A STEP TOWARDS THE DESIGN OF COLLABORATIVE AUTONOMOUS MACHINES
A STUDY ON CONSTRUCTION AND MINING EQUIPMENT

Martin Frank
A Step Towards the Design of Collaborative Autonomous Machines
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Licentiate Dissertation in Mechanical Engineering

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“If we have data, let’s look at data. If all we have are opinions, let’s go with mine.”

Jim Barksdale, former Netscape CEO
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ABSTRACT

Fully autonomous construction and mining machines are not science fiction anymore. For special applications, these types of machinery are well known for several years. The construction and mining industries are ripe for innovative product and service offers, including automated and fully autonomous machines at a larger scale. Nevertheless, commercially available autonomous machines for the main markets are still rare. Driven by the advancements in sensor technology, increased connectivity, and on-board computational capabilities, automation of machine functions and subsystems led to the development of advanced operator-assistant functions in certain fields like material handling, predictive maintenance, and operator guidance. Semi-automated machines, supporting the machine operator during normal operation, are well accepted by users and customers and show beneficial effects on the productivity of the machine and the overall work process. The purpose of this thesis is to generate a deeper understanding of the specific requirements needed to support the design decisions during the development of fully autonomous machines. Complementary, deeper insights into the efficient collaboration between autonomous machines and human collaborators are explored.

The thesis summarizes the research performed by the author, as an industrial Ph.D. student and Specialist for Intelligent Machines at Volvo Construction Equipment. Performed research comprises the investigation of the state-of-the-art approaches in the automation of machines and dedicated functions with special emphasis on the connectivity of the different systems and components up to the site management solution. Further, the work includes the exploration of data-mining through early experience prototyping as a step towards data-driven design of a product-service system. In addition, the research covered the support of on-site collaboration between autonomous machines and humans by investigating team behavior and trust development among humans.

Conclusions from this work are that autonomous machine design requires new sets of requirements to support early decision making during the development process. Dedicated data collection based upon different methods such as, data-mining, needfinding, and observations, supported by multiple physical and virtual artifacts can generate useful data to support the decision-making. Trust between humans and machines, and the preconditions of developing this trust need to be captured as specific requirements. To support further development in the area of autonomous machine design, an interaction model had been proposed to map possible interactions of an autonomous machine with objects and collaborators within the same work area. To capture the different nature of the possible
interactions, several levels had been introduced to enable the distinction between cognitive, and physical, as well as intended, and unintended interactions.

**Keywords:** Engineering Design, Systems Engineering, Autonomous Machines, Human-Machine Collaboration, Human-Machine Trust; Interaction Model, Construction; Mining
LIST OF PAPERS

This thesis is based on the following studies, referred to in the thesis by their roman numerals.


Related Work

The following publications had not been included in this thesis:


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INTRODUCTION

The Introduction chapter comprises a high-level discussion of the background as well as a motivation for the selection of the presented research area.

Background and motivation to the research area

During recent years, the increased focus on productivity and efficiency increase in nearly every industry sector is obvious. OECD [1] defines: “Productivity is commonly defined as a ratio of a volume measure of output to a volume measure of input use.” (p11). Research has been conducted to map out the productivity against compensation [2] as well as productivity per industry sector [3]. Both references utilize labor productivity for their reasoning and further calculation. The labor productivity is defined [1] as the “quantity index of gross output per quantity index of labor input”, (p14). In the definition, productivity is based on the gross output. OECD also provides a labor productivity definition based on value-added. Here the numerator changes to “...quantity index of value added”. Both definitions are used in [2] and [3] to compare different industry areas.

Focusing on the productivity of a construction or mining machine, the productivity is given by mass per time unit. In addition to the productivity, the machine efficiency also needs to be taking into account the efficiency defined as mass per used energy. [4]. Filla [4] highlights the role of the operator and that this operability of a machine has a substantial influence on the productivity and efficiency of the overall human-machine system. Frank et al. [5] published this relation in their research. Boudreau-Trudel et al. [6] examine the productivity of innovative mining equipment and the impact on the total site productivity. Performance comparison of semi-automated and manual operated load-haul-dump (LHD) truck, used in underground mining had been performed and presented by Gustafson et al. [7]. For the case of forest harvesting, the implications on machine and task productivity by human factors had been presented by Häggström et al. [8].

Taking these different definitions into account while talking about increasing productivity on a mining or construction site, it is necessary to focus either on the machine (or site) productivity increase or labor productivity.

OECD [1] lists the drawbacks and limitations of the definition of productivity, highlighting that: “It is easily misinterpreted as technical change or as the productivity of the individuals in the labor force.” (p14). Thus, labor productivity
is a measure to describe the productivity of the industry sector, company or organization, not the productivity of an individual worker or a team.

Nevertheless, the statistics shown in Figure 1 and Figure 2 give indications that the mining and construction sector has improvement potential. However, it is also clear that the “productivity gap” to other industry areas cannot be closed only by optimizing machines or systems.

Figure 1 Productivity and compensation by sector, 1987-2015 adapted from [2]

Figure 2 Global productivity growth trends, adapted from [3]
New technologies like the Internet of Things, digitization, electrification, and autonomous systems enabled increases in productivity and efficiency in nearly all industrial applications [3] as well as in the private domain [9]. Legislative and regulatory obligations [10] targeting on and off-highway equipment applied in the construction and mining industry put the spotlight on decreasing emissions while customers, in parallel, constantly demanding equipment with increased productivity and efficiency. During the past years, the development had been focused on automation of systems and subsystems as a method of choice to increase efficiency. In parallel, optimization of systems and subsystems enabled decreasing the energy consumption of a machine. Especially in the mining industry, hauling applications have been of high focus for automation and electrification.

The first steps towards the implementation of fully autonomous systems in the construction and mining area have been conducted by utilizing existing machine types and adding the automation layer on top of the existing machine architecture and its control systems [11–13]. The shortcoming of this approach is that the base machine design satisfies the needs of a human operator and not necessarily the needs of a computerized system.

The research presented in this thesis should highlight the need for a methodology to develop autonomous systems based on their application and the intended utilization of the equipment. Just a few steps toward this direction has been conducted so far [14–16]. Due to simple applicability in existing mining operations, mostly driverless hauling vehicles have been developed at this stage. Focusing on the automation of machine and work tasks with higher degrees of freedom, methods, and tools is needed to support decision-makers and designers during the different development stages.

Typically, the design of new machines and products is based on updates or evolutionary steps of existing products but very rarely conducted as the design of a new machine, system or product. Eckert et al. [17], described this as: “Designers hardly ever start from scratch, but design by modifying existing products. Complex products such as aircraft or jet engines evolve from generation to generation, often over decades, through the transfer and revision of design elements” (p3).

This can be seen in the design of traditional and still used mobile machines like excavators, wheel loaders, tractors, trucks, and other kinds of heavy mobile equipment. While the system components changed over time, due to optimization
and to fulfill legal requirements, the machine appearance and its utilization patterns remained nearly unchanged for most of the equipment types.

With the increased demand for automated and fully autonomous systems, a new approach for designing these systems and products is needed. The traditional knowledge-based design process is suitable only to a limited extent during the creation of new products.

To enable informed design decisions, all types of interactions of a potential autonomous machine or system need to be considered. The obvious interaction is the cooperation between machines. This can be broken down to the interaction between an autonomous machine and a manually operated machine. In addition to that, the interaction between highly automated or fully autonomous machines with humans needs to be considered. Last but not least the interaction between machines and the material to be handled or transported needs to be taken into account and documented. To enable informed design decisions, all these interactions need to be described by data. This means that the entire process of a quarry site or mine needs to be described by physical measures without the bias of having mobile machines running in it.

New types of interaction need to be considered during the design of automated systems since unknown and unexpressed customer and user needs are arising with these new types of equipment. Therefore, the basic interactions on a job site need to be described to understand the needs of the autonomous system and the human operator, or bystander. There is also a need for understanding the interaction types between machines and machines, but also between machines and the material to be moved.

The purpose of the research is to support the decision-making process during the design of autonomous systems in the mobile machinery segment.

**Problem Background**

The development and design of industrial goods and products, for instance, engines, airplanes, and construction equipment, is a continuous and iterative process. Modifying and optimizing existing products and design is a common approach in industry to reduce risk and development time while keeping the product performance and appearance. Eckert et al. [17] described in their paper that there are many relations to previous designs and thus existing products and services. It is intuitive that the reutilization of components and designs along with well-established approaches and solution principles are economically worthwhile.
Major industries, such as, consumer goods production, automotive, manufacturing, and also the construction and mining sector needs to increase productivity and efficiency of operations. Optimizing and improving existing, traditional machine types is seen as a possibility to increase the productivity of a typical operation [18–20]. Therefore, the optimization and improvement of existing machine types and their utilization is a logical approach towards a more efficient and productive machines [4], [5].

Following the examples given by the manufacturing area, another possibility to improve efficiency and productivity in the construction and mining sector could be the implementation of semi-autonomous and fully autonomous machines. Especially in mining operations, the implementation of autonomous systems, mainly for hauling, can be seen as state-of-the-art for big open pit mines. [11], [21], [22]. Similar approaches can be seen in underground mining applications where the automation of load-haul-dump (LHD) machine functions is continuously researched [13] and implemented.

The above presented approaches utilize existing products and machine designs to automate either the complete machine or dedicated subsystems. It can be stated that these approaches automate machines with respect to the work task but not focusing on the automation of the work task itself.

The presented research in this thesis can be seen as a first step to define fundamental design requirements needed for the design and development of automated and fully autonomous machines and systems not based on a previously known product. The goal of creating fully autonomous machines pose additional challenges to the designers and researchers because different interaction models need to be developed, and further on considered during the design process. As an example, the collaboration between autonomous machines and humans can be stated as one of these new requirements that needs to be addressed. In addition to these emerging needs in the design of autonomous machines, the existing requirements like durability, strength, and efficiency of mobile working equipment need to be considered.
**Research Questions**

This thesis aims to understand the underlying needs and challenges of autonomous mobile machinery in construction and mining applications concerning the machine design. The research questions are stated as follows:

*How can requirements for the development of autonomous machine be discovered and captured?*

Due to the fact that the autonomous machines need to cooperate, collaborate and interact within the respective environment, a subsequent research question can be stated:

*How can different interactions of autonomous mobile machines be described?*

**Delimitations**

The research was performed by the author as part of his job as a researcher at Volvo Construction Equipment. The conducted research was partly performed during different advanced engineering initiatives and research projects with the scope of automation, autonomous machines and site safety. Therefore, the focus on construction and mining equipment including their application are predominant in the thesis and the appended papers.
RESEARCH APPROACH

In this chapter the research approach is described, starting with the research methodology, the research environment, followed by the data collection, literature review and the data analysis.

Research Methodology

The overall research work was planned and carried out according to the Design Research Methodology (DRM) as proposed by Blessing and Chakrabarti [23]. In addition to DRM, further research approaches such as ‘Action Research’ [24], and ‘Case Study Research’ [25], was evaluated to be utilized as the main research approach for this work. All evaluated research approaches had some advantages while advancing research in a particular direction. Case study research, at the early stage of this research, was found to be less helpful due to the lack of existing real-world study objects. Action research, in contrast, was found to be very useful in an industrial environment due to its focus on the constant exchange between researchers and practitioners. It was assumed that action research could be helpful in the later stages of the research when certain knowledge is gained around the research topic. It was concluded that DRM was an appropriate methodology for the conducted research due to its grounding in the design domain and the strong focus on structured research concerning design in an industrial environment. It was assumed that the research on autonomous machines and its design has major implications on the current design process as well as other processes within the industrial organization. With the structured approach and the grounding in design, DRM was considered to also support the communication between the research, product development, and the business part of the organization. Considering the industrial focus setup of the research as it is presented in this thesis, DRM was expected to support the researcher by avoiding the research to be reduced to a problem-solving activity. According to Blessing and Chakrabarti [23], typically there is an issue of

“- Lack of overviewing existing research
- Lack of use of results in practice
- Lack of scientific rigor” (p6)

while formulating issues and during problem-solving in an application-driven industrial research setting. Utilizing DRM should support in identifying the relevant research areas as well as structure and reduce the existing references methodologically. DRM provides a structured approach to research this
environment by the definition of four stages: Research Clarification, Descriptive Study I, Prescriptive Study, Descriptive Study II.

**Figure 3 DRM framework, adopted from [23]**

Figure 3 shows the DRM framework and how the different stages inform the other ones. Also, the respective inputs, basic means, and main outcomes are illustrated. At the beginning, the research activity was performed iteratively in the Research Clarification and the Descriptive Study I stages. Through literature reviews, reviews of company internal research and development projects, interviews, and initial group work and workshops – ongoing trends and directions in the academic and industrial areas could be retrieved. Utilizing these preparatory findings, the areas of relevance for further research could be determined. On the basis of the clarification of the existing knowledge and understanding, as well as the challenges and expectations, a set of research questions, was defined.

Blessing and Chakrabarti [23] describe DRM as a serial process to conduct design research. Nevertheless, it has to be considered that the main parts of this research have been performed in iterations and partly parallel to one another, supporting the definition and redefinition as well as the further shaping of the research scope and path. Figure 4 illustrates the appended papers of this thesis and their relation to the DRM stages.
Research Environment

The research has been performed in the frame of the Model-Driven Development and Decision Support (MD3S) research profile at Blekinge Institute of Technology, BTH. The Project is funded by the Knowledge Foundation, KKS, BTH, and industrial partners. The overall goal of the project is to, via research, create solutions and methods to support the development and decision-making process of complex new products during the full life cycle of the intended solution. A subpart of the research focuses on the development of new and innovative products and product-service systems in the mobile machinery area, especially targeting the construction and mining industry. The author is also part of a research department within a globally acting construction equipment OEM and therefore the research was conducted by focusing on both, academic and industrial aspects of the project.

As case studies, several company-internal projects have been utilized. For the experience prototyping and engagement with new types of products and services, a research and development project to fully automate and electrify a quarry site was utilized. For the interaction with traditional and potentially autonomous machines and solutions, a research and development initiative focusing on on-site
safety served to gather additional information and conduct interviews with users and other stakeholders. In addition, a collaboration project ME310 between Blekinge Institute of Technology, Stanford University, and Volvo CE as the industrial partner has been used to gather additional data and conduct interviews with the focus on human-robot collaboration and how to facilitate the interaction between autonomous machines and human workers.

Data Collection

Various data collection methods have been applied during the presented research. According to the different stages described in the chapter Research Methodology, the data collection has not been performed sequentially but the different activities have run in parallel.

During the early phases, the informal communication and face-to-face discussions represented a major part of data collection for the research conducted. As Kraut et al. [26] defined, high-quality informal communication in a research team is important to develop common interest on the topic. Discussions between different researchers in smaller and bigger teams had supported the direction and the information gathering for the research activity presented in this thesis. The discussions were conducted during team meetings, company site visits, research project reviews, and informal conversations. The content of the meetings has been transcribed by the author and stored for further analysis. Illustrations, sketches, and drawings utilized during the discussions were digitized and included in the research database.

Experimental prototyping had been utilized to generate and gather data. Participants of the study had been asked to perform a questionnaire to generate quantitative data. In addition to that, open-ended interviews and observations were conducted to complement the gathered data set with qualitative data.

Additional data was gathered during 17 site visits. During these visits, 49 semi-structured interviews, according to the method outlined by Qu and Dumay [27], were conducted. Since the interviews took place at typical construction and mining sites, the basic population of the interviewees had a clear connection to the work operation and the processes on the site. On each site, workers with different task descriptions (e.g., machine operators, construction workers, mechanics, ground workers, supervisors, and safety officers) were interviewed and observed. To gather as much, and as diverse information as possible, the researchers interviewed up to 100% of site staff to cover the different tasks and also the aspect of diversity in experience, age as well as cultural background. Since the researchers had no influence on the composition of the team on a site,
only male workers had been interviewed at this stage of the research. The interviews were performed at the respective worksites, giving the participants the possibility to underline their statements with direct illustrations and presentations in the real application environment. A set of pre-organized open-ended questions served as an entry into a conversation, leading to further questions emerging from the dialogue between interviewer and interviewees [28].

Supplementary observations were performed to complement the data gathered during the interviews and conversations on site. Observations can reveal important details about customer needs while watching customers use an existing product or perform a task for which the new product is intended for [29]. The acquired information was video-recorded and transcribed by the author for further analysis.

Subsequent workshops were used as a possibility to broaden the database and gather additional information regarding the research topic. Internal workshops with researchers, engineers and practitioners took place in three different countries (Germany, Sweden and Korea). Further analysis also included teams in the USA and Poland. The participants had access to all generated data and could review the material before the workshop. During the workshops, different needs of the construction and mining workers had been revealed and documented. Dialogues and discussions among the workshop participants were used to add additional insights to the gathered data artifacts for further analysis. The generated material like post-its, papers, sketches, tables, and simple prototypes was collected and digitized for further analysis.

**Literature Review**

During the described phases of the research in the Chapter Research Methodology, different literature review activities were performed. While examining the existing publications as an initial step, the literature review was used to define the research problem.

Existing literature concerning the development and design of autonomous mobile machines were studied in order to understand the approaches and principles applied in this area.

Furthermore, snowballing techniques [30] were utilized to broaden the base for the literature review in order to extract further relevant keywords as well as identify relevant state-of-the-art references. The databases Scopus [31], Web of Science [32] and Google Scholar [33] had been used to retrieve relevant references. Key works utilized in this research had been ‘autonomous machine design’, ‘mobile robotics’, ‘human-robotic interface’, ‘data-driven design’, ‘field robotics’, ‘autonomous construction equipment’. During a subsequent step,
additional literature review activities have been performed. Based on the results of the preliminary research, the focus for the newly conducted literature review was focused on human-machine collaboration and trust-building among human teams (i.e. coworkers) as well as trust development between humans and autonomous systems.

Insights from participation in doctoral courses, workshops and academic, as well as industrial conferences, guided the author during the selection and review process. The retrieved information was used to avoid bias in the literature selection and the subsequent analysis of the publications.

**Data Analysis**

The collected material was continuously analyzed. The retrieved information had been clustered according to the different themes. During an initial step, the analytical focus was on the automation of construction and mining equipment and the development of autonomous machines. Three main clusters emerged from this first analysis. Concerning machine automation and autonomous machine development, it was possible to list key enablers, ongoing trends in the industrial application and the approaches within academia. Expert interviews, as well as literature references, were analyzed in this step. Throughout a second step, the analytical lens was focused on the concept of data mining through experience prototyping, including how users interact with new types of equipment and services. Literature analysis was used to explore the body of knowledge while interviews and observations of study participants had been utilized to evaluate study assumptions. An additional analytical focus was set on the aspects of construction or mining site safety, interaction and collaboration with construction equipment. Conducted interviews and conversations with stakeholders have been video recorded and subsequently transcribed. Additionally, the observations taken at construction and mining sites have been recorded by video and photography enriched with notes of the investigator putting different aspects of the observations into a bigger (site-specific) context. The material has been made available to the research group, engineers and practitioners for individual review. Feedback, comments, and findings had been reported to the author and the research team. The generated results from the different workshops served as additional data points for the research. Discussions, ideas, sketches, concepts, and prototypes have been recorded to identify basic needs and aspects of the respective workshop subject.
KNOWLEDGE DOMAINS

In this chapter the knowledge domains are described. Relevant domains are automation, human-robot interaction/collaboration and engineering design and product development.

Automation

Ample definitions of automation can be found in the literature. Parasuraman and Riley [34] defined automation as: “... the execution by a machine agent (usually a computer) of a function that was previously carried out by a human.” (p230). Frohm et al. [35] researched the field of levels of automation (LoA) in the manufacturing area. According to the findings, the automation in the manufacturing area can be split into two main areas: the mechanization - automation of physical tasks as well as the computerization - automation of control and information handling. Frohm et al. [35] concluded, that the number of levels of automation as well as the taxonomy, in manufacturing, highly depends on the task and the division of the task between the human and the technical system.

The Society of Automotive Engineers developed their definition of Levels of Automation (LoA) and the underlying taxonomy, described in the SAE J3036 [36]. In this technical report, six (0 to 5) distinct levels of driving automation are described. The spectrum of automation reaches from

i.) Level 0; no driving automation;
ii.) Level 1; driver assistance,
iii.) Level 2; partial driving automation,
iv.) Level 3; conditional driving automation,
v.) Level 4; high driving automation, to
vi.) Level 5; full driving automation.

The LoA defined by the SAE [36] focusing on the application of on-road motor vehicle use cases. Especially for the higher levels of automation (3-5), the structured environment of an on-road use case is beneficial for computerized control systems and advanced driving assistance systems. Nevertheless, the basic division and the taxonomy of the LoA can be adopted to the off-highway sector with few modifications. Reflecting on the purpose of the mobile off-highway machines, the term driving needs to be replaced by operation and adapted to the utilization of the respective machine.
Container port automation represents a special case in the automation of off-highway equipment. Automated guided vehicles (AGVs) are commonly applied in this industry sector for decades [37]. Similar to the on-highway automation the environment at container ports can be considered as highly structured. In addition to that, access control and the full observation of the working area support the implementation of automation by reducing the potential of objects at the pathways of the AGVs, e.g. humans or non-autonomous vehicles. Stahlbock and Voß (2008) [37] reviewed the existing literature on the optimization of container ports and highlighted the positive effect on efficiency by the implementation of the AGVs and port automation.

Today’s design of autonomous machines, especially in the construction and mining sector, focuses on the sensing, processing and actuation capabilities of the machine platform. The approaches described in [18–20] using existing machines as a basis for automation or robotization. The development of ad-hoc systems to automate existing machine types are an obvious solution to generate a basic understanding of the task as well as the machine to automate. Nevertheless, the base machines have been designed towards the needs of human operators with partly limited possibilities for automation.

In the agricultural sector, automated machines are of high interest as well. In the paper on “Robotics for sustainable broad-acre agriculture”, Ball et al. [16] investigated the application of a small robotic platform to replace a, typically, large type of equipment, in this study, a sprayer. By analyzing the basic task, the group could scale down the equipment size while utilizing the 24/7 operation capability of the robotic version to maintain production. The researchers concluded that the robotized system has the potential to be more productive than its full-scale original due to lower cost, less negative effects on the field and smarter application of herbicides and fertilizers.

Few research and development projects are focusing on the task to solve and subsequently also, indirect, the machine design. Petersen et al. [38] presents a hardware system and high-level control for an autonomous three-dimensional construction under conditions of gravity as a multi-robot solution. The authors show that dedicated design towards the task to solve, as well as the collaboration between the robots is one key to a successful automated construction process. Recently published concept vehicles from Volvo [39], Scania [40] as well as Komatsu [41] use the transport of material as the basic task for the automated vehicles. Unlike earlier mentioned automation approaches, Volvo and Komatsu designed vehicles without a dedicated operator station.

Raibert et al. [42] based their reasoning for the design decision for a four-legged vehicle on the fact that less than half the Earth’s landmass is accessible to wheeled
and tracked vehicles. In contrast to the automation of existing vehicles or machines, here the team chose the task first and designed the system based on derived task requirements. Even though the early version of the BigDog was remotely controlled by a human, the complex motion control was carried out by the system itself, enabling further automation of the concept in subsequent steps.

**Human Robot Interaction/Collaboration**

Lynas and Horberry [43] reviewed the issues with human factors associated with the implementation of automated equipment in the mining industry. Most of the research focused on automated systems that still require a human operator to function as intended. Associated issues with such an implementation are the acceptability of automation to operators, loss of situation awareness, deskilling, and operator behavioral changes based on different levels of automation. It has been indicated, that a user-centered design approach is likely to overcome these issues with a parallel focus on system automation rather than component automation.

Vaussard et al. [44] conducted a study to, among other topics, investigate the human-robot interface of domestic robotic vacuum cleaners. During their study, they had been able to split the direct and indirect interaction between humans and robots into three main parts, which are similar to the intended construction/mining application of this research: 1. How users operate and give commands to the robot, 2. How the systems give feedback to the user and 3. Indirect interaction with the users and robots shared environment. It has been stated that users wish to understand how the robot is working, which could be described as transparency. The study also revealed, that inadequate information sharing is decreasing the long-term acceptance of the robotic system, which was also stated in [43].

Breazeal et al. [45], as well as Jung et al. [46], highlighted the importance of the human-robot interface, and its design, as a key success factor for the human-robot teamwork. Jung et al. [46] found that when robots used backchanneling, the team functioning improved and the robots were seen as more engaged. On the other hand, the research also revealed that robots using backchanneling were perceived to be less competent than those that did not use it. Like in [45], Jung et al. performed their study by means of a collaborative game (in this case, Urban Search and Rescue), including participants, confederates and robots.

In their study about resilient autonomous systems, Matthews et al. [47] highlight the challenges for the teaming between human operators and autonomous systems. The research showed that these challenges are mainly associated with the cognitive demands, trust, and operator self-regulation. The study suggests, as one
part to solve the challenges, to design an interface that enables the autonomous system to effectively signal its capabilities and its intent to the human operator.

**Engineering Design and Product Development**

In his publication, Penny [48] states that: “*Engineering design is concerned with problem solving*” (p344). Furthermore, Penny elaborates, that engineering design is in the center of two intersecting cultural and technical streams [49] as shown in Figure 5.

![Figure 5 Center activity of engineering design; adopted from [48]](image)

In addition, Penny states that all engineering tasks involve:

i.) Recognition and definition of a need to be fulfilled,

ii.) The design of a system that meets the need,

iii.) Production, and

iv.) Action after production.
Pahl et al. [49] highlights that: “designing is the optimization of given objectives within partly conflicting constraints” (p2). A systematic approach is needed to handle the uncertainties and the different requirements put on an intended product by the user and the different stakeholders within an organization. This is typically reflected in a product development process. Ulrich and Eppinger [29] claim that successful product development results in products that can be sold, with special emphasis on for-profit enterprises.

The authors list 5 distinct dimensions which relate to profit and are used to assess the performance of the product development actions.

i.) Product quality
ii.) Product cost
iii.) Development time
iv.) Development cost, and
v.) Development capability

Ulrich and Eppinger highlight that other performance criteria are important as well but that a high performance along these five dimensions should lead to economic success.

**System Engineering and System of Systems Engineering**

Pahl et al. [49] highlights the importance of system theory in engineering design processes. Complex systems and products require special methods, procedures, and aids to support the development and analysis, the planning and selection as well as the optimum design. It is mentioned that system science is an interdisciplinary effort involving multiple technical areas. Within the system theory, products are commonly described as technical artifacts. In theory, these technical artifacts can be artificial or tangible and generally have a dynamic characteristic.

The International Council on Systems Engineering (INCOSE) [50] defines a system as: “An integrated set of characteristics that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people information, techniques, facilities, services and other elements.” (p265). In this context, it is also stated that the system, as it is used by the INCOSE and in this thesis, has to be seen as a “mental representation” of the real-world system. According to the International Organisation for Standardisation (ISO) [51], a system is a: “combination of interacting elements organized to achieve one or more stated purposes.” (p9). Furthermore, key-properties of the so-called system-of-interest (SOI) are given by:

(a) defined boundaries encapsulate meaningful needs and practical solutions;

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(b) there is a hierarchical or other relationship between systems and elements;
(c) an entity at any level in the system-of-interest can be viewed as a system;
(d) a system comprises an integrated, defined set of subordinate system elements;
(e) humans can be viewed as both users external to a system and as system elements (i.e., operators) within a system; and
(f) a system can be viewed in isolation as an entity, i.e., a product; or as a collection of functions capable of interacting with its surrounding environment, i.e., a set of services. [51]

These definitions are crucial in the approach of systems engineering (SE). Systems engineering is defined as an interdisciplinary approach to enable the realization of successful systems and products. A key activity is the definition of customer needs and the definition and documentation of the requirements of the functionality during the early phase of the product development cycle. Subsequently, the approach proceeds with the design synthesis and system validation while taking the complete problem into account. Besides the technical needs, systems engineering considers the business needs of all stakeholders as well as the ultimate goal of providing a quality product that meets all user and customer needs. Decisions made in the early development phase of a system can have tremendous implications in the later stages of the life cycle of the system. Therefore, the SE approach considers the whole life cycle of a system-of-interest containing concept, development, production, utilization, support, and retirement.

The term system engineering can be expanded to system-of-systems (SoS) engineering. This distinction is necessary to handle more complex situations and relations between systems and elements. A system of systems, as it is described in [51], can be regarded as a system-of-interest whose elements are themselves a system. The system of system notion summarizes a set of systems for a specific task none of the individual systems can accomplish on its own.

Keating et. al. [52] defines the system of systems engineering as: “The design, development, operation and transformation of metasystems that must function as an integrated complex system to produce desirable results. These metasystems are themselves comprised of multiple autonomous embedded complex systems that can be diverse in technology, context, operation, geography and conceptual frame.” (p41).
SUMMARY OF APPENDED PAPERS

Paper I

Summary
Concerning construction and mining equipment, the paper outlines the different layers of automation and its respective need for connectivity to fulfill a given target function. A key factor for effective automation of the mobile machine or worksite is the connectivity between the different system layers responsible for the machine or system automation. Each layer poses different needs to the connectivity depending on its function and location at the machine or in the overall process.

Relation to the thesis
This paper contributes to the thesis as a listing of the need for connectivity for the automation of off-road machinery. It has been shown that the different levels of automation call for different needs towards the communication infrastructure on different levels. The need for communication and thus the connectivity is given by the topological location and the possible interactions with stakeholders sharing the same workspace. Connectivity is an enabler for automation and thus subsequently for the increase in efficiency and productivity of machines and whole mining and production processes. The paper also elaborates on the various functions to achieve the efficiency gains and how they could be combined to a more sophisticated system throughout the different layers. It has been shown that the combination and connection of all possible operator assistant functions, as well as the semi-autonomous features, will not necessarily lead to a fully automated system. Nevertheless, data collection and subsequent analysis can support the design of fully automated systems.

Author’s contribution
The author researched that topic on existing examples within the Volvo Group. Technical reports, publications, and standards had been reviewed to classify the different ongoing research projects into the six distinct levels for driving automation for on-road vehicles, defined by the SAE. The levels for on-road automation had been transferred into the off-road sector, as well as a transformation of the driving task into a work task-related classification.
Paper II


Summary
The paper proposes an approach of data collection in early development stages for new and complex systems. By using the possibilities of virtual reality (VR) combined with scaled-down versions of existing machinery, an interaction hypothesis had been tested and documented. The paper highlights the importance of a dedicated interface to facilitate efficient interaction between humans and automated machines. It was shown, that the prototype system can serve as a communication and information exchange platform to generate curiosity while simultaneously generating feedback data for product development.

Relation to the thesis
The work leading to Paper B has created a further understanding of the different needs in terms of data collection and representation for the design decision-making process. In essence, the paper showed the basic need for increased data collection to describe the interaction styles between humans and machines, especially when semi-automated and/or fully autonomous machines are involved. The utilization of virtual reality tools, as well as scale site operations, are able to serve as additional data gathering sources, to support the design decision process, and also serve as a test field for data acquisition tools equipment and tools.

Author's contribution
The author wrote part of the text and contributed to the definition of the paper. The author also investigated the theoretical background and drove the literature study to define the knowledge domains of the paper. In addition, the author also contributed during the definition and describing the test scenarios and defining the overall structure of the study while Ryan Ruvald was the lead researcher for the study and corresponding interviews. Ruvald wrote the first draft and also conducted the final review of the paper. Christian Johansson contributed to the theoretical background of the paper and the review of the draft versions. Tobias Larsson supported with knowledge and advise in structuring the study and the paper to fulfill the formal requirements and ensure research quality.
Paper III


Summary

The paper further elaborates on the needs of human-machine, or human-robot, interaction to ensure a safe, productive, and efficient cooperation between humans and automated systems. Since no human-robot teams are operating in the construction or mining industry today, the researchers needed to find a solution to generate data about team collaboration to understand the basic principles of collaboration at ever changing worksites. Utilizing the approaches of design thinking and need-finding, a system has been developed and tested in the prototype stage to show that communication between autonomous machines and humans can be facilitated by utilizing simple but efficient wearable solutions. One main finding of the study was that trust is the basic collaboration principle that needs to be ensured between human coworkers but also between humans and automated machines.

Relation to the thesis

Paper III shows the basic needs of interaction between automated systems and human coworkers. This very unique interaction style needs to be included in further data gathering so it can be taken into account during the design decision-making process. It has been shown that, due to the complex and ever changing environment of the worksite, the interaction styles between human workers and automated machines are very different based on the given task. The paper shows that during a comprehensive data acquisition, quantitative data needs to be taken into account. To ensure high data quality and to enable the goal of describing a full worksite only by data, the interaction i.) between humans and machines, ii.) between machines and machines, and iii.) between machines a working material needs to be captured and documented for further analysis.

Author's contribution

The author wrote the main parts of the text and conducted most of the interviews and questionnaires by himself. Additionally, the literature study had been performed by the author. The fundamental analysis of the gathered data and the description of the contents as well as the preparation for further workshops and utilization within the research group but, also in the company had been conducted by the main author of the paper. Ryan Ruvald contributed to the studies and questionnaires and also during the data analysis. Parts of the theoretical
background and the literature study had been performed by Ryan Ruvald. Christian Johansson supported with a part of theoretical background and contributed to maturing the paper to its final shape. Tobias Larsson and Andreas Larsson supported with the advice and knowledge in design thinking and the research.
A STEP TOWARDS THE DESIGN OF
COLLABORATIVE AUTONOMOUS MACHINES

Construction- and mining- industries experience a lack of increased productivity compared to other industry sectors such as, manufacturing or agriculture. It is stated that the difference in productivity is based on the lack of innovation in construction and mining and that automation, connectivity, and digitization could close the existing gap [2], [3]. The argumentation is based on the labor-productivity (i.e., quantity index of gross output per quantity index of labor input) and therefore careful analysis of the influencing factors on the sector productivity is needed. The operational complexity of construction activity, as well as the dynamic environment of a construction site, explain parts of the productivity differences compared to the agriculture and the manufacturing industries.

The productivity and efficiency of equipment increased over the last decades and research showed that the results are highly dependent on the human, operating the machine [4], [5]. Based on these studies it can be claimed that the development of operator assistant functions, defined as conditional automation of equipment, is an obvious development stream to increase productivity and efficiency of the equipment and the operator.

Automation

Automation has become a major trend in all industry areas. The construction equipment manufacturers drive automation based on different purposes. Operability and the increase of efficiency and productivity can be seen as main drivers for the function and equipment automation [4], [Paper I-III]. As elaborated in Paper I, the introduced automation on a lower systems level, such as the braking system, gear shifting and propulsion are incorporated into the basic machine without changes to the overall machine design. In this context, Parasuraman and Riley [34] state that “what is considered automation will therefore change with time. When the reallocation of a function from human to machine is complete and permanent, then the function will tend to be seen simply as a machine operation, not as automation” (p231). Therefore, it can be argued that every automation activity will ultimately become a basic machine function as long as the operator has full control of the machine operation. This circumstance has implication on how humans perceive machines and its capabilities. Paper III showed that bystanders and collaborators trust the system machine/operator based on the utilization of certain automation and assistant systems. The assumption that these type of systems are integrated in all machines on a jobsite can potentiality create dangerous situations.
The research on construction machine automation and the enabler [Paper I] showed that, successful automation concerns all levels of an operational system. In the case of the conducted research, this operational system was represented by a construction and mining site. A distinction of the different layers to be automated was appropriate in Paper I to enable the description of the different needs and requirements for the automation activities. System automation represents the lowest layer of the researched automation efforts. At this layer, machine sub-functions such as gear shift, position control and cruise control are automated to satisfy a specific individual goal – in most instances the optimization of a component or a subsystem behavior. Gains in efficiency and operability are the main driver behind these automation activities. The next dedicated layer in Paper I was described as machine automation. At this layer, several sub-functions and additional control functions work together to satisfy a common goal that could be a semi-autonomous operation, path following, or trajectory planning/control for the machine’s attachment (e.g., lift frame or boom-arm-bucket arrangement). The highest layer of automation represented process automation. Here, the target function of the automation effort could be described as an increase in productivity and efficiency on the site and process operation. All applied subsystems (i.e., machines and equipment as well as human operators) in the operational environment are connected to the main control system. Adaptations to changing conditions are automated and propagated to all subsystems without human intervention.

**Requirement definition for autonomous machines**

The research area of designing dedicated autonomous systems for the deployment in dynamic and ever-changing work environments, like in construction or mining sites, can be considered as a new direction in engineering design. The main aspects of the interaction between the human and the machine are about to change with the introduction of fully autonomous machines. Not only the needs of the users, operators and bystanders need to be considered, also the emerging needs of the autonomous machines need to be documented and further processed to define requirements. The definition of these very specific and new requirements demands a novel approach in need finding and engineering design. Data mining through experience prototyping [Paper II] and needfinding combined with forecasting [Paper III] resulted in useful insight generation for the design and development of autonomous machines and the product-service systems offers. Especially the aspect of interaction and the collaboration had been researched extensively. To make appropriate design decisions during an early phase of the design and development of an autonomous machine, as many as possible requirements need to be known. A vast majority of the requirements can be taken from traditional machine development to define the mechanical properties of the machine. In
addition to that, autonomous machines also require an effective and intuitive interface to their environment and coworker. Depending on the task the machine will be applied in, this could be a simple indication system or a more sophisticated system to facilitate interaction and collaboration [Paper III]. The notion of trust and trust development needs to be considered in the early design of autonomous machines. Trust as a design requirement is a new item in the requirement list and needs to be described more thoroughly.

**Autonomous system design**

Control and optimization of state-of-the-art mobile machinery are impossible without data. During recent years, the amount of automated functions and systems on a typical construction machine has increased [53] as a result of technological advances in sensing-, computational- and data handling capabilities [Paper I]. As it was shown in Paper I, the control and optimization are not only restricted to the machine and its physical boundaries. The process that the machine is applied to can benefit from dedicated control and optimization activities as well. In Paper II, the connection between the product (i.e., machine) and the overarching service (i.e., innovative business model) as a product-service system is described. The exchange of data between the different objects and artifacts of the system is crucial for the overall performance and, in the case of the research in Paper II, the acceptance and thus the interaction of users with the proposed system.

Considering the machine design, most of the sold equipment today is based on proven design concepts and successfully sold previous versions of the equipment. Increases in productivity and efficiency had been achieved by an increase in machine size (to enable more material to be handled per time unit) along with optimization of core machine components such as hydraulics, drivetrain, engines and the mechanical structure.

Reviewing the traditional development and design of autonomous mobile machines, the interaction between humans or other autonomous machines in the same work area has not been of high focus. Different research groups developed mobile robotic platforms and the focus of their research was on control systems and sensor infrastructure off the mobile robot [13], [18], [19]. Just a few projects and research papers highlight the aspect of human-robot interaction and the need for creating an intuitive interface for efficient work. Research on intuitive interface development can be found in many fields like computer science as well as engineering design. In addition to traditional engineering tasks, also psychology has to be included in the research and design work. Especially the aspects of interaction and trust can be considered as a fundamental basis for the design of automated and autonomous machine [43–47], [54], [55]. Paper III
focuses on collaboration between human collaborators and how this could be transferred to autonomous machines.

Taking the notion of intuition and trust into account, data needed to be collected to evaluate the needs of the different stakeholders on a construction or mining site. In Paper II and in Paper III, interviews and observations were used to generate a basic understanding of the design challenge. The utilization of augmented reality together with a scaled-down site, illustrated in Figure 6 representation enabled the researchers to evaluate concepts of potential product-service systems. In addition, the interaction and collaboration with fully autonomous (scale) machines, depicted in Figure 7 could be observed and further analyzed.

Figure 6 Scale Site

Figure 7 Scaled down autonomous machine
In contrast to traditional construction projects, the mining industry also focuses on the deployment and application of autonomous systems in their operations [Paper I, Paper II]. In this industry sector, mainly the hauling tasks are in focus of the current development and research activities [Paper I]. Figure 8 illustrates a schematic operation of a mining site with all different aspects of the operation. Here, the position 9 loading/transport – face to crusher, and 11 stockpiling/rehandling are considered in Paper I, Paper II and partly in Paper III.

Paper II elaborated on the design of a product-service-system in conjunction with the design and development of autonomous machines. Such combinations of physical products with business solutions can be seen as crucial for a successful implementation of autonomous machines in real world scenarios. In combination with the presented research of Paper III, it is obvious that the application of autonomous machines into traditional work environments requires a novel design of the entire process (including labor training, site setup, safety concept, on-site communication and process tracking) as well as a redesign of the business and solution offer towards the customer.
Interaction model

Further analysis of the data collected during the research of Paper II and Paper III led to the development of an interaction model to sketch the fundamentals of autonomous system interaction with its working environment. This is necessary to describe the occurring interaction styles on a site level governed by the application of autonomous systems.

To get a comprehensive picture of all interactions happening at the site level, a holistic view needs to be taken to describe all possible interactions and touchpoints. As depicted in Figure 9, there are different interaction styles between the autonomous system and other stakeholders on-site. The research leading to Paper I suggests that information exchange between machines and the control system is needed. In addition, an information exchange between the collaborating autonomous systems and, if present in the proximity, additional mobile equipment is required. It is worth to mention that the information might be encapsulated in

Figure 9 Interaction model
quantitative data and therefore, the data needs to be analyzed by the receiving machine or system before the desired information is accessible. As an example, data streams from the control system or broadcasted position data from another equipment can be stated here. Paper II and Paper III led to the incorporation of information with qualitative character into the interaction model (red connectors). This information is characterized by the fact that the receiver needs to interpret the receiving data to react in an appropriate manner. Environmental information, such as ground conditions and weather conditions, are available to the autonomous machine at all time through its sensing capabilities. The sensed data needs to be interpreted and included in the machine’s decision-making process autonomously. Another example is given by the interaction and collaboration between humans and autonomous machines. Both sides need to interpret the behavior of the counterpart and need to react accordingly. Unlike the information exchange between automated systems, here no handshake procedure can be applied to ensure proper information distribution. Thus, it cannot be assumed at all times that a human collaborator nor an autonomous machine received the information as intended. This poses additional requirements on the design of an effective interaction and collaboration interface.

Besides the information exchange, the physical interaction between the different objects on a site had been captured in the interaction model. To capture additional, yet unknown, artifacts and possible interactions on a work site, the box with the description N.N. had been introduced. Material transfer between the autonomous machine and the environment, the site infrastructure as well as collaboration equipment had been sketched in Figure 9. The described physical interactions between the different objects need to be broken down into ‘intended’ and ‘unintended’ physical interaction to describe all possible interaction styles.
Facilitation of collaboration and interaction

The deployment of automated and fully autonomous machines demands new styles of interaction and collaboration on a site. Especially the capabilities as well as the intentions of the machines need to be clear to the human collaborator [Paper II; Paper III]. Observations and interviews at construction sites supported the understanding of the development of trust among human teams. Non-verbal communication, experience, the stable formation of the team and a comprehensive understanding of the work task supports the inter-team trust development and its maintenance [Paper III]. In addition, a rule-based framework, applied at all sites, serves as an entry point into the trust development because new team members can rely on the ‘dos and don’ts’ and that everyone follows the same company-wide rules.

Similar to the development of trust between humans, the trust development between a human and an autonomous machine (or a robot) can be facilitated. Transparency, constant feedback, reliability, and durability exposed by the autonomous system supports the development of trust on the human side [Paper III]. Observations and the predictability of the machine behavior can be seen as a high influence factor as well. With respect to the assigned work task on a construction or mining site, the workflow of the machine and the human worker has to be maintained throughout the operational period. Facilitation systems are required to ensure safe and efficient collaboration and side-by-side working of humans and autonomous machines within the same work area [Paper III]. The research presented in Paper III indicates that there are several levels of information to be presented to the human, based on the respective work situation. A first facilitation system is proposed to enable the propagation of dedicated information from an autonomous machine towards a human teammate or collaborator. It is sketched out that the human and the machine do not necessarily need to work on the same task but still share the same work area.
CONCLUSION

Automation is a method of choice to increase the efficiency of a process and to increase the productivity of a machine and processes throughout many industries. The automation of existing machines and processes is an ongoing trend, also in the construction and mining sectors. Especially the automation of machines by applying operator assistant functions and by automating the machines’ sub-functions increased the productivity of the machine compared to its non-automated reference machine. There is a clear trend towards the implementation of fully automated or autonomous machines into construction, and especially into mining sites. Enabled by technological advances, the automation addresses current issues of labor shortages as well as low productivity numbers per industry sector.

The application of dedicated autonomous machines in mining and construction is comparably low. Mostly, existing well-established machine types are automated to achieve semi-automated or fully autonomous operation. It can be claimed that the drawbacks of this approach lay in the fact that the machine design is based on human operators.

Useful information is required to make appropriately informed decisions during the early stages of any design and development initiative. The presented research shows that the information needed for the design of autonomous machines is rare and needs to be collected with special means. Traditional knowledge engineering can support the development to some extent but has limited capabilities in the application of new and innovative solutions.

The research shows that the applications of automated and fully autonomous machines will result in human-machine collaboration due to the complexity of the task and due to the necessity of a human observer involved in the process. Thus, the collaboration between humans and machines has high relevance for the design of the machine and, even further, the design of an effective interface. While making conclusions from only human teams, trust between teammates is a crucial success factor of collaboration and ultimately of the successful task execution.

**RQ:** How can requirements for the development of autonomous machines be discovered and captured?

- The discovery of specific requirements for the design and development of autonomous machines (expanding the traditional requirements) can be supported utilizing observations and interviews of current site staff. The cooperation, collaboration and the interaction of humans among each
other and with manually operated machines can be utilized to define requirements for the development of autonomous machines.

- Data mining and needfinding with respect to autonomous machines and the application in real-world cases can generate data to be converted into requirements. Stating the needs of the autonomous machines can reveal additional information about the application, interaction and the overall utilization of the machinery type.

- An interaction model can support to define different levels of wanted and unintended interaction of an autonomous machine. The described interaction directly leads to the definition of the requirement to either facilitate the interaction or avoid the interaction.

- A review of existing and well-accepted solutions can be utilized to capture additional requirements. Existing aspects of operability and intuition need to be expanded to facilitate the on-site collaboration of the different workforce members, regardless if they are humans or machines.

**RQ: How can different interactions of autonomous mobile machines be described?**

- Employing an interaction model, crucial interaction styles can be defined, and the characteristics of the interactions can be defined. An interaction model of the autonomous machine can support the revelation of the interaction on different physical as well as cognitive levels. Besides wanted interactions, also unintended interactions should be considered and mapped in a model for further utilization.
FUTURE WORK

Future work is needed to further define the requirements for the design of autonomous machines. To describe a site operation, the decoupling of work tasks and process flows from machine characteristics is currently a subject of research.

The presented interaction model should be expanded to capture possible interactions, on different physical and cognitive levels, of an autonomous machine. The connection with a digital twin on site and machine level is considered and a planned next step. Combining the different data sources as well as the different data types into a usable format will be investigated and researched subsequently.

Furthermore, needfinding methods and specific data collection should be investigated to adapt to the special needs and requirements autonomous machine development has. Research on pure human team behavior and trust development among humans have resulted in beneficial insights, which can be utilized to facilitate trust development between humans and machines. Additional exploration and formulation of the proposed methods is needed to be applied during further research activities.
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*Connected Machinery – Enabling Automation –*

ABSTRACT

With the increased demand on fuel efficiency and productivity of the different construction equipment types, the connection of the equipment’s sub systems, the connection between the different on site machines and the connection to the site management gets more and more important. By analyzing the different systems and the underlying requirements, several optimization possibilities arise with the connection of the different data sources. It will be shown that the connection of the different system on machine level as well as the connection between machines will have a big impact on performance and efficiency of the systems and subsequently of the machine itself.

INTRODUCTION

Looking at the increasing number of sensors and information source at the different types of construction machinery as well as the increasing data sources on a typical worksite the analyzing possibilities has not been as big as they are today. By using the growing calculation and processing capabilities of the standard vehicle ECU’s (Electronic Control Unit) the data is used to continuously optimize the machines subsystems towards the predefined target functions. Traditionally, the generated sensor information was used in the machines subsystems as input for control loops as well as information source for the operator. There is still a big value to use this information to optimize the machines systems and performance but with the increased possibility to share the data with connected off-board system makes each single machine to a data mine itself.

The different levels of connectivity and automation require a different handling and transmission of the system, machine and process data. The SAE Standard J3016 defines levels to describe and distinguish the stage of automation [1]. The defined levels are shown in Figure 1. Levels for automation are defined for on-road vehicles but also can be applied to off-road vehicles and construction equipment in the same manner.

In close conjunction with the automation also the connectivity of the systems and vehicles will increase and therefore can be clustered into the same numeration as well. While the level of automation is increasing also the requirements on the communication and connection between the vehicle components and systems are increasing. This is driven by the safety features but also by the need to exchange system data on a higher level to enable sophisticated control and optimization.

Different communication technologies are used for the different levels of automation. Low level automation of vehicles systems still relying on analog data transmission as well as CAN communication on a basic system layer. On machine level, these communication technologies are not sufficient to support further machine and vehicle automation. The trend towards advanced communication technologies in the commercial vehicle domain is recognizable. CAN FD as well as on-board Ethernet communication could be possible solutions.
CONNECTIVITY AND AUTOMATION

From a system perspective a split into three main levels can be done as well. This very simplified differentiation is very useful during the development process of the diverse stages of automation for construction equipment.

System automation

Looking to the machine as a working system of different interacting components and subsystems, the connection is the backbone of the whole system and crucial to perform the given work task as well as the necessary basic machine functions. During the machine operation, data is generated to control the components and subsequently the machine or vehicle in total. The low level communication and automation, or the component control, is the very first step into the automation of complex functions and tasks. With the connection of the different data sources as well as the basic machine and vehicle parameters, additional information can be generated and utilized as input to control loops. In such a principle is explained for the force and motion controller of an excavator arm.

The main purpose of the system automation in today’s machinery is the reduction of the mental operator workload and the increase of efficiency of the working system. Due to that, the requirements on the subsystem and the automation of the same are different to a full autonomous solution. The described low level system can be used to create operator assistant functions as well as automated functions for the machine actuation. The so called high level control will still be done by the human operator. This fact needs to be included into the development of the automated systems and functions. It is required that interfaces and the connectivity be tailored towards the smooth and efficient interaction with the human operator.

In theory it can be assumed that the summation of all different assistant systems, automated functions and semi-autonomous features will result into a fully autonomous machine. Due to the fact that all these systems have been designed to collaborate with a human operator, the theoretical assumption is not totally valid. The underlying requirement for these developments is the availability of a human operator. Therefor the system automation will not necessarily lead to a full autonomous machine.

Machine automation

The next higher step in the automation of vehicles and machines is to take a comprehensive view on the whole system. This will reveal that a vehicle or machine consists of many, sometimes independent, systems and functions. A high level control system or control layer is required to plan and coordinate the work task of the autonomous machine. This system is the replacement for the human operator and takes care of the high level control and command structure. Schmidt [3] showed this by creating a high level control system for a trajectory planning module of an autonomous excavator.

The low level component control layer is carrying out the commands form the planning module constantly. In parallel several other task are needed to be carried out. To ensure a safe working, a safety module needs to continuously monitor the environment to be able to detect objects and to calculate possible collisions for
the planed trajectories. It can be assumed that the result of the different modules inherit each other to secure a safe and stable operation of the autonomous machine. One possible solution to create a functional control network has been published by Proetzsch [4]. The feasibility of the approach has been shown during several applications [3], [5] on different platform but remains still as a research approach for full vehicle automation.

For the automation a suitable communication backbone is required to be able to run critical functions in a stable and efficient way. Due to the fact, that the human operator will not be the last control layer on the machine the interconnection between the subsystems and functions needs to be ensured. Base on the setup of the control system, the connection and communication will differ from the lower level connection. The high level planning system does not necessarily require a continuous data stream from and to the connected low level components. A simple state feedback could be sufficient to plan the following step. To ensure a safe and robust operation a certain redundancy or fault detection is required. In parallel the safety system could require a continuous information flow from the perception sensors as well as from the low level control layer to evaluate potential risk and critical situations.

This different requirements needs to be included into the system design. Hence the connectivity of the autonomous system will differ from the traditional low level control approach. It can be assumed that the increased demand on data bandwidth for safety calculations will exceed the capabilities of the current on-board communication networks used in construction equipment and today. Several approaches and solutions are known to solve these challenges. A more suitable communication protocol like vehicle based Ethernet can be established to meet the requirements of the safety systems. The stability and robustness of such systems needs to be optimized for the described usage. In contrast to that, distributed systems could be another solution to address safety features while reducing the need for full raw data transmission. Embedded systems could preprocess or process data where it is generated and transmit the results based on priority scheduling.

All automated systems have in common that a powerful and stable communication layer is essential for the system performance. The ongoing connection of the information source on a machine or vehicle also opens up for new possibilities in the machine / vehicle state detection. The information sources as a whole contain useful, unmeasurable data about the state and condition of the system. By using adequate algorithms and models, like the hidden Markov model, this information can be used to extract useful process data.

**Process automation**

The described automation layers only included one machine executing a specific work task. Typical construction equipment machinery will have to collaborate with other equipment types / infrastructure or humans on site. The generation of collision-free trajectories has been shown in [6] for a fleet of quadrocopters. It is stated, that the overall approach is applicable to other autonomous machines as well. The paper is presenting that the collaboration of the machines is controlled by an high level system gathering all machine / vehicle and environmental information. The Information subsequently will be used to generate collision free trajectories which will be commanded to each single interacting machine while the low level control remains as vehicle / machine responsibility. The communication between the machines and the high level control layer is crucial for the operation of the whole system.

In case of loading and hauling machines, the level of interaction needs to be investigated further. Vehicle to vehicle (V2V) communication and vehicle to infrastructure (V2I) communication will add additional layers for task planning and data distribution. In comparison to the approach shown in [6] different configurations has to be considered:

1.) Interaction between autonomous systems and humans

2.) Interaction between autonomous system and manually operated equipment

3.) Interaction between autonomous systems and the infrastructure

4.) Interaction between autonomous systems

**Figure 4** shows in principle the work tasks in the industry segment “Quarry and Aggregates”. It is obvious that the collaboration and interaction of the different types of machinery is crucial for the site production process. The overview can also be utilized to cluster the different tasks according to the stated configuration to develop appropriate semi-autonomous or autonomous solutions.

While the requirement on the connectivity stays the same for the different configurations, the execution and data representation needs to be adjusted.
OPTIMIZATION POTENTIALS

A big driver for the vehicle automation is the possible gain in efficiency and productivity that could be achieved in some specific applications. Automated construction equipment like wheel loaders and articulated dump truck will be utilized in niche applications with defined boundaries and requirements. Such an application could be the material loading and transport within a quarry.

To verify the potential efficiency increase for semi-autonomous and autonomous operation of construction machinery several investigations can be utilized.

In [8] the deviation in the efficiency and productivity among a group of operators has been investigated and analyzed. It has been shown that the assisted work could improve the efficiency and productivity of the operators while using function and vehicle automation. Depending on the skill level of the operator the efficiency gain could be up to 150% in a typical application. Taking all measured operators into account, a fuel efficiency gain between 20% and 40% can be observed for specific applications. The measurements and assumptions by B. Frank only consider the usage of a wheel loader corresponding to SAE J3016 level 1 and level 2 automation. Comprehensive investigations for higher levels of automation have to be performed to verify the efficiency and productivity increase. It can be assumed, that semiautonomous and autonomous machines will result in a more stable efficiency in a specific application due to better controllability and the high level planning possibilities.

Similar assumptions, both for assisted and autonomous operation, can be made for other equipment types as well.

Connecting the interacting machines and vehicles on a typical quarry will lead to an increased efficiency and productivity on site. Basic analyses of the overall benefits of such a connection have been made by Rylander. Applying the lean production thinking on a construction site or quarry, different types of waste have been determined [9]. Some types of waste could be eliminated by simple communication between the different machines and vehicles. A basic set of transmitted date like GPS, heading and machine type could be utilized by a site management system optimize traffic and material flow. The increase in fleet efficiency at this stage is independent from autonomous features and can only be achieved by proper connection of all on site vehicles and machines. Connecting the different information sources to one database could be beneficial to plan the material flow, machine usage and subsequently the cost and income in advance.

Adding semi-autonomous and autonomous vehicles and systems offers further optimization potential. Having the possibility to control the material flow as a...
multidimensional function with respect to machine properties, order income, material stock, environmental conditions, traffic, etc. the site production could be optimized while maintaining a high efficiency of the utilized machinery. In this case the site control level will govern the target function which will subsequently affect all other control layers down to the single machine component. The driving strategy of a hauling vehicle, for example, could be optimized depending on the requested production and the "global" efficiency target of the site. Subsequently the shift strategy of the gearbox could be optimized to meet the "local" target function of the vehicle. This can be achieved by means of sophisticated data exchange and process optimization across different control layers.

CONCLUSION

The application of operator assistant function, semi–autonomous and autonomous machines will lead to an increase of efficiency for specific work tasks. The underlying technologies for controlling the functions as well as the connection of the components, systems and machines needs to be optimized towards the utilization in the commercial vehicle domain. With respect to reliability and safety some of the presented approaches are still in the research phase but showing promising results justifying further investigation.

While fully autonomous construction equipment will be a niche product for well-defined applications in confined areas, automated systems and semi–autonomous features can be applied in a wider range of applications. The recognizable trend in the automotive and truck industry towards operator support through smart features will expand to the construction machinery as well. Already automated subsystems like gear shift; cruise control etc. will be connected to intelligent functions to further increase efficiency and productivity as well as the comfort of the operator.

The research on fully autonomous machines will generate valuable results for the development of integrated and expandable operator assistant functions. Coincidently the requirements on the connectivity will increase based on the necessity of safety features which require a certain amount of reliable data as basis for the risk calculation. State-of-the-art technologies like CAN Bus communication will not be sufficient to support higher system and machine automation. Distributed systems could be a solution for an additional safety layer for autonomous features.

REFERENCES


ABBREVIATIONS

ECU Electronic Control Unit
V2V Vehicle to Vehicle communication
V2I Vehicle to Infrastructure communication

Data Mining through Early Experience Prototyping - A step towards Data Driven Product Service System Design.

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Data Mining through Early Experience Prototyping -
A step towards Data Driven Product Service System Design

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Abstract: The construction industry is ripe for disruption through innovative solutions that provide added productivity. Equipment manufacturers are attempting to disrupt their industry with investments in autonomy, electrification and product-service system business models. Designing solutions that will operate in completely new systems or modify an existing complex system require new approaches to address the uncertainty of system impacts. An iterative approach can help tackle ambiguity through cyclical validation of design decisions. Data mining in each cycle adds a quantitative dimension to the rationale of decision making, but data is sparse and difficult to collect in parallel with design of theoretical product-service systems operating in future scenarios. This can be combated using experiential prototyping techniques to design flexible infrastructure that supports contextualized data gathering in a variety of focused design sprints using Design, Build and Test approach. The intricacy of designing innovative solutions to increase productivity in the construction industry can be untangled by framing aspects of the problem in small sprints and testing them in a contextualized setting built to generate functional data to drive design.

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Keywords: Product Service System, Data Mining, Experience Prototyping, New Machine Development

1 Introduction:
Over the last 60 years, global increases in productivity for construction based industries have lagged behind similar industries such as agriculture (by a factor of 15) and manufacturing (by a factor of 8) particularly due to a lack of innovation (Barbosa, et al. (2017)). Much of this deficit in innovation can be attributed to construction’s level of operational complexity when compared to agriculture and its constantly changing operational environment in contrast to manufacturing’s static workflows (Abderrahim and Balauger (2008)). Yet, as technological capability continues to increase, opportunities exist to be the best smart construction equipment supplier.

Attempting to expand into a non-existing market reveals a plethora of ambiguity concerning the form and function of new products, services and systems. Compounding the challenges associated with ambiguity is the difficulty of gathering data to drive design when addressing hypothetical future scenarios and environments. For instance, a Swedish Construction Equipment Manufacturer is developing autonomous and full electric machines as part of their committed to a 10x increase in efficiency (Volvo Concept Lab (2017)). But, introducing autonomous construction equipment results in an unknown hybrid interaction of new and original artifacts consisting of complex and dynamic interactions with converging hardware and software, products and services, humans and machines.

By integrating the system components toward the provision of a functional solution rather than individual products, manufacturers can arrive at Product Service System (PSS) solutions (Tukker (2004)). When purposefully designed, PSS’ provide increased customer value, improved long-term return on investment, built-in environmental-friendly aspects and possible, spare part and waste reductions (Tukker (2004)). However, focusing on the functional integration of products and services affects the manufacturer’s development process ie. how development work is organised and which tools and methods are used.

Engineering design thinking provides sets of tools and methods capable of unpacking the ambiguity in PSS development through a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients’ objectives or users’ needs while satisfying a specified set of constraints (Dym et al. (2005)).

Generation and evaluation of concepts can be accelerated through the incorporation of data-mining to drive design decision rationale. This concept is engendered by the emerging field of data driven design (Bertoni and Larsson...
(2017)). Set in the context of PSS development for construction equipment manufacturers, various types of data must be collected ranging from quantitative machine performance factors to qualitative user experience factors (Isaksson, Larsson and Rönnbäck (2009)). Considering the intangible nature of new machine concepts and future construction operations, efforts must be made to simulate these elements.

Simulations, in this data-gathering context, include all elements necessary to elicit realistic interactions in a theorized future scenario. Utilizing experiential prototyping, designers can engage with users in a contextualized representation of the envisioned PSS solution. Ideally, this serves to create a shared sense of empathy with the ultimate goal of guiding design decision towards the satisfaction of true system needs.

1.1 Objective

The objective of this paper is to explore data driven design for the purpose of guiding product-service system development in the construction industry via flexible experiential prototyping infrastructure.

1.2 Methodology:

This work was based on a case study (Yin, 2004) focusing on the development of Human-Robot Interactions between construction workers and prototype autonomous vehicles. More specifically, how the elements of an augmented reality interface can facilitate a building of trust between human and autonomous machine. Testing of the interface was conducted via Microsoft Hololens paired with scaled down functional model machines on a scaled down construction site with digging, loading and dumping operations.

Data was gathered in the form of user feedback via questionnaires and qualitative data from researcher conducted observations and interviews. Analysis of the data was done by identifying trends and converging opinion statements from the collective body of feedback.

2. Scientific Background:

2.1 PSS Design

Complexity in product development is emphasized when hardware, software and services are packaged into a single ‘total offer’ (Alonso-Rasgado et al. 2004). Product-Service Systems (Mont, 2002) is one of the industrial trends representing the shift in manufacturers’ strategic focus from selling a physical product to providing performance and availability, as a way to satisfy more sophisticated needs and expectations (Baines et al. 2007; Williams, 2007). Eight types of PSS are proposed by Tukker (2006), which have been are further synthesized by Cook et al. (2006) in:

- Product-oriented PSS: the ownership of the physical artifact is transferred to the customer and services are offered to ensure the “utility of the product”, such as warranties and maintenance.
- Use-oriented PSS: the service provider retains the ownership of the physical artifact and the customer pays for its use over a period of time or units of service.
- Result-oriented PSS: the service provider, as in use-oriented PSS, retains the ownership rights of the physical artifact, and the customer pays a fee proportional to the expected outcome rather than for the mere usage of the product. For instance, instead of leasing or buying a haul truck the customer can sign an agreement for material transport by mass with an full service provider.

Compared to the traditional one-sale model, designing these PSS types challenges engineers to raise their awareness on customer and stakeholders needs along the entire product lifecycle, so to realize solutions that are value adding for all the actors involved (Isaksson et al. 2009). Furthermore, PSS development is known as functional product development, where the solution of any combination of hardware, software and services is developed in a coordinated development effort.

2.2 Data Mining:

Data mining is defined as the discovery of non-trivial, implicit, previously unknown, and potentially useful and understandable patterns from large datasets (Anand and Buchner, 1998). When it comes to application of data mining in industrial environments, the term is often associated with the concept of machine learning, i.e. the study of computer algorithms that improve automatically through experience (Mitchell, 1997) Data mining and machine learning are used in engineering both with the predictive goal of forecasting the value of a variable and with the descriptive goal of understanding and discovering patterns in the available data (Anand and Buchner, 1998). Data mining can thus be used to support data driven rationale during a design process.

2.3 Experiential Prototyping

Overall, the venture of prototyping is to gather information to help in the decision-making process of design. The designers at IDEO have a saying, “if a picture is worth a thousand words, a prototype is worth a thousand meetings”. They provide opportunities for fast feedback, new inputs and a hands on user experience readily available. Furr and Dyer (2014) assert that rapid prototypes have a fundamental role in hypotheses validation. They also discovered that in some cases it can be beneficial to fake the capability of a product if the experience is your key point of investigation (Furr and Dyer (2014)).

Experiential Prototyping techniques endeavor to accomplish three goals towards addressing the problem: Understanding existing user experiences and context, Exploring and evaluating design ideas, and Communicating ideas to an audience Buchenau and Suri (2000).
2.4 HRI
Vaussard et al. (2014) had been able to split the direct and indirect interaction between human and robot into three main parts:
1. how users operate and give commands to the robot,
2. how the systems gives feedback to the user and
3. indirect interaction with the users and robots shred environment.
It has been stated that users wish to understand how a robot is working, what could be described as transparency. The study also revealed, that an inadequate information sharing is decreasing the long-term acceptance of the robotic system, what was also stated by Lynos and Horberry (2011). It has been indicated, that a user-centered design approach is likely to overcome collaboration issues with a parallel focus on system automation rather than component automation by Lynos and Horberry (2011).
Brezeal et al. (2013) as well as Jung et al. (2013) highlight the importance of the human-robot interface, and especially its design, as key success factor for the human-robot teamwork. In their study about resilient autonomous systems, Matthews et al. (2016) pinpoint the challenges for the teaming between human operators and autonomous systems. The study suggest to design an interface that enables the autonomous system to effectively signal its capabilities and its intent to the human operator.

3. Results:
3.1 Prototype Results
To construct an effective prototype experience flexible enough to test a variety of interface functionalities, generic scenarios from real construction operations were needed. Collaborating with a Swedish construction manufacturing company’s marketing department provided the necessary relevant activities to be included in the prototype.
As large scale organizations (such as: Uber and University of Michigan) heavily invest in autonomous transport they have recognized the importance creating models of cities to test and simulate their specific concept’s operation in realistic context. Most other high fidelity investigations into autonomous vehicle intention communication and pedestrian interaction, create scaled functional machines based on golf carts or smaller vehicles [e.g., Matthews et al. (2017), Florentine et al. (2016), St.Clair et al. (2011)] in order to have an artifact for testing a range of interfaces or interaction techniques. In contrast, an autonomous construction site will involve multiple machines collaborating to complete specific tasks (Ameeen and Safawizadeh (2017)), requiring humans to process information from multiple sources simultaneously.

To address this distinct difference, the developed prototype platform consisted of a 5m x 5m scaled down site including two autonomous haulers’ loading and dumping interactions (figure 3.1) typical of a quarry or mine operation.

![Figure 3.1: Hauler and excavator loading operation on scale site.](image)

The machines were 1:11 scale remote control versions of Volvo CE’s currently available EX01 excavator and LX01 wheel loader concepts, with the addition of the prototype HX02 autonomous hauler. To best reflect the reality of the operation, loading machines (excavator and wheel loader) were left as remotely controlled machines, while the HX02s were fitted with sensors, control boards and communication devices to enable an autonomous experience for the user.
A Microsoft HoloLens was acquired to build a functional prototype of an AR interface resulting in an application transmitting voice commands to haulers and display an information panel with fictional data. (fig 3.2)

![Figure 3.2: Deployed Hololens interface testing layout](image)

3.2 Data Generation
Experiential Prototyping is not normally found in the construction industry, but it is essential when the goal is generating/gathering feedback data from a large number of diverse users interacting with a limited production prototype designed for a hypothetical construction site. With the scale site constructed as a research platform the stage was set to generate testing data on the HRI prototype’s feasibility to meet the needs of future construction scenarios including manually operated machines, autonomous machines and human laborers.
In testing with the infrastructure, data gathered consisted of quantitative responses to a questionnaire aimed to confirm desired emotional responses to the inclusion of user interface elements. To complement the questionnaire and broaden the scope of potential learnings, qualitative observations and interviews were conducted of users and non-user observers.

The questionnaire were designed to measure emotional responses to the drivers identified in a previous case study Winqvist (2016). The range of available response variables was intentionally narrowed so data gathered indicated a binary presence of the desired emotional components rather than the degree which is less reliable at the designed fidelity.

The response prompts were:
1. HoloLens app made me feel connected to the machines
2. HoloLens app increased my trust of the haulers
3. Voice commands made me feel in control
4. The AR display was more helpful than distracting
5. Overall site experience felt realistic in its operation

The responses of 15 respondents are gathered in the Graph 3.3 below.

![Liker Scale Prototype Feedback Survey](image)

**Figure 3.3: Questionnaire responses to AR experience**

The 15 respondents do not make for statistically significant quantitative data, but basic trends in the response create useful qualitative data. Lowest scores were found in the perceived realism of the scale site. Interview questions confirmed this stemmed from the RC controllers connected to the scale wheel loader and excavator being seen as “toys” more so when combined with low skilled drivers demonstrating “unrealistic operations” that would create “unsafe and inefficient performance”. Responses to questions 1-4 indicated an optimistic attitude towards the HoloLens AR platform as an interface.

Interviews, in the unstructured format they were conducted, more resembled conversations. Not shockingly, most conversations started with the question, “what is it?” The researcher answered this question the same to all who asked, describing it as “A scaled site demonstration platform for autonomous vehicles in construction operations, currently being used to test HMIs with the autonomous haulers”.

Following this description people either totally disengaged or became curious at the word “currently”. Suddenly, people began to give their own interpretations for its potential function.

One such quote include the concept of aligning the user involvement with collaborative actions between humans and autonomous machines not just other humans, “you should find ways to include more users interchangeably, like an MMO game”. This would allow more people to craft more unique individual experiences with the same equipment. Expansion and immersion of the user experience was addressed by the following two quotes, “okay, well how will people in the machines communicate with those autonomous ones?” “It would be more interesting to drive the manual machines from that simulator” (referring to a Volvo CE wheel loader operator simulator). While this functionality would create functional training mechanisms they also enrich the context of the user experience. Adding these dimensions to the site could serve as a bridge to acclimate humans to the collaborative nature of future semi-autonomous sites.

Some key quotes revolved around the autonomous demonstration site activities and features. While watching the machines perform tasks, someone logically scanned to see who was controlling them, they asked, “So, nobody’s driving that right now?” in reference to the hauler running its route. The answer was no and to their delight the concept of the site became one of the future, not just a playground with fancy toys. Additionally, while observing HMI testing a spectator was curious about the verbal command over the haulers, they were not aware of how much control or when the connection was active in their question, “Is the machine listening to me?”. These questions reflected the designed features for testing trust derived from the functionality in the HMI features.

Other’s statements captured the observer’s perception of the real operations being simulated. Due to the scaled down nature of the demo site, perspectives were automatically shifted to reflect theorized future collaborative roles captured in this quote, “I feel like a site manager staring down at the operation”. This theme gained traction building off the genuine interest in the future scenarios of construction. Curiosity about the infrastructure requirements came in questions like, “How long can the real ones run for?” and “where and how do they charge up?” This even expanded to the HMI potential with feedback about its real roll out features in the quote, “If they were real I’d like to see more granular data on the interface”. This kind of comment shows the users immersing themselves in the future usage.

4. Discussion:

Over the last decade, data mining has been recognised for its potential to profoundly shift decision making to be more transparent, informed and autonomous, and with less bias. While this has become a reality for the design of certain artifacts in the construction industry, the same cannot be said
for PSS or functional solution development. The work conducted in this case study aimed to address the issue of creating adequate user context for generating feedback on the human element in future scenarios. In this way, future PSS scenarios can be dissected and tested with minimal effort compared to construction of full scale machines and test sites.

The scale infrastructure in this case study was built to recreate the key interactions identified in a foresighting of future autonomous construction sites. Although the data generated from the conducted testing was primarily qualitative in nature, the components of the site (i.e., machines and interface devices) are entirely capable of producing quantitative data similar to that collected by Akhavian and Behzadan (2013) who highlight the importance of factual data for as input for a construction simulation model.

It is claimed, that there is a trend in the simulation of construction fleet activities on estimating input parameters using expert judgments and assumptions. To have a reliable source of simulation input parameters, the authors used a model site and laboratory environment to validate their statement that a construction fleet operation can benefit from knowledge-based data-driven simulation model generation.

By streaming equipment data (such as position, weight and angle) and subsequently applying fusion and reasoning algorithms, Akhavian and Behzadan (2013) show promising trends in simulation quality of site operations. Based on this, equipment manufacturers have begun to take steps to include data gathering capability on active machines, yet this data serves to improve mainly maintenance and use phase services. This can lead to the sub-optimization of system elements when the goal is actually functional solution or PSS.

The application of new technologies in the construction and mining sectors is very much dependent on the productivity of the solution and how well it fits into the existing operation. Isolating the impact of individual changes in a complex system can be difficult which is why in engineering design, prototyping as a verb is an essential philosophy to finding flaws in concepts early when investment is low and design freedom is still broad (Furr and Dyer (2014)).

An overarching principle behind the scaled down site operations rests on the following theorem. Through a tangible experiential prototype platform embodying the idealized PSS concept environment, designers could backcast a series of iterative development missions for the five stages of PSS design: Planning, Idea generation, Sub-System, Detailed Design, Deliver and Use-Phase. With a scale site, more variations of PSS scenarios can be explored at an increded pace leading to more informal early phase decision making.

An important aspect is the flexibility of the prototype platform elements to support investigations into the various interactions engendered by functional system solutions. Furthermore flexibility extending to the customizable fidelity of the elements can focus the data gathering to answer specific design questions avoiding irrelevant feedback on external components. This can benefit the parallel development processes required for successful PSS design by creating a shared foundational vision of the future scenario across all perspectives during inquiry.

5. Conclusions:
Through targeted inquiry, a cyclical approach can be applied to generate/mine data on future scenarios to drive their development. Beginning with designing the future PSS scenarios to explore before applying experiential prototyping techniques to create a holistic interaction exposing users to tangible artifacts set in the desired context. Data is generated from the user engagement with the scenario and its artificial components, then mined to provide input for design decisions.

Thus, data driven design, as it is defined by the authors, is the deployment of data, generated through data mining activities, during all design process stages of a product or a specific service as well as product service systems. In that context, the data can have different characteristics such as temporal physical machine and / or process data, contextual data, factual data, user feedback etc. but adds to generate a basic knowledge about the nature of the observed system.

7. Future Work:
Taking the next logical step with this research is to add more granular data capturing devices to the site equipment while at the same time finding the conversion factors for translating the scaled down data to full scale operational inputs. Additionally, converging this quantitative data with qualitative user feedback as a holistic way to drive design decisions.

8. References:
Paper III

Frank, M., Ruvald R., Johansson, C., Larsson T., & Larsson A.; (2019 accepted, unpublished)

Towards Autonomous Construction Equipment - Supporting On-Site Collaboration Between Automatons and Humans.

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Towards Autonomous Construction Equipment - Supporting On-Site Collaboration Between Automatons and Humans

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Abstract: To support the application of automated machines and collaborative robots in unstructured environments like in the mining, agriculture and construction sector the needs of the human co-worker should be investigated to ensure a safe and productive collaboration. The empirical study presented includes the prototyping of a solution for human-machine communication, which has been supported by a design thinking approach. An understanding of the human needs had been created through jobsite observations and semi-structured interviews with human workforces working in close proximity to heavy mobile equipment. The results shows that trust and communication have a big impact on the jobsite collaboration.

Keywords: Human-Robot Collaboration, Autonomous Machines, Construction Sites, User Experience, Design Thinking, Human-Robot Trust, Human-Robot Teamwork
1 Introduction

To increase the productivity in the construction and mining sector, the application of automated and autonomous machines are considered to enable these productivity gains. Depending on the size of operation, different approaches can be observed in the mining and extraction sector, ranging from automated hauling systems (Caterpillar Inc, 2018; Komatsu Ltd., 2018) to fully electric, fully autonomous transport solutions (Sjöberg et al., 2017; Volvo Construction Equipment AB, 2016). As Hyder et al. (2018) highlighted, mining sites provide an excellent launchpad for autonomous vehicles. Compared to public roads, the roads on a mining site are similarly structured and certain traffic rules are in place to maximize control of the site. Unlike the public area, the mining and extraction sites can be designated to automated and autonomous vehicles only and the infrastructure can be created to facilitate the application of these systems.

De Visser et al., (2018) defined automated systems as systems carrying out a limited set of pre-programmed supervised tasks on behalf of a human user, while autonomy is a technology (hardware and/or software) that carries out a user’s goal, but that does not require supervision. Nevertheless, a certain amount of interaction and collaboration with human-operated vehicles or humans will remain, even for highly automated or fully autonomous systems.

The application of automated and autonomous machines on construction and mining sites could lead to higher productivity and increased safety of the site operation. Manufacturers claim an increase in productivity of 25 percent in automated hauling operations compared to human-operated hauling equipment (Caterpillar Inc, 2018). These increases are mainly due to optimization and a higher machine utilization. In addition to the mentioned gains in productivity, the skilled labor shortage, especially in the mining sector, can be addressed with the application of highly automated and autonomous machines (McNab et al., 2013).

On typical construction sites, automated machines could be utilized to take over repetitive and hazardous task from the human workforce. Nevertheless, the human will not be taken out of the construction or mining site; his/her responsibility will instead shift from physical labor towards controlling, observing and collaborating with the machine fleet. (Boudreau-Trudel et al., 2014; Bradshaw et al., 2013; Lynas and Horberry, 2011; McKinsey Global Institute, 2017)

Besides the physical interaction between the teammates also the non-physical interaction, in this case the communication, defines the efficiency of the collaboration to a large extent. The level of required interaction is defined by the intermediate or ultimate goal of the team. Discovering, describing and utilizing the available communication channels of hybrid construction and mining teams, combined teams of humans and autonomous machines, with respect to the ever-changing application environment will be further discussed in this paper.

The aim of the presented research is the exploration of the needed support and facilitation methods for an efficient application of automated and autonomous machines at worksites with human co-workers. Recent applications (Caterpillar Inc, 2018; Komatsu Ltd., 2018; Rio Tinto, 2014) in mining and developments (Sjöberg et al., 2017; Volvo Construction Equipment AB, 2016) in the aggregate industry shows that humans will still play a key role on the automated site and therefore a system to link the human with the automated or autonomous teammate has some beneficial implications for productivity, quality and safety of work.
2 Methodology

Data is collected from 49 semi-structured interviews (Qu and Dumay, 2011) with different stakeholders at and around construction and mining sites in Switzerland, Belgium, Denmark and Sweden; focusing on automation, work site communication, team collaboration and safety around machinery. The interviewees had the freedom to discuss and have opinions related to team collaboration, on-site safety, safety around construction machines, as well as increased utilization of intelligent and automated systems in the construction, extraction, and mining sector to facilitate collaboration, safety, and productivity. In addition to the interviews, the interviewees were encouraged to share specific situations out of their professional work experience which were related to collaboration, communication and safety on site.

Furthermore, 17 site visits and process observations serve as secondary data, leading also to the adaptation of questions for the primary data collection. Especially the observations are crucial to compare the answers and comments of the interviewees with their behavior during normal operation on site. Being on site and talking to the interviewees in the work environment enabled the researchers to generate further insights and understanding of the overall circumstances of typical construction and mining sites. The interview questions can be viewed in Appendix at the end of the paper. The interviews have been transcribed and recorded to ensure traceability and have a higher reliability.

The collected data was shared with a bigger group of engineers and researchers to extract important insights while using the different professional and cultural backgrounds of the analysts. The analysis was performed in different locations including South Korea, USA, Germany, Sweden and Poland. The different teams had access to all collected and recorded data for further analysis. At each site, workshops were performed to ponder the questions: “How might we create a safe work environment around construction machines?”, and: “How can we facilitate on-site collaboration?” The workshop participants extracted findings and insights and subsequently clustered and prioritized the created categories. Four main categories were created addressing solutions being 1.) Site based 2.) Machine based 3.) Human worker based and 4.) Work process based. Running workshops globally gave the benefit of utilizing the different cultural backgrounds and thus the different ways to solve problems and analyze data by the respective participants.

3 Scientific Background

Collaboration on site level has many aspects that need to be considered for the development and testing of possible support and facilitation systems. The main research areas in this context are the human trust and its development, the trends in automation and the development of fully automated or even autonomous machines as well as the efficient collaboration between humans and machines/robots as a subarea of the human-robot interaction.

3.1 Human Trust

Effective and efficient collaboration between human beings requires good communication and trust among collaborators (San Martin-Rodriguez et al., 2005). San Martin-Rodriguez et al. analyzed the determinants of successful collaboration in a professional setting. Among others, trust is an important factor to form collaborative and
efficient teams, especially for interdisciplinary teams with different educational, cultural and organizational background.

According to Rempel et al., (1985), there are three distinct and coherent dimensions of trust that can be seen as main components of interpersonal trust; predictability, dependability, and faith. Especially the predictability of an individual’s action can be seen as the most important factor to build and maintain trust. Madhavan and Wiegmann, (2007) highlighted, that this component largely depends on the stability of the individual performance over a period of time. Dependability in Rempel et al., (1985) models refers to the internal dispositional characteristic of an individual. Faith is based on the individual’s beliefs of the future behavior and accuracy of the collaboration partner.

Mayer et al., (1995) define trust as “... willingness of a party to be vulnerable to the actions of another party based on the expectation that the other will perform a particular action important to the trustor, irrespective of the ability to monitor or control that other party. ” [Mayer et al., (1995), p. 712].

For the collaboration between humans, trust is an essential enabler for safe and efficient collaboration. This does not always require a deep personal relationship between the collaborators, it is more the shared moral system and generalized beliefs based on a large number of diverse experiences (Lee and See, 2004). This enables the efficient collaboration in daily situations, for example when pedestrians seek the driver’s eye contact when they are about to cross a road. A small moment of connection gives enough confirmation for the pedestrian to establish the trust that the driver will apply the brake and stop the vehicle. The reason why people have this confidence in humans they never met is based on the basic human level of morality to not harm others.

Analyzing collaboration in a professional environment, like a construction or mining site, trust plays an even bigger role due to the higher risk introduced by the dynamic and unstructured work environment, the machines and the work tasks. It can be stated, that eye contact and even further gestural confirmation is a common means to reduce risk around construction machines. It is common practice that workers need to get in contact with an operator of a construction machine before they enter the potentially hazardous areas near the equipment. This contact can be established by eye contact, gestural confirmation or by verbal means of radio communication. In this context, also company-wide rules and best practices are established as a basis for on-site communication.

3.2 Automation

Automation in manufacturing has long been a staple to increase productivity, quality and safety. With the introduction of industry 4.0, and thus the increased utilization of cyber-physical systems, a further increase in productivity, quality and safety is recorded (Schuh et al., 2014). For instance, by installing robots in production lines higher efficiency, fewer errors and reduced risks of personal injury can be achieved, thus even backshoring manufacturing to higher-wage countries, which were previously off-shored for cost-saving purposes (Dachs et al., 2017; Kolberg and Zühlke, 2015). The transportation sector, in recent years, has aggressively pursued autonomy for the same benefits. If a car or truck is driven autonomously there are potential gains to be had in road safety, environmental impacts and productivity (Kunze et al., 2011; Tsugawa et al., 2011). So far the construction industry, as a whole, has been reluctant to cultivate an autonomy-friendly landscape to reap the potential gains from its full implementation. Sources of this reluctance can be traced to unique characteristics of construction sites operating in a constant state of flux requiring highly adaptive decision making and collaboration between both machines and humans (Ameen and Safawizadeh, 2017).
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Automation is structured by the degree of control shared between operator and machine from not autonomous at all to fully autonomous by the Society of Automotive Engineers (SAE) (SAE International, 2016).

Within level 0 automation, the driver has full control over all vehicle functions. He / she is assisted by functions like park distance control or blind spot observation which trigger appropriate information but do not control the motion of the vehicle.

Level 1 automation, often described as “hands-on”, describes that the driver shares control with automated systems. Commonly available systems are adaptive cruise control (driver in control of steering, system in control of speed, acceleration and deceleration) and parking assistant (driver in control of speed, acceleration and deceleration while the system is in control of the steering).

The level 2 automation, also known as “hands off”, describes systems which are in control of acceleration, deceleration and the steering of the vehicle. The driver has to monitor the driven at all time and needs to be prepared to take back control immediately. For example, Tesla’s Autopilot function can be considered as Level 2 automation.

Audi’s 2018 A8 models are offered with a traffic jam pilot which should take care of all aspects of the dynamic driving task in slow traffic condition (up to 60 km/h / 37mph). Such a function falls under the Level 3 automation (Schrepfer et al., 2018) (“eyes off”) since the driver are allowed to focus on other tasks like texting, reading or watching a movie but still needs to be prepared to take back control from the system within a certain time.

Level 4 automation expands the level 3 in such a way, that the driver does not need to be prepared to take back control. The driver can engage in other tasks even like sleeping while the system controls all functions of the vehicle. Only in special circumstances does the driver need to support the system such as in traffic jams or limited space situations.

With Level 5 automation, no driver involvement or support is needed. This is typically the vision of the autonomous taxi where the role from the driver is shifted towards the customer of the system.

Currently operating construction vehicles regularly integrate features up to level 2 (Frank, 2015) in the form of automated drivetrains and loading functions. Rare test sites run level 3 and 4 equipped material haulers for long range driving in remote large-scale construction (Caterpillar Inc, 2018; Komatsu Ltd., 2018; Lecklider, 2017; Rio Tinto, 2014).

As level 3- and 4-equipped machines progress in capability it will become inevitable for them to be deployed in close proximity to human workers. In the transitional time from semi-autonomous functional machines to fully independent construction sites, humans will perform active roles in the process. The foresight conducted by Winqvist, (2016) and team identified two major drivers for the perpetual inclusion of humans. One reason is while many tasks are ripe for automation, not all tasks are cost-effective to automate at this point, the sweeper and the trash collector for example. The second constitutes a lack of trust in automation to complete complex jobs safely and to the customer’s satisfaction because autonomous machines can be as inherently flawed as their human designers. Translated, this requires humans to remain on site through the transition as managers, (quality and maintenance) engineers, surveyors, and niche operators.

3.3 Human-Robot Collaboration

During the conversion of manual operations into increasingly automated environments, the roles of humans and machines evolve into collaborative partnerships
resembling fellow co-workers rather than human and tool (Wajcman, 2017). Examples from the third and fourth industrial revolution include the automated production line workers and their automated welding and assembly robots or astronauts in the International Space Station benefiting from automation of complex onboard tasks (Schwab, 2015). This new type of relationship requires new avenues for communication. Numerous researchers are currently investigating the psychology behind human-machine interactions (Dragan et al., 2013; Fong et al., 2006; Hoc et al., 2009; Shah and Breazeal, 2010), and much of the work addresses the challenge by comparing how humans and machines interact in comparison to how humans interact with each other. Bickmore and Cassell, (2001) summarize a symbiotic path forward for Human-Robot Collaboration: “By building off of human-human interactions, autonomous systems in industrial areas like manufacturing plants or space applications are evolving to the point where they can be relied on as teammates instead of replacements. With this approach to integrating autonomy, humans have been shown to be more receptive to robotic instructions when there is some dialogue taking place between human and machine.” [Bickmore and Cassell, (2001), p. 2].

Both references, Bickmore and Cassell, (2001) and Robinette et al., (2013), support the notion that in order for robots to function as teammates, similar to human-to-human relationships, shared trust is a key factor in overall productivity. In this field, the word trust can be replaced with the reliability of intention to action. Given that, it is both this and the purely human experience of trust as it pertains to the emotional response elicited between human co-workers.

3.4 Trust in automation

There is a constant flow of new technology research concerning robotics and automation (Hanowski et al., 1994; Keller and Rice, 2009; Walker et al., 2016). Clear attention is being paid to the factors and impacts of trust in today’s automated/robotic collaborative partnership landscape. For example, in automobiles, designers include complex networks of autonomous features to simplify the driving experience. However, users frequently trust these features without understanding the ideologies or mechanisms behind them (Walker et al., 2016). Here, drivers are putting their lives in the hands of technology that is unidentifiable to them, yet they trust it to keep them safe. Horswill and Coster, (2002) attribute much of this is due to driver’s extreme sensitivity to observation of system performance in terms of capability and reliability. Plainly, if the driving experience is consistent with the degree to which a driver is accustomed, they gain confidence in the outcome of the interaction.

In Hancock, Billings and Schaefer’s trust model (Hancock et al., 2011), the underlying factor for building trust in a mechanized co-worker, is the number of repeatedly successful interaction outcomes over time.

Some factors for deep trust development lie on the human side as well, but from the machines it is derived from the inclusion of multiple human desired factors including desire of constant feedback, feeling in control, reliability, durability, capability and understanding of both components and intentions (Hancock et al., 2011; Horswill and Coster, 2002; Muir and Moray, 1996; Schaefer et al., 2014; Walker et al., 2016). Hancock et al., (2011) identified some guidelines to incorporate the possibility to develop human-robot trust in the design of robotic systems. Therefore transparency can support the development of trust while enabling the human to monitor and observer the robotic teammate to increase the understanding about the system. In addition to that, knowledge of the robotic co-worker can facilitate the development of trust as well. Here
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4 Results

To facilitate the collaboration of the future automated construction site, basic knowledge has to be gathered about the collaboration of workers on traditional, human-labored sites. Since the topic of the research is the development of a collaboration support system for automated or autonomous sites, the collaboration between the workforce of the human-labored site needs to be reviewed to create basic insights for the following development steps.

4.1 On-site challenges and opportunities

Moving on to asking the construction workers about the potential application of automated and autonomous systems in the construction sector, it is interesting to gauge both their awareness about the new technologies coming in and also about their potential in their every-day working context. On the question of whether construction workers think autonomous machines will be seen on construction sites in the future, one of them answered: “Definitely not, they have never worked. What would they do if there was a water leak? or when something unexpected happens? How do you design something like that? Much of our work is solving tasks that look completely different (every time) and we have to adapt our work to the situation.”

The answer above illustrates a limited understanding of the capabilities of automated and autonomous machines. The benefits of automation need to be communicated and demonstrated towards the workforce on site. On the other hand, it also shows that typical construction work is highly dynamic and unstructured and can be affected by many unforeseeable issues where human intervention might be needed to take action or decide the next step. The workers’ comments also show the necessity to design systems from a site-wide perspective that are able to adapt to changing situations and, more importantly, to facilitate collaboration in all work situations.

In contrast to the statement above, some workers and operators see a potential of automation of repetitive tasks: “...the dozers for grading roads often run back and forth. It should be possible to make it more accurate with GPS and navigation. Because the only thing they do is to drive back and forth and change the position and angle of the blade and drive back and forth again.” Many tasks on the construction site are routinized and with little complexity and few unknowns. In this case, the workers are aware of the capability of the machine and also of the repetitive and tedious character of the task that needs to be carried out, where the task parameters are well within the operational envelope of the machine. This is mainly based on the long experience the individuals have with the human-operated machines and the traditional way of working with that type of equipment.

It can be stated, that the common perception on construction and mining sites today is, that existing machine types will be automated to increase efficiency in the short- and mid-term future. However, full automation is still far away, so there will be a division of labor between the machine and the human. It is difficult for workers and operators to imagine a new machine design that is executing tasks autonomously and acting more as a collaboration partner than a tool or traditional machine. Especially the mentioned machine type of a dozer does usually operate on its own and typically far away from
other workers. Little to no cooperation is needed today. This also implies that it is a non-trivial task for the interviewees to imagine the possible collaboration and communication with a potential automated co-worker working in close proximity to humans.

Therefore, it is important to investigate and challenge the traditional way of collaborating and communicating in order to create a better understanding of the needs hybrid teams will have in the future. Getting a bit deeper into the necessary communication that needs to happen in traditional construction and mining sites, these answers generate some useful insights; on the question of how the operators see and communicate with people in their path, one operator says: "Often it's enough with a simple nod or thumbs up when we work with each other. For more complex conversations, I turn off the machine and talk to my colleagues or use the radio."

This is a typical answer when workers and operators had been asked about communication on site. It can be stated that there are several levels of communication during normal operation, which range from non-verbal cues such as, eye contact via gestural confirmation (nodding, thumbs up, waving etc) towards verbal communication to convey a more complex issue.

However, it is not always easy to maintain a full vision and awareness around the machine: "To see people in my surroundings I look around, it's extra hard to see people behind the boom (the arm that is on the right side of the cabin), where my field of view is limited. I have seen that the newer machines have cameras all around. Sure, I like this, but at the same time it puts more pressure on me. More technology and displays simultaneously convey responsibility to me (as an operator), and I lose my efficiency if I have to sit and watch the screens all the time. With all the technology, I believe, groundworkers believe I see them all the time."

The answer can be verified by comments from the ground workers. "... the operator checks where we are in the monitor..." and "... he sees us through the sensors". It shows that the people around the machine have developed a certain level of trust in the supporting technology like camera monitor systems as well as ultrasonic and radar-based object detection. At the same time, the answers also underline that the main responsibility for a safe operation is transferred to the machine and the operator. This issue of overtrust must be addressed by a supporting system and an adequate education of the workforce. The comment shows the importance to actively share the capability of the co-worker no matter if collaboration with humans or autonomous machines.

Asked about the collaboration as a team, a group of two ground workers and one excavator operator elaborated on the importance of: "... we would like to work together with the same guys all the time. After a while, we know what to do without talking to each other." It can be stated, that the close collaboration over a long time increases the trust among the workers and thus affects the efficiency of the team. The same interviewees also stated that: "... they have huge trust in the operator of the machine." Their company had invested in a sophisticated camera-monitoring system to increase the safety around the machine, which leads to the comment "... the operator sees us with the sensors.". It is interesting that the application of an assistant system for a machine operator increases the trust of co-workers in the operator. Both, the knowledge that the workers "are seen" and the trust in the decision taking human operator, as a result of successful interactions over time, enable the efficient collaboration.

Table 1 summarizes the main findings of the interviews, site visits and observations as requirements for a system proposal. The domain describes the party on site having the highest need for the listed requirement.
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Table 1 Requirements for support system, based on empirical study.

<table>
<thead>
<tr>
<th>No.</th>
<th>Domain</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Machine</td>
<td>indicate status towards humans</td>
</tr>
<tr>
<td>2</td>
<td>Machine</td>
<td>indicate intention towards humans</td>
</tr>
<tr>
<td>3</td>
<td>Machine</td>
<td>confirmation / communication</td>
</tr>
<tr>
<td>4</td>
<td>Worker</td>
<td>get confirmation from the machine</td>
</tr>
<tr>
<td>5</td>
<td>Worker</td>
<td>focus on own task without distraction</td>
</tr>
<tr>
<td>6</td>
<td>Worker</td>
<td>retrieve information in real-time</td>
</tr>
<tr>
<td>7</td>
<td>Worker</td>
<td>access to detailed information on demand</td>
</tr>
<tr>
<td>8</td>
<td>Worker</td>
<td>possibility to interact/collaborate/ interface with the machine</td>
</tr>
<tr>
<td>9</td>
<td>Worker</td>
<td>maintain personal safety on site</td>
</tr>
<tr>
<td>10</td>
<td>Site</td>
<td>manage data flow</td>
</tr>
</tbody>
</table>

4.2 System proposal

With the application of operatorless construction vehicles, such as the HX01 / HX02 Hauler Concept Vehicles (ref. Figure 1) in the Electric Site Project, Volvo Construction Equipment together with the collaboration partner Skanska, who operates the quarry site, open a new area of development in terms of autonomous machine size, autonomous machine design and suggested use case application for autonomous systems. Typically, automation technologies had been used to automate rigid dump trucks and haulers in very confined and structured mining (Caterpillar Inc, 2018; Komatsu Ltd., 2018; Rio Tinto, 2014) where huge amounts of material need to be moved in order to extract the desired valuable materials like gold, raw earth metals and diamonds. In contrast to that, Volvo CE and Skanska apply the autonomous systems in the production of rocks, gravel and sand. (Sjöberg et al., 2017; Volvo Construction Equipment AB, 2016) With a capacity of 15 metric tonnes, the autonomous haulage system is comparably small (ref Figure 1) compared to the < 100 tonne automated rigid dump trucks used in open pit mines.
Since the process of loading the HX haulers is not fully automated, humans and autonomous machines will share the same operational space in the loading area of the quarry. Therefore, a system is required to facilitate a safe and efficient collaboration between humans and the HX machines. Based on the findings from the interviews, site visits, and observations, a prototype system has been developed to address the main components needed for efficient collaboration.

Very few studies cover areas concerning trust development and communication, as it relates to autonomous vehicles, in the construction domain. The foresighting conducted in this research discovered that roles for humans on future construction sites will increasingly involve collaboration with autonomous vehicles. Both Hancock et al., (2011) and Winqvist, (2016) purport that collaboration with new partners will require fundamental trust to be established in order to obtain the desired increases in productivity and safety.

Through a design thinking/lean start-up approach and iterative prototyping (Product Development Research Lab, 2018), a suite of components has been developed, working in unison to provide a communication platform supporting each of the factors involved. The system provides communication and information on different levels.

The three central components of the system (see Figure 2) are the machine-based indicator, the helmet-based indicator, and the wrist-mounted display, which are all described below.

4.2.1 Machine-based indicator system:

The machine-based indicator system provides basic information about the machine intention. As a fixed part of the autonomous machine, the machine’s indicated intention, using a specially designed light-system, can be swiftly gauged by bystanders at a glance. To realize the intuitive character of the indication system, three colors are used to express the most important objectives of the machine, see Table 2. As mentioned by Wright, (2009), colors can be used as a universal language that most humans can relate to.
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Figure 2 Communication platform for human-machine communication, including machine-based indicator, helmet-based indicator, and wrist-mounted display.

Table 2 Color status, mediated intention and expected interaction of the machine-based indicator system.

<table>
<thead>
<tr>
<th>Color</th>
<th>Status</th>
<th>Intention</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>normal operation</td>
<td>autonomous working</td>
<td>no interaction</td>
</tr>
<tr>
<td>Orange</td>
<td>normal operation; aware of human presence</td>
<td>receptive to collaboration; interacting; continue working</td>
<td>receptive for interaction; interacting with human</td>
</tr>
<tr>
<td>Red</td>
<td>warning, low safety distance</td>
<td>slow down all machine motions</td>
<td>human detected, avoid collision</td>
</tr>
</tbody>
</table>

4.2.2 Helmet-based indicator system:

A helmet-based indication system is used to enable the efficient and productive work of the human on the automated job site. The system provides machine status information to the human teammates who are not necessarily working on the same task. Lights integrated into the helmet provide the same information about the approaching machine as with the machine-based system described above. This enables the workers to focus on their tasks without taking away the attention to focus on the upcoming machine. In addition, the system also features a bone-conduction headset to enable the machine to send more detailed information and collaboration requests via audio to the human co-worker.
4.2.3 Wrist-mounted display:

For more detailed information about the machine fleet status and possible collaboration requests, a wrist-mounted display is utilized. It serves as an interface to the machine as well as to the site management system and provides real-time access to required information when needed by the human worker. Via this device the capabilities, as well as the limitations of the respective machine, can be displayed and are accessible by the human co-worker with little effort. The two-way communication allows to place collaboration requests (by the machine and by the human) and call or send away machines for e.g. material dispatch. The display also features a vibration alert possibility, serving as a fall-back solution to attract the workers’ attention if required. A second connection to a site management system provides even further information about the status of the whole site and potential new work task or changes in the schedule etc.

While each individual component is essential, it is determined that the greatest amount of value can be derived from the overall reliability of the system. The proposed components work independent from the site management system and thus support the collaboration between automated machines and humans at all time. Even if one component fails to work, all other components can, to some extent, provide the needed support and facilitation for the collaboration until the faulty component is replaced.

5 Discussion

It is stated, that there is a common misinterpretation of the term automation versus the terms autonomous or autonomy. According to de Visser et al., (2018) automated systems can be described as "designed to carry out a limited set of pre-programmed supervised tasks on behalf of the user" [de Visser et al., (2018), p. 1] whereas in contrast "autonomy is technology (either hardware or software) designed to carry out a user’s goals, but that does not require supervision" [de Visser et al., (2018), p. 1].

This fundamental differentiation can also be applied in the construction and mining sector, where machines are automated to carry out repetitive tasks or, on the other hand, designed from scratch to carry out tasks which are not carried out by machines today or tasks which emerge with the introduction of new materials, processes and requirements on construction sites.

The research shows, that collaboration support is needed to introduce the automated machines into an ever-changing, unstructured environment like a construction site where humans and automated machines will share the same work area. Unlike a pure tracking system or collision avoidance solution, the proposed system allows each party on a job site to carry out its own task without major disturbances from the co-workers. With the increased knowledge about each other’s task and the possibility to indicate the intention a machine does not need to stop when a human is detected, it just needs to adjust the speed and communicate the intention to pass by the human. Through this, the productivity of a site operation can be maintained while safeguarding the human without increased risk.

Another finding is also, that there is a need to re-educate the workforce on site to enable an efficient and productive collaboration with the autonomous teammates. Especially the capabilities and the intentions of the machines need to be clearly communicated towards the human bystanders.

It could be shown, that the collaboration on a current construction site depends to a high portion on the trust between the different party (on ground level and in the machine). It can be stated that this will be also valid for the automated teammates and thus, a system is needed to enable building and maintaining trust throughout the normal operation. The
presented system is a first step to provide a basic level of the needed communication to enable the building of trust into the new technologies. Further test needs to be done to show the applicability in the real world scenario with automated machines.

Lee and See, (2004) highlighted the issues with generalizing trust in people to trust in automation due to the lack of intentionality of the automated system. The presented prototype included, to some extent, features to show the intentionality of the machine towards the human.

6. Conclusions

The research at hand shows a need for a facilitation and support system to apply autonomous machine in an efficient way in existing job sites. Since the collaboration at a construction site depends, to a high extent, on the trust between the teammates a system needs to facilitate and enable the development of trust between humans and the automated system. Verbal and non-verbal communication, typically through gestures, is the state of the art communication means of today’s job sites. To enable safe operation, information between the collaborators has to flow immediately without taking away attention from the task to be solved. The presented system enables the collaboration between humans and autonomous construction machines by using different input channels of the human worker, i.e. vision, haptic and acoustics.

With the introduction of automated functions and machines, and soon fully autonomous construction vehicles, systems are required to safeguard the human workforce on the autonomous construction and mining site. To enable and even further increase productivity on a site level and to increase the quality of work, the application of automation technologies on mining and construction sites can benefit from systems and methods to support and facilitate on-site collaboration and human-machine trust.

7. Future Work

Further research on this topic will be performed Within a joint research project including academic partners as well as heavy equipment manufactures and customers respectively users of heavy mobile machinery. The intention is to gather further data while testing the proposed system in a real automated quarry to validate the performance and the support of collaboration. In addition to that, further research on the design of autonomous construction machines, also with respect to human-machine interaction, will be conducted by utilization of automated data gathering and connect the digital data artifacts to traditional need finding activities i.e. interviews, site visits and observations. By that, guidelines for the design of autonomous system can be created, including systems to support and facilitate efficient and effective human-machine / human-robot collaboration.

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M. Frank, R. Ruvald, C. Johansson Askling, T. Larsson and A. Larsson


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Appendix: Interview Questions

- Do you think autonomous machines will be seen on construction sites in the future?
- How do you look at the surroundings from the machine?
- How do you see people in your environment and how do you communicate with each other?
- How do you get in contact with the man in the machine?
- What are the most dangerous machines / situations on site, from your perspective?
- Does your company have specific rules for working with and around machines?
- Have you already used advanced assistant systems for construction site safety?
- If so, what is your impression?
ABSTRACT

Fully autonomous construction and mining machines are not science fiction anymore. For special applications, these types of machinery are well known for several years. The construction and mining industries are ripe for innovative product and service offers, including automated and fully autonomous machines at a larger scale. Nevertheless, commercially available autonomous machines for the main markets are still rare. Driven by the advancements in sensor technology, increased connectivity, and on-board computational capabilities, automation of machine functions and subsystems led to the development of advanced operator-assistant functions in certain fields like material handling, predictive maintenance, and operator guidance. Semi-automated machines, supporting the machine operator during normal operation, are well accepted by users and customers and show beneficial effects on the productivity of the machine and the overall work process. The purpose of this thesis is to generate a deeper understanding of the specific requirements needed to support the design decisions during the development of fully autonomous machines. Complementary, deeper insights into the efficient collaboration between autonomous machines and human collaborators are explored.

The thesis summarizes the research performed by the author, as an industrial Ph.D. student and Specialist for Intelligent Machines at Volvo Construction Equipment. Performed research comprises the investigation of the state-of-the-art approaches in the automation of machines and dedicated functions with special emphasis on the connectivity of the different systems and components up to the site management solution. Further, the work includes the exploration of data-mining through early experience prototyping as a step towards data-driven design of a product-service system. In addition, the research covered the support of on-site collaboration between autonomous machines and humans by investigating team behavior and trust development among humans.

Conclusions from this work are that autonomous machine design requires new sets of requirements to support early decision making during the development process. Dedicated data collection based upon different methods such as, data-mining, needfinding, and observations, supported by multiple physical and virtual artifacts can generate useful data to support the decision-making. Trust between humans and machines, and the preconditions of developing this trust need to be captured as specific requirements. To support further development in the area of autonomous machine design, an interaction model had been proposed to map possible interactions of an autonomous machine with objects and collaborators within the same work area. To capture the different nature of the possible interactions, several levels had been introduced to enable the distinction between cognitive, and physical, as well as intended, and unintended interactions.