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Safety and dependability implications of electrification in mobile machinery

Abstract: Electric and hybrid technologies are being developed in the non-road mobile machinery (NRMM) sector to improve efficiency of operations and to reduce emissions. NRMM are used in many different domains and applications. Thus, the business cases and technical solutions for electrification can be very different depending on the application area. In addition to their benefits, electric systems introduce also new types of safety and dependability related uncertainties and risks that need to be controlled. In this paper, we present findings of semi-structured interviews and a literature study focusing on electrification in the non-road mobile machinery sector. As a result, we provide an overview of the different electrification strategies and a structuring of safety and dependability implications of these strategies.

Keywords: mobile machinery, electrification, safety, dependability

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1 Introduction

For decades, internal combustion engines (ICE) have been the predominant means of powering non-road mobile machinery (NRMM). Currently, the quick advances in electrification (i.e., using electricity as the primary energy source) and related technologies bring many opportunities for the NRMM sector. Major driving forces are improvements in energy efficiency and reduction of greenhouse gas emissions. In addition, improvements in performance of the machines are expected. In heavy machinery, especially important factors are the high torque and tractive force enabled by an electric powertrain [1]. These are necessary in applications like carrying heavy loads and working in areas with uneven surfaces. Additionally, the increasing level of automation is a major driving force for electrification [2]. Some examples of currently available electric NRMM are depicted in Figure 1. However, electrification is a target in virtually all domains where NRMM are applied. NRMM are typically highly specialized and the approaches for electrification vary between the different applications. Depending on the electrification strategy, electrification introduces different types of uncertainties and risks related to both dependability and safety of NRMM systems.

Figure 1. Examples of NRMM electrification: Ponsse hybrid forwarder [3], Kalmar battery-electric forklift truck [4], and Sandvik cable-electric loader [5].

As with development of any new technology, the related challenges and risks need to be identified and assessed over the entire lifecycle of the system. In this paper, we focus on the electrification of the drivetrain, i.e., propulsion of the machine. In mobile machines, there are usually also actuators that are used for work tasks like load handling and manipulation. While the actuators were not in the focus of this study, it is noteworthy that also the actuators need to be considered when developing electrified machines. In many machine types, hydraulics is currently used to create the forces required for example in lifting of objects. Especially linear hydraulic systems are challenging to replace with completely electric actuators. This has led to development of various hybrid hydraulic-electric (HHEA) architectures (see e.g. [6]). Regardless of their implementation, the actuators may have effects on the overall dependability of the machine.

The effects of electrification have been studied especially in the automotive industry, but there is only limited research in the machinery sector. For NRMM, various scenarios and strategies for electrification have been proposed [7]. Even more limited research is available on the effects of different electrification strategies on machine safety and dependability performance. In this paper, we focus on the new safety and dependability implications (both opportunities and challenges) of the drivetrain electrification. As a result, we provide an overview of the different electrification strategies and examples of potential use cases for these approaches in the NRMM sector. Based on this, we provide a structuring of safety and dependability related opportunities and risks related to the main electrification approaches.

2 Methods

The research presented in this paper is based on a combination of a literature study on electrification in NRMM, literature-based learnings from safety and dependability implications of electrification in road vehicles, as well as interviews with companies in the NRMM sector.

Semi-structured interviews were performed with four companies involved in mobile machinery manufacturing and electrification of vehicle technologies. For each of the companies, the business cases and approaches for electrification are different as each of the companies operate in different roles (three original equipment manufacturers (OEM), one electrification technology supplier) and in application areas with very different characteristics. In all interviews, the company representatives were from R&D senior and management roles.

The interviews provided insights to the technological questions related to electrification in different contexts. In the interviews, the focus was mainly on the safety and dependability issues and not so much on the economic feasibility of the different electrification strategies. However, the basis for the selection of electrification strategies in companies are based on techno-economic considerations.

In addition to the interviews, a literature study was performed focusing mainly on NRMM drivetrain electrification and safety and dependability of electric road vehicles. The literature study findings were used to identify the different strategies for electrification, bottlenecks for dependability and safety, and to complement the company interviews.

3 Electrification strategies for mobile machines

Currently, a large majority of NRMM are powered by ICEs. Especially battery-electric machines are still rare, while cable electric machines are used in some environments where it is feasible to build the required infrastructure for such use. However, operators and equipment manufacturers are investing increasingly in development of electric battery electric and hybrid machines. In research literature, electrification of NRMM has been studied both from technical and economic viewpoints, focusing on the feasibility of different technical configurations.

According to Forsgren, et al. [8], the total cost of ownership of NRMM can be reduced by electrification if the application area is suitable (e.g., the usage patterns are predictable enough to plan operations), but some barriers also remain. Downtime from charging and unreliable power supply at remote worksites are mentioned as potential bottlenecks for wider electrification.

Ratzinger, et al. [9] have studied three different drivetrains (battery electric, parallel hybrid, and series hybrid) of wheel-driven construction machines from the perspective of reduction of CO_2 emissions. In each drivetrain configuration, the presence of a battery is of key importance as it allows recuperation of energy when decelerating. The study concludes that all the drivetrain types can reduce the emissions when compared to similar diesel-powered machines, with series hybrid being the most promising. Quan, et al. [10] present an overview of powertrain technologies for earth-moving machinery. The study focuses mostly on electrification of the actuators using power electronics or a hydraulic-electric hybrid powertrain.

Lewis, et al. [11] have studied feasibility of electrification in the context of large mobile cranes. In this study, energy storage systems were identified as the major technical bottleneck for electrifying such systems: power requirements lead to the need of very large batteries. In addition to battery electric and hybrid solutions, also hydrogen fuel cell based systems have been proposed as an alternative. Also in these cases, the energy storage becomes a challenge [12].

The previous research on electrification strategies suggests that the feasibility of the electrification and the applicable strategy for it are highly dependent on the intended application of the machine. In all the cases, however, the energy demands and reaching a sufficient energy storage capacity are key issues.

4 Safety and dependability implications of electrification

Automotive sector is a forerunner in electrification and since the recent rapid increase in the number of electric vehicles (EVs), more data is becoming available also related to possible safety and dependability issues. In principle, electric motor as a power source is simple and presumably very reliable when compared to ICE, but other technologies within EVs may cause issues. In consumer use, the reliability of electric vehicles is reported to be under the industry average [13], but the issues are not necessarily related to the drivetrain itself. Hybrid vehicles, on the other hand, perform well in such rankings. Thus, the reliability issues are seen to be mostly related to novelty of the EV technology and the new features incorporated in EVs [13]. In mobile machines, the reliability requirements for components are even higher as the machines are applied in demanding uses.

One key aspect relevant to electrification is the reliability of the batteries, as well as the capacity loss of the batteries over time. The driving cycles, the battery type and the rate of charging all influence the battery reliability [14]. On the other hand, applicable experiences gained from the automotive industry can be utilized when electrifying NRMM.

The use of large batteries creates new challenges also related to fire safety. Batteries are subject to impacts that can lead to heating, ignition, and fire development [15]. Especially Li-ion batteries are subject to the thermal runaway phenomenon, that further increases the risks related to fires and makes extinguishing the fires challenging. The fire safety and handling of battery fires need to be considered in the design of the entire work site.

Batteries are currently expensive and therefore it is profitable to plan the charging procedures to optimize the size of the batteries and the number of machines and charging stations. This has also an effect on complexity of the operations, which can furthermore affect risks. The charging related practices affect the Overall Equipment Efficiency (OEE) of the machines. Whereas EVs can be mostly charged when not in use, such as overnight, mobile machines are typically used with much more demanding duty cycles with limited opportunities for charging. Another approach would be battery swapping, so that the machines can be used without long charging breaks. The reliability of the charging infrastructure is an important aspect to be considered. The availability of the charging devices needs to be fitting for the reliability targets set for the NRMM system.

5 Results

Three main strategies for NRMM drivetrain electrification were identified: battery electric, cable electric and hybrid (with various implementations). Formulated based on the literature study and interview findings, Table 1 provides an overview of key safety and dependability related risks and opportunities of electric machines when compared to ICE powered machines. In the table, the example use cases represent only a small section of possible machine types as most of the machines can be electrified in many ways.

In Table 1, battery electric refers to machines in which all the machine functions are powered by on-board batteries. Cable electric means that there are no large batteries on board, and the electricity is provided using a retractable cable or fixed infrastructure. In some cases, the electric power is provided by wire only when the machine is performing certain tasks that require high power, but the machine can move with an electric or diesel powered tramming capability without the wire connection.

Hybrid in this case means that the propulsion is done by electric motors, but there is an ICE for loading the batteries that power the motors, or to directly take part in the propulsion. Hybrid can also be chargeable from grid (plug-in). As discussed in previous sections, there are various ways for the technical implementation of the hybrid system [4], but in terms of dependability and safety, the different variations seem to have similar impacts.

Table 1. NRMM electrification strategies covered in this study and related opportunities and risks when compared to ICE powered machinery.

Electrification strategy	Example use cases	Dependability		Safety	
		Opportunities	Uncertainties and risks	Opportunities	Uncertainties and risks
Battery electric	Port forklift trucks, Loaders, Automated guided vehicles (AGV), Straddle carriers.	Reduced number of components, Reduced vibration, Inspection and/or maintenance work is possible during charging.	Charging times may interfere with the operative goals, Electromagnetic compatibility (EMC) with other systems, Access to electricity and reliability of charging (or battery swapping) infrastructure, Reliability of the batteries in demanding use, Battery capacity loss over time.	No need for refueling infrastructure and no need to store fuels at worksite, No exhaust fumes, Reduced noise, Precision in operation (good traction control).	High fire load in batteries, Hazardous gases in case of fire, Difficulties in extinguishing battery fires (thermal runaway phenomenon), Electrical safety in maintenance work, Machines are inherently less noisy and more difficult for nearby workers to detect.
Cable electric	Mining machines (loaders, drill rigs).	Reduced number of components, Reduced vibration.	Damage to the cables is expensive and difficult to repair, Electromagnetic compatibility (EMC) with other systems, Reliable access to electricity. Automatic cable handling is challenging for autonomous operations.	See above, also: no high capacity batteries needed.	Occupational safety risks when operating with the cable on the ground, Cable may obstruct onboard safety sensors, Automatic cable handling is challenging for autonomous operations.
Hybrid	Forest machines, Straddle carriers.	ICE can be run at optimal RPM range. Possibility to use only the ICE if needed (parallel hybrid).	Higher number of components and increased complexity due to hybrid technology, Electromagnetic compatibility (EMC) with other systems. In case of plug-in hybrid, need infrastructure for both fueling and charging.	No high capacity batteries needed.	Electrical safety in maintenance work.

6 Conclusions

Electrification of NRMM is quickly advancing. With the wide range of application areas of the machines, the strategies towards electrification are equally varied. This leads also to a wide spectrum of new advanced opportunities for NRMMs but it also introduces new emerging dependability and safety risks. In battery electric and hybrid machines the issues are related to the need of large batteries, charging infrastructure, and increasing system complexity. In cable-electric machines, the risks are mainly related to operation without damaging the cable.

To support the successful development and commissioning of electric and hybrid technologies in NRMMs application area specific safety and reliability analyses are needed to fully understand the implications on safety and dependability in different applications. Such analyses need to be conducted at a system level, covering the entire lifecycle of the system, and also considering the surrounding infrastructure and processes. As a future work, safety and dependability analyses should be more deeply incorporated into the techno-economic considerations of NRMM electrification.

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Acknowledgement

This research has been conducted in the Future Electrified Mobile Machines (FEMMa) project funded by Business Finland and the participating companies.