed interface can be a way to distinguish from competitors and HMI demonstration projects are important in order to receive user feedback. The user interface is wanted to be used intuitively with reduced learning curve in a way that as the user perceives new information, it instantly realizes the situation in a transparent way. The operation principle of an autonomous machine forces to design user interface solutions that are not focused purely on controlling the machine, but on overseeing the machine operating autonomously in a transparent way. This is a challenge in HMI design.

It was discussed by a second interviewee from 2nd group that the user interface design has been successful based on user research and interviews. When considering the interface between human and machine, more specifically customer and system, it was discussed by a second interviewee from the 2nd group that it is a challenge for the customer to embrace the operation of a new AMS. Thus, plenty of resources have been put into making sure that the customer thoroughly learns the new AMS.

It was discussed by a third interviewee from 2nd group that an important cost benefit that can be gained from advanced HMI research and development is that the operation principle can be optimized to a point in the future where a single operator is responsible for overseeing a fleet of various machines, instead of having multiple operators on the task. That level of operation may be feasible for operation with single machine type, but as the environment becomes more heterogeneous with varying types of machines and processes, more research on HMI is required to reach such cost benefits. However, it was mentioned that *there is still a lot of work to be done with HMI and we are still beginners in HMI.*

Physical HMI

It was discussed by a fourth interviewee from 2nd group that a way to think of HMI is how humans operate side-by-side among the AM's and what types of interactions happen between them. An HMI design approach in AMS design includes empirical research utilizing physical test scenarios. Since there is infinite number of possible scenarios between human and machine interactions, limited test scenarios are performed to find what type of features the system should include. Such test scenarios, including human and machine in the same operation environment, are simplified by limiting automation, manual operation and environment to a degree that allows less challenging analysis. Various physical test scenarios with humans and machines interacting are experimented to discover different types of requirements for the system. The end goal is to build a safe system and with limited HMI test scenarios it is found to push development towards discovering new requirements. It was mentioned that *this subject requires a lot of further research.*

Digital HMI

In addition to physical HMI testing approach, test scenarios are also run in digital environment. For instance, it was discussed by the fourth interviewee from 2nd group that a gaming environment with players assessed to different roles within an autonomous operation is used for running test scenarios such as hazards and autonomous operation. It is found more efficient than physical environment in terms of accelerating development and creating scenarios that would be unfeasible to create in physical environment. It was discussed by a system integrator that digital environments can be used for training machine operators to collaborate with autonomous machines: An operator can be in control of a digital regular machine that collaborates with autonomous machines. Thus, the operator is simultaneously being trained to collaborate with autonomous machines and the autonomous machines operation can be validated in the digital environment. The first interviewee from 2nd group discussed that use of Unity 3D game engine in UI design is beneficial instead of drawing squares and buttons on a sheet. In such environment other indicators than textual information is utilized in attempt to make the use of the UI intuitive for the user.

Analysis
The HMI research is an important point of view for designing AM's. Based on the interviews, the HMI research can be divided roughly into the user interface research and the human and machine interaction research in physical operation. The design of user interfaces is an important topic for regular type of machine operation as well, but for autonomous systems, the type of information to be displayed has different kinds of requirements, since the user interface is responsible for providing the operator (or overseer) awareness of environment, operation and machine condition. A similar challenge of HMI design can be identified based on the discussion by Debernard *et al.* (2016) and interviews, which is to choose what information, how and when to display the information to the user when the operation itself is autonomous. It was mentioned that HMI still requires further research and this is being in cooperation by mobile machinery manufacturers, thus, efforts towards HMI seem to become important in AMS design. Czarnowski *et al.* (2018) discussed that HMIf design includes remote operation and advanced perception, AS's oversight and tactical awareness, and based on the interviews, the mobile machinery companies are researching HMIf design together with remote operation and advanced perception.

As for physical HMI, it was discussed by Nguyen (2018) that the V&V design should be simplified, where sources of non-deterministic events are minimized, and similarly based on the interviews HMI related physical test scenarios aim to utilize simplified limited test scenarios. Thus, having the capability to perform limited, simplified and deterministic physical test scenarios is important for AMS design. It can be concluded that HMI is an important research topic in which the co-design of human interaction with the system and the technologies may provide new opportunities for new types of operating principles with reduced operating costs in the future.

3.5 Data acquisition, management and analysis

Providing customer information about the work process
It discussed by an interviewee from 2nd group that there is a customer segment that are interested in understanding their operating processes in a more profound way and seeking productivity gains by utilizing advanced data acquisition, management and analysis (AMA) methods. The data acquisition from machine and infrastructure are found interesting, since the machines are seen to be efficient in their operation already, but the overall work process can be enhanced by further developing data AMA methods. Most of the time the customer may not realize the potential that it could receive from the machines, but at the same time from the overall process and infrastructure. For instance, dataflow about varying operation cycles can be useful for analyzing the root cause of a main process stop, thus providing a method for reducing operation downtime.

It was also discussed by an interviewee from 1st group that there is a need to develop methods for measuring features of the work process and data AMA. For instance, acquisition of data for maintenance purposes, estimation of fuel consumption and utilizing cloud services were seen to *come before autonomous operation*. A second interviewee from 1st group discussed also about data AMA being an ongoing R&D topic. At the moment, the data is utilized in fault diagnostics, but in the future data AMA will probably be utilized in new business models. In addition, it was discussed that *system development, server-infrastructure, data storing, interfaces and services to stakeholders are to be considered.*

Challenge to realize what information is valuable

An interviewee from 2nd group discussed that it is not found difficult for the OEM's to provide information about their machines, but to find the key information from the customers process that supports the customer is a challenge (the customer being the end user of the OEM's machine). This was also discussed by a system integrator who cooperates with many mobile machine OEM's that the readiness for data AMA is there, but cooperation with OEM's is required to identify valuable data. It was suggested that sources for finding valuable data could be further researched from maintenance cases.

Malfunctions and faulty operation need to be understood

It was discussed by a system integrator that when considering autonomous machines, it is required to realize faulty operation of a machine through data. Such feedback is found crucial for autonomous machines, or they end up suffering from the same problem as neural networks, which is the uncertainty of result (why something happened the way it did?). To understand operation especially in case of malfunction through gathered data is a goal. For instance, a sensor that is used to analyze a fault after a hazard does not fulfill its highest potential and provide true value. Instead, using the sensor for intelligent diagnostics could provide information about misuse. It was discussed by an interviewee from 2nd group that combining and utilizing different components require methods for data AMA in order find limitations for components. Another interviewee from 2nd group also discussed that gathering data for R&D purposes was seen important part of the future, where large amounts of data from components is analyzed for optimization purposes.

Data for ML purposes: Optimization of process

It was discussed in three interviewees from 2nd group that they are gathering data for ML purposes. For instance, it was discussed with an interviewee from 2nd group that data is being gathered for further real-time optimization purposes with ML for the future, but for now, more data is required for such actions. A second interviewee from 2nd group discussed that ML models have been used in algorithms optimizing work processes to guide operation and ensure accuracy. Depending on the type of work process, advances in the use of ML are developed to various degrees. For instance, a careful analysis of process enables to avoid unnecessary damage and optimize efficiency. Depending on the type of work process, the use of ML is developed to various degrees. For instance, a careful analysis of process enables to avoid unnecessary damage and optimize efficiency. Data gathered from operation is stored in cloud and being analyzed in offline after detecting issues. Data recorded can be rewind to the moment of failure, and for instance, the data presented in user interfaces can be displayed. In future, it is a plan to apply the learned knowledge from offline data processing into added intelligence on-board the machine.

Data is in key role as part of the added intelligence, but this is in early development phases.

Data for ML purposes: Perception
It was discussed with all interviews in 2nd group that data for image recognition and ML purposes is being utilized and gathered. It was seen by an interviewee from 2nd group that to push development forwards, the use of different components, such as LIDAR and camera, in combination is being used and further researched. Often components, like sensors used for perception, are optimized for a single purpose and to apply use of such components to various purposes is studied by gathering test data. For now, ML has not been applied to ensure safety. However, ML is used as part of on-board functions such as object recognition for operative purposes and creating situational awareness. It was discussed by a second interviewee from 2nd group that test data from real environments is being gathered, and instead of using synthetic data to teach ML models, the real data is found necessary to ensure reliability. A third interviewee from 2nd group discussed that in the future there is a need for ML and CV applications as part of the AMS.

Business benefits
It was discussed by an interviewee from 2nd group that creating methods for data AMA provides chance for business benefits and new business models. To statistically prove accuracy, quality, machine health over time and other highly valued information supports business by being able to show comparison between options, for example between autonomous and regular operation. Another interviewee from 2nd group discussed that research is being made on what types of business models the data AMA enables. Data collected from autonomous on-board operation is only one source for data: the environment, supporting infrastructure and autonomous operation provide possibilities for new business models.

Analysis
It can be concluded based on discussion from all interviews that there is a growing need for data AMA in mobile machinery industry. The existing autonomous systems have been proven for increased productivity, and part of this is due to the developed knowhow on how to collect data from machines and systems, how to store and manage it, how to analyze and present the key information. However, challenges arise in identifying valuable data. Data AMA has a great role in supporting R&D, optimizing work processes, providing methods for predictive maintenance, developing the use of ML and CV applications and providing business opportunities.

3.6 Safety

Future goals
For now, the safety for autonomous mobile machines has been ensured with isolating the autonomous operating area from pedestrians and other unknown objects to autonomous machine. According to the interviews with 2nd group, zero tolerance for safety-related accidents is a common goal for autonomous system design. It was discussed by an interviewee from 2nd group that a problem with restricted environment is that it lacks

flexibility. The physical restriction of an operating environment is not wanted from the customer in the future. Thus, new methods for providing safe operating environment for both autonomous machines and other agents are being researched and tested. It was discussed by a second interviewee from 2nd group that pedestrians, bicyclers, regular machines and other various autonomous machines should be able to co-exist in the same environment in the future. Future standards aim to address the problem of ensuring safety in an unrestricted operating area. How the standards assess the issue and possibly solves it is still under work.

Design for safety

It was discussed by a system integrator and first interviewee from the 2nd group that functional safety standards provide guidelines for software and hardware design, and combinations of standards assessing safety integrity and performance levels are used for ensuring current safety methods. The safety guidelines affect the onboard autonomous machine design. But to ensure overall safety of an AMS and its unrestricted operating area is something that still waits for guidelines from standards. A third interviewee from 2nd group discussed that established methods such as safety case were used for V&V. FTA and FMEA are being utilized and autonomy is something that was seen to add in more cases for evaluation and analysis. Systems Theoretic Process Analysis has been tried out, but with it was found not feasible with new and immature technologies.

Outdoor components

It was discussed by the first interviewee from 2nd group that indoor environments benefit from the use of certified safety components, which makes it simpler to perform a safety analysis: Being able to trust on component reliability and on manufacturers' guarantee on compliance of components with existing standards is important. But such trust does not exist in the same way for outdoor environments and their components. The lack of similar trust results in performing excessive and resource-consuming testing and analysis on components used in outdoor environments.

Open source solutions to provide safety

It was discussed by the first interviewee from 2nd group that new possibilities arise as programmable safety logics have entered the market. Ready built modules, certified components and certified software components are used to make the design of an AM simpler. Components and ready built systems for outdoor environment use are also being sought from the automotive suppliers. The use of automotive components provides possibilities for autonomous mobile machines in outdoor environments, but for now, more research and testing of those components and systems is required. Open source software libraries and licensed software make resources available for developing company's own core competence. However, to use open source components in a correct way, licenses such as General Public License have to be obeyed which was seen difficult.

It was discussed by a second interviewee from 2nd group that it is risky to rely on an open source solution in case it has not been ensured with enough validation. The one responsible for ensuring safety may not want a faceless source for their solution. However, open source solutions with a large user base and design proven through validation were seen to provide an approach for safety solutions. For instance, an open source safety component that is supported by an open source community and audited by a 3rd party member would help AM designers push development forwards.

Role of standards

According to a systems integrator and first interviewee from 2nd group functional safety standards such as IEC 61508 or ISO 13849-1 are utilized for onboard purposes. It was seen that semi-autonomous onboard functions can make well use of a design tool such as "Functional safety of machine control systems" (KOTOTU), as long as the system is not utilizing AI. According to a third interviewee from 2nd group a standardized approach for system integration is needed. Such standard should define clearly the functions of interfaces and how the systems operate. The main idea is that following a standard would help to understand how systems interact with each other and for example, the standard would help to understand how a system works when a failure occurs. A standardization could improve reliability of a system, since now different applications are integrated in creative ways, which result in questionable reliability.

It was discussed by a second interviewee that in the future, it is difficult for the OEM to take full responsibility for overall safety for outdoor autonomous mobile machine systems in unrestricted environments. A system for overall safety can be agreed with OEM and the customer together but agreeing with who is responsible for safety and how it is defined is a difficult task. Test requirements agreed with OEM, customer and other stakeholders can be validated in real life test scenarios to provide some safety for unrestricted operating area. Meeting the requirements through test scenarios push the development forward towards enabling an unrestricted autonomous operation area. The problem is that the shared view by OEM, customer and other stakeholders for safety requirements in unrestricted environment is not equivalent to a standardized method. A respected standardized method would make it simpler to assess requirements for safety and most importantly, coming to a common agreement about who is responsible for ensuring safety could be simpler when a standard could be relied on.

Analysis

It can be concluded based on the interviews that a major challenge in developing AMS's is the lack of supporting standards. The standards would help in ways to create trust for the system and autonomy specific standards could be relied upon when designing for autonomous operation.

It can be concluded that an autonomy specific standard should define guidelines for design and validation of an autonomous machine in order to design a machine with sufficient safety and reliability. In theory, if safety methods for autonomous mobile machinery would be developed as open source solutions and validated by manufacturers developing AS's, the safety solutions could be developed to a level where they would gain plenty of trust and even a standardized position due to having a large mass of manufacturers proving their feasibility. In the future, if an open source safety solution becomes part of a technology disruptive AMS, the solution would benefit all the stakeholders and even possibly enable to reach a degree of sufficient safety and reliability. This could provide better acceptance for the AMS and trigger market interest, when the safety is being proven by many. On the other hand, spending significant resources on developing a technology disruptive AMS is something that provides great advantage over competitors.

Based on the interviews it can be concluded that for the AM's that are supported by an autonomy specific standard are uncompromising. The level of safety required must be provided, and there are no shortcuts. However, when there is no specific standard giving guidelines, it gives freedom for creating a method for sufficient safety. When there are no autonomy specific standards supporting the development, it seems that creating an AM with some agreed safety methods may become a business risk before a standard appears, since later appearing standard could make the self-assured system inapplicable.

3.7 Cyber security

Increasing demand for cybersecurity
Based on the discussion from the interviews with 2nd group it was found that there is a growing demand for cybersecurity and its value and importance is increasing. Some emerged drivers behind increasing cybersecurity are the digitalization of operation in general, to avoid production downtime and to secure operations with social significance. It was seen that with increasing degrees of automation, the impact of cyber hazard becomes more severe. The digitalized infrastructure and system that provides autonomous operation requires protection against cyber threats.

Efforts to increase cybersecurity
Based on three interviews with 2nd group cybersecurity has been previously outsourced from companies providing cybersecurity services and research projects have been performed. Now the cybersecurity knowledge is being increasingly applied by the means of hiring experts and building cybersecurity competence as part of OEM knowledge. First interviewee form 2nd group argued that previously and currently in some occasions, cybersecurity has been the customers matter. Since the first occurrences of cybersecurity attacks on systems with autonomous machines operation, in some occasions the customers have begun to require means for cybersecurity from the AMS manufacturer.

It was discussed by the first interviewee from 2nd group that building competence around cybersecurity takes time. An example of a built competence is design guidelines with respect to cybersecurity used in code generation. The use of ML models in finding anomalies and potential risks in dataflow is being developed. Means for testing for cybersecurity and developing different systems has taken place. For example, the design of system architectures is affected by cybersecurity goals, which aim towards isolating threats and providing easier and more efficient recovery mechanisms. It was seen that when OEM's become expert on their own systems cyber security, the built knowledge may provide cybersecurity services provided by the OEM.

It was discussed by a second interviewee from 2nd group that a challenge for cybersecurity is the quick evolution of the domain, and to stay up to date requires effort, such as validating the updated systems. It is important to find the critical updates. System hardening days, demonstration projects and outsourced penetration testing have provided experience on the efficiency of cybersecurity means, and system level issues have been discovered.

Safety when disconnected
It was discussed by a third interviewee from 2nd group that *autonomous machine should make it on its own if something goes wrong.* The basis for design is that the machine operation is safe even when disconnected. This has been mostly solved with one-way dataflow from the machine, but for autonomous systems and machines such solution is stiff. Sending data to the machine is needed for efficient operation, and simultaneously the cybersecurity must be provided both on system and machine levels. Onboard cybersecurity means to process the incoming data and to detect threats, but also to detect incomplete information in case of a disconnection. Safe operation in such situation should be considered in design. Solutions such as 5G and LTE technologies are being used to provide highly secure private networks in autonomous operation environments.

Analysis
Cybersecurity is a mean for securing operations with increasing data AMA. It can be concluded that the cybersecurity is a product for securing digitalized operations which include autonomous operation. It seems that the level of cybersecurity affects the autonomous operation profile: With a low cybersecurity level, autonomous system may have to be disconnected as a threat occurs, and the operation may have to be continued manually or stopped completely. With advanced means for cybersecurity the operation may continue during a threat. However, it seems that even in the case of a threat or disconnection, means for providing safe operation with onboard functions becomes important. Connectivity may be necessary for safe and reliable autonomous operation, thus means for onboard safety and cybersecurity become both important. It was discussed by Malm *et al.* (2018) that security risk assessments on automated systems are suggested to be done separately from safety analysis. It can be concluded based on interviews and literature that having experts and competences for cybersecurity separately (not as an outsourced semi-important project within a safety analysis) part of AMS design seem to be important already and even more in the future.

3.8 Digital design practices

A basis for developing autonomous functions
The idea of developing autonomous functions as close to ready as possible without a physical product was found important based on interviews with 2nd and 3rd groups. It was discussed by 3rd group and three interviews from 2nd group that AMS development should happen using digital design environments (DDE) such as digital twins, which represent the digital design tools and practices for developing AMS's. A view on the use of DDE's arose from a system integrator and interviewee from 2nd group: It is found desirable to design repetitive processes, such as automated operations, in a DDE from the beginning.

As the design advances towards a higher degree of automation with added intelligence and decision-making capabilities, the development process from the automation design work as a good basis for designing AMS's. A systems integrator discussed that to first have experience with digital design capabilities, such as simulation of machine control system and environment, is found beneficial for AM development in the future. This view is supported by digital design practices used by the interviewed companies developing AM's as in forms of varying types of simulations.

Varying types of simulations

The interviewed companies developing AS's use digital design tools in forms of different types of simulations. It was discussed by an interviewee from 2nd group that with AS's the field of problems in its operation is so large that simulation was seen necessary in order to visualize the operation before entering prototype phase in design. Simple simulations include simulating AM operation cycle without detailed modeling of environment and system. A second interviewee from the 2nd group discussed that simulation with simple models enable to receive feedback from different stakeholders and to visualize the operation of a large system with AM's in it. Simplified rough simulations, which do not yet consider minor technical details, are used in assessing requirements for the AM and the operating process, based on first and second interviews from 2nd group. Simulations are used to prove that some requirements are met in early design.

It was discussed with the 2nd interviewee from 2nd group that simulation models built in early design phases work a basis for further development of the product using more advanced level simulations. The most advanced simulations include physics-based real-time simulations, also called digital twins, with detailed model of environment physics, machine dynamics and software and hardware models. Detailed and accurate simulations enable to develop specific capabilities for autonomous operations.

Digital twin

Digital twins were mentioned to be widely used as a design approach to developing regular machine control systems. But according to a system integrator to develop autonomous functionalities with the control system was seen helpful with a digital twin model. For instance, it was discussed by a system integrator that it was found as a goal to develop the autonomous perception and decision-making capabilities in with a digital twin model. For example, virtual perception capabilities such as radar or LIDAR can be modeled to virtually detect environment and it can be tested whether the system reacts and decides in a correct way. A second system integrator discussed that the use of digital twins is feasible for developing a control system and autonomous guidance and algorithms can be developed on top of the control system. It was discussed by the first system integrator that the software development providing these capabilities need a lot of data and synthetic data can be generated in a digital twin environment to be used for development purposes. However, it was discussed by the system integrator and an interviewee from 2nd group that the use of synthetic data was seen not enough for validating the product. Thus, data from real environments are required for validating the AMS. It was also discussed by an interviewee from 2nd group that use of control system and machine functionality simulations is something that benefits from the use of digital twins now and even more in the future with more complex systems.

It was discussed by a system integrator that the autonomous machine decision making algorithm and software development requires a digital design and testing environment. A virtual replica of a machine and environment can be simulated, in which the decision-making algorithm responsible for controlling the autonomous machine is developed. For instance, it was seen that in a digital form the software and hardware can be developed to a degree where software and hardware are implemented on a prototype without requiring large scale iterative development with a physical environment. It was also discussed by the second interviewee from 2nd group that iteration of an AMS in digital form is a lot simpler than iteration process in physical form. It was discussed by the second interviewee from 2nd group that the simulation models are validated in physical environments.

Interface for disciplines

It was told by the second interviewee from 2nd group that important part of AM design process is to have different disciplines of engineering such as mechanical, automation, electrical and software work together efficiently. The process includes defining interfaces between these disciplines. It was seen that digital design environments using simulation models can provide a common interface between disciplines, which was also discussed by a system integrator. The system integrator also discussed that, for instance, digital twins can work as a common model that is developed by multiple disciplines. Having a common development model makes concurrent development simple by being able to detect and solve issues by developers from different disciplines. Being able to visualize the product in its real operating environment with realistic physics is found important, so that the developers understand common development needs. When common development needs are detected, it can be easier to fix issues with the most feasible solutions provided by the right discipline, for example, creating a simple software solution can be less resource consuming than attempting to fix an issue with a mechanical solution.

Model-based design approach

Model-based design approach was discussed during the interviews and it was understood in varying ways by the interviewees. It was understood as working with various kinds of models and simulation, as mathematical modeling, as a DDE system that can be created from separate or large-scale commercial design tools, as a design approach that reduces time for engineering and testing and as a DDE system that could be integrated into with the existing design tools.

It was discussed by two interviewees from 2nd group that many resources have been invested to build the knowledge around model-based design approach, which in this case means simulations and the design approaches related to simulation. It was seen by the first interviewee from 2nd group that model-based design approach is an important part of design. For example, in an environment with autonomous machines providing subprocesses to a main automated process, it is required to create a model of process and the systems within it in order to ensure clear interaction between systems. It was discussed by the first interviewee from 2nd group that the interfaces between systems need to be understood and the model-based approach supports this. In addition, creating mathematical models from systems were seen part of the model-based approach by a second interviewee from 2nd group. It was seen that well implemented model-based approach reduces the time required for engineering: For example, the time used for safety analysis and the workload upon the people doing the analysis are both reduced. In addition, the traceability of requirements is easier to ensure with such approach. A third interviewee from 2nd group discussed that in future, the use of digital twins is seen easier when model-based design approach is already familiar.

Value of digital design tools
Both self-made design tools and commercial digital design solutions were utilized by the interviewed companies. It was discussed by the first and second interviewees from 2nd group that the benefits of using self-made tools is that the contents, limitations and strengths are better known than with commercial tools, which do not require similar expertise from the designer as the self-made tools. It was seen as a difficult process to integrate large scale commercial tools, especially when existing self-made tools are being utilized, and the cost of such design tools are great. However, it was seen that the benefit of large-scale commercial tools is that they provide traceability of requirements, which is required by functional safety standards. Since the cost of tools is great, it was seen that it is important to evaluate separately and invest carefully in the design tools that fit the specific design needs of an OEM. It was mentioned that some promising solutions have arose to aid in the development of autonomous mobile machines: Tools for developing autonomous automotive technologies have entered the market and similar commercial tools can bring benefits to the mobile machine development as well, but they were seen rather expensive. It was discussed by a third interviewee from 2nd group that there are several separate commercial design tools, other than large scale commercial tools, for specific simulations that may be more flexible to implement as part of the network of tools already built.

Challenge with harsh conditions
Some practical issues arise even with a highly realistic simulation model. It was discussed by a system integrator and fourth interviewee from 2nd group that it is difficult to realistically simulate harsh conditions virtually for perception capabilities, such as dust, fog and rain, which results in not being able to develop the autonomous system for all operating conditions in a digital form. Based on the discussion by a system integrator and two interviewees from 2nd group the quality and type of sensor signal for perception capability needs to be assured. It was discussed by a system integrator that, a virtual LIDAR signal input is not based on a virtual laser pulse, but in a mathematically modeled signal input based on the distance information gained from the model and the LIDAR sensor data sheets provided by the sensor manufacturers. It is difficult to assure the quality of input signal from LIDAR sensors within the digital twin model, since the data sheets from various quality types of LIDARs are meant to represent the signal in its optimal condition. A difference in quality between LIDARs in a real environment can be

detected and this is why the physical testing is required. In the future, more comprehensive signal modeling techniques for harsh conditions are required. In addition to the perception modeling challenges, simulating an AMS is simpler in an environment with easy to detect objects than in an environment with various types of objects and shapes. Since the environments are most likely changing during the autonomous operation, simulating the operation correctly in a dynamic complex environment is challenging and generating such environments requires plenty of resources.

Data from real machine and environment imported to digital twin
It was discussed by a system integrator and two interviewees from 2nd group that it is being further developed to use the sensor feedback from real situations as an input signal for the software in a digital twin model. For instance, the signal produced by LIDAR operating in rainy or foggy circumstances is being gathered and further used in part of a simulation. The AMS within the digital twin model can be tested with the real input data from a real environment. Data from real environments is also required to compare the data generated in digital twin model and to further develop the accuracy of the models. It was mentioned by the first interviewee from 2nd group that some approximations are required in the models, but the physics of a digital twin model can be developed to a very accurate level.

Future developments in simulation
It was mentioned by system integrators and three interviewees from 2nd group that the digital twin models have focused on developing the autonomous control system and the second interviewee and a system integrator discussed the digital twin being utilized for software providing autonomous functions. It was discussed by a fourth interviewee from 2nd group that the degree of accuracy within the digital twin models is being further developed and evaluated, by the means of experimenting with large scale system and component dynamic modeling. It was discussed by the first interviewee that varying types of simulations exist and it is important to evaluate what degree accuracy within a simulation is necessary.

Since a very important element of machine diagnostics is missing with an autonomous machine, which is the human operator paying attention to changes in the machine and its environment, the diagnostics must be developed in new ways, such as utilizing physics-based simulation models for detecting phenomena by improving sensor usage in more efficient ways than before. It was discussed by the second interviewee from 2nd group that in the future, diagnostics and maintenance development is seen to benefit from digital twin models. To be able to simulate failures with a physics-based model, the autonomous machine diagnostics and predictive maintenance can be further developed. For instance, the digital twin models enable to develop new ways for sensing important changes by adding sensors to the autonomous machine or using the data of existing sensors in a new way, in order to diagnose the machine state efficiently.

Analysis
Based on the interviews, it can be concluded that a challenge in AMS design is to manage and guide the multidisciplinary design process. A solution for this challenge arises

from the methods of model-based approach and systems engineering competences. A tool within that solution seem to be a digital design practices, such as digital twin model and varying types of simulation, which can be concurrently developed by many disciplines. The use of varying types of simulations for different design needs were discussed within interviews and similarly, Goodin *et al.* (2018) presented three types of different simulators for different design purposes. Thus, it can be concluded that varying types of simulations are beneficial in AMS design process.

The term digital twin was discussed in all interviews and it can be concluded that it was understood as a physics based real-time simulation of machine and environment. It did not become clear whether the interviewees considered that is the digital version of a machine dependent on the existence of a real machine ("twin") or not. However, it was seen and discussed in multiple interviews that the benefit of a digital twin is to develop a system as ready as possible without building a physical prototype. Thus, it can be concluded that the digital model of a machine is not dependent on the existence of a real machine prototype.

The importance of utilizing digital design tools is already great for AMS design, and the importance is also growing towards further use in the future for developing systems with increasing complexities. Since there is a need for such tools, it becomes important to understand whether to invest in developing own tools or buying commercial ones. However, it can be concluded that investment in such tools and developing methods such as model based design approaches bring benefits such as reduced time in engineering and resources spent in physical testing. This does not mean that physical V&V and testing is unnecessary, but the development of autonomous capabilities faster and more feasible in a digital form and it can be complemented by the physical testing for V&V and R&D purposes. For instance, since there are challenges in replicating the perception sensor signal in the digital model, physical testing comes to aid in this challenge.

It was discussed by Worm and van der Made (2019) that model-based system engineering methods were beneficial with the use of digital twin simulation tools for design optimization purposes. According to interviews, it seems that a similar benefit of implementing model-based approaches with digital design tools used for simulation has been realized by interviewed companies. It can be concluded that for complex system development (such as AMS) the use of model-based design approaches and advanced digital design tools such as digital twin is beneficial and should be a considered as part of AMS design.

3.9 Partnerships and ecosystems

What is an ecosystem?

It was a common view discussed during interviews that partnerships, often mentioned as ecosystems, are needed to further develop AM's. When new complex systems are created, new competences are required, and this can be in forms of creating ecosystems. It is to be mentioned that an ecosystem was not seen as the same as a supplier chain. It can be interpreted that ecosystems were seen as cooperative development partnerships that will most likely be utilized more in the future. There was not an accurate uniform view on what an ecosystem is, but the following subchapters aim to provide a view on features of ecosystem-like partnerships that were discussed within interviews.

Ecosystem to increase resources

A common view included that it requires great amount of resources to build the whole AMS and the resources are sought from cooperative partnerships. It was seen that the more complex the AMS is, the more ecosystem is needed to create an AMS. Practically there exist AMS's without efforts from great size ecosystems and thus, it is important to understand that ecosystems were seen to be required for AMS's with increasing complexities in the future. For instance, it was discussed by an interviewee from 2^{nd} group that the infrastructure supporting the autonomous operation can be outside the core competence of the OEM. Such infrastructure can include competences for building networks, data transfer and cloud services for example. A second interviewee from 2^{nd} group expressed that *to find high skilled competences is as a challenge*.

Ecosystem business

A view arose on an ecosystem cooperation by a third interviewee from 2^{nd} group: When the core competences of multiple parties of the ecosystem work together, it should be accepted that each stakeholder benefits from the product that was created together. Fourth interviewee discussed that the business models of a cooperative ecosystem are something that are being researched. Since business-to-business operation does not work with the same principles as retail, it is being researched what business model options are most suitable for AMS ecosystems. The business model could depend on the solution created by a third party or stakeholders together within the ecosystem.

Open towards sharing data

It was found important by the fourth interviewee from 2^{nd} group to recognize and withhold core competences to ensure competitiveness. Core competences represent the competences built around autonomous functionality development. However, to ensure effective operation of an ecosystem it was seen necessary to provide the ecosystem data and expand interfaces to support it. Interfaces in this context does not mean the technical interface of a module within a system, but interfaces between stakeholders within an ecosystem. What information is required to be shared for the ecosystem, and what information is withheld and where the interface lies between these options are important questions to consider. It was seen by a system integrator and the fourth interviewee from 2^{nd} group that the competence including the knowledge of autonomous function, such as autonomous navigation or autonomous operation of a device, is a competitive edge that is sought after.

Simulations within ecosystem

As mentioned previously, it was seen important to integrate various engineering disciplines together and an ecosystem helps in that. It was discussed by a system integrator that using varying types of simulations, stakeholders can give feedback based on visualization by simulations and these stakeholders can be parties from the ecosystem. For example, it is possible to share simulations and models within the ecosystem with a standardized method such as Functional Mock-up Interface (FMI). In addition, bringing together competences in forms of ecosystems could enable to develop a future AMS with enough acceptance, since the AMS would be a result of cooperation of large mass of companies and their core competences.

A software-ecosystem

A view about ecosystems came up from a system integrator, where ecosystems for autonomous mobile machine development were seen mostly as software-ecosystems, since the autonomous capabilities are mostly provided with software, there should not be great design competences for the mechanical engineering that are sought from an ecosystem. Mobile machine OEM’s who may design AMS’s in the future face a design challenge with a software-ecosystem, since there might not be much experience with software development methods. A modular design principle is part of software design and it was seen as important aspect to consider within an ecosystem. In practice, this means that there can be modules that provide autonomous functionalities, and such modules need to be easily integrated with well-defined interfaces. For example, a module for simultaneous localization and mapping can be a development of OEM or 3rd party member, and this module among other modules must cooperate to provide autonomous function such as autonomous navigation. Another example is that various stakeholders within the ecosystem can be developing modules that are integrated into an AMS, and some modules or functionalities can be brought from commercial or open source solutions. Since the product may include modules from various parties, it was found important to be able to ensure that the modules exchange information correctly requires well defined interfaces and modular design principles support this.

Development of CV applications

To develop methods for image recognition were mentioned by the interviewees. It was mentioned by the fourth interviewee from 2nd group that there are ready built commercial solutions built for AMS, for example, solutions for a machine vision system, and it was found that the use of such ready built systems can help to speed up the AMS development. The knowledge for developing such system was not seen feasible or as a core competence. It was seen that machine vision systems are better to buy from elsewhere and the overall AMS development becomes faster when resources are not spent on developing such system. It was discussed by the second interviewee from 2nd group that there are ongoing research projects with universities and partners that focus on development of the machine-vision and image recognition. For example, a partnership of multiple parties includes developing a simulating software, where the image sent by camera is simulated to replicate rainy or foggy conditions. It was mentioned by a system integrator that there are ongoing research projects that aim to develop the environmental perception to a level that enables efficient use of remote operation of a machine.

Short-term nature

It was discussed with the fourth interviewee from 2nd group that to define interfaces, share data, develop software-architectures and modular designs are practical challenges for ecosystems, but another interesting challenge to ecosystems arose. The current trend in cooperative partnerships suffer from short-term nature: The lifetime of ecosystems is too short. Companies' measure results within short time limits and results are wanted fast. It was seen that there is a contradiction with building an ecosystem and searching for the service with the lowest price simultaneously, which results in short term projects, and then new and better offerings are considered outside the ecosystem. This was seen as a problem, when the end product of the ecosystem is a complex AMS, which will most likely require a lot of time to develop. Cooperation of an ecosystem may be inefficient in the beginning, which is why enough time is required to learn the common field of problems. In addition, methods for cooperation need to be developed and common knowledge should be gained. For example, commitment to an ecosystem for three years can be too short to develop common competence. It was also discussed by the second interviewee from 2nd group that it is a challenge to develop new type of solutions within the expected time limit set by the customer.

Analysis
It can be concluded based on the interviews the arising challenges in AMS design are complex to a degree where long term partnerships with varying core competences become important. It may be that building an ecosystem between OEM's may be necessary in order to create trust towards the autonomous operation and receive acceptance from regulators and customers. Sharing simulations within the ecosystem could be a solution for further developing AMS's and providing more requirements to the system. This kind of approach where simulations are shared benefits model-based design approaches. It seems that the software ecosystems and software practices are something new that may benefit mobile machinery OEM's developing AMS's in the future, but to learn such practices may be a challenge. However, it can be interpreted from the interviews with 2nd group that agile and modular software design principles, or design principles derived from them, become important, since such principles are utilized.

3.10 Conclusions on interview research

It was interesting to find that actual R&D efforts mentioned as future development projects in literature was done by interviewed companies. For instance, implementing model-based systems engineering methods into the development process was suggested by Worm and van der Made (2019) and it was found important as well within the interviews. Research efforts towards found in interview research were an interesting topic that is being considered. The things that are being research must be something that are important, and the competence learned from research is found valuable. The research on utilization of data, business models, HMI, HMIf's, remote operation and applications for CV were topics of interest and thus could be considered as factors for readiness of engineering practices. Robotics, cybersecurity, functional safety, software and system design, systems engineering, operational domain, computer vision and ML seem to be competences wanted in future for autonomous system design.

Design practices from automation and software engineering provide important aspects to consider in engineering practices for designing AMS. The automation engineering practices consider an operation principle where reducing human operator involvement and costs are important ways to provide cost efficiency. The engineering practices that consider the operation principle of a regular operating mobile machine, where reducing human operator involvement and costs are not the means for cost efficiency, probably need to reconsider the operation principle and learn from automation and software engineering in order to develop an AMM.

It can be concluded based on the interviews, especially based on the group division of 1st, 2nd and 3rd groups, that the mobile machinery industry in general may be conservative in such a way that bringing a new design approach towards a fully autonomous operation may prove difficult, since the methods of product development have focused on the operation principle of a regular machine for a long time and the customer base has become used to the regular operation principle. This seem to set a requirement for the autonomous operation to prove clear added value compared to a regular operation.

Some of the findings were difficult to interpret, whether the finding (e.g. a design method such as agile software development, or increased efforts for cyber security) was directly utilized in order to develop an AMS or was it part of overall design development, which included autonomous and other products. For example, the data acquisition, management and analysis development needs are occurring partly due to need of creating more efficient systems by analyzing operations. This is also becoming more feasible to perform than before because of the digital transformation trend in industry. Furthermore, the digital transformation of operations and connections to internet result in need for means to ensure cyber security. The point is, that the design of AMS's benefits from these concurrent R&D topics. For example, data AMA development is important as more is learned from the autonomous machines, their operations and the supporting infrastructures. Autonomous machines are a way to provide operation efficiency next to data management methods. These concurrent R&D topics benefit regular machine operation as well as AM operation.

Another difficulty in interpretation comes from the anonymization: Some of the findings are more closely related to a certain industry of mobile machinery than other industries, and when a finding is presented without the certain industry context, generalization happens to some degree. However, it has been taken in consideration when anonymizing the presented material that the presented findings answer to the research question *what new requirements does the increased autonomy produce?* The analysis including presentation of interview results under themes and further conclusions presented under *Analysis* aim to answer the research question.

4. RESEARCH OUTCOME

The research objectives included the idea that there are new challenges and practices emerging in the design of AMS that are produced by increasing degrees of autonomy. The challenges and practices have been discussed in the literature and interview researches. The question *What are the challenges and practices in design and validation of autonomous systems?* is answered according to the interview research thematic analysis. The design of AMS's includes a wide range of challenges directly related to the design of the AM, such as perception capability and safe and efficient operation. In addition to the design challenges of the AM, important concurrent R&D topics emerge such as methods for requirements management, cyber security, new business models and data acquisition, management and analysis.

Based on the interview research, and the analysis backed up by literature research, the question *what new requirements does the increased autonomy produce* is answered to. The research question *what kind readiness factors should be considered when designing an autonomous system* is answered as a readiness assessment in the summary. The research outcome aims to answer the research objectives and questions presented in chapter 1.2. This is done within a summary presented in table 2, where a readiness assessment is presented in a similar way as presented by the readiness assessment methodologies in chapter 2.10.

4.1 Readiness assessment

In order to summarize the research outcome, factors for readiness assessment are defined. The readiness assessment is a summary that is based on the interview research presented. The themes, subthemes and the findings within the thematic analysis are summarized in this table, thus, the literature findings reviewed within analysis together with interview findings are part of the summary. The readiness elements presented in the first column represent the main topics to be considered. Factors and descriptions presented in the second column provide further details to the readiness element in the same row. The readiness assessment can be used for identifying design needs and considerations of engineering practices for developing AMS. A such assessment table can be utilized by company management level personnel, with a goal to increase the level of autonomy within their machines.

Table 2.*Readiness elements, factors and descriptions of engineering practices for designing autonomous industrial mobile machinery.*

Readiness elements	Factors & descriptions
Operation principle Understanding the current operating process thoroughly is crucial in order to identify how autonomous operation could provide benefits.	Conceptualization **of a new operation principle with added value** and the **levels of autonomy** (e.g. operator assistance functions, remote control, semi-autonomous operation or full autonomy). **Identifying technological requirements** for the machine and infrastructure, and maturity of the autonomy providing functions. **Identification of a new business model** with the new operating principle, where operating costs of the end user may be reduced, but there may become needs for new services such as maintenance, data management and cyber security that can be provided by the OEM.
Design practices and competences Being capable to utilize a set of identified competences and design practices important for AMS design means positive readiness.	Design process of complex systems benefit from **cooperation of varying engineering disciplines** and **well guided design process management to ensure synchronization of design tasks** and ensuring **architecture integration with clearly defined interfaces** between systems. **Cross skilled** design team relevant for designing the corresponding autonomous function (e.g. robotics, automation, mechanical, software, electrical, safety, cyber security, information technology, CV, ML and operational domain). **Agile** and **modular software design approaches.** **Model based design approach** together with **model-based systems engineering** help to manage a large field of complex design tasks in all phases of the design lifecycle. **Systematic requirements modeling and management methods** for defining requirements for AMS. **Data acquisition, management and analysis practices** development for AMS **R&D** and **V&V** purposes, but also **to provide customer valuable information.** Cooperation of customer and developer to **identify valuable data**. Design for **maintenance based on data analysis**. **HMI** R&D in physical and digital environments. **Design of infrastructure** supporting the AMS operation.
Digital design practices and tools Product design in a digital form as close to ready as possible saves time used for engineering and enables the development of autonomy providing functions.	**Digital V&V practices** involving running operational scenario simulations for soft- and hardware development of autonomous functions leading to physical environment testing. **Utilizing data from real environments in design.** **Simulation of operational scenarios** that are not feasible to replicate in real life. Varying types of simulations: **Simple simulations** to help in requirements management, **detailed simulations** for autonomous functionality development (e.g. navigation algorithm), **mathematical modelling, semi-empirical** simulations with real data combined with a digital model, and **digital twin simulations.** **Identifying necessary tools** (e.g. large-scale commercial tools, small scale commercial tools, open source tools).
Physical testing practices Physical testing is necessary to V&V the product, but also to generate data for R&D purposes.	**Physical testing of operating scenarios** that are not feasible for digital development such as harsh environmental conditions and varying autonomous operation scenarios. **Simplified, limited and deterministic** test scenarios with component and system level testing of autonomous functions. **Data collection methods from real environments**. Data from simulations should be validated against data from real environments.
Partnerships and ecosystems More resources are required to design a complex AMS in forms of partnerships and ecosystems.	**Core competences** of varying engineering fields should be represented in the ecosystem. An ecosystem with a **common design goal** requires for the stakeholders to **learn the common field of problems** and **methods for cooperation and communication**. Openness towards **sharing data** within an ecosystem. **A type of business model** where stakeholders are satisfied in working in an ecosystem. **Longevity** of an ecosystem should be considered in decision making, since building a complex AMS may not yield profit in short term projects.

The table 2 includes a set of considerations for practices, competences and experiences to be considered as readiness factors of engineering practices for designing autonomous industrial mobile machinery. For example, to what extent have the digital design practices utilized varying simulations? If there is experience on complementing the digital simulation models with data from physical testing, there is some experience and readiness to design AMS involved. If there are partnerships that would be interested in beginning a cooperative development on an AMS, and there is good experience on partnerships longevity, there is some readiness of engineering practices for that element. If there are existing methods for creating varying operation scenarios for V&V in difficult operation scenarios, and methods for acquiring and analyzing data from physical testing there is some readiness for physical V&V practices. This type of readiness assessment can be utilized in order to find out what type of methods could be established in order to further develop AMS's. In addition, some of the readiness factors may be there for a company with an autonomous machine as a future vision, but further inspecting the table gives ideas for allocating existing resources and finding out what type of new competences and actions may be required.

The specific needs of engineering practices for designing AMS capabilities vary within use cases, thus the readiness elements and factors provided in table 2 can provide a general overview on the topics, but not an accurate view on specific readiness requirements for a single mobile machinery industry. For example, a manufacturer for agricultural machinery may consider very different factors for digital design practices important than a manufacturer for mining construction equipment. It is possible, that a mobile machine OEM developing machines with added intelligence can already have a lot of readiness to design AMS.

The first factor to consider in readiness assessment is whether the autonomous operation principle bring enough benefits and added value to the customer compared to the operation principle of a regular machine. If it is found possible, a concept of new operation principle, the technological requirements and business models should be inspected as part of assessing how the benefits from autonomy could become reality. Being able to conceptualize these factors in a formal way, such as defining the operation principle according to varying levels of autonomy and maturity of autonomy providing technologies, can enable to push AMS design forwards and they imply that there is positive readiness.

The requirements for design practices, competences, practices, partnerships, digital design and physical V&V practices should reflect the autonomous operation principle, business model, and technologies and infrastructures providing the autonomous operation. Thus, it becomes crucial to define the operational scenarios and the AMS requirements in a comprehensive way. Also, a comprehensive way for defining requirements may include simulations, demonstrations and feedback from varying stakeholders, task analysis, and modeling methods.

Cross skilled competences, design practices from software development and well managed design process seem to become important part of AMS design practices. Thus, developing practices for managing a multidisciplinary design process becomes important. A lot of the competences that are required to develop autonomous functions can be difficult to find end employ, thus, partnerships and ecosystems should be considered. This is not a typical type of partnership of supply chain, but more as a network of suppliers and partners where longevity of cooperation plays a major role. To learn the common field of problems, methods for cooperation and communications becomes important part of ecosystem cooperation.

The way of digital design practices and physical testing complement the overall design process could be considered using varying types of simulations and validating the results of simulations to the data generated from real environments. Methods for acquiring, managing and analyzing the data of autonomous operations could be developed. In addition, the real environments provide data to be imported for R&D purposes and are required for validating the AMS.

A lot of barriers seem to occur in the way of AMS design. One of them is a conservative mindset revolving around serving a customer base used to machines with regular operation principle. The conservative nature of a specific mobile machine industry can reduce the innovativeness required for AMS design and the acceptance that a new AMS product would require. Thus, enthusiasm from engineers and companies should be great in order to provide a disruptive technology to a conservative market. However, it is to be noted that the customer centric business is to serve the customers need, and to do this with an autonomous operation principle is a challenge.

4.2 Further research suggestions and critique to research

After presenting elements and factors for readiness, it is important to mention that they are assumptions of one researcher. The difficulty in defining readiness elements and factors is to identify and choose the main topics from a very large field of challenges affecting readiness. In addition, the topics that were not closely discussed in this research, such as questions related to the ethics and acceptance of AMS, could be further researched to provide a more comprehensive view of readiness factors, and they would probably bring interesting considerations for designing AMS. But an issue arises with bringing in more and more themes to consider: Each of the themes are important things to consider and make this subject interesting but also make this subject heavy and hard to process and the validity of chosen elements and factors may suffer.

The validity of the readiness elements and factors related to engineering practices should be more carefully inspected with knowledgeable engineers with experience on autonomous systems development, whether the elements and factors represent the domain (domain being mobile machinery) and if there are new viewpoints to add or perhaps something to remove or modify. The validity of such assessment should consider the factors and descriptions as being key points to self-evaluation for a possible AMS manufacturer. With the support of experts, the validity of the readiness assessment could be proven and further developed to a questionnaire.

A questionnaire could be formed based on the factors and descriptions after the validity has been proven. The readiness assessments presented in chapter 2.10. (Excluding the readiness index from KMPG, 2019) were score based assessments where a questionnaire on the factors and descriptions provide a score for each element. A similar type of questionnaire could be formed and targeted to an audience of companies interested in AMS development. The result of such assessment could be visualized in a spider graph presentation where scores gained from the questionnaire represent readiness elements. The score would then tell what type of readiness of engineering practices exist to develop AMS. It is important to notice that the assessment methodology from Karandikar *et al.* (1993) considers what the current state of critical element utilization is and where it is desired to be. In a similar way, a readiness assessment could present elements and factors to be considered as what is done now (current state) and what is preferable to be done in the future (desired state).

Since this has been ongoing learning process of new topics, there is an effect from the literature and interview researches on the researcher bias, especially on the thematic interviews where the emerged topics and discussions from previous interviews are affecting the interviewer's understanding of the domain. Thus, the generation of new questions as part of a thematic interview is affected by the researcher bias, where the questions generated may be leading the interviewee to a direction of an answer that is waited for.

One way to improve a validity of an interview research is to have the interviewer trained appropriately with interview training. According to Hirsjärvi and Hurme (2011) one becomes a good interviewer through learning. Learning to become good through interview training is found important. The training should include teaching how to make interviews and skills required in it, and to unify the methods of interviewing different people and reduce variance between interviews. More interviewer training methods are inspected by Hirsjärvi and Hurme (2011), but the main point is that the validity of interview is affected by the skills of the interviewer, which can be enhanced by interview training.

Another aspect for criticism for this research is that the existing autonomous mobile machines are a result of years of R&D on machine automation and automation engineering. They are often understood as highly automated machines, where the level of automation has been developed to a very advanced level. In addition to the level of automation being advanced, the design processes and practices have advanced to a high level. It is possible, that when the term autonomous machine is used when considering next development steps of mobile machines, it is forgotten that the existing commercial autonomous mobile machines are the result of years of automation R&D with efficiencies being sought from reducing operator involvement and costs by automation. With mobile machines that have an operation principle where efficiencies are not sought from reducing operator involvement and costs, the autonomous operation may not be a natural next step of R&D. Thus, it could be said that a readiness factor for engineering practices is years (even decades) of expertise in automation R&D, and to assess readiness of current engineering practices focusing on completely different operation profile with different driving forces than in automation R&D is difficult. Years of expertise in automation R&D does not sound very attractive neither feasible when assessing readiness of engineering practices to design autonomous mobile machinery in general. However, new developments in autonomous mobile machine developments have appeared, which prove that partnership cooperation enables to develop autonomous products. For example, a proof-of-concept demonstration for snowplowing runways from Finnish companies proved that the readiness of engineering practices to design autonomous mobile machinery exists in forms of partnerships and ecosystems (Valtra, n.d.).

5. CONCLUSIONS

In this thesis, it is presented what the increasing autonomy in mobile machines produces for the design. Many of the design approaches, paradigms, methodologies and novel frameworks etc. presented in literature, come from various fields of engineering and the principles proposed and researched complement each other. Since there is no field of “autonomy engineering”, the various fields give take-offs or important knowledge on designing an AMS. For instance, the importance of co-designing environment and an AMS could be complementing the idea of designing HMIf’s, autonomous operation and requirements together. The research presented in literature gives some considerations for what is being required of engineering practices for designing autonomous industrial mobile machinery, thus, knowledge from varying fields of engineering where AMS have been developed complement the engineering practices development for autonomous industrial mobile machinery.

The interview research gave many interesting considerations on mobile machinery in general. It is important to notice, that each specific industry has its own challenges, and they are mostly context related. However, the main findings and conclusions based on the interviews are presented in the summary as a method for assessing organizational readiness and readiness of engineering practices. The summary, the readiness assessment, can benefit companies interested in developing AMS, by giving them a means for self-evaluating on where to utilize resources when considering to develop an AMS. At least it can give a starting point and chances to realize how far the current practices have come and where should they develop.

The greater operational and environmental complexities are, more difficult challenges seem to arise within autonomy development. The level of autonomy required for providing a new operation principle in complex environments and missions with enough benefits compared to traditional operation principle may be difficult to achieve. However, advances in technologies and engineering practices make it worth to consider new operation principle, even in forms of semi-autonomous functions perhaps leading to full autonomy in the coming years.

REFERENCES

Alexander, R.D., Herbert, N.J., Kelly, T.P. (2008). Structuring Safety Cases for Autonomous Systems. 3rd IET International Conference on System Safety, Birmingham, UK, October 20-22. DOI: 10.1049/cp:20080730

Alho, T., Hickson, M., Kokko, T., Pettersson, T. (2015). Conversion to automated straddle carrier terminal. Kalmar, part of Cargotec. © Cargotec 2015. URL: https://www.kalmar.fi/4ad329/globalassets/equipment/pdfs/whitepaper_conversion-to-automated-straddle-carrier-terminal.pdf (Accessed 1st August 2019).

Ansys. N.d. Digital Twin. Ansys Inc. URL: https://www.ansys.com/products/systems/digital-twin (Accessed 1st August 2019).

Balsa-Comerón, J., Guerrero-Higueras, Á.M., Rodríguez-Lera, F.J., Fernández-Llamas, C., Matellán-Olivera, V. (2016). Cybersecurity in Autonomous Systems: Hardening ROS Using Encrypted Communications and Semantic Rules. ROBOT 2017. Advances in Intelligent Systems and Computing. Vol 694. Springer, Cham. DOI: https://doi.org/10.1007/978-3-319-70836-2_6

Behere, S., Asplund, F., Söderberg, A., Törngren, M. (2016). Architecture Challenges for Intelligent Autonomous Machines. In: Menegatti E., Michael N., Berns K., Yamaguchi H. (eds) Intelligent Autonomous Systems 13. Advances in Intelligent Systems and Computing, vol 302. Springer, Cham. DOI: https://doi.org/10.1007/978-3-319-08338-4_120

Bermejo-Alonso, J., Sanz, R., Rodríguez, M., Hernández, C. (2010). An Ontological Framework for Autonomous Systems Modelling. International Journal on Advances in Intelligent Systems. Vol 3. No 3 & 4.

Czarnowski, J., Dąbrowski, A., Maciaś, M., Główka, J., Wrona, J. (2018). Technology gaps in Human-Machine Interfaces for autonomous construction robots. Automation in Construction. Vol 94. pp. 179-190. DOI: 10.1016/j.autcon.2018.06.014

Danks, D., London, A.J. (2017). Regulating Autonomous Systems: Beyond Standards. IEEE Intelligent Systems. Vol 32. Issue 1. DOI: 10.1109/MIS.2017.1

Debernard, S., Chauvin, C., Pokam, R., Langlois, S. (2016). Designing Human-Machine Interface for Autonomous Vehicles. IFAC-PapersOnLine. Vol 49. Issue 19. pp. 609-614. DOI: https://doi.org/10.1016/j.ifacol.2016.10.629

Denney, E., Pai, G. (2018). Tool support for assurance case development. Automated Software Engineering. September 2018. Volume 25. Issue 3. pp. 435-499. DOI: https://doi.org/10.1007/s10515-017-0230-5

Durst, P.J. and Gray, W. (2014). Levels of Autonomy and Autonomous System Performance Assessment for Intelligent Unmanned Systems. US Army Engineer Research and Development Center, pp.9-21.

European Commission, n.d., Mobile Machinery. URL: https://ec.europa.eu/growth/sectors/mechanical-engineering/mob_machinery_en (Accessed 22th July 2019).

Fong, T. (2018). Autonomous Systems: NASA Capability Overview. URL: https://ntrs.nasa.gov/search.jsp?R=20180007804 (Accessed 22th July 2019)

Fong, T., Frank, J., Badger, J., Nesnas, I., Feary, M., (2018). Autonomous Systems Taxonomy. URL: https://ntrs.nasa.gov/search.jsp?R=20180003082 (Accessed 22th July 2019)

Goodin, C., Doude, M., Hudson, C.R., Carruth, D.W. (2018). Enabling Off-Road Autonomous Navigation-Simulation of LIDAR in Dense Vegetation. Electronics. Vol 7. pp. 154. DOI: https://doi.org/10.3390/electronics7090154

GE Power. (2016). GE Digital Twin: Analytic Engine for the Digital Power Plant. GE Power. URL: https://www.ge.com/digital/sites/default/files/download_assets/Digital-Twin-for-the-digital-power-plant-.pdf (Accessed 1st August 2019)

Gustafson, A. (2011). Automation of load haul dump machines, Research report. Luleå University of Technology, Lulea, Sweden.

Halterman, R., Scrapper, C. (2017). A systematic approach to autonomous unmanned system experimentation. Proc. SPIE 10195. Unmanned Systems Technology XIX. 101950M. DOI: 10.1117/12.2266798

Hirsjärvi, S. and Hurme, H. (2011). Tutkimushaastattelu. Gaudeamus Helsinki University Press. pp. 66-67, 69-72,141-143,173.

Hietikko, M., Malm, T., Alanen, J. (2009). Koneiden ohjausjärjestelmien toiminnallinen turvallisuus: Ohjeita ja työkaluja standariden mukaisen turvallisuusprosessin luomiseen. VTT Tiedotteita – Research Notes; No. 2485. Espoo: VTT Technical Research Centre of Finland.

Huang, H-M., Pavek, K., Novak, B., Albus, J., Messina, E. (2005). A Framework For Autonomy Levels For Unmanned Systems (ALFUS). Proc. SPIE 5804, Unmanned Ground Vehicle Technology VII. DOI: 10.1117/12.603725

Huhtala, K. (2018). Autonomous energy efficient wheel loader research at TUT, Int. J. Hydromechatronics, Vol. 1, No. 1, pp.107–125.

Hämäläinen, J., Yli-Paunu, P., Peussa, P. 2018. Automated container terminals and self-driving cars: Industry outlook. Kalmar. URL: https://www.kalmar-global.com/globalassets/dam/2018/12/19/white-paper-automated-container-terminals-and-self-driving-cars.pdf (Accessed 22th July).

ISO 17757. (2017). Earth-moving Machinery and Mining – Autonomous and Semiautonomous Machine System Safety. International Organization for Standardization, Switzerland.

ISO/FDIS 18497. (2018). Agricultural machinery and tractors – Safety of highly automated agricultural machines. International Organization for Standardization. URL: https://www.iso.org/standard/62659.html (Accessed 23.7.2019).

Kalmar. (2011). Kalmar Automatic Horizontal Transportation System. Kalmar, Part of Cargotec. URL: https://www.kalmar.fi/492994/globalassets/equipment/straddle-carriers/kalmar-automatic-horizontal-transportation-system.pdf (Accessed 1st August 2019).

Kalmar. (2014). Kalmar automated terminals. Kalmar, Part of Cargotec. © Cargotec 2014. URL: https://www.kalmar.fi/4b007f/globalassets/equipment/pdfs/autoequipment_brochure_web.pdf (Accessed 1st August 2019).

Karandikar, H.M., Fotta, M.E., Lawson, M., Wood, R.T. (1993). Assessing organizational readiness for implementing concurrent engineering practices and collaborative technologies. Proceedings of the Second Workshop Enabling Technologies: Infrastructure for Collaborative Enterprises. pp. 83-93. DOI: 10.1109/ENABL.1993.263060

Kendoul, F. (2013). Towards a Unified Framework for UAS Autonomy and Technology Readiness Assessment (ATRA). Intelligent Systems, Control and Automation: Science and Engineering. Vol 63. Springer, Tokyo. DOI: 10.1007/978-4-431-54276-6_4

Kobayashi, Y., Kondo, M., Hiramatsu, Y., Fujii, H., Kamiya, T. 2018. Mobile robot decision-making based on offline simulation for navigation over uneven terrain. J. Robot. Mechatronics. Vol 30. pp. 671-782. DOI: 10.20965/jrm.2018.p0671

Komatsu. 2019. Komatsu first to operate Autonomous Haulage System over dedicated private LTE network. Komatsu America Corp. URL: https://www.komatsuamerica.com/our-company/press-releases/2019-01-21-ahs-lte (Accessed 22th July 2019).

Koopman, P., Wagner, M. (2016) Challenges in Autonomous Vehicle Testing and Validation. SAE Int. J. Trans. Safety. 4(1). DOI: 10.4271/2016-01-0128

Kukko, A., Kaijaluoto, R., Kaartinen, H., Lehtola, V.V., Jaakkola, A., Hyyppä, J. (2017). Graph SLAM correction for single scanner MLS forest data under boreal forest canopy. Elsevier B.V. on behalf of International Society for Photogrammetry and Remote Sensing. Vol 132. pp. 199-209. DOI: https://doi.org/10.1016/j.isprsjprs.2017.09.006

Lyons, J.B. (2013). Being Transparent about Transparency: A Model for Human-Robot Interaction. Trust and Autonomous Systems: Papers from the 2013 AAAI Spring Symposium. URL: https://pdfs.semanticscholar.org/bf51/f5448981d985e082f2d9511d276ca6519944.pdf (Accessed 1st August 2019).

Magnusson, G., Diep, M., Phillips, T. Lindvall, M. (2018). Modeling Requirements of Autonomous System. Fraunhofer USA, Center for Experimental Software Engineering. URL: https://ntrs.nasa.gov/search.jsp?R=20190001490 (Accessed 25th July 2019).

Malm, T., Ahonen, T., Välisalo, T. (2018). Risk assessment of machinery system with respect to safety and cyber-security. Research Report. VTT Technical Research Centre of Finland.

Meltz, D., Guterman, H. (2019). Functional Safety Verification for Autonomous UGV - Methodology Presentation and Implementation on a Full-scale system. IEEE Transactions on Intelligent Vehicles. © 2019 IEEE. DOI: 10.1109/TIV.2019.2919460

Mevea. N.d. The Digital Twin at the center of R&D. URL: https://mevea.com/resources/ebooks/the-digital-twin-at-the-center-of-rd/ (Accessed 22th July 2019).

Mevea. N.d. Digital Twin and AI: Roadmap to Autonomous Machines. Webinar. URL: https://mevea.com/digital-twin-and-ai-roadmap-to-autonomous-machines/?hsCtaTracking=8ba3f6ba-3bea-4d42-b0ad-d201b4480d72%7C8028d017-bfdd-4f9a-8341-854b57be7832 (Accessed 31th July 2019).

Müller, M., Casser, V., Lahoud, J., Smith, N., Ghanem, B. (2018). Sim4CV : A Photo-Realistic Simulator for Computer Vision Applications. International Journal of Computer Vision. September 2018. Volume 126. Issue 9. pp. 902-919. DOI: https://doi.org/10.1007/s11263-018-1073-7

Nortio, J. (2019). Digitaalinen kaksonen on täällä tänään. Automaatioväylä 1/2019, pp. 8-11, URL: http://www.automaatiovayla.fi/verkkolehti/verkkolehti20191zsexdr/index.html#/article/14/page/1-1 (Accessed 1st August 2019).

Ngyuen, N.T. (2018). Verification and Validation Challenges for Adaptive Flight Control of Complex Autonomous Systems. NASA Ames Research Center, Moffett Field, CA United States. URL: https://ntrs.nasa.gov/search.jsp?R=20180001223 (Accessed 30th July 2019).

Panuwatwanich, K., Stewart, R.A. (2012). Evaluating innovation diffusion readiness among architectural and engineering design firms: Empirical evidence from Australia. Automation in Construction. Vol 27. pp. 50-59. DOI: 10.1016/j.autcon.2012.05.009

Paraszczak, J. (2014). Maximization of productivity of autonomous equipment in underground mines. Society for Mining, Metallurgy, and Exploration, Inc. URL: https://search.proquest.com/docview/1554531268?accountid=27306 (Accessed 22th July 2019).

Pendleton, S.D., Andersen, A., Du, X., Shen, X., Meghjani, M., Eng, Y.H., Rus, D., Ang, M.H.Jr. (2017). Perception, Planning, Control, and Coordination for Autonomous Vehicles. Machines. 2017. 5, 6. DOI: 10.3390/machines5010006

Raczon, F. 2018. Autonomous Mining Trucks Approach Milestone. Construction Equipment. URL: https://www.constructionequipment.com/autonomous-mining-trucks-approach-milestone (Accessed 22th July 2019).

Rakkatec. N.d. Rakkatec. URL: http://rakkatec.fi/ (Accessed 22th July 2019).

SAE Standard J3016_201609. (2016). Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, SAE 2016.

Schaefer, K.E., Hill, S.G., Jentsch, F. (2019). Trust in Human-Autonomy Teaming: A review of Trust Research from the US Army Research Laboratory Robotics Collaborative Technology Alliance. Advances in Human Factors in Robots and Unmanned Systems. DOI: 10.1007/978-3-319-94346-6_10

SFS-EN ISO 13849-1. (2008). Safety of machinery. Safety-related parts of control systems. Part 1: General principles for design. Finnish Standards Organisation SFS, Helsinki.

SFS IEC/TR 61508-0. (2012). Functional safety of electrical/electronic/programmable electronic safety-related systems. Part 0: Functional safety and IEC 61508, Finnish Standards Organisation SFS, Helsinki.

Shockley, J.M., Dillon, C.R., Shearer, S.A. (2019). An economic feasibility assessment of autonomous field machinery in grain crop production. Percision Agriculture. pp.1-18. URL: http://link.springer.com/10.1007/s11119-019-09638-w (Accessed 22th July 2019).

Sifakis, J. (2019). Autonomous Systems – An Architectural Characterization. Models, Languages, and Tools for Concurrent and Distributed Programming. Lecture Notes in Computer Science, vol 11665. Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-21485-2_21

Tan, N., Mohan, R.E., Watanabe, A. (2016). Toward a framework for robot-inclusive environments. Automation in Construction. Volume 69. pp. 68-78. DOI: 10.1016/j.autcon.2016.06.001

Taylor, D. (2017). Digital twin capabilities in Siemens PLM products and solutions. Siemens PLM Software. URL: https://community.plm.automation.siemens.com/t5/Digital-Twin-Knowledge-Base/Digital-twin-capabilities-in-Siemens-PLM-products-and-solutions/ta-p/432998 (Accessed 1st August 2019).

Tirkkonen, J. (2018). LIIKKUVAT TYÖKONEET. Business Finland. URL: https://www.businessfinland.fi/globalassets/julkaisut/liikkuvat_tyokoneet-kehityspolkukatsaus_1_2018.pdf (Accessed 22th July 2019).

Tiusanen, R. (2014). An approach for the assessment of safety risks in automated mobile work-machine systems. VTT Science. Vol 69. ISBN 978-951-38-8173-3

Tiusanen, R., Malm, T., Ronkainen, A. (2019). An overview of current safety requirements for autonomous machines - review of standards. Finnish Society of Automation, Automaatiopäivät23 Extended Abstracts. URL: https://www.automaatioseura.fi/site/assets/files/1896/23_au-23_paper_23ea.pdf (Accessed 24th July 2019).

Valtra. n.d. The Runway Snowbot. URL: https://www.runwaysnowbot.com/images/ (Accessed 22th July 2019).

Vasconez, J.P., Kantor, G.A., Cheein, F.A.A. (2019). Human-robot interaction in agriculture: A survey and current challenges. Biosystems Engineering. Vol 179. pp. 35-48. DOI: https://doi.org/10.1016/j.biosystemseng.2018.12.005

Vassev. E., Hinchey, M. (2013). Autonomy Requirements Engineering. Proceedings of the 2013 IEEE 14th International Conference on Information Reuse and Integration, IEEE. DOI: 10.1109/IRI.2013.6642470

Visser, R. 2018. Next Generation Timber Harvesting Systems: Opportunities for remote controlled and autonomous machinery. Forest & Wood Products Australia Limited. URL: https://www.fwpa.com.au/resources/resources/1474-next-generation-timber-harvesting-systems-opportunities-for-remote-controlled-and-autonomous-machinery-prc437-1718.html (Accessed 22th July 2019).

Worm, M., van der Made, R. (2019). Verifying ADAS and autonomous driving performance. Siemens PLM software. URL: https://www.bsim-engineering.com/wp-content/uploads/2019/04/Siemens-PLM-Verifying-ADAS-and-autonomous-driving-performance-wp.pdf (Accessed 1st August 2019).

Yağdereli, E., Gemci, C., Aktaş, A.Z. (2015). A study on cyber-security of autonomous and unmanned vehicles. Journal of Defense Modeling and Simulation: Applications, Methodology, Technology 2015. Vol. 12(4). pp. 369-381. DOI: 10.1177/1548512915575803

Young, S.H., Mazzuchi, T.A., Sarkani, S. (2017). A Framework for Predicting Future System Performance in Autonomous Unmanned Ground Vehicles. IEEE Transactions on Systems Man and Cybernetics: Systems. Vol 47. No 7. pp. 1192-1206. DOI: 10.1109/TSMC.2016.2563403

Zeng, F., Lu, M., Zhong, D. (2012). Software Safety Certification Framework Based on Safety Case. International Conference on Computer Science and Service System. IEEE. pp. 566-569. DOI: 10.1109/CSSS.2012.147

Zhang, T., Li, Q., Zhang, C-S., Liang, H-W., Li, P., Wang, T-M., LI, S., Zhu, Y-L., Wu, C. (2017). Current trends in the development of intelligent unmanned autonomous systems. Frontiers of Information Technology & Electronic Engineering. Vol 18. Issue 1. pp. 68-85. DOI: 10.1631/FITEE.1601650