TAMPEREEN
AMMATTIKORKEAKOULU

SAFETY REQUIREMENTS OF REMOTE OPERATING STATION FOR CONTAINER HANDLING EQUIPMENT

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TÄHTINEN OSKARI:
Kontinkäsittelylaitteiden etäohjaimen turvallisuusvaatimusten määrittely

Opinnäytetyö 63 sivua, joista liitteitä 2 sivua
Maaliskuu 2018

Kontinkäsittely satamaterminaaleissa muuttuu jatkuvasti automaattisemmaksi. Automatiikka ei kuitenkaan ainakaan nykyisellään kykene huolehtimaan jokaisesta konttikentän operaatiosta. Ihmisen suorittamaa ohjausta vaaditaan esimerkiksi, kun sensoridata ei ole riittävää tai toiminnan turvallisuutta ei pystytä takaamaan täysin automatiikan hoitamana. Tämän kaltainen poikkeustilannekäsittely tehdään yleensä kauko-ohjauksena tätä tarkoitusta varten valmistettua ohjainlaitetta käyttäen. Kauko-ohjaaja ohjaa videokuvan perusteella nosturia laitteen ohjaimia käyttäen.

Tämän opinnäytetyön tarkoituksena oli analysoida ja määrittää kauko-ohjaimelle asetettavat turvallisuusvaatimukset. Tavoitteena oli täydellisen riskianalyysin tekeminen näihin vaatimuksiin perustuen. Turvallisuusvaatimusten määrittely edellytti laajaa tutkimustyötä koneturvallisuuden standardeista ja aihetta käsittelevistä tutkimuksista. Tällä hetkellä erityisesti satamanostureiden etäohjausta käsittelevää turvallisuusstandardia ei ole olemassa. Turvallisuustyö vaatikin runsaasti erilaisten tulkintojen tekemistä ja eri lähteistä hankitun tiedon yhdistämistä.

Työn merkittävin löydös oli ihmisen vaikutus etäoperoinnin turvallisuuteen. Monet nykyisen etäohjainlaitteen turvaominaisuuksista perustuvat käyttäjän tekemiin havaintoihin, vaikka operointiympäristö ei itsessään tue käyttäjän tarkkaavaisuutta millään tavalla. Ongelman todettiin olevan suurin, kun etäoperointia tekee henkilö, joka on aiemmin ajanut manuaalista satamanosturia. Muutos nosturin hytistä toimistoympäristöön johtaa helposti kyllästymiseen ja tarkkaavaisuuden laskemiseen.

Etäohjainlaitetta koskevat riskianalyysit tehtiin perustuen tutkimustyön aikana tunnistettuihin turvallisuusvaatimuksiin. Analyysien yhteydessä määritettiin riskinhallintamenetelmät, joiden tavoitteena on ennaltaehkäistä käyttäjän kyllästymisestä sekä tahattomista ohjainliikkeistä johtuvia vaaroja. Tutkimustyön aikana tehtyjä löydöksiä pystytään käyttämään hyödyksi myös tulevaisuudessa, kun etäoperoinnin turvallisuutta pyritään parantamaan.

Asiasanat: kontinkäsittelylaite, etäohjaus, koneturvallisuus, standardi, riskianalyysi

ABSTRACT

Tampereen ammattikorkeakoulu
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TÄHTINEN, OSKARI:
Safety Requirements of Remote Operating Station for Container Handling Equipment

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The level of automation in container terminals is constantly growing. The automation cannot handle reliably every single phase of the container handling, at least for now. Human intervention is needed if the sensor data fails or if the situation cannot be automatically performed at a required safety level. This type of exception handling is usually done remotely using a designated remote control desk. The remote operator uses the controllers on the desk and executes the task at hand with the aid of live video feed from the terminal.

The purpose of this thesis was to analyze the safety requirements for a remote control desk. The objective of the thesis was to produce a complete risk analysis for the design of the desk. Determining the relevant safety requirements required extensive research on the machine safety standards and studies on remote operation. Currently there are no specific standards for remote control of container handling equipment. This meant that the safety work required a great deal of interpretation and combining relevant aspects of different kinds of studies and researches.

The most important finding in this study was the effect that human factors have on the safety of remote operation. Many of the safety features in the current design of the remote control desk rely on the observations made by the operator yet the remote operation desk does not promote the operator’s alertness in any way. The issue is greatest when the remote operator is a person who has previously worked in the cabin of a manual crane and is transferred to the office environment. This can result in boredom and lack of concentration.

A preliminary hazard analysis and an operational hazard analysis were made on basis of the safety requirements recognized during the research on standards and studies. The analyses provided risk reduction methods to prevent risks arising from an operator’s lack of concentration and unintentional operating commands. The findings of the survey can also be utilized and further developed in the future projects around the concept of remote operation.

Key words: container handling equipment, remote control, machine safety, standard, hazard analysis

SISÄLLYS

ABBREVIATIONS AND TERMS

CHE	Container handling equipment
OHA	Operational Hazard Analysis
PHA	Preliminary Hazard Analysis
RC	Remote Control
ROS	Remote operating station
Stacking area	Container stack and area around it at terminals
STS	Ship-to-shore
UX	User experience design
Quayside	Quay and area around it at terminals

1 INTRODUCTION

Remote operation station is a device used for remotely operating container handling equipment. It is mainly used for exception handling, which means that the remote operator can take control of the automated crane when the onboard automation system fails to complete the task in hand. Kalmar's current remote control station was developed back in 2006. Since then the desk has been updated several times and this thesis was part of one major renewal.

As a part of the development of the console, risk analysis was done. The new desk was intended to support safe operation and operator well-being. Currently there are no specific safety and health requirements for remote operation stations of container handling equipment. This thesis is part of the work done to recognize the valid safety requirements of the console design and is done for Kalmar's Safety and Risk Management.

As an outcome of this project, clear requirements for the console design are provided. The specification of the requirements is done by a broad research on the machine safety standards and studies regarding machine and remote operation. The findings from the standards and studies are documented for future use and the ongoing design work for the console is going to meet these requirements. The findings are further utilized whilst making a preliminary hazard analysis and operational hazard analysis for the console.

This thesis is structured as follows: chapter 2 introduces Cargotec and its operations. Chapter 3.1 provides a sweeping description of the machinery the ROS is used with, creating a baseline for the risk assessment. Chapter 3.2 consists of theoretical basic information of remote operation and in particular remote operation of CHE. Chapter 4 presents the main part of this thesis: it provides a detailed overview of the recognized safety requirements and design objectives, which have an effect on the safety of the operation. Chapter 5 introduces briefly the risk analysis for the ROS. The analysis are company confidential so the description is very high level. Thesis concludes with discussion of the results of the project and the future possibilities.

2 COMPANY

Cargotec is a global company based in Helsinki Finland. It is a leading provider of cargo handling equipment and solutions with a mindset on becoming the global leader in intelligent cargo handling. Cargotec consists of three separate business areas; Kalmar, Hiab and MacGregor all focusing on different specific areas of cargo handling. It had 11 184 employees in 45 countries at the end of year 2016. The headquarters of the company is based in Finland but the company also has production facilities in several other countries. Cargotec's production facilities can be found in, for example, Malaysia, Poland, Germany and Sweden. Majority of the production has been outsourced to business partners operating in Asia. (Cargotec 2018a.)

As a company Cargotec was born in year 2005 when Finnish company called Kone oyj was split into two separate independent companies Cargotec and KONE. However, the history of Cargotec is much longer since Kalmar, which is nowadays part of Cargotec, saw the light of the day for almost hundred years ago. Since 2005 Cargotec has undergone several major changes cultivating Cargotec to the company it is now. (Cargotec 2018b.)

In 2007 Cargotec completed several takeovers on the smaller companies in the industry thus increasing the total amount of employees of Cargotec by over a thousand people. In 2010 a new Cargotec factory was opened in Poland. By the time of opening the factory was one of the most important production facilities for Cargotec in Europe since its location perfectly served the constantly growing markets in Europe. The factory also presents state of the art technology when it comes to factory automation and energy efficiency. 2011 became one of the most distinct years in Cargotec's history as Cargotec bought Navis from Zebra Technologies Corporation. Navis was back then and still is the leading provider of Terminal Operating Systems in the world. With the takeover of Navis Cargotec really took a step forward into coming a software lead company and a provider of intelligent cargo handling solutions. In May 2013 Cargotec opened a Technology and Competence Centre in Tampere Finland. The Centre serves as a home for research and development of intelligent terminal equipment and automation. The building itself, being illustrated in picture 1, is one of the most energy efficient office buildings in Finland. In the most recent years Cargotec has continued on its path towards becoming the leading provider of terminal automation. The year 2016 saw two significant milestones for Car-

gotec. It bought a company called Interschalt Maritime Systems AG, which provides maritime software and solutions. Cargotec also founded Cargotec IoT Cloud as a platform for products utilizing the digitalization. (Cargotec 2018b.)

PICTURE 1. Cargotec Technology and Competence Centre in Tampere is one of the most energy efficient office buildings in Finland. (Cargotec 2018b)

In the first three quarters of 2017 Cargotec's total sales were a bit over 3 300 million euros. Geographically Cargotec's sales are divided quite evenly as illustrated in the figure 1. Majority of the sales was done in EMEA area being shortly followed by the AMER area and APAC area. (Cargotec 2018c)

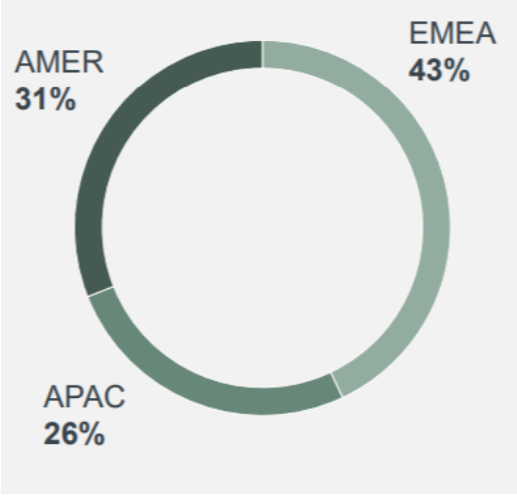


FIGURE 1. Geographical split of Cargotec's sales between Q4/16-Q3/17. (Cargotec 2018c)

Kalmar is offering equipment and solutions for cargo handling in ports. In the first three quarters of 2017 Kalmar's net sales were a bit over 1 600 million euros making about 50 percent of the total sales of Cargotec. Kalmar's sales is divided into equipment and services and Kalmar software and automation. The equipment and services makes about 1 200 million euros of Kalmar's sales rest being covered by the sales of automation and software. Kalmar's main global competitors are such companies as Konecranes, Terex and Liebherr. (Cargotec 2018c.)

Hiab on the other hand focuses on providing cargo handling solutions for inland transportation. In the first three quarters of 2017 Hiab's net sales were a bit over 1 000 million euros making about 32 percent of the total sales of Cargotec. Hiab's sales have gone up about 13 percent in the last twelve months making it the highlight of Cargotec's year 2017. Hiab's only main global competitor is a company called Palfinger. (Cargotec 2018c.)

MacGregor's products are used at seas thus completing the full range of equipment provided by Cargotec. The sales made by MacGregor make up the smallest portion of total sales of Cargotec being just over 600 million euros. MacGregor's main competitor globally is Rolls-Royce. (Cargotec 2018c.)

3 BASIS FOR RESEARCH

3.1 CHE in the scope

Kalmar is providing support for all kinds of container handling equipment. The level of automation in the container terminals is still very limited and just a few terminals have developed totally automated processes. However the level of automation in the terminals is constantly increasing and Kalmar is developing solutions to answer this demand of equipment ranging from semi-automated to totally automated. (Kalmar. 2018a.)

Kalmar's current mindset is that all automated and semi-automated machinery should be operable with a remote control device. The remote control desk being designed is going to be able to control five different kinds of control handling equipment; Automated Straddle Carrier, Automated Shuttle Carrier, ASC, AutoRMG and AutoRTG. (Kalmar. 2018a.)

Before starting the safety work on the renewal of the ROS it was necessary to familiarize with the CHE in the scope of the project. All machines are used for different kinds of operation in the terminal area and this way the use cases for the remote operation station consist of a variety of situations. It would also be practically impossible to determine the hazards arising from the ROS without knowing the operation of each machine. For example, determining the possible risk level is completely different if the machine is operating inside a fully automated area where no humans should be present versus the machinery operating with humans always in the vicinity of the machine.

3.1.1 Automated Shuttle Carrier

Shuttle carriers are used to transport the containers from the quayside to the stack to be handled by a machinery operating at the stacking area. Typically, an STS crane unloads the containers from the vessel. The STS can load the containers directly to the ground or on top of a trailer of truck or terminal tractor. The most efficient way is to unload the container to the ground thus enabling the STS crane to unload the vessel at a maximum speed without having to wait the CHE to come and receive the container. Shuttle carriers, illustrated in picture 2, can pick and land the containers directly on the ground so other cranes will not have to wait. (Kalmar 2018b.)

Kalmar shuttle carriers are known to be very flexible and agile machines as their lifting capacity reaches 50 tons and they can handle containers ranging from 20 ft to 50 ft. Shuttle carriers can also handle two 20ft containers simultaneously when fitted with a twin-lift spreader. Kalmar's shuttle carrier's each wheel can be steered individually enabling it to turn round its own vertical axis. In addition, the carriers are featured with an active stability control which monitors the movements of the machine slowing it down in hazardous situations helping the operator to drive the machine safely. Kalmar provides its customers with three possible drive units for shuttle carriers to choose from. (Kalmar 2018b.)

PICTURE 2. Kalmar shuttle carriers have a lifting capacity up to 50 tons. (SAE International 2008.)

Kalmar Shuttle Carrier has a diesel-electric drive and it has been engineered to meet the latest exhaust emission regulations. The fuel efficiency and noise levels have also been minimized to provide terminal operators with a cost-efficient solution for quayside container movement. (Kalmar 2018b.)

Kalmar Hybrid Shuttle Carrier combines traditional combust engine and energy harvesting. The energy generated when braking and lowering the carried load is captured and stored in lithium-ion batteries. Compared to the traditional shuttle carrier the hybrid uses up to 40% less fuel and the carbon dioxide emissions are reduced by up to 50 tons per annum. (Kalmar 2018b.)

Kalmar FastCharge Shuttle Carrier is electrically driven and has a rechargeable battery system which can be charged at the terminal between operational moves. The FastCharge shuttle carriers operate in combination with a FastCharge charging station which is illustrated in picture 3. The stations are placed on site thus enabling the shuttle carriers being charged in the middle of normal operation. The machines are typically charged between 30 to 180 seconds at a power of 600 kilowatts. (Kalmar 2018b.)

PICTURE 3. Kalmar FastCharge charging station enables the shuttle carrier to operate continuously. (Kalmar 2017a.)

Regardless of the type of the power unit all Kalmar's shuttle carriers can be automated. Automatic shuttle carriers can operate independently and complete a variety of terminal operation tasks.

3.1.2 Automated Straddle Carrier

Straddle Carriers are very similar to the shuttle carriers when it comes to technical details or the intended use of the machinery. Kalmar's straddle carriers are also delivered with three possible selections for the drive unit of the machinery; **FastCharge**, **Hybrid** and

Diesel-electric. Compared to the shuttle carriers the straddle carriers are even more versatile and can complete every task regarding the operations on the stack field. The straddle carries can stack containers up to four containers high and have a lifting capacity up to 60 tons enabling them to also move the containers on stacking area. Straddle carriers are also used for delivering containers from the stack to the trucks. As seen on picture 4 the straddle carriers are technically almost identical to shuttle carriers but significantly higher. (Kalmar 2018c.)

PICTURE 4. Straddle carriers are much higher than shuttle carriers. (Konecranes 2018.)

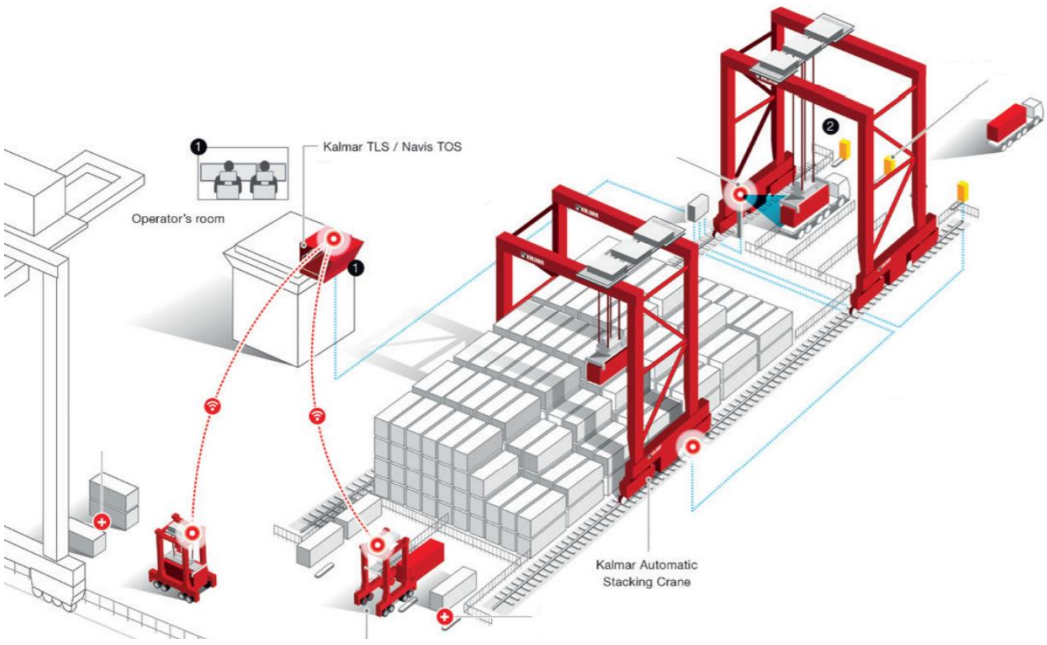
Straddle carriers can also be fully or partly automated according to the requirements set by the terminal operator. Also the already existing manually controlled machines can be transformed to be even fully automatic. (Kalmar 2018c) The automation of straddle carrier operations is becoming more and more popular.

3.1.3 ASC

ASC stands for Automated Stacking Crane and it is a fully automated crane used for stacking area operations. The ASCs are seen as a complete system rather than individual machines. The ASC system consists of variety of different levels of automation solutions and software. The system is managed by Kalmar TLS which is a control system handling the operation of the ASCs. TLS controls routing and planning in the stacking area and executes the automated operations. (Kalmar 2015.)

TLS combines the automated machines of the fleet with the terminal operating system. The TLS receives desired container movements from the terminal operating system and manages the operations of each machine based on their status and location. TLS can monitor the status of the whole fleet as well as status of each individual machine. This enables the TLS to plan the movements of machinery as well as containers in the most efficient way. (Kalmar 2017e.)

With automatic stacking cranes the whole procedure of getting the container from the vessel to the truck can be automated. Typically, automated shuttle carriers collect the containers from the STS crane unloading them from the vessel. The shuttle carriers then deliver the containers to the stacking area in which the automated stacking crane moves them to the desired location. The ASC can also operate the truck lane automatically based on the orders received from the terminal operating system. The system is illustrated in picture 6. The automated truck handling is based on laser measurement illustrated in a conceptual picture 7. The system measures the locations of a truck trailers twistlocks and this information is fed to the crane. With the known location of the twistlocks the ASC can pick or ground the container automatically. In normal operation there is no need for human intervention. Operators control the crane only during exception handling situations. (Kalmar 2014.)



PICTURE 6. Automated stacking crane system. (Kalmar 2015.) edited.

PICTURE 7. Laser measurement enables automated truck handling. (Kalmar 2014.)

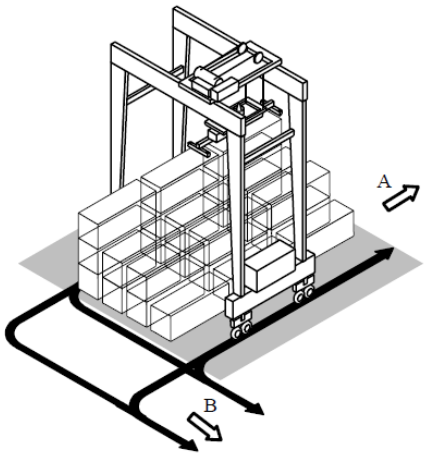
The ASC crane itself moves on rails and has three degrees of freedom. The movement on the rails is called gantry movement and can be understood as a movement towards water-side and away from the waterside. “Sideways” movement is called trolley movement. Trolley is mounted with the lifting equipment of the crane. The up and down movement is called hoist movement.

3.1.4 AutoRTG

Kalmar’s RTG or Rubber Tyred Gantry is a machine used for similar kinds of operation as the ASC so the basic operation for RTG crane is to manage the incoming and outgoing containers at the container stack. RTG cranes are typically operated by an onboard driver and run on diesel engines although electrically driven ones are also available. The width of the RTG is typically between five and eight containers and the height is typically between three and five containers. (Conductix Wampfler 2018.)

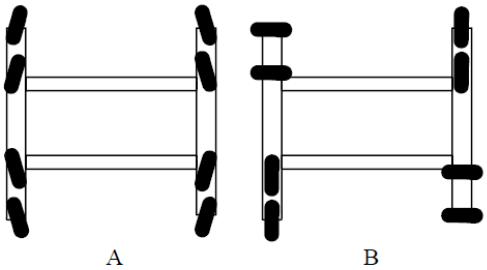
RTG crane uses air inflated tyres for the gantry movements and the direction of the gantry movement can be changed by turning the wheels which is one core feature separating it from the rail mounted cranes such as ASC or RMG. The crane has four separate drive

modes which affect the position of the wheels in relation to the structure or frame of the crane. The four drive modes are called traverse drive, longitudinal drive, carousel drive and parking position. Longitudinal drive and traverse drive are illustrated in picture 8, the A being traverse and B being longitudinal drive. (Kalmar 2017f, 29-30.)



PICTURE 8. Drive modes of the RTG crane. (Kalmar 2017f, 30.)

The crane can be steered in longitudinal and traverse drive modes. Steering is controlled by alternating the speed of the drive motors of the wheels instead of turning the wheels. (Kalmar 2017f, 30.) In the carousel mode the wheels are turned to a position which enables the turning movement of the crane and in the parking mode the crane is locked in position by turning the wheels in a position which makes moving impossible (Kalmar 2017f, 73.). The position of the wheels in parking mode and in carousel mode can be seen in picture 9 in which the A stands for carousel mode and B for the parking position.



PICTURE 9. Position of RTG cranes wheels in carousel and parking modes. (Kalmar 2017f, 74.)

The operational difference between RTG cranes and ASCs is that on the RTG operation the truck lane is located below the crane in between the container stacks but in the ASC operation the truck lane is located at the end of each container stack as seen in picture 7. The location of the truck lane in RTG operation is illustrated in picture 10.

PICTURE 10. Location of the truck lane in RTG operation. (Kalmar 2016.)

Existing manually controlled RTG can be automated or the RTG can be built automatic from the beginning. The automated RTG operation can be built with certain level of automation. Regardless of the level of the automation the operation is controlled by the Kalmar TLS system. There are five possible levels of automation. (Kalmar 2017g.)

Remote control means that the operator controls the crane remotely with a remote operation station. The operator is provided with live camera views from the RTG fleet and the operator utilizes them and the controllers provided in the remote control desk to operate the crane. The remote operation station is usually located at a separate yard control center. (Kalmar 2017g.)

At the **Supervised automatic moves** –level the remote operator supervises automated operation in the stacking area consisting of all hoist, gantry and trolley movements but executes the truck lane operations remotely using the remote control desk and the provided camera views. (Kalmar 2017g.)

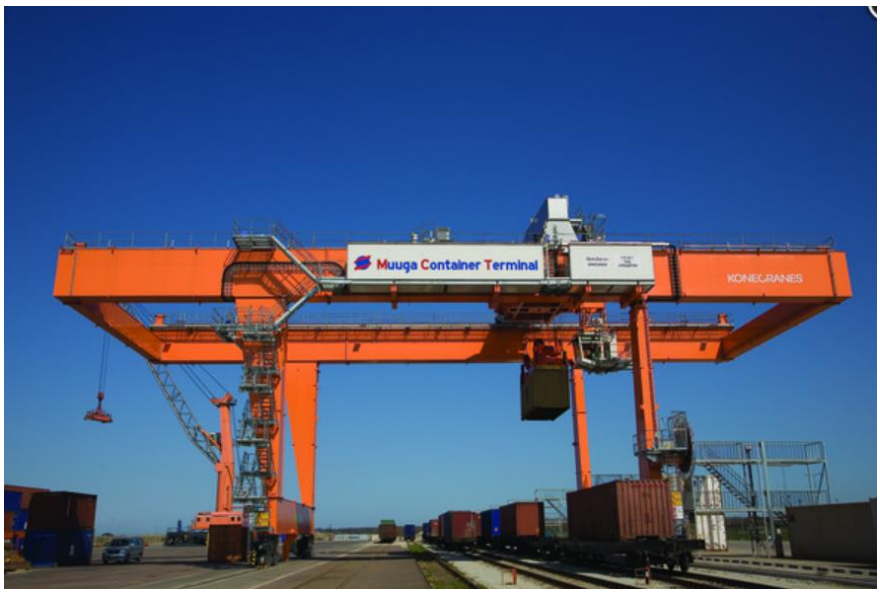
Automatic pick and place on stack means that the hoist and trolley movements are fully automated in the stacking area but the gantry movements are supervised by the operator. The operator still has to control the truck lane operations. (Kalmar 2017g.)

The next level of automation is called **automatic gantry.** At this level all the movements done on the stacking area are fully automated and the operator has to do only the truck lane operations using the remote control desk. (Kalmar 2017g.)

Fully automated level combines automated stacking area operations with automated truck lane operations. There is still need for remote operator when the automated system fails to execute the operation for some reason e.g. insufficient location data. This type of operator interaction is called exception handling. (Kalmar 2017g.)

3.1.5 AutoRMG

RMG crane or Rail Mounted Gantry crane is a very similar machine as the RTG crane. The biggest difference is that on RMG the gantry movement is done on rails instead of tyres. The operation done on the RMG crane is almost identical to the operation of RTG crane. The most differentiating feature of the Kalmar RMGs is the cantilevers illustrated in picture 11. The RMG can be delivered with either one or two cantilevers depending on the terminal layout. The cantilevers make the use of space more efficient since the truck lane is moved out from the area between the cranes “legs” thus making it possible to fill that area with containers. (Kalmar 2017h.)



PICTURE 11. Rail mounted gantry crane with cantilevers. (Konecranes 2018b.)

3.2 Teleoperation

3.2.1 General

In addition to getting familiar with the machinery, it was also important to study the basics of teleoperation before starting the safety work on the remote operation station. The safety work would be done based on research of standards and studies on machine safety. Most of those would consider the machine as cabin controlled and adapting those to remote control would require detailed knowledge of remote operation and its characteristics. Not only the technical execution of control is different, but also the environment and the relevance of the operator are completely different. Both of these play a major role in the safety of the operation. (Aalto University.)

Remotely controlling machinery is probably most utilized in the field of robotics but in the most recent years it has come more and more popular in the heavy machinery also. The word *teleoperation* is defined as controlling a system over a distance. This distance can be anything from few millimeters up to millions of kilometers. There are a few different ways of how the controlling of the machinery can be done over a distance. (Aalto University.)

In **remote operation** the operator has a straight visual contact to the operated machine. The operating commands can be transferred to the machine electrically by wire or wirelessly. One example of this kind of teleoperation can be seen on picture 12. The operator is using a pendant controller to control the movements of a demolition robot based on the visual feedback he is getting. (Aalto University.)

PICTURE 12. The operator is operating the demolition robot remotely. (Konepörssi. 2014.)

Normal or standard teleoperation means that the operator controls the machine from a distance without a direct visual. The operator is executing the operating commands based on the visual feedback provided to him via camera. For example, terminal cranes are operated this way. (Aalto University.)

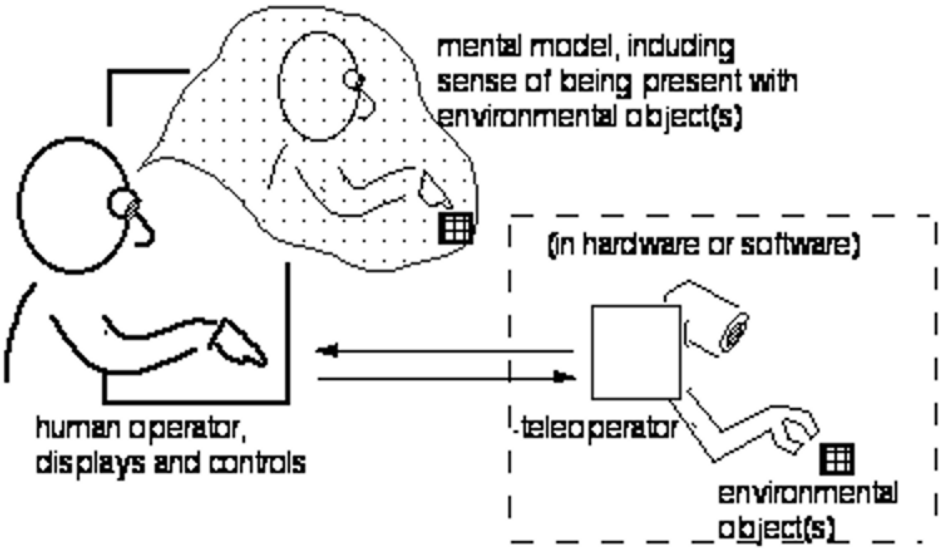
Teleoperation does not necessarily mean that the operating commands are constantly fed to the machine but it can also be supervisory control. In supervisory control, the onboard automation of the machine executes most of the operating commands and human interaction is needed only in situations where the automation cannot handle the task in hand. (Aalto University.)

3.2.2 Telepresence

Situational awareness is usually compromised when teleoperating thus generating problems regarding the safety of the operation. This can be quickly demonstrated with a little

mind game; let's think about a rock that is thrown towards a person's head. The moment the person sees this object on a collision course to his forehead he/she blinks or moves his head. If this person is controlling a terminal crane via remote operation controller relying on the visuals provided through cameras and monitors when he sees an oncoming collision, does he take the appropriate action to evade this collision by reflex? (Sheridan 1992, 4.)

Thomas B. Sheridan, professor of mechanical engineering and Applied Psychology Emeritus at the Massachusetts Institute of Technology, defines telepresence as "sense of being physically present with virtual object(s) at the remote teleoperator site". He also defines virtual presence as "sense of being physically present with visual, auditory or force displays generated by a computer". These terms and their relation is illustrated in picture 13. (Sheridan 1992, 1.)

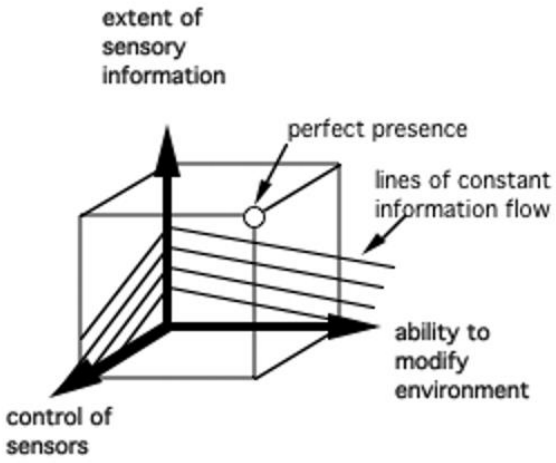


PICTURE 13. The operator creates a mental model of him/herself being present in the actual environment of the machine he/she is controlling. The virtual presence on the other hand means that the operator feels he/she is present at the environment created by the computer software. (Sheridan 1992, 2.)

According to Sheridan, the interfaces supporting the telepresence allegedly have an improving effect on the sensorimotor and cognitive performance of the operator. Defining the presence or telepresence is problematic thus making it difficult to improve them by the design of the interface. Sheridan proposes that the feeling of presence is mostly affected by three independent variables: extent of sensory information, control of relation

of sensors to environment and the ability to modify physical environment. The **extent of sensory information** can be seen as range of bits of information provided to the operator related to the task in hand**. Control of relation of sensors to environment** means that the operator has a chance of modifying his viewpoint.The **ability to modify physical environment** can be seen as a possibility of actually modifying the objects in his view or their relation to others. (Sheridan 1992, 2-4.)

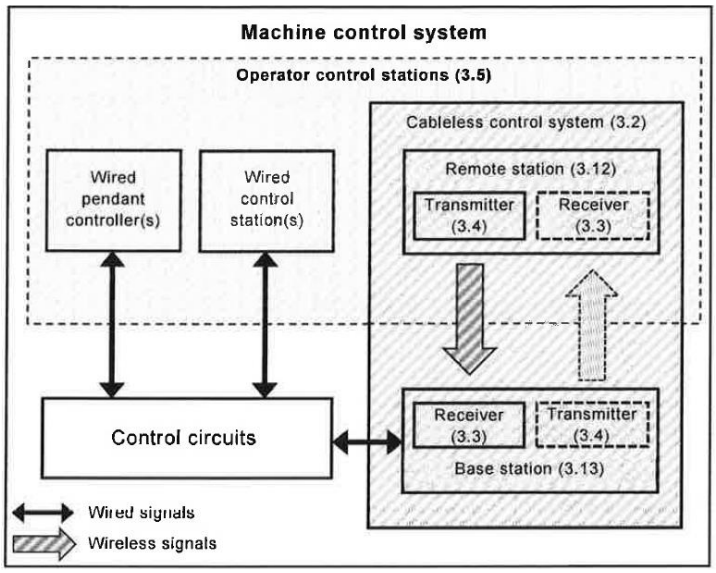
Sheridan illustrates these three variables as three orthogonal vectors as seen in picture 14. The greatest feeling of presence would be the combination of the maximum of all these. It should be noted that this is a very simplified illustration and the actual feeling of presence is not a simple sum of these three independent variables. (Sheridan 1992, 2-4.) More on how the safety work on Kalmar's renewed remote control station took into consideration the enhanced feeling of presence on chapter 4.2.



PICTURE 14. Three variables of presence (Sheridan 1992, 5)

3.2.3 Wireless control

Wireless control is becoming more and more popular method of remotely controlling machinery. Cableless or wireless control can be simply defined as transmitting the operator's commands to the machine without wired connection. Cableless control system in the other hand is a system, which has at least one remote station, one base station and a wireless transfer of data between them. Functional parts of the cableless control system are illustrated on the block diagram at picture 15. The block diagram also illustrates how the cableless control system interacts with the machine's control system. (IEC 2017, 6-9.)



PICTURE 15. Functional parts of cableless control system (IEC 2017, 12).

The operator is interfering with the control system via remote station. The transmitter is sending the information to the receiver at a base station. The term base station generally refers to a part of a cableless control system, which communicates with the machine control system. For example, the data transferred via cableless control system can be operating commands or error codes. (IEC 2017, 9-11.) Standards define several specific safety requirements regarding the cableless control of machinery. More on how these requirements were utilized in the safety work of the remote operation station on chapter 3.3.4.

3.2.4 Remote operation of terminal equipment

Remote operation is constantly taking more and more space in the container terminals. The increased level of automation has decreased the need of human intervention as most of the cranes operations is controlled by automation. The main tasks left for the operator are supervising the movements of the crane and so called exception handling. Exception handling means situations where the task in hand can't be done automatically. Reason for this can vary a lot. At some situations automation system cannot reach an adequate level of safety and human supervision or control is required. The need for exception handling can also arise from a failure in the automation system. For example, a thick layer of snow on top of a container can cause the automation system to fail to recognize the profile of the container thus giving the task to human operator. (ABB. 2018a)

The remote operators supervise and control the crane based on the video views provided to the remote control station. The design and video views of Kalmar's current remote control desk can be seen in picture 16. It should be noted that in this picture the views on the screens are created by a computer-based simulator, not an actual camera on the site. The benefits of remote operation can be clearly identified. The viewing-areas of the operator are significantly improved because the on-board cameras can be situated into places out of sight of the operator in the cabin. In addition, the operator is provided with sensor information of the height and speed of the machine. A variety of different kinds of equipment can be operated from the same desk making the operation more flexible. Safety of the operation is also increased when the operator is moved away from the machinery. (ABB. 2018a)

PICTURE 16. Kalmar's design of the remote control desk. (Kalmar. 2015b.)

One of the core benefits of remote operation is moving the operator from the cabin to the operating room. According to ABB, a manufacturer of ROS, bringing the whole team of terminal professionals together results in enhanced collaboration and team spirit. This is known to promote well-being at work. With remote operation the costs of transporting the operators to the machinery as well as costs of their working clothes and gear can be reduced. (Henriksson.)

The control rooms are typically situated within the terminal premises even though the idea of a one global operating room is not new. The most limiting factor of the location of control room is the safety classified communication. The terminal crane has a ton of

safety rated functionality, such as the emergency stop function. According to Fredrik Johansson, marketing and sales manager at ABB Crane Systems, the communication between cranes and remote operation stations is done on terminal operators own communication network. This way all the components in the network and their performance and quality is known. The speed of the network and the time in which the operator's commands reach the cranes control systems can be defined accurately. Transmitting the video streams from the cranes on-board cameras in real time requires a huge amount of network capacity. These elements make it reasonable to keep the operation within a relatively close distance to the terminal operations. (Johansson 2015.)

4 REMOTE OPERATION STATION SAFETY REQUIREMENTS

4.1 General

Determination of the safety requirements for the remote operation station was carried out based on broad research over the machinery standards and studies. At the very beginning of the project, user experience was recognized as one of the most highlighted aspects of the renewal. The affect that user experience has on safety of operation was not that obvious at the beginning of the project but it constantly popped up during the research work. One significant research illustrated the fact that user experience might actually be one of the most important ways of improving the safety of remote operation. The case study on remotely controlling CHE, made by Hannu Karvonen, Hanna Koskinen and Helena Tokkonen, highlighted the UX issues related to the user experience of remote control stations. This study raised an interest towards user experience and the possibilities of increasing alertness of the operator and thus improving the safety of operation significantly. Unfortunately, very little information was found on the effects that human performance has on the safety of machinery operation.

Discovering Robert B. Sheridan's theories of telepresence steered the research work more towards articles and studies on psychology. It became evident that enhanced sense of presence results in enhanced sensorimotor performance of the operator. This helped to understand that the solutions for improving the safety of operation were not exclusively connected to remote operation. The solutions or aspects making the environment more immersive would be more or less the same whether the human was remotely operating a container crane or watching a movie in a theatre. The research was expanded outside the machine industry. The concept of presence did not seem to be very well covered by the psychological research either. Finding proven techniques for improving the sense of presence required even more digging. By combining the findings of different studies with known technical solutions, it was still possible to define how the design of the ROS could improve the sense of presence. Findings concerning the user experience are explained in more detail at chapter 4.2.

Research on the standards was relatively straight forward. Most of the standards addressed cabin controlled cranes but the safety requirements could be adapted to the remote

operation. Usually standards do not give a direct guidance or requirements for the design of the system. Defining the standard based safety requirements for the ROS required a lot of interpretation. Identifying the relative standards was done based on the knowledge of the operation and the hierarchy of standards. Chapter 4.3 of this thesis introduces the interpretations and requirements arising from the standards.

Defining the safety requirements should involve opinions of several people in order to recognize all the possible risks and hazards. This was executed during this project by consulting other safety engineers working for Kalmar but also by getting familiar with literature on machine safety. Chapter 4.4 introduces safety requirements defined based on interpretations of standards found on literature.

4.2 User experience

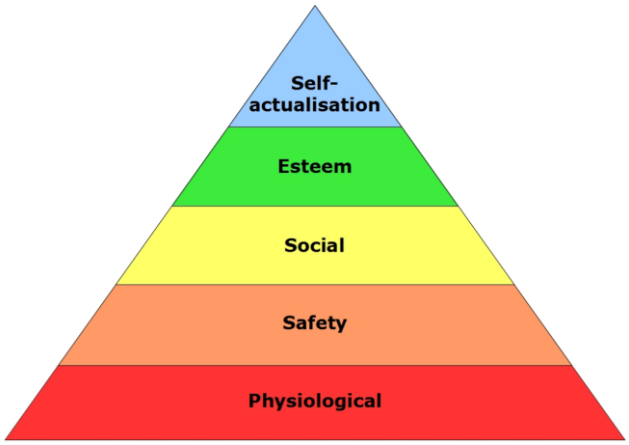
4.2.1 General

Manually driving a container crane is a very immersive experience. The operator is at the heart of the operation feeling every little vibration the machine is creating. According to surveys, the operators rely heavily on visual and audible signals whilst operating the crane. All this is taken away when the operator is moved from the cabin to an office environment in front of remote control desk. The office environment can be very passive providing very little feedback on the actual behavior of the machine. It is actually pretty much the opposite. Audible signals, which have nothing to do with the operation, become highlighted and the operator's concentration is taken away from the monitors. Many of the safety features of remote control heavily rely on the observations made by the operator. For example, the operator has responsibility of noticing a hazardous situation within the camera views and act accordingly to avoid the accident. The operator is also provided with alerts or warnings and it is crucial that the operator spots them. In addition, the findings of Robert B. Sheridan support the importance of user experience for the safety of operation.

Some studies have been made regarding the user experience of remotely operating container cranes. According to the study made by Hanna Koskinen, Hannu Karvonen and

Helena Tokkonen, a few fundamental targets for achieving a greater user experience in remote operation are identified. Sense of control and feeling of presence were recognized as the most important factors. Sense of control is closely connected to the feeling of safe operation. The operators are familiar with the fact that the cranes can cause a severe accident in just seconds if the operator makes a mistake. (Karvonen, Koskinen, Tokkonen 2013.) The feeling of safe operation is fundamentally important for the wellbeing of the operator.

Psychologist Abraham Maslow researched the subject of human motivation in the 1940s and came up with a theory, which stated that people are motivated to achieve certain fundamental needs. Maslow created a hierarchy of needs illustrated in picture 17. According to Maslow, the needs have a certain hierarchy. This means that people would have to satisfy the lower degree needs before being able to climb up the pyramid towards the satisfaction of higher needs. This way any failure of meeting the lower needs would also mean the failure of meeting the higher needs. (McLeod 2017)



PICURE 17. Abraham Maslow stated that human needs have a certain hierarchy (McLeod 2017).

As seen in the Maslow's hierarchy of needs, the safety needs are amongst the very basic needs at the lower section of the pyramid. The safety needs consist of such aspects of life as protection from elements and laws but also freedom of fear. (McLeod 2017.) The hierarchy of needs is originally a theory in psychology but it can give significant support for the evaluation of design aspects of the ROS. For instance, the design of the ROS should include a broad enough video view of the cranes environment. This way enabling the operator to evaluate the effects of the cranes movements. According to the study made by Karvonen, Koskinen and Tokkonen, the perception of kinetics is also crucial to the

feeling of safe operation. The user interface of the remote operation station could support this by providing a clear indication of the cranes speed and direction. The information of the kinetics should also include the crane's load. The operator should get information of the current hoist height and the weight of the load to feel more in control of the operation. (Karvonen, Koskinen, Tokkonen 2013.)

4.2.2 Feeling of presence

The causal connection between feeling of presence and the safety of remote operation has already been introduced in chapters 3.2.2 and 4.2. This clause focuses on the design solutions by which the feeling of presence could be improved. Probably the most important and the easiest way of increasing the sense of presence is by the amount of sensory information provided for the operator. It is generally believed that the greater the number of simulated human senses, the greater the feeling of presence. Studies have reported that interaction with a device providing audio-visual information creates far greater social presence than the one providing only audio information. With the current technology, creating information, which simulates body movements would be possible but it has been noted that the feeling of presence is greatly dominated by the visual and aural information. (Ditton & Lombard 1997.) Remote operators are currently provided with only visual information of the crane and its surroundings. Implementing audible information should be considered as a design factor at the renewal of the remote operation desk. This would require further studies on the scope of the audio signals provided for the operator. Capturing the complete audible environment of the terminal would not necessarily be the most optimal solution. Distracting noise should be cancelled the same way as in the cabin environment.

As mentioned above, the visual information has a huge effect on the sense of presence and many qualities of the video stream can be used for enhancing the sense of presence. Image quality, consisting of resolution and sharpness of the image, has a proven effect on the immersion of the situation. This has been studied in video conferences. The reports show that high-resolution video created a feeling of communicative presence for the participants of the conference. (Ditton & Lombard 1997.)

In addition, the size of the image has a reported effect on the sense of presence. The effect of the image size has been researched a lot. One great example is the so called motion sickness study made by D. M. Parker in 1971 and its follow-up study made in 1975. During the test, subjects were shown a few minutes video of car driving shot from the driver's point of view. Many of the subjects reported severe nausea. During the follow-up study, the subjects were shown the same video but this time on a significantly smaller screen. Subjects' reaction was reportedly far less severe. Similar kind of research was conducted in 1995 when subjects were shown video scenes both on 46 inch and 12 inch screen. The subjects who watched the videos from larger screen reported more "sense of movement" and "sense of participation". Closely related to the image size, is the viewing angle. According to some studies, the image size itself may not be the fundamental factor in boosting the sense of presence but the viewing angle. The effect that a large picture has on the proportion of visual field can be achieved also with a small screen and small viewing distance, similar way as in virtual reality glasses where the screen is placed just a few centimeters from the person's eyes. It has been suggested that the small screen and small distance would actually create a stronger sensation of reality. (Ditton & Lombard 1997.)

Video screens are the most important way of delivering information of the cranes status and the biggest single factor affecting the sense of presence the operator is feeling. However, the video quality is limited by the time required for the data transmission between the cameras and the remote operating station as described in chapter 3.2.4. The proportion of visual field can be modified with the design of the desk. Enlarging the screen size has some limitations too. The screens should be small enough for the operator to see the whole screen without constantly lowering and raising his head. The screens should be situated similar way as in picture 18 creating a bit like a curve around the operator making the proportion of field larger and the situation more immersive.

PICTURE 18. The screens should be mounted on a slight angle to expand the field of vision (Siemens 2018.).

Even though the visual information is the dominant stimulation for the operator, the possibilities of audible signals should be researched and evaluated, especially because the current design of the remote operation station does not support audible information. The two most important characteristics of sound are quality and dimensionality. When researching the effects of image quality, it became evident that the better the quality the greater the sense of presence. However, in the audible signals the research findings are diverged. Studies show that generally the high quality sounds are more realistic but the lower quality sounds are found more immersive. The effect of three-dimensional sound on the sense of presence has also been researched. The results are again mixed. Some studies show no difference between monaural and dimensional sounds yet some studies show that multi-speaker systems create higher feeling of presence than the single speaker ones. Despite the lack of research results, it is still believed that dimensional sound creates greater sense of presence. The volume of the sound can also have an effect on the sense of presence. Very low and very high volumes are seen as unrealistic and these should be avoided. (Ditton & Lombard 1997.)

Ways of improving the immersiveness of remote operation are not limited to the information provided to the operator. According to researches, the feeling of presence is affected by the interactivity of the operation. Meaning how easily the operator can alternate the virtual environment. The interactivity of the operation can be affected by the number of inputs the operator has on the system. These inputs can be voice commands or haptic inputs delivered via buttons or touch screens. The effect of each input channel is yet to

be studied but it is generally believed that those have a significant effect on the telepresence. (Ditton & Lombard 1997.)

The interactivity of the operation is closely connected to theories of Robert B. Sheridan introduced in chapter 3.2.2. Sheridan stated that one of the most important characteristics of telepresence is the user's ability to modify his environment (Sheridan, 1992 2-4). Modifying the environment can be done in several different ways. For example, the user can have a possibility of rearranging the objects presented in the virtual environment or a possibility to change the color or size of the objects. One way of modifying the environment is also by alternating the point of view the operator has on the virtual environment. This would result in similar effect that turning head has on the real world. Interaction with the virtual environment should still be as natural as possible and the environment should respond to the user inputs without any lag. (Ditton & Lombard 1997.)

Similar themes arose during the case study made by Karvonen, Koskinen and Tokkonen. For the operator, the possibility of manually adjusting the operating view was seen as a significant aspect of the user experience. The ROS should also support the co-operation between the remote operator and the yard personnel. Communication should be natural and effortless. (Karvonen, Koskinen, Tokkonen 2013.) These being just a few examples but showing a great correspondence between the psychological studies and real life observations, all supporting the assumption of the importance of user experience to the employee well-being.

The user experience unquestionably has a huge effect on the employee well-being and the operator's concentration on the work in hand. Operating any kind of machinery demands a huge amount of skill and effort from the operator. Studies show that lack of sleep results in significant drop of humans' sensorimotor and cognitive performance (Feyer & Williamson 2000, 649). It is hard to imagine why general lack of concentration and boredom would not have similar kinds of effects on the performance of the remote operator. Improving the sense of presence has some major technical limitations, for example the data transfer and the camera technology, but some improvements can be made relatively easily. The safety analysis made for the Kalmar's new remote operation station took into consideration the safety aspects of the remote operation station and risk analysis were made to cover the risks generated by the operator's lack of concentration.

4.3 Standards

4.3.1 EN 13557:2008

Standard EN 13557 covers the control stations and controls of cranes. Standard is mainly made for cabin-controlled cranes but it can also be applied to the design of remote control stations. This clause deals with the relevant safety requirements, which were recognized during the safety work on the renewal of Kalmar's remote operation station.

The standard contains a table of significant hazards identified with the controls and control stations of cranes. This table was used as guidance whilst working on the hazard analysis in appendix 1 and appendix 2. The hazardous situations and events resulted by these hazards are described in the hazard analysis as well as possible mitigation methods for each individual hazard. (SIS 2008, 7-10)

The standard introduces safety requirements for the controllers, cabins and consoles of the control stations. The requirements set for the controllers aim to prevent unintentional operating commands. The movement of the control levers should be consistent with the cranes motion. In addition, there should be fixed symbols near the control levers to indicate the action triggered by the controller. The control levers themselves should be hold-to-run type meaning that they return to neutral position when released. The standard also defines forces required to actuate certain controllers. Control lever's forward or backwards movement should require the force between 5 to 60 Newton as the same figure for sideways movement is between 5 to 20 Newton. Forces required to activate push-buttons shall not exceed the value of 10 Newton but the standard does not define a minimum value which makes it possible to use touch screen for certain operations whilst still complying with the standard. Some non-functional requirements are also set. Protection against electric shock should be designed as defined in EN 60204-32 and the temperature of the controller should remain below 43 degrees Celsius in any condition. (SIS 2008, 7-10.) Requirements set for pedals and hand-driven movements are not valid within the scope of the remote operation station.

The requirements set for the cabins of the cranes are mostly not valid when designing an ROS for office environment. Still some requirements set for cabin can be used as instructions for the recommended working conditions of the operators. Such requirements are the free standing height of 2 meters and the requirements of the cabins climate. The standard states that the operating temperature should be above 18 degrees Celsius but under 30 degrees Celsius within the limits of external climate conditions. The operator should be provided with an adjustable seat. (SIS 2008, 12-15.) These requirements are not relevant considering the physical design of the remote operation station but have a significant effect on the well-being and thus concentration of the operator. Even though the design of the station cannot address these issues it is possible to include instructions of the preferred working environment with the station.

Standard also defines the safety critical aspects of the design of the console itself. Again the requirements are mostly set to prevent unintentional operating commands made by the operator. Controls and their surroundings should be designed so that they can be activated only as a result of intentional operation. The standard gives examples on how this requirement can be met. Such design features are recessing the actuator and surrounding the control levers on a panel by a guard rail. The most usable solution for avoiding unintentional usage is probably free space around the controller. Free space between rows of push-buttons should be at least 10 mm and at least 15 mm between separate push-buttons. The free space of 5mm is seen adequate for push-buttons which don't operate any movement of the crane or its lifting accessories. Each crane console should have a controller for acoustic warning device located in the crane. The controller should be different from the cranes operating controllers. (SIS 2008, 15-16.) The remote operation station is not machine specific meaning that each crane can be operated via several different control stations. According to EN 13357 measures should be taken to make sure that only one console is active at a time, except for the emergency stop function. The standard does not define more closely the measures that should or could be used. (SIS 2008, 16.)

4.3.2 EN 60204-32

EN 60204 is a standard defining safety critical aspects and requirements of the electrical equipment of machinery. Part 32 of this standard includes particular requirements for

hoisting machines. Defining the requirements related to the remote control station required a lot of interpretation and research. Requirements defined based on EN 60204 were closely related to the physical design of the desk's structure.

The remote control station is an electric device and it should fulfill the required protection methods to protect the user from electric shock in the event of failure. Adequate protection methods are introduced and covered by the standard and detailed itemization of them is not in the scope of this thesis. The safety work defines the electric design to be done according to the standard but yet the detailed itemization is not rational.

However, few distinct requirements were identified from the standard with a close connection to the remote operation. Colors of push-buttons and indicator as well as illuminated push-buttons are defined in EN 60204-32. Requirements for push-button actuators are illustrated in picture 19 and requirements for indicator lights are illustrated in picture 20.

Colour	Meaning	Explanation	Examples of application
RED	Emergency	Actuate in the event of a hazardous situation or emergency	Emergency stop Initiation of emergency function
YELLOW	Abnormal	Actuate in the event of an abnormal condition	Intervention to suppress abnormal condition Intervention to restart an interrupted automatic cycle
BLUE	Mandatory	Actuate for a condition requiring mandatory action	Reset function
GREEN	Normal	Actuate to initiate normal conditions	
WHITE	No specific meaning assigned	For general initiation of functions except for emergency stop (see note)	START/ON (preferred) STOP/OFF
GREY			START/ON STOP/OFF
BLACK			START/ON STOP/OFF (preferred)
NOTE Where a supplementary means of coding (for example, shape, position, texture) is used for the identification of push-button actuators, then the same colour WHITE, GREY, or BLACK may be used for various functions (for example, WHITE for START/ON and for STOP/OFF actuators).			

PICTURE 19. Desired colors for push-buttons (CENELEC 2008, 68).

Colour	Meaning	Explanation	Action by operator
RED	Emergency	Hazardous condition	Immediate action to deal with hazardous condition (for example, switching off the hoisting machine supply, being alert to the hazardous condition)
YELLOW	Abnormal	Abnormal condition Impending critical condition	Monitoring and/or intervention (for example, by re-establishing the intended function)
BLUE	Mandatory	Indication of a condition that requires action by the operator	Mandatory action
GREEN	Normal	Normal condition	Optional
WHITE	Neutral	Other conditions may be used whenever doubt exists about the application of RED, YELLOW, GREEN, BLUE	Monitoring

PICTURE 20. Desired colors of indicator lights (CENELEC 2008, 69).

The standard also obligates to take protective measures in such applications where the malfunction of an electronic device could lead to a hazardous situation. It should be noted that the standard obligates to take measures to minimize the risk of the occurrence of such failure. This means that emergency stop device is not adequate enough since it does not affect the risk of the component failure by any means. The standard gives some examples for reducing the risk, one of them being the use of redundant signals. (CENELEC 2008, 62-63.) The movement controlling joysticks were recognized as such devices. Failure in the joysticks could result in unintentional operating moves, such as the crane moving to different direction than intended by the operator. Based on the standard the joysticks used in the ROS should be equipped with redundant signals.

4.3.3 IEC 62745

IEC 62745 was launched in 2017 and it is the first machine safety standard specialized in cableless control of machinery. The standard defines general safety requirements for the safety of wirelessly transmitting control data between the controller and machine's onboard control system. This section of the thesis does not introduce all the safety requirements set by standard but focuses on the most relevant ones. It should still be noted that the design of the remote control station should meet all the requirements if it is used as a cableless control device.

The standards requires that measures are taken in order to prevent unintentional or unauthorized operating commands. For example, commands resulting from dropping the

controller to the floor should be prevented if such a scenario is possible. Again, the standard does not provide specific solutions to be used for protection but it gives examples. The standard suggests that unauthorized use could be prevented by using a key-operated switch or an access code to power up the transmission of data. Similar kind of suggestions are given for ensuring that the operating commands only affect the intended base station and that the operating commands initiate only the intended function. The standard also sets technical requirements for the serial data transfer and the interruption and establishment of the communication. (IEC 2017, 12-14.) These requirements should be followed during the design of the remote control device.

IEC 62745 requires that the cableless control device is equipped with automatic stop function and at least one additional safety rated stop function, which is initiated by a human action and by using a dedicated controller on the control device. The different stop functions and their characteristics are introduced in picture 21. (IEC 2017, 14.)

Function	Clause	Safety-related function	Type of stop (see Fig.2)	Effect on CCS	Availability & operability	Control actuator	
						Type	Colour
Control stop	4.7.3.2	Either	Active, passive, or active followed by passive	Defined state of (a) stop output(s), or of another output associated with release of a hold-to-run control actuator or, if safety-related: OFF-state of all safety-related stop output(s)	Operational when the CCS is in control of the machine	See IEC 60204-1	Black White Grey
General safe stop (GSS)	4.7.3.3	Yes	Active, passive, or active followed by passive	OFF-state of all safety-related stop output(s)	Operational when the CCS is in control of the machine	See 4.7.3.3	Black (preferred) or red. Red shall not have a yellow background
Emergency stop (EMS)	4.7.3.4				Operational at all times	Device that complies with IEC 60947-5-5	Red with a yellow background
Automatic stop (ATS)	4.7.3.5				Operational when the CCS is in control of the machine	Not applicable	Not applicable

PICTURE 21. Stop functions of cableless control system (IEC 2017, 15).

Control stop refers to a stop function which is manually controlled by the operator. The control stop function is only active when the cableless control station is in control of the

machine. The control stop function should be engineered in accordance with IEC 60204-1.

General safe stop is a safety related stopping function and initiating it should result in OFF-state of all the safety-related outputs at the base station. After actuating the general safe stop controller it shall not automatically return to un-activated state. Disengagement of the general safe stop controller shall only be possible by intentional manual action delivered from the remote station. The controller for the general safe stop function should have a direct opening action in accordance with IEC 60947-5-1.

Emergency stop function shall meet the requirements of the general safe stop and it has some additional requirements. The actuator shall be marked as an emergency stop device and comply with the relevant standards and fulfill the requirements of ISO 13850. Activation must result in OFF-state of all the safety-related outputs at the base station and the function must be operational at all times. The information of use shall also instruct that the system integrator takes responsibility of making sure that the requirements are met when incorporating the cableless control system to the machines control system. If multiple cableless control stations are simultaneously communicating with the base station, the disabling of any of the remote stations shall initiate automatic stop function.

Automatic stop function is a safety-related control function, which initiates an OFF-state of safety related outputs at base station. The automatic stop function is automatically initiated under certain conditions which could result in hazardous state of the connected machinery. Automatic stop function is initiated when transmission ceases, when a fault in safety-related part of cableless control system is detected or when no valid signal is detected within the determined time. This time is declared by the manufacturer of the cableless control system but it can't be more than 500 milliseconds. It should be noted that these are the absolute minimum requirements for the conditions under which the automatic stop function shall be initiated. The manufacturer can engineer the automatic stop function to initiate under the additional conditions determined by the hazard analyses. (IEC 2017, 15-17.)

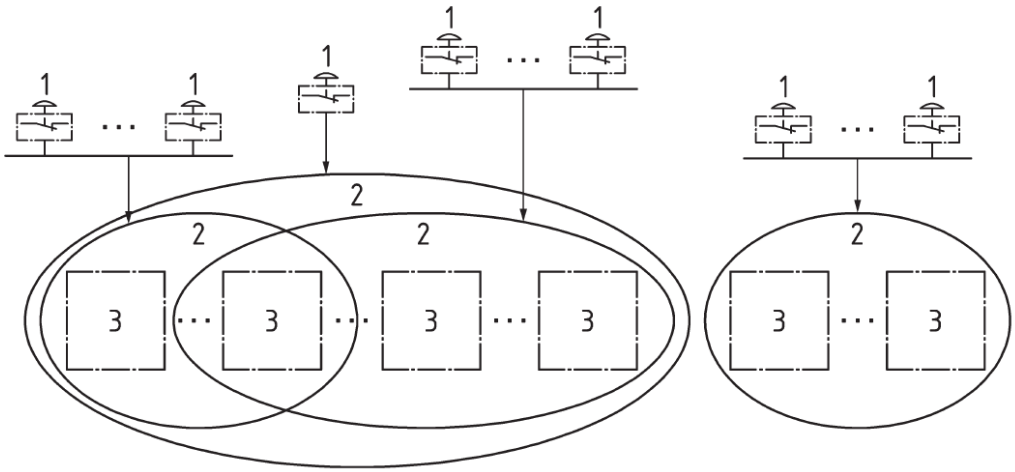
Resetting after general safe stop or emergency stop shall require a deliberate action from the operator. The resetting function can be done only from the remote station from which the stop function has been initiated. If disengagement of the general safe stop or emergency stop controller results in communication between cableless control station and the

base station, it should be closely evaluated if there is a need for additional manual reset at the remote station. The risk assessment and hazard analyses shall provide such information. (IEC 2017, 17.)

In addition, the standard sets requirements for configurability protection, behavior on loss of supply and latching control functions. These requirements need to be reviewed and studied whilst making risk analyses for cablelessly controlled machinery.

4.3.4 EN 13850

EN 13850 is a standard defining the technical features of emergency stop function. This chapter introduces the requirements set for the span of control of emergency stop function and the requirements set for the controller of the emergency stop function. The emergency stop function shall be operative at all times and override all other operating functions. When emergency stop function is activated it shall remain activated until it is manually reset and start commands shall not be effective while the emergency stop function is activated. The span of control of the emergency stop function shall cover the whole machine. Exception to this can be made when stopping all linked machinery would create additional hazard or affect unnecessarily to production. Span of controls of each separate emergency stop function may overlap. (SIS 2015, 3-5.) The concept of span of control is demonstrated in picture 22.



Key
1 emergency stop device
2 span of control
3 section of machine or machine

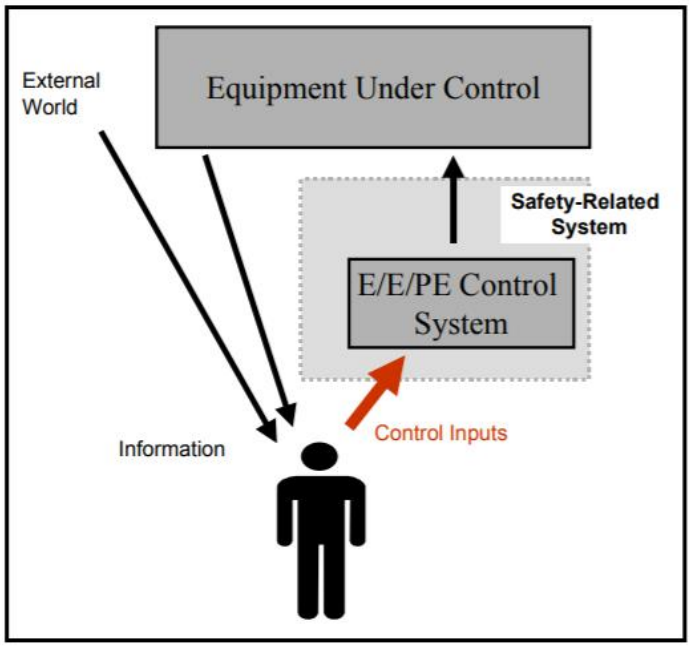
PICTURE 22. Demonstration of span of control. (SIS 2015, 5.)

The emergency stop device shall be designed so that it is easily identified and actuated. The device shall be handle, wire, rope, bar, foot-pedal or a push-button actuated with a palm. The device itself has to be colored red and the possible background of it yellow. The device or the background should not be labelled with either text or a symbol. Electrical emergency stop devices shall have a direct opening action and they shall be mechanically latching. The stop command must be delivered even in case of malfunction of the latching functionality. Using the emergency stop device in a cableless or portable controller brings some additional requirements. The machine should always have at least one emergency stop device permanently attached on the machine. The confusion between active and inactive devices has to be prevented. This can be done by illuminating the active device, automatically covering the inactive emergency stop device or by storage of the detached cableless controller so that there is no risk of confusion. (SIS 2015, 6-8.)

4.4 Human behavior

As described earlier the human operator can have a huge effect on the safety of the operation. The role and effect of the human operator on the system can vary depending on the automation level of the machinery. ROS can be classified into category where the electric

system is concerned as a remote control system. The operator provides inputs to the system and the control system operates the actuators accordingly. The relationship between operator and equipment under control is illustrated in picture 23. (Carey 2001, 26-27.)



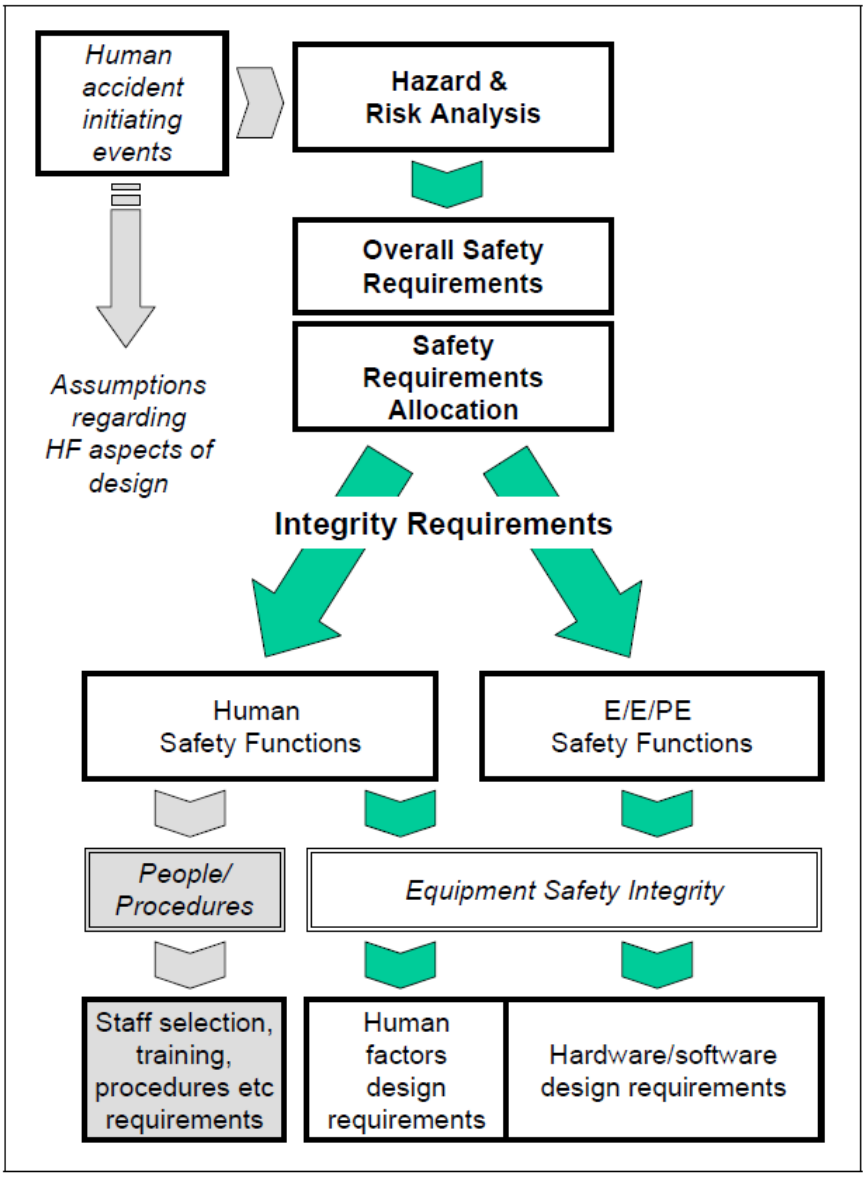
PICTURE 23. Relationship between operator and equipment in remote operation (Carey 2001, 26).

In this case, the operator is fully in control of the machine and performs a safety-related function such as pressing the emergency stop actuator. The operator input will be critical when safety is concerned and special consideration should be given into the design of the input device especially into location ad characteristics of the control device. The electrical control system will support the safety of operation. The more critical the operation is the higher the required quality of human factors. The risk analysis should identify the human-dependent safety functions. (Carey 2001, 27.)

In order to analyze how human behavior can influence risk and how the design of the system can address those, few objectives have to be understood:

- How a human can cause or contribute a hazardous situation
- What safety functions require human interference
- Required integrity of the system (Carey 2001, 33.)

The analysis of human factors requires an additional analysis to be made alongside the "normal" integrity analysis for hardware and software. The purpose of this kind of analysis is to recognize and determine what needs to be done on the design of the hardware and software to make sure that they support the human safety integrity. (Carey 2001, 33-34.) The process is outlined in picture 24.



PICTURE 24. Determining the human safety factors (Carey 2001, 34).

According to the table in picture 24 the required level of integrity of human safety function can't be achieved only by technical aspects but also people and processes must be considered. Unfortunately, current standards focus mainly on the requirements of hardware and software. The framework made by Amey Vectra Limited gives advice on how

to include the human factor issues in the risk and hazard analysis. The consequence of the event will determine how detailed the analysis should be. For example, if the hazardous situation would lead to major injuries and fatalities, the human reliability analysis should include a detailed level analysis on operational tasks, modelling of risks arising from human error and human failure considered within main top-down system hazard identification process. The advice are listed based on the consequences on table at picture 25. The examples are intended to be only illustrative. (Carey 2001, 35.)

Severity of Consequences	***Possible Requirements for Human Reliability Analysis***
Minor injury	• Human failure explicitly considered within main top-down system hazard identification process.
Major injuries	• Operational tasks analysed at high level to identify safety functions. • Human failure explicitly considered within main top-down system hazard identification process.
Major injuries and fatalities	• Operational tasks analysed at detailed level to identify safety functions. • Human failure explicitly considered within main top-down system hazard identification process. • Risks arising from human error assessed quantitatively and modelled
Multiple fatalities (Major disaster)	• Operational and maintenance tasks analysed at detailed level to identify safety functions. • Human failure explicitly considered within main top-down system hazard identification process. • Potential errors of commission identified (i.e. actions on wrong system or non-required actions, rather than just failure to perform required action) • Human error dependency assessed • Risks arising from human error assessed quantitatively and modelled

PICTURE 25. Human reliability analysis requirements (Carey 2001, 35).

The study made by Amey Vectra Limited also proposes how the design could take into consideration the human factors. The proposal is illustrated at SIL 1, SIL 2 and SIL3 in pictures 26-28. The proposal links requirements for human factor design to the integrity level of the electrical system. In these examples the requirements for human factor design amplify when the SIL level of the system increases. This is again just an illustrative example of the execution. (Carey 2001, 37-38.)

SIL 1	
Aspect	*Requirement*
Understanding and defining the context of use	• Key tasks, user groups and operating environments have been described as part of the requirements documentation
Derivation and definition of HF design requirements	• Selected mandatory standards and specifications have been identified for application to the HF aspects of the design
Documentation of design	• The user interface has been described as a design deliverable (e.g. within the operating/maintenance manuals)
Evaluation and testing of HF performance	• Critical tasks and aspects of the HF design and requirements have been identified and subjected to documented review by the design team
Specification and delivery of training	• All staff who are to operate or maintain the equipment have received instruction that covers all relevant aspects of the equipment
Development of documentation	• Sufficient documentation necessary to operate or maintain the equipment has been produced and its accuracy/completeness has been verified
Evaluation in use	• Support arrangements are in place to address significant problems that may arise when the equipment is in use

PICTURE 26. Proposed requirements of human factors at SIL 1 system (Carey 2001, 38).

SIL 2	
Aspect	*Requirement*
Understanding and defining the context of use	• Key tasks to be performed by operations and maintenance staff have been identified (those that are concerned with safety related functioning of the equipment). • Key operator and maintainer groups have been identified, along with their roles and responsibilities. • Typical operating environments have been identified and described
Derivation and definition of HF design requirements	• Selected mandatory standards and specifications have been identified for application to the HF aspects of the design, along with additional context specific HF requirements
Documentation of design	• The conceptual design of the user interface is documented as a design deliverable (e.g. within the operating/maintenance manuals)
User evaluation and testing of HF performance	• Critical tasks and aspects of the HF design have been identified and subjected to systematic, documented review by the design team • The design has been reviewed in detail during the design phase by representative operations and maintenance staff and any problems raised have been resolved • The design has been evaluated against the original HF design requirements and any shortfalls have been resolved
Specification and delivery of training	• All staff who are to operate or maintain the equipment have successfully completed training that covers all relevant aspects of the equipment and its application
Development of documentation	• All documentation necessary to operate or maintain the equipment has been produced and its accuracy/completeness has been verified
Evaluation in use	• Support arrangements are in place to address significant problems that may arise when the equipment is in use

PICTURE 27. Proposed requirements of human factors at SIL 2 system (Carey 2001, 39).

SIL 3	
Aspect	*Requirement*
Understanding and defining the context of use	• All relevant tasks to be performed by the operators/maintainers have been defined, described and verified by staff representatives. This includes operations under normal, abnormal, degraded and emergency conditions. • The roles and responsibilities of all potential user and maintainer groups have been identified and their key characteristics defined (e.g. training, skills) • Typical operating environments have been systematically identified and assessed for potential implications for the design

Aspect	*Requirement*
Derivation and definition of HF design requirements	• Selected standards and specifications have been identified for application to the HF aspects of the design • Appropriate functional and user performance requirements have been specified for the HF aspects of the design
Documentation of design	• The processes utilised in developing the design are specified and controlled • The conceptual design of the user interface is fully documented and controlled
Operational performance assessment of HF design	• Critical task sequences and activities have been identified and all relevant aspects of human performance have been assessed and found to be acceptable (e.g. speed, workload, reliability) • Key physical aspects of the design have been reviewed against operational design requirements and other relevant aspects of human factors best practice and any problems resolved (e.g. screen design, dialogue design, control room environment)
Maintainability assessment of design	• Critical maintenance tasks have been identified and all relevant aspects of human performance have been assessed and found to be acceptable (e.g. maintenance reliability, speed) • All physical aspects of the design which are novel or critical have been reviewed against maintenance design requirements and other relevant aspects of human factors best practice and any problems resolved (e.g. access, component identification, software diagnostic tools)
User evaluation and testing of HF performance	• The HF aspects of the design have been subjected to evaluation by typical users performing or simulating typical tasks with design mock-ups and problems fed back into design improvements • The design has been evaluated against the HF design requirements and performance goals and any shortfalls have been resolved
Specification and delivery of staffing	• Job and person specifications have been developed, validated and implemented in screening or selecting operations and maintenance personnel
Specification and delivery of training	• Training specifications and material have been developed that covers both equipment use training and job related training • Training has been delivered within an assured and validated process to all staff who are to operate or maintain the equipment
Development of documentation	• All documentation necessary to operate or maintain the equipment has been produced in a suitable format and its content/usability has been verified
Evaluation in use	• Support arrangements are in place to gather information on problems in use, to address significant problems and to feed forward improvements into future upgrades/designs

PICTURE 28. Proposed requirements of human factors at SIL 3 system (Carey 2001, 39-40).

The human factors should definitely be included in the risk analysis especially in such a system as remote operation station. However, no clear instructions on how this should be done exists.

4.5 Other

Tapio Siirilä, a well-known machine safety expert, has written several books around the topic of implementing machine safety requirements to practice. Siirilä's literature was researched within the safety work on Kalmar's remote operation station and relevant requirements were adopted. Many of Siirilä's opinions had already come up during the research on standards and studies but Siirilä's literature provided ways on preventing unintentional operating commands, which were seen as one of the most likely hazards already during the preliminary hazard analysis. The preliminary hazard analysis is introduced in chapter 5.

The controllers must be designed in a way that they are activated only intentionally. Unintentionally activating a controller can create a hazardous situation when a human is near the machine and it unexpectedly starts up or changes the direction of movement or speed. There are several ways on executing the prevention of unintentional operating commands. Listed below are few known ways.

- The speed-area of the machine can be changed only from a standstill.
- The protection of sensor and the control system have to be designed in a way that the sensor can't be accidentally affected or that affecting won't have an effect on the machine.
- Use of two-hand controllers
- Prevention of operating commands resulting from dropping portable pendants.
- Protecting the control devices so that accidentally leaning on them won't activate the controller. This can be done by protecting the controllers with lids or collars or by mounting them on their surroundings. (Siirilä 2009, 242-243.)

The renewed RC desk was planned to include a touch-screen used to control some operations of the connected crane. Touch-screen is considered as a multifunctional operating device and the risk of unintentional operating commands is significantly higher compared to the controllers which are used always for activating the same operation. Unintentional operating commands can be minimized by using a so called double-actuation. The first activation of the icon on the touch-screen brings up a pop-up window or similar indicator, which has information on the operation to be activated. The operator has to touch or click the icon again to actually activate the operation. The second activation doesn't necessarily

have to be done on the same control device as long as it requires a deliberate effort from the operator. (Siirilä 2009, 242-246.) This type of activation was analyzed as very frustrating for the operator. Many operations which were planned on being activated from the touch-screen were not safety-critical. In addition, the onboard control system of machinery has safety functions preventing hazardous situations resulting from unintentional operation commands. In such cases, the double activation was seen unnecessary. The operating commands requiring a double activation were determined during the operational hazard analysis, which is introduced in chapter 5.

Unintentional operating commands can be made even less likely by clearly indicating the functionality of control levers. This can be quite tricky when the control station is portable or there is no visual contact to the machine being operated and the machines positon related to the operator can vary. In these situations such labeling as right, left, up and down is not adequate for safe operation. The direction of movement should be indicated by well-known symbols. The functionality of controller should be designed in a way that they are used naturally and inherently as intended. For example, increasing the speed should be done by moving the controller right or forward, not the opposite way. Multifunctional control devices should be used only for non-hazardous operation. (Siirilä 2009, 242-246.)

5 HAZARD ANALYSIS

5.1 Preliminary Hazard Analysis

5.1.1 General

Preliminary hazard analysis is used for identifying possible safety critical areas of the process or product at the very early phase of the development. In addition to identifying the possible hazards the PHA also gives recommendations on risk mitigation methods. The PHA is sometimes described as the most important analysis of the system safety process since it is the first analysis on the process under development. Target for the analysis is to isolate the possible hazardous areas in the design and figure out the need for further analysis. In order to complete the analysis, the safety engineer needs detailed information of the product under development. The data should include at least the following information:

- Scope of the product
- Environment in which the product will be used
- Hardware to be used with the product
- End use of the product. (Vincoli 2014, 71-72.)

The analysis can be done using a dedicated worksheet. One example of such worksheet is illustrated in picture 29. The content of the worksheet can vary depending on the organization or the product but the worksheet in picture 29 illustrates the relevant aspects, which are addressed in preliminary hazard analysis.

PRELIMINARY HAZARD ANALYSIS

PROGRAM: _____ DATE: _____

ENGINEER: _____ PAGE: _____

ITEM	HAZARDOUS CONDITION	CAUSE	EFFECTS	RAC	ASSESSMENTS	RECOMMENDATIONS
Assigned Number Sequence	List the nature of the Condition (refer to Generic Hazard Group, Group, if necessary).	Describe what is CAUSING the stated condition to exist	If allowed to go uncorrected, what will be the effect or effects of the hazardous condition?	Hazard Level assigned	Probability or Possibility of occurrence: • Likelihood • Exposure • Magnitude	Recommended actions to eliminate or control the hazard NOTE: Use the Hazard Reduction Precedence Sequence

PICTURE 29. Example of PHA worksheet (Vincoli 2014, 75).

The analysis should answer to a few specific questions. Some of these questions may seem obvious but the analysis should still include an answer to those to make sure that the analysis is complete. These questions include

- What is the analyzed system?
- Are people involved?
- What is the functionality of the system?
- What the system should not do?
- What are the relevant standards?
- Has the system been used before?
- What does the system produce?
- What elements are the input to the system?
- What elements are the output of the system?
- What could cause a hazard?
- What are the energy sources?
- Is timing critical for safety of the operation?
- What are the inherent generic hazards in the system?

- How could control of the system be improved? (Vincoli 2014, 77-78.)

After the analysis, a report should be written. In addition to the worksheet, the report should include brief description of the system and recommendations of the following analyses. (Vincoli 2014, 77-78.)

5.1.2 Preliminary hazard analysis for remote operation station

The preliminary hazard analysis for common RC desk was done during the end of year 2017. The scope of the analysis was to identify and mitigate key risks in planned usage of the RC desk. The analysis also covered requirements from relevant standards. The analysis was divided in different sections regarding the RC operation. The **operation** section covered the risks identified to be present during handling of manual or automated equipment or inventory of container maps. The **maintenance** section covered the risk identified to be present during maintenance activities, such as stopping the machine for maintenance or driving it inside the segregated maintenance area. The **standards** section covered the safety requirements and risks set by the recognized and relevant standards. Different machine types were not addressed individually but the risks were recognized to be in general level and applicable to all types of machinery. For each identified hazard an ID of the hazard, risk proposed by the hazard and mitigation methods were recognized. The complete analysis is attached as a company confidential annex A of this thesis. Picture 30 illustrates one identified risk at the PHA.

ID	Cause	Risk	Mitigation	Responsible System point of view / comment	Comment
14		Connection lost or a fault in safety related part -> controlling the machine might not be possible -> risk of collision	RC desk shall provide an automatic stop (ATS) function. ATS shall initiate an OFF-state of all safety related outputs at the base station. ATS function shall be initiated under conditions that include but are not limited to: -when a fault in safety related part of the CCS is detected -When no valid signal has been detected at a base station within a determined time period (max 0,5s.) -when transmission ceases IEC 62745	Kalmar	Review existing design

PICTURE 30. Example of risk identification in PHA.

The risk has been identified to arise from the lost connection between the desk and the machines onboard system. After losing the connection the machine could possibly continue its movement without the operator having control. This in the other hand could lead to a collision and possibly injuring people. The proposed mitigation method has been recognized from the standard IEC 62745, which is introduced in chapter 3.3.3. The desk shall have an automatic stop function, which stops the movement of the crane in the event of lost connection. The responsible party for this risk mitigation is the manufacturer of the device, in this case Kalmar.

5.2 Operational Hazard Analysis

5.2.1 General

The operational hazard analysis or OHA is done after the preliminary hazard analysis. The purpose of it is to identify all the hazards, which are dangerous for humans and provide risk mitigation methods to minimize the identified risks. (Vincoli 2014, 99.) After the identification of the hazard, the risk related to it needs to be evaluated. The level of the risk is a combination of the severity of the consequences of the hazardous situation

and likelihood of the occurrence of the situation. Standards and handbooks provide several different techniques for the risk estimation. Methods can vary a lot. For example, some can highlight human errors as some focus on the failures of technical components and devices. The estimation is always a subjective decision and can be highly affected by the personality of the estimator. The estimation of the level of the risk should not be main concern of the analysis but the most important thing is recognition of the hazards. (Siirilä 2008, 95-96.)

After the determination of the level of the risk, it has to be determined if the risk is tolerable or not. Again, the standards and workbooks provide several different kinds of methods on determining whether the risk is tolerable or not. It should be noted that all the risks cannot be fully disposed and machines will always have risk factors. These risks should be documented and presented in the manuals. If the level of the risk is seen as unbearable, measures have to be taken to minimize the risk to an acceptable level. These mitigation methods are presented in the hazard analysis and the risk is estimated again post the mitigation methods. (Siirilä 2008, 107-112.) Literature, standards and accident reports provide guidance for determining the appropriate reduction methods.

The risk analysis is a significant part of the designing the new machine or a retrofit and the analysis should always be properly documented. The standard SFS-EN ISO 14121-1 requires that the documents of the analysis include the following information as far as suitable:

- Information of the system in scope of the analysis; technical details, limits, intended use etc.
- Assumptions of the system; lifespan, strain, safety factors etc.
- Recognized hazards, dangers and dangerous situations
- Information of the references used to support the evaluation of the risk level
- Targets of the risk reduction
- Implemented risk reduction methods
- Remaining risks
- The outcome of the risk analysis
- The documents, memos and other records made during the analysis process. (Siirilä 2008, 126.)

5.2.2 Operational hazard analysis for remote operation station

The operational hazard analysis for Kalmar's remote operation station was done during the spring of 2018. Focus on the assessment was to recognize all the hazards related to the remote operation desk. In other words, the risks which could be affected by the design of the desk. The hazards were addressed in different sections depending on the use case and the source of the hazard. Firstly, the analysis addressed general hazards which were present regardless of the type of the machine the desk is connected to. These hazards were divided to two different categories.

Hazards related to the use of desk –section covered hazards which would result in harm to the operator himself. Such issues being the ergonomic design of the desk or protection against electrical faults.

General RC operation hazards – section covered the operational risks which are common to all types of machinery. An example of such common hazard is the mode change of the controllers. If the functionality of the controllers changes in the middle of operation, without any input from the operator, the operator may accidentally perform a hazardous movement. More detailed example of such a situation is the mode change from supervised to watch mode. In supervised mode the operator is required to monitor the movements of the crane and keep the hold-to-run device activated. Releasing the actuator will result in stopping the movements of the machine. In watch mode the operator can watch the movements of the crane but none of the controllers are active (except for the emergency stop). Now if the mode is changed automatically from the supervised mode to the watch mode the operator may get confused of the functionalities of the controllers since in supervised mode he can stop the crane by releasing the hold-to-run but in watch mode that is not possible anymore.

Machine specific hazards were also analyzed within the operational hazard analysis. RC operation of each of the machine in the scope of the project was analyzed individually. The machines are introduced in the chapter 2.2. The operational hazard analysis process highlighted the importance of knowledge of machinery. It would have been practically impossible to complete the analysis without detailed information of the machinery and their operation. The hazards were further categorized depending on the source of the hazard to make the analyzing work more detailed and systematic.

Container tip-over hazards -section covered the hazards resulting in containers being tip-over or shunted from the container stack. In such a situation the container could drop on top of a truck or a truck driver resulting in severe injury. For example, container tip-over can happen if the trolley drive is started before the spreader is hoisted high enough. There are several methods on how this can be prevented but those are confidential and thus not introduced in this thesis.

Gantry driving hazards –section covered the hazards related to the gantry movement of the operated machine. These hazards would result in crane colliding with CHE or terminal personnel. There are several reasons why the collision would happen and each of the sequence of events was analyzed individually. For example, such reasons would be the CHE being parked at the gantry drive path of the crane or the crane being driven out of the gantry drive path. The RC operator has a very limited vision on the actual site through the camera views and there is always some latency in the picture. This way the RC gantry driving is particularly dangerous and needed to be analyzed thoroughly.

Interchange lane container handling hazards and Truck lifting hazards –sections covered the hazards present during the interchange lane operations. During the interchange lane operations, the spreader/container is being moved at a very close distance to humans. Even the slightest mistake or malfunction can result in a hazardous situation. For example, the operator usually uses micromovements for fine positioning of the container to the trailer. During the micromovements the range of motion and the speed of the crane is very limited. Now if the operator inadvertently activates gantry movement the cabin of the truck can be crushed by the spreader.

Stacking area container handling hazards –section covered the hazards related to the container handling inside the stacking area. Normally people should be isolated from the stacking area but there is always a risk that personnel are inside the segregated area. These risks had to be taken into consideration and find the proper reduction methods.

Reefer operation hazards –section covered the risks being present during the reefer operations. Reefer racks are used to store reefer containers and have personnel to connect the power cables to reefer containers after those have landed. Generally colliding to the reefer rack would cause severe harm to the reefer personnel. In addition, the RC operator

may not be able to spot if the power cable is disconnected or not and hoist a connected container. This would possibly lead to electrocution of the reefer personnel.

Block change hazards and Maintenance hazards –sections covered the risk related to block change and maintenance operations. These hazards do not necessarily originate from the RC operation but the operator may have an opportunity to avoid a hazardous situation if he operates correctly. One of the most important risk reduction methods is the proper training of the operators.

6 RESULTS

The recognition of the safety requirements of remote control of container handling equipment included a research on standards and studies. During the research, it became evident that the remote operation poses significant risks, which have to be addressed in the design of the remote control desk. The most significant risks were recognized to arise from the data transfer and unintentional operating commands. The risks related to the data transfer could be mitigated by complying with relevant standards. The already existing design of Kalmar's remote control desk had safety features regarding the transfer of information between the desk and the machine. The prevention of unintended operating commands proved to be more complicated than first expected. Standards provided several technical solutions for this, such as free space between the controllers and minimum forces required to actuate the controllers, but none of these really enhanced the operator's concentration. Looking into studies and researches in the field of psychology it became evident that the remote operator's concentration and sensorimotor performance is highly dependent on the feeling of presence. This finding expanded the research work outside the machine industry. For example, several studies can be found on techniques on improving the feeling of presence in movie theaters or video games. These findings were then adapted to the remote operation of container cranes which resulted in a completely new way of looking into the safety of remote operation.

The preliminary hazard analysis and operational hazard analysis were made based on the recognized safety requirements. The analysis work resulted in detailed safety measures, which the design of the desk should comply with. Safety measures consisted of requirements for the physical controllers of the console and their layout, the ergonomics design of the desk and the office environment in which the desk is used. Some requirements were set for enhancing the immersion of the operation. The graphical user interface and the video user interface would have the most significant effect on the feeling of presence. The safety measures included, for example, requirements for the information to be delivered to the operator and the possibilities for the operator to adjust his working posture and field of vision.

7 CONCLUSIONS

The constantly growing level of automation in the container terminals promotes the use of remote control. Safety-wise remote control is still a very poorly covered section of the industry. The lack of standards and safety guidelines regarding the remote control creates some significant challenges in the design of remote control solutions. For an average engineer the concept of human factors can be difficult to grasp. Traditionally engineering is based on items that can be measured or adequately estimated and calculated. However, the immersion of the operation and the employee well-being definitely have an effect on the safety of remote operation. Now this is a combination that must be taken into consideration when designing solutions for remote control. During this thesis work, information was gathered from several different fields of science combining psychology and machine safety standards. This proved to be an excellent decision providing tons of new aspects to the concept of supporting safe operation.

As an outcome of this thesis, human factors were taken into consideration during the design work of the renewed ROS. It was ensured that the risks arising from such human behavior as lack of consideration were reduced significantly. By creating an immersive environment and ensuring that controller layout minimizes unintentional operating commands the safety was increased significantly.

The survey is not complete by any means. The effects that human behavior have on the safety of remote operation have to be further examined to ensure that everything possible is done during the design work of such solutions. Analysis on human behavior should be taken as part of a normal hazard analysis for man operated machines. Possibilities of such integration must be further examined.

This thesis provided an interesting challenge since no guidelines or standards existed. The research work was very rewarding since it provided chances of innovation through combination of different levels of scientific studies. Successfully analyzing the potential use cases required profound knowledge of terminal operations and container handling equipment. This way the thesis work was also a very educating experience combining machine safety, technicality and psychology.

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APPENDICES

Appendix 1. Preliminary Hazard Analysis

Confidential.

Appendix 2. Operational Hazard Analysis.

Confidential.