Safety and Dependability of Autonomous Systems in Container Terminals: Challenges and Research Directions

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Abstract: Increasing use of autonomous machine systems is a major trend in port logistics, especially in container handling. Over the past decades, large seaports have automated parts of their operations. Currently, also smaller ports are looking to apply automated and autonomous solutions. This is expected to increase efficiency and safety, but also to introduce new mixed-traffic situations between humans, manual machines and machines of different levels of autonomy. This is likely to introduce safety risks and dependability challenges for system development and operation. In this paper, we discuss selected key challenges that need to be solved to ensure that autonomous container handling solutions can be implemented safely and profitably. We also present topical research directions that are planned and ongoing to solve these challenges.

1 INTRODUCTION

Container terminals consist of different functional areas and various container handling systems and equipment. In the design of terminals, one key aspect to consider is the potential for automation in the different operations using a variety of machinery types (Brinkmann, 2011). Over the past decades, especially large seaports have been investing in automation to increase efficiency of operations. To do so, they often aim to automate large parts of terminal operations at once, creating autonomous operating zones that are physically isolated from manual operations. Thus, the safety aspects can be controlled with relative ease, as all access to the operating zone of autonomous machines can be prevented.

In the future, also smaller terminals look for increases in efficiency and safety through use of automation and increasingly autonomous systems. In smaller terminals, however, it is not usually feasible to completely fence off the areas where autonomous machines would operate. This potentially creates a number of new scenarios where machinery of various levels of autonomy may work simultaneously in the same area with humans and different forms of transportation. This kind of mixed-traffic operation introduces many opportunities for increasing the efficiency of operations, but it also brings along a number of risks that need to be considered in development. In this paper, we discuss selected key challenges in developing autonomous port machinery, and describe topical activities in research towards solving these challenges.

1.1 Autonomous Systems for Port Operations

Currently, there is no single agreed definition for autonomy in the logistics or mobile machinery sectors, but typically the term is defined based on the system’s ability to achieve goals and operate independently. Key characteristics for an autonomous system are the ability to perceive surroundings using sensors, plan actions according to the situational awareness created by the sensor data, decide further actions and act accordingly (Pendleton et al., 2017).

In many industries, categorizations have been created to define different levels of autonomy. The most widely known of such categorizations are the ones described in automotive industry for road vehicles, such as the driving automation levels defined by SAE (2018). Based on the SAE levels for

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driving automation, a categorization has also been proposed for container terminal automation as described in Table 1 (Hämäläinen et al., 2018).

Table 1: Automation levels proposed for machinery in container terminals (adopted and modified from Hämäläinen et al., 2018).

Level	Description
Level 0: Manual operation with process automation	Human driver controls machinery, but other terminal processes are improved using automation, e.g. container identification and tracking.
Level 1: Remote control	Operator controls all machinery moves from a control centre. One operator can control several machines.
Level 2: Supervised automatic moves	Machines can perform some defined moves automatically under the continuous supervision of a human operator.
Level 3: Semi-automated operation	Most moves are automatic and require less supervision, only truck lane operations and exception handling are done by remote control.
Level 4: Fully automated operation	All operations are automated and the human operator is only needed for exception handling.

In container handling, different concepts for implementing automation systems of various levels have been proposed and developed (PEMA, 2016). These range from partial automation to fully automated terminals. Electrification of machinery also plays a major part in these developments. A typical implementation of a current automated container terminal is presented in Figure 1. The system consists of machinery for loading and unloading the ship, horizontal transport of the containers to the actual container yard where the containers are rearranged as needed. Additionally, there are facilities for transferring the containers to and from land transport, which may include both rail and road transport.

In the future, increasingly autonomous machines may be used flexibly to allow different layouts and combinations of machines to achieve optimal performance. For example, new machine types may emerge that are able to conduct tasks in various parts of the terminal. In most cases, it is likely that a human remote operator will remain in a supervisory role even when the level of autonomy increases (Tähtinen, 2018). In addition to the container handling operations within the terminal, the interfaces to ship, road and rail traffic also need to be considered in these developments (Fiedler et al., 2019).

There are several benefits that are expected from the use of autonomous machinery in small and mid-sized terminals. For instance, it may enable continuous operations whereas currently small terminals may only work in specific shifts.

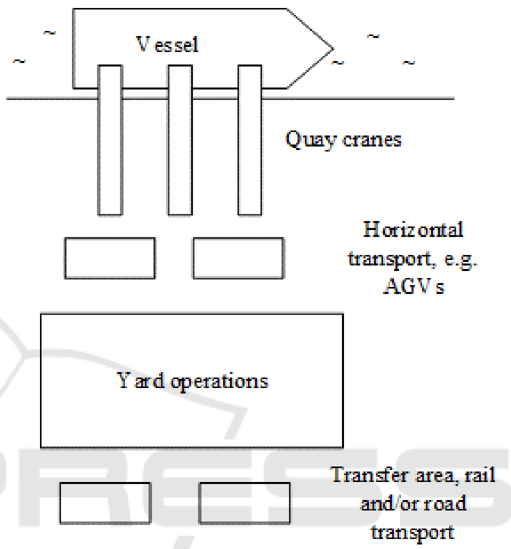

Figure 1: A simplified schematic of functions in a typical automated container terminal. In small terminals, the functions could be implemented differently, e.g. the amount of different machine types utilized may be drastically smaller.

Machine system developers aiming for autonomous systems face a number of challenges related to capabilities of designing and implementing safe autonomous functionality (Vuorimaa, 2019). In this paper, we introduce selected key safety and dependability challenges machinery developers face when aiming for increased level of autonomy especially in mixed-traffic operations for container handling. Specifically, we focus on the following challenges identified by the authors in the ongoing AUTOPORT (2020) project:

- Lack of safety standardization for autonomous machinery in container terminals (section 2.1).
- Identification and assessment of new autonomy related uncertainties and safety risks (section 2.2).

- Challenges in availability of enabling technology, focusing especially on available safety certified sensor technology for outdoor use (section 2.2.1).
- Safety and dependability challenges caused by the increasing software intensity of machinery (section 2.2.2).

We also review some of the research directions and solution proposals that are currently being investigated within research & development activities in the field of port logistics to pave the way towards increasingly autonomous systems.

2 CHALLENGES OF AUTONOMOUS SYSTEMS IN CONTAINER TERMINALS

Autonomous systems introduce several new challenges that need to be considered in different phases of product development (Tiusanen, et al., 2019a). In the following, we focus mainly on the challenges related to the early concept design phases of autonomous container handling machinery.

2.1 Safety Standards for Autonomous Mobile Machinery

Lack of domain-specific standardization is a major issue in development of autonomous machinery for container handling. This can be seen to increase the responsibility of the machine manufacturers, as manufacturers need to be able find a suitable framework of standards and methods to assure the safety of new technologies.

Heath, T. (2018) has stated that the two main aspects in the overall safety of machine autonomy are: the lack of applicable standards, legislation and guidelines regarding the autonomy of machines and vehicles; and the paradox that arises from balancing the desired level of autonomy with the needed level of safety. This means that complex and advanced autonomous machines are already technically achievable, but they lack a common and thorough method for ensuring an adequate level of safety.

One approach to compensate for the lack of domain-specific standardization is to follow relevant standards from other fields with similar characteristics – mostly mobile machinery in other types of outdoor environments. The available standards, however, are not concise in their approaches. Instead, different safety strategies are preferred in different domains (Tiusanen et al. 2019b).

As an example of a standard specifically aimed for autonomous systems, ISO 17757 is directed at autonomous machine system safety in earth-moving machinery. The basic principle presented in this standard is that the autonomous area is restricted from manual vehicles, but access control may allow persons or manual machines to enter automated area in special occasions. The special occasions are defined and include e.g. tagged vehicles.

For driverless trucks there is also a standard and a standard proposal, which describe autonomous systems aimed for indoors use. In this case, the autonomous system can be open (free access), but the system is well defined and, in the open case, speed limit is sufficiently low to enable stopping the machine before collision.

For container handling, the challenge is that the need is often somewhere between the closed and open system. In port environment there are many actors and the areas can be large, and therefore it is difficult to have completely closed system. On the other hand the open system requires good on-board sensors to detect objects before collision.

2.2 Identification of New Autonomy Related Uncertainties and Safety Risks

Autonomous machinery systems are emerging and they are essential for enabling new automated material handling and autonomous transportation in sea ports and other terminals. Autonomous technologies will be a huge step towards safer and more efficient terminal operations, but the software solutions and advanced control systems in various system levels also involve complexities that pose challenges to identification and control of new functional failures, safety issues, and security concerns (Ramos et al. 2019).

Autonomous container handling system represent one specific domain of autonomous and cooperating systems and they can also be thought of as Systems of Systems (SoS) in nature (Čaušević (2017). Autonomous container handling system can be connected to public or semi-public communication networks in the port area, they typically involve multiple stakeholders, have dynamic system reconfigurations, and they are operated in an unpredictable operating environment

Čaušević (2017) also expressed that a common challenge concerning all autonomous systems refers to safety, reliability and security goals. Reliable autonomous system executes an action each time perfectly right but, in conjunction with unexpected external circumstances, such a reliable action can lead to an accident.

According to Baudin et al. (2007) hazards related to the operation of autonomous machinery can be separated into endogenous and exogenous hazards. Endogenous hazards are caused by faults introduced in the machine itself, such as design failures or component failures. Exogenous hazards are operational hazards including faults due to external interference, operators' unsafe actions or unforeseen events in the operating environment.

One of the complexities that, in general, characterize autonomous systems is the strong interaction among its different components. The component here mean equipment, software, computer hardware and the human operator or supervisor, when applicable. Software malfunctioning, and cyber threats are different types of risks compared with risks caused by hardware failures and human errors. Past failures do not indicate future behaviour which means that calculation of the expected likelihood or frequency is not feasible. (Ramos et al. 2019)

In general, it can be said that autonomous machinery can introduce hazardous situations not normally encountered on conventional manned worksites (ISO 17757:2017).

According to Ramos et al. (2019) the complex human-technology interaction is one of the main challenges for safety risk assessment of autonomous systems. Most current quantitative assessment methods used in conventional risk and safety assessments rely on the separation principle. System components are assumed to be independent of each other and are often analyzed separately. Ramos et al. (2019) emphasize that the interaction among components and emerging complexity is often neglected or reduced to a minimum. This makes it possible to use proven methods; however, complex systems may be abstracted and not sufficiently represented.

Risk identification and assessment in unique autonomous container handling applications should be understood as a top-down process wherein upper work site level assessment results represent input and requirements for the next level, ensuring that the system-safety requirements and risk-reduction solutions are based on the actual site specific factors involved. The risk estimation methods and risk-evaluation practices need to be appropriate for the specific needs of risk assessment activities at the various levels of systems engineering and in the individual phases in the system life cycle. (Tiusanen, 2014)

Some qualitative systemic methods like STPA (System Theoretic Process Analysis) (Leveson, 2012) or FRAM (Functional Resonance Analysis Method) (Hollnagel, 2012) include the different system elements and system interactions, and assess also the emerging properties of the system elements. According to Ramos et al. (2019) these methods, while providing useful qualitative analysis, are still very limited in unravelling complex failure modes and mechanisms in addition to being qualitative and of limited value in prioritizing risks and risk reducing measures.

2.3 Technology Development Challenges

2.3.1 Challenges in Sensor Technology Availability

Sensors are developing continuously, but for safety purposes there seems to be limits. During 2019, the first two safety sensors capable of operating in outdoor environment, came to the European market. One of these is a laser scanner (SICK outdoorScan3) and the other is a radar (Inxpect LBK System). The laser scanner is accurate, but it is still sensitive to dust, moisture and rain. The radar, on the other hand, is not so sensitive to the environmental conditions, but the detection angle is not so accurate.

In heavy rain, snow or fog the sensors are not applicable, but on the other hand, the port operations would be difficult or dangerous also for manual operators in such conditions. The safe detection range for the sensors is currently about 4 m, but it may increase in the next few years up to 7 m. The indoors safety sensors have often a detection range of 9 m. The laser scanners for outdoors use differ from indoors laser scanners in the capability to emit a lot of beams. The idea is that, by having a lot of beams, some beams could navigate between raindrops and detect a distant object. The outdoors sensors need to differentiate objects and raindrops and, in general, bad weather or operating conditions.

In addition to challenges with detection range, there are specific cases that are difficult for on-board sensors. Sensors cannot see behind corners or objects. Also objects beside a container or objects with dimensions at high (e.g. reach stacker) or low heights can be very difficult to detect. Thus, there are challenges to detect objects in the port environment in all conditions.

Instead of on-board sensors, it is also possible to apply a central tracking system, which knows the positions of all moving objects within a specified area. This requires tagging of objects and the uncertainty of position correctness needs to be handled with a safety system. This kind of approach seems promising from safety point of view, but it lacks some properties related to freedom.

2.3.2 Challenges of Increasing Software Intensity

Autonomous systems differ from traditional machinery systems especially in terms of the amount of software used. Sophisticated software is needed to interpret the vast amounts of sensor data collected and to make decisions based on the situational awareness created. Additional software elements are also required e.g. for communications and functions related to remote monitoring and operation.

As software complexity increases, the amount of software errors typically increases as well. In complex software, errors are always present, which requires that sufficient error handling measures are in place. A majority of software errors can be traced back to the requirements specification phase. (Malm et al., 2011)

To develop high-quality software, concept design phase and systematic requirements management during it play a central role. Focus should be placed on identification of the critical areas of the software as early as possible to prevent costly fixes later in the product development process. It should also be noted that cybersecurity shall be considered as an integral part of the development process when designing autonomous machine systems (Pentikäinen, et al., 2019).

For software, the assessment of safety, reliability and security aspects is more difficult to establish. Reliability of software is approximated by such measures as the remaining amount of errors in the software, which does not clarify how the software may fail. In the context of large automation systems the interaction of different software modules and components, from different suppliers, is challenging. (Ramos et al. 2019)

As a relatively new type of software element, autonomous systems usually employ various machine learning based artificial intelligence (AI) elements, for example in recognizing objects from sensor data, as well as in various condition monitoring and optimization tasks. From the dependability point of view, such systems may be highly effective: they can improve predictability of machine performance and can be used to optimize operational parameters and maintenance tasks. On the other hand, these technologies are fairly new and lack a background of demonstrated use in industrial environments. Thus, the importance of data quality and procedures for design and verification of AI systems becomes increasingly important also from the safety and dependability point of view. Additionally, the systems may lack the transparency that is needed to assure that the system operates correctly in all plausible operational scenarios. (Heikkilä & Välisalo, 2018)

Increasing software intensity can be seen as a broad systems engineering issue. In the context of port equipment, safety is one of the main issues to be considered. From the perspective of safety analyses, the increasing software intensity calls for means to describe the system in a way that support in managing the complexity. In all cases, thorough hazard identification needs to take place. As a new approach in hazard identification, systems-theoretic methods have been proposed to facilitate hazard analysis of complex systems. Their use in the context of port automation, however, is largely unexplored.

3 CONCLUSIONS AND RESEARCH DIRECTIONS FOR AUTONOMOUS CONTAINER HANDLING SYSTEMS

Autonomous port logistics face several challenges. Currently, single technical solutions for autonomous machine fleet safety systems in port environment seem to be challenging. Apparently, several means are need to implement a safe autonomous system. In all cases, a thorough risk assessment is needed, where the specific conditions of the automated fleet solution are taken into consideration.

In the AUTOPORT project, research is conducted to solve some of the challenges that have been identified and were described in this paper. Based on the initial findings, key research directions that support the development of safe and reliable autonomous port logistics can be identified:

- Development of reliability, availability, maintainability and safety (RAMS) related design procedures so that the effects of autonomy can be addressed. This includes specification of data models for a database-centric approach to support RAMS management.
- There is clearly a need for a joint functional safety, reliability and security approaches for risk assessment. A holistic approach is

required for the assessment of safety, reliability and security risks of autonomous logistic systems. Special focus should be put on considering the interactions between subsystem and their potential outcomes and implications. Knowledge on Cyber Physical Systems (CPS) and Systems of Systems (SoS) theories is important in handling the system complexity.

- Application of systems-theoretic approaches to support safety assessments of new autonomous technologies. This will support especially the identification of software-based safety issues and issues in challenging mixed traffic situations.
- Application of relevant standards from other domains to account for the lack of domain-specific standardization for port machinery.

The challenges presented in this paper cover only a part of the larger number of socio-technical and economic challenges that need to be solved to enable increasing automation in small and mid-size terminals. In addition to the mostly technical safety and dependability aspects presented in this paper, the entire business case and various operational and asset management strategies need to be considered to form a comprehensive understanding of the effects of autonomy. Solving these challenges could lead to major advances in container logistics, increasing efficiency and safety within the terminal, but also helping in optimization of the entire logistics chain.

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