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A Study towards the Potentials of Robotic Technologies to Decrease Risk to Personnel's Safety in Statnett

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Environmental Physics and Renewable Energy

Foreword

This master thesis where written at the Norwegian University of Life Science at the Department of Mathematical Sciences and Technology, during the spring semester of 2016.

My fascination for new technology, desire to increase personnel's safety and an actual opportunity to make a difference where my main motivations to write this thesis. Even though this thesis does not provide sufficient information to implement new technologies from tomorrow of, it contributes to a fundamental core for future decision making towards risk reduction.

The thesis was executed on behalf of Statnett SF and I would like to take this opportunity to thank everyone, from the personnel at Statnett to the manufacturers of robotic technologies, who have answered questions and followed up with further suggestions. Thanks to Bergit Svenning and the other workers from Statnett´s office in Bjerkvik, who put together a field trip to Narvik so that I could observe the construction process, and a special thanks to Rebaioli SPA with Fabio Frassini who guided me around the construction sites.

Special thanks to my main supervisor Sonja Berlijn and my supervisor at Statnett, Matthias Hofmann who have provided great advises, opened doors and guided me through my thesis.

After five years of study at the university, I would also like to thank friends, family and university staff who have contributed to make this the best years of my life (at least so far)!

Oslo, 16th of May 2016

Jørgen Tideman Retvedt

Summary

Background of the project

Health, safety and the environment (HSE) is Statnett´s nr.1 priority and Statnett has a zero vision towards accidents. Unfortunately, Statnett and their entrepreneurs experience accidents each year. With an increasing activity level towards 2020, it is natural to estimate that the number of accidents will increase in line with the activity. It can therefore be interesting to study new technologies with high potential to reduce risk, if it is rapidly implemented.

Goals

There were three goals with this thesis. The first was to identify robotic technologies, available now or within a five-year period with potential for use in Statnett. The second goal was to identify dangerous operations performed by Statnett or Statnett´s entrepreneurs. The third goal was to provide a recommendation of which robotic technologies that can both execute the identified operations and reduce the risks of the operations.

General information about the thesis

This report was made as a master thesis at the end of a five-year study towards a Master's Degree in science at Norwegian University of Life Science(NMBU). The study was performed between January and May 2016, and represent 30 ECTS. The thesis is written under collaboration between Statnett and NMBU.

Method

This thesis is based on literature study, interviews, observations and data analysis.

Results

The main outcome was the following:

- There are many types of robotic technologies with different abilities and potential for implementation in Statnett and Statnett´s entrepreneurs, all with a high level of technology readiness(TRL) or already in use. There are however limitations with every type of robotic technologies, e.g. many of the line suspended robotic devices have problems crossing suspension towers and there is actually only one that is supposedly able to cross dead-end towers.
- There is no doubt that Statnett and their entrepreneurs perform dangerous operations. Many high risk operations are identified, but there are still reasons to believe that even more could be found. All of the identified operations contain different factors of risk. Some of the risk factors have led to tragic accidents ending with death or severe illness. The biggest identified risk factors are working with helicopter and working at height.
- There are several robotic technologies with the possibility to both perform and reduce the risk of some of the dangerous operations identified in this thesis.

Recommendation for further work

Based on the robotic technology with the highest potential to both execute operations and reduce the operations risks, eleven technologies are recommended for further research and development towards permanent implementation in specific operations.

Sammendrag

Bakgrunn for prosjektet

Helse, miljø og sikkerhet (HMS) er Statnetts topp prioritet. Statnett har en visjon om null ulykker, men opplever ulykker hvert år sammen med sine entreprenører. Frem mot 2020 er det planlagt økt aktivitet og det er derfor naturlig å anta at antall ulykker vil øke i takt med aktiviteten. Det kan derfor være interessant å se på ny teknologis mulighet til å redusere risiko, hvis det kan implementeres raskt.

Mål:

Oppgaven har tre mål. Det første er å identifisere robotteknologi tilgjengelig i dag eller innen en femårs periode med potensial for bruk i Statnett. Mål nummer to er å identifisere farlige operasjoner utført av Statnett eller deres entreprenører. Det siste målet er å gi en anbefaling av hvilken robotteknologi som har størst mulighet til å både utføre operasjonene samtidig som den kan redusere operasjonens risiko.

Generell informasjon om oppgaven

Oppgaven er skrevet som en masteroppgave i siste semester av et femårig masterstudie på Norges miljø- og biovitenskapelige universitet (NMBU). Oppgaven representerer 30 studiepoeng og er skrevet som et samarbeid mellom Statnett og NMBU.

Metode

Oppgaven er basert på litteratur, intervjuer, observasjoner og analyse av innsamlet data.

Resultat

Hovedresultatene var som følger:

- Det er identifisert mange typer robotteknologi med forskjellige anvendelser og potensial for implementering hos Statnett og Statnetts entreprenører. Alle teknologiene var langt i utviklingen, høy ”technology readiness level” (TRL), eller var allerede i bruk. Det var like vell utfordringer med alle teknologiene, som f.eks. at få ”line suspended robotic devices” kan krysse bæremaster og at det faktisk bare er en som skal klare å krysse ankermaster.
- Det er ingen tvil om at Statnett og deres entreprenører utfører farlige operasjoner. Det er identifisert mange høy risiko operasjoner, men det er fortsatt grunn til å tro at enda flere kan identifiseres ved et grundigere studium. Alle operasjonene inneholder forskjellige risikofaktorer og noen av risikofaktorene har ført til tragiske ulykker som har endt med død eller alvorlige skader. De største risikofaktorene er identifisert som bruk av helikopter og arbeid i høyden.
- Det er identifisert flere robotteknologier med potensial for å både kunne utføre og redusere risikoen til noen av de identifiserte operasjonene.

Anbefaling for videre arbeid

Basert på den robotteknologien med høyest potensial for å bade utføre og redusere risikoen til noen av de identifiserte operasjonene er elleve teknologier anbefalt for videre arbeid.

Table of contents

List of figures

List of tables

Abbreviations

Acronym	**Definition**
ACSR	Aluminium Conductor Steel Reinforced
ACSS	Aluminium Conductor Steel Supported
BLOS	Beyond Line of Sight
BVLOS	Beyond Visual Line of Sight
FLIR	Forward Looking Infrared System
HSE	Health, Safety and Environment
LIDAR	Light Detection And Ranging
OPGW	Optical Ground Wires
R&D	Research and development
ROV	Remotely Operated Underwater Vehicle
RPAS	Remotely Piloted Aircraft System
T&D	Transmission and distribution
TRL	Technology Readiness Level
TSO	Transmission System Operator
UAV	Unmanned Aerial Vehicle

1 Introduction

1.1 Background

The Norwegian transmission system operator (TSO), Statnett SF have recently started on a large scale development and upgrade of the national power grid, both on lines within Norway and abroad to neighbouring countries [1]. Health, safety and the environment (HSE) is Statnett´s nr.1 priority so new technology and methods have great potential to reduce risks, costs and time if it is implemented before the development period ends in 2020 [1, 2].

Since Statnett is a state enterprise the new development and upgrade is based on what is best for the Norwegian society. This makes safety of the workers, impact on the environment, construction costs and construction time key factors during Statnett´s planning of the future power grid. Due to the confined amount of entrepreneurs for construction of power lines the competition for each project can be limited [3]. This can undermine Statnett´s focus if the few entrepreneurs are more concentrated on high profits than on completing Statnett´s goals within HSE. Furthermore, some of the operations that might be necessary during a construction period are so specific that there are limitations regarding qualified personnel and methods [3]. Implementation of robotic technology might have the ability to introduce new working methods, reduced risk and accelerate construction while still keeping the costs down.

Even though robots and robotic technology have been used in large scale by other sectors like the car industry for decades now, TSOs experience is limited [4]. Statnett have focused their use of robotic technology on deep water operations with ROV. The robotic technology with potential for the transmission and distribution industry is spread over a large spectre of classifications and are somewhat young, with many developers, making it time-consuming to find all the specifics details for every type of technology. Therefore, the technology in this thesis is meant as an indication and recommendation for further work.

1.2 Goals

This thesis goals are three parted, whereas the main goal is based on the two secondary goals. The first goal is to identify robotic technologies, available now or within a five-year period with potential for use in Statnett and Statnett´s entrepreneurs. The second goal is to identify dangerous operations, with risk of causing harm to personnel, performed by Statnett or Statnett´s entrepreneurs. The third goal is to provide a ranking of which robotic technologies that can both execute the identified operations and reduce the risks of the same operations.

Note that this thesis does not look at implementation or business cases, which is a logical next step.

1.3 Research methods

The first two goals are meant to identify robotic technologies and dangerous operations. Therefore, the focus is to identify as many technologies and dangerous operations as possible, without digging too deep into each technology or operation. However, the identified information is specific enough to provide a recommendation of which technology that provides the highest probability to perform and reduce risks of the operations.

The thesis is based on literature, statistics and personal communication, together with the authors observations and experience. The analysis is performed using tables to compare differences between the operations or technologies. Since the results are three-parted, different sources and methods are used to achieve them. More details of the methods are described under each of the chapters; ”Robotic technology”, “Dangerous Operations” and “Implementing robotic technology”.

1.4 Structure of the report

Definitions and description of the methods used to obtain the results are found in each relevant chapter. The chapters containing results are “Robotic technology”, “Dangerous operations” and Implementing robotic technology”. The Robotic technology chapter list all of the identified robotic technologies. The chapter Dangerous operations identifies risk factors and list all of the identified operations, before the risk factors of each operation is determined. In the chapter Implementing robotic technology, robotic technologies with the possibility to perform the dangerous operations are identified. Thereafter, the technology and operations with highest potential to reduce risks are ranked. In the chapter Discussion the results are discussed together with the method and sources. The conclusions and recommendations for further work are found in the chapter Conclusion and further work.

2 Robotic technology

2.1 Definition of robotic technologies

This thesis identifies robotic technologies and devices with potential applications for Statnett. The terms robotic technology and robotic devices are used interchangeable in this thesis. Robotic devices and -technologies are for the sake of this thesis defined, based on EFLAs definitions in a report for Statnett, [5]:

– A physical equipment for repeated use having

- A programmable computer based control system
- Sensors to respond to the environment
- Mechanical parts to either move or perform operations

Note that the definition of robotic devices has no requirement for autonomous operation as that would exclude most of the devices being used and researched for the transmission and distribution industry. Fully- and semi-autonomous robotic devices are in this thesis referred to as robots to show that they have autonomous abilities.

This thesis excludes robotic technology such as stand-alone robotic arms, industry robotics, military robotics, standalone programs and toys.

Sensors are a huge part of the robotic technology, but not a robotic technology in its self. This thesis does not look specific at sensor technology. Even so, sensors are mentioned as parts of the devices and are often interchangeable.

2.2 Method used to identify robotic technology

The robotic technology in this thesis is primarily identified through literature study, albeit some new devices are discovered through interviews and meetings with employees at Statnett, through skype, telephone, email correspondence or in person. Some of the technologies are found as a result of a blog post on Statnett´s internal blog system. There have also been sent out a request for information to obtain information about new technology and providers of services with the use of robotic technology. If more specific details where needed, they were found through e-mail correspondences with personnel specialised on the specific device and through search of literature in Statnett´s databases, Google, BIBSYS brage, Oria and IEEE Xplore.

When the robotic technology is identified, the technology readiness level(TRL), described below, is estimated and the device is classified in one of the following types of robotic technology:

- Line suspended robotic devices
- Unmanned Aerial Vehicles (UAV)
- Unmanned underwater Vehicles (ROV and AUV)
- Ground based robots
- Climbing robotic devices
- Other types of robotic technology

Some of the technologies identified during the study process do not fit the definition of robotic technology. This technology might however be useful and are therefore listed in Appendix A.

Technology readiness level [6]

Often shortened and used in the form TRL is a method to evaluate how mature a technology in research and development is. TRL describes the level of readiness, where a new level is achieved when all criteria on the current level is fulfilled. Different designers and areas of applications have different approaches on TRL. However, TRL is in this thesis based on Statnett's research and development department's approach. The different levels with overall criteria are described in Figure 2.1.

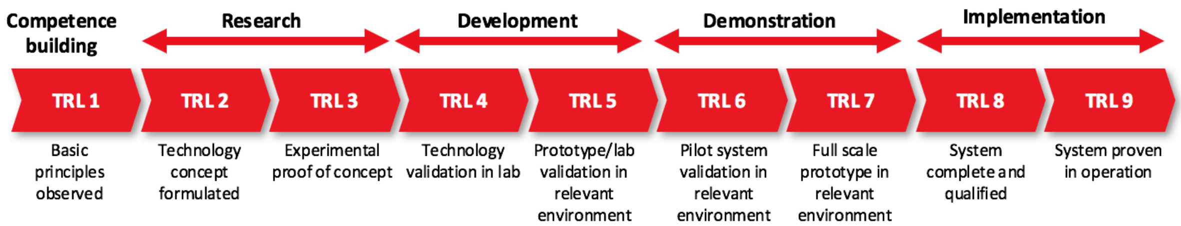

Figure 2.1: Description of the criteria's for the different technology readiness level

2.3 Line Suspended Robotic Devices

Robotic devices that are suspended on the phase conductors or ground wires are called line suspended robotic devices. There are different technological approaches to line suspended robotic devices and they are able to perform different tasks. In this section some examples of line suspended robotic devices are described.

Installation of fibre optic cable on existing wires

The company AFL have developed a robotic device called SkyWrap® (see Figure 2.2) to install fiber optic cables along overhead power lines by wrapping cable around already existing ground wires or phase conductors [7]. The cable can be installed on the ground wires under live conditions and have according to an AFL Project Manager been used at a 500 kV utility in California [8]. SkyWrap has also been used by the Swedish TSO [9].

Figure 2.2: SkyWrap® wrapping a fiber optic cable around a conductor. Photo by permission of AFL

Replacement of existing ground wires using cradle block method during live conditions.

Both ZECK GmbH and Hydro-Québec have developed line suspended robotic devices for replacement of existing ground wires by new optical ground wire (OPGW) under live conditions, using the cradle block method [10, 11]. Figure 2.3 show ZECK´s LKE 85 Pulling Robot moving along an existing ground wire while pulling a fiber rope with cradle blocks. In this method the cradle blocks are mounted at suitable distances on the fibre rope and placed along the ground wire [10].When the operator has placed cradle blocks all the way along the ground wire, a second rope is pulled through the other end of the cradle blocks using a puller [10]. This second rope is then connected to the OPGW who is pulled through the cradle blocks and over the span [10]. Both devices must be operated through a remote radio controller [10, 11].

Figure 2.3: LKE 85 Pulling robot for replacement of ground wires. Photo by permission of Zeck.

De-icing of ground wires and conductors [11].

Hydro-Québec designed a remotely operated robotic device called LineROVer for de-icing of ground wires and conductors, shown in Figure 2.4 . LineROVer is able to work on conductors with a diameter between 10 to 37 mm, it is electromagnetic immune up to 315 kV and 1000 A, but it is only made to operate down to a temperature of -10 °C.

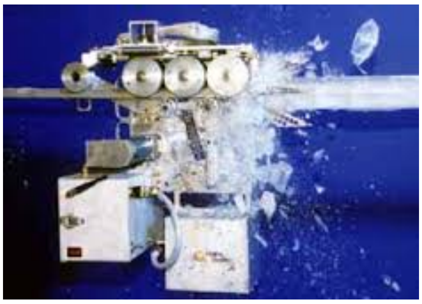

Figure 2.4: LineROVer by Hydro-Québec de-icing a ground wire. Photo by permission from Hydro-Québec.

Line inspection

There are several designs for line suspended robotic devices made for inspection and their inspection methods vary. Table 2.1 shows an overview of some robotic devices with their inspections abilities. Most of them are able to pass over small obstacles like splices, but the Transmission Line Inspection Robot from grid operator Transpower New Zealand is the only one designed to pass anchor towers [12, 10, 11, 13, 14]. Transpower´s robotic device is lightweight; only 20 kg, and designed to use jumper cables for safely deployment onto a live line via a hot stick, as shown in upper right picture in Figure 2.5 [12]. LineScout from the transmission operator Hydro-Québec, shown in the lower right picture in Figure 2.5 and Expliner developed by the company HiBot are able to cross suspension towers [12, 14].

ROBHOT™ by Power Inspection Sweden AB measure electrical resistance in phase conductor joints under live conditions while being hung below a helicopter as shown in the left picture at Figure 2.5 [15]. The device is placed on the conductors and moves along a span with the use of its own motors, while still being connected to the helicopter through the ropes [16]. Because the device is always connected to the helicopter, it is possible to fly it over to the next span [17]. ROBHOT™ is commercially available and have been used by the Swedish TSO, Svenska Kraftnät [15].

Figure 2.5: Left: Power Inspection Swedens ROBHOT™ for measuring electrical resistance in phase conductor joints under live conditions. Photo by permission from Power Inspection Sweden AB
Top right: Transmission Line Inspection Robot from Transpower New Zealand Ltd. Image by permission from Transpower.
Down right: LineScout from Hydro-Québec crossing an insulator string. Photo by permission from Hydro-Québec.

The company Kinectrics have made a remote controlled robotic device, LineVue™ able to measure the loss of metallic area to determine the remaining cross-sectional area of the steel core wires in conductors to determine the conductors condition [18]. The device was also made to detect local breaks and deep pits in the steel core wires [18].

Shannon Developments Corp. have developed a conductor corrosion assessment system for conductors by measuring the volume of galvanizing on the steel core bundle [19]. To move along the conductor, the instrument is placed on a small trolley with a sensor coil behind and a remotely controlled tug to pull it in front [19].

Table 2.1: Some robotic devices and their abilities within inspection.

Name	Producers	Visual inspection	Infrared inspection	Measurement of electrical resistance in splices	Corrosion detection within conductors	Electro-magnetic immunity
LineScout	Hydro-Québec	Yes	Yes	Yes	Yes (with LineCore [20])	735 kV/ 1000 A
LineROVer	Hydro-Québec	Yes	Yes	Yes	No	315 kV/ 1000 A
ROBHOT™	Power Inspection Sweden AB	No	No	Yes	No	
Expliner	HiBot	Yes	No	No	Yes	500 kV
Transmission line inspection robot	Transpower New Zealand	Yes	Yes	Yes	No	
LineVue™	Kinectrics	Yes	No	No	Yes	
Conductor Corrosion Assessment System	Shannon Developments Corp.	No	No	No	Yes	

Temporary repairs [13]
LineScout by Hydro-Québec, shown in lower right picture in Figure 2.5 is also able to make temporary repairs. The device is equipped with a 3-axis robotic arm carrying a pointable camera at one end and a mount for equipment at the other. LineScout is able to tightening and loosening of bolted assemblies, and make temporary repairs of broken conductor strands.

Cleaning of conductors [11]
Hydro-Québec have also written in their factsheet that cleaning of conductors are an application under study for LineROVer. LineROVer is shown in Figure 2.4.

2.4 Unmanned Aerial Vehicles (UAV)

This section focus on Unmanned Aerial Vehicles (UAV) or drones as it is more commonly called. UAVs have with its rapid improvements conquered new markets over the last years and the transmission and distribution industry could be the next big market. UAVs vary in shape and size from small helicopters like Black Hornet at 18 grams to large fixed wings like global hawk with a gross take-off weight of over 14 tons [21, 22]. They are classified into different categories depending on design. Some UAVs are called fixed wing because they are designed like an airplane with two wings, and they use of forward speed to gain height [23]. This means that it depends on movement to maintain lift. There are also UAVs designed with the ability to hover, like unmanned helicopters and multicopters with more rotors [24]. UAVs are also classified on the way they are operated, whether it is through Visual Line of Sight (VLOS) or flying Beyond Visual Line of Sight(BVLOS) [25].

Vegetation encroachment monitoring [26]

Delair-tech provides a package consisting of a fixed wing UAV operated BVLOS and an analytic software with the ability to analyse vegetation encroachment from images captured from the UAV. Transmission lines are one of the areas where the package can be used. First the UAV have to fly over the area to capture data, then the software will generate reports on the vegetation encroachment. The report includes location of encroachment, the distance from vegetation to infrastructure, and the amount of vegetation needed to be cut. Delair-tech provides two different UAVs, where the largest one can fly for two and a half hours and has a range of 150 km. Figure 2.6 show how Delair-techs software present the output with colour marking of the monitored landscape surrounding the line.

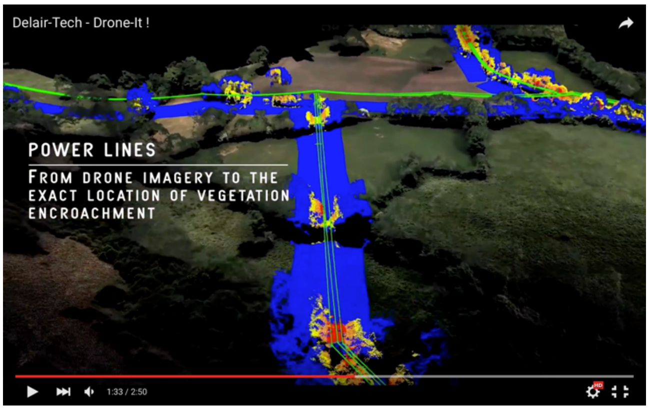

Figure 2.6: Vegetation encroachment monitoring by Delair-tech. Photo from YouTube by permission from Delair-tech.

Tower and line inspection

There are now a few providers of tower and line inspection using UAVs. Most of the UAVs can be equipped with cameras, but the Swedish TSO, Svenska Kraftnät concluded that other lenses than wide-angle lenses must be used because of the distortion it creates [27]. Some providers like Orbiton (down right in Figure 2.7) can equip their UAVs with thermal sensors and GPS for precise localization of sensor data [28]. Hålogaland Kraft, a Norwegian power supplier (down left in Figure 2.7) and Møre UAS (up right in Figure 2.7) are two of the providers of services within inspection and photography using UAVs [29, 30]. They are certified to operate and educate pilots for missions beyond visual line of sight (BVLOS) [29, 30]. Another provider of inspection services are Cyberhawk (up left in Figure 2.7) who claims to have inspected thousands of transmission and distribution towers in the United Kingdom [31]. To inspect towers and lines, UAVs with the possibility to hover close to the inspection area might be favoured because of the increase in photo quality. Fixed wing drones have the ability to rapidly reach a site during difficult weather conditions, returning important information to the operator.

Figure 2.7: ***Up left:*** *Cyberhawk performing aerial inspection of a transmission tower using an UAV. Photo by permission of Cyberhawk.*
Down left: *One of Hålogaland Kraft AIRs UAVs performing a tower top inspection. Photo by permission of Hålogaland Kraft.*
Up right: *Møre UAS making an UAV ready for tower inspection. Photo by permission of Møre UAS.*
Down right: *Orbitons RPAS inspecting a transmission line. Photo by permission of Orbiton.*

Aerial survey
One of the more common applications of drones are aerial survey with companies like Cyberhawk (up left in Figure 2.7) and Hålogaland Kraft AIR (down left in Figure 2.7) offering survey applications within [32, 29]:

- Orthophoto
- Topographic surveys
- Volumetric analysis

Obstacle avoidance
The companies Intel and Ascending Technologies have developed UAVs with obstacle avoidance [33]. The technology is based on a UAV equipped with cameras that detect obstacles plus powerful hardware and software that calculates new movements [33]. Unmanned full-scale helicopters have also been successfully tested on autonomous landing using obstacle detection and avoidance [34].

Pulling of pilot line [35]
Statnett have tested multicopters to pull out and place pilot lines on towers. The UAVs tested went through the tower instead of treading a needle through. There are still room for improvement when placing the pilot line at the right spot, even though the different UAVs where able to perform the task. Figure 2.8 shows a UAV pulling and placing a pilot line on a temporary tower construction during a test performed for Statnett.

Figure 2.8: UAV placing a pilot line in a temporary tower. Photo with permission by Knut Stabell, captured on the 27th of april 2016 at Sørkedalen during the testing of UAVs to pull pilot lines. UAV operator was Nordic Unmanned.

2.5 Unmanned underwater Vehicles

The development for unmanned underwater vehicles have been going on for a while in oil and gas companies, due to difficulties related with deep diving [36]. Remotely operated underwater vehicles (ROV) have already been implemented by Statnett in construction and inspection projects with underwater cables [37]. The list below include some of the different approaches of unmanned underwater vehicles.

Survey and inspection

Today Statnett performs underwater route surveys using ROVs in the planning period and as a last check right before cabling [37]. They also use a ROV to survey after the cable is buried down [37]. Sometimes ROVs are used to take samples from the seabed and measure the resistivity during the planning period [37]. Until 2014 Statnett used work-ROVs with a speed of 0.7 knot for inspection of existing subsea cables [38]. Statnett writes in an internal report, with a reference to the company MMT's commercial for their survey ROV called Interceptor, that it is able to gather data at 6 knot, while an autonomous underwater vehicle (AUV) will have an operational speed between 3.6 and 4 knot [38]. The report also suggest that an AUV might be used from a fishing vessel which will result in lower cost of renting a vessel [38].

Cabling [37]

Sometimes the length and weigh of the cable makes it too difficult to lay in one length, the cable is therefore produced and laid in shorter lengths that needs to be jointed. To join the two cables a ROV is used to retrieve the old piece up from the seabed. ROVs are also used to place the cable at a wanted location by moving just above the seabed and adjusting the cable right before it falls down on the seabed.

Underwater trenching

To protect the cable, it is often buried under the seabed [37]. There are several providers of underwater trenching machines and one example of a trenching ROV is Capjet®, shown in Figure 2.9 [39]. Capjet use high preasure water jets on both sides of the cable so that the soil is removed and a trench is made [39]. The cable falls down into the trench and the trench is then filled again as the fluidised materials falls down again [39].

Figure 2.9: Capjet burying a cable. Graphic by permission of Nexans.

Rock burying of cables [37]

Sometimes the cable is buried with rocks to protect it. This is done with a vessel carrying rocks and a pipe leading the rocks down to the cable. A ROV is placed at the outlet of the pipe to control the placement of the filling mass.

2.6 Ground Based Robotic Devices

This section lists some of the different remotely controlled or autonomous devices traveling on the ground. Remotely controlled ground based vehicles are quite common due to toys like radio controlled cars, but this section only list professional equipment with possible implementation in the transmission and distribution industry.

De-Icing Vehicle [40]

Hydro-Québec have also made Remotely Operated De-icing All-weather Vehicle (RODAV) for de-icing substation disconnectors and other equipment under live conditions up to 330 kV using superheated steam. The steam is led through an insulated hose on a 16 meter long non-conductive telescope mast mounted on a truck. The unit is operated through a remote control with a range of 300 meter. Figure 2.10 show a picture of RODAV.

Figure 2.10: Remotely Operated De-icing All-weather Vehicle by Hydro-Québec. Photo by permission of Hydro-Québec.

Remote controlled construction machinery

Specto Remote AS provides a solution for remote control of dump trucks and excavators, and they claim that their solution can be tailor-made to most vehicles [41]. The solution consist of live video feed and customized chairs so the operator can work from a safe location and they also have a solution for autonomous driving of dump trucks via GPS navigation [41]. An article in the Norwegian magazine Vi Menn showed how Gjermundshaug Anlegg AS cleared a closed artillery range at Hjerkinn for mines and unexploded bombs using remote controlled vehicles [42]. Figure 2.11 show an excavator being remotely controlled from a secure room with customized chairs.

Figure 2.11: Operators from Gjermundshaug Anlegg AS remotely controlling construction machinery from the marked hilltop in the background. Photo: © Harald Grevskott, Vi Menn Magazine.

Self driving cars

Figure 2.12: Googles self-driving car manovering in traffic by itself. Photo by Grendelkhan, via Wikimedia Commons

Google, among others are developing fully-autonomous cars like the one in Figure 2.12 [43]. The car uses sensors to spot objects like pedestrians, cyclists and vehicles, and then calculate a safely route around [43]. According to an article at recode.net the self-driving car project director Chris Urmson plan to release the autonomous car to the public by 2020 [44]. Half-autonomous cars or semi-autonomous as they are also called are already on the market providing different level of sensor technology. Most of the vehicles have sensors that enables the car to follow the vehicle in front on highways and stay within the marked lane without the driver touching the steering wheel, accelerator or brake [45]. This technology demand that the driver follows every action so that he or she can intervene if necessary [45]. Collision warning with auto brake is also an extra feature on new cars that uses sensors to detect when a collision is likely and warning the driver if there is time or simply brake by itself if necessary [46].

Substation robotics

Figure 2.13: Transpowers Substation Robot with its arm raised for a better camera view. Photo by permission of Transpower New Zealand.

Transpower New Zealand have also developed a substation robotic device, shown in Figure 2.13, to undertake assessments and deliver live video of remote substations captured with video cameras mounted at an arm that can be raised up to 1.8 m and sent back to a regional operator, who control the vehicle through a computer [47]. It is made with four-wheel-drive to traverse across the rugged external surface of a substation so that it can observe all of the equipment present and to provide services like remote switching assistance, condition surveillance, construction and maintenance witnessing and visual imagery for training [47]. Transpower also mention implementing a way pointing system, allowing the vehicle to drive around the switchyard automatically in the future [47]. Other inspection vehicles that might be used at remote substations are robotic vehicles made for bomb disposal. The company Endeavor Robotics is one producer of such robotics and some of their devices are made with tracks instead of wheels that allows it to climb stairs and drive through difficult terrain [48].

2.7 Climbing robotic devices

This section list robotic devices with the possibility to climb on vertical surfaces or other constructions like poles.

Snake-like robotics

There are numerous types of snake-like robotic devices and they can use their many internal degrees of freedom to pass through small volumes and access difficult locations [49]. One example of a device is the Skin Drive Snake from Carnegie Mellon University (CMU) which claims to have high speed and mobility due to a technology that let the entire surface of the robot provide continuous propulsive force [50]. The Norwegian University of Science and Technology together with SINTEF are developing a device for pipe inspection using joint modules, motorized by wheels [51]. The pipe inspection device can be seen in Figure 2.14. CMU have also developed another snake-like robotic device with the abilities of [52]:

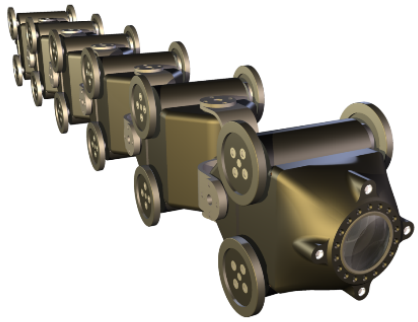

Figure 2.14: NTNU and SINTEFs pipe inspection device. Photo by permission of ROBOTNOR/SINTEF

- Linear progression
- Sidewinding
- Swimming
- Channel climbing
- Pipe/tube climbing
- Pole climbing
- Cornering
- Pipe rolling

Window cleaner robots [53]

There are now robots for window cleaning meant for professionals as well as for ordinary consumers. The larger professional ones as the GEKKO Facade from SERBOT AG needs to be fastened with a rope from a higher point using a cherry picker or a monorail from the top of the building as shown in Figure 2.15. The GEKKO robot attach itself to smooth surfaces like windows using vacuum and have the ability to turn and move in any direction. The robot has the possibility of fully automated deployment and washing so there is no need for an operator. It is however able to be remotely controlled through a radio controller, if wanted.

Figure 2.15: GEKKO Facade performing window cleaning. The robot is fastened with a rope from the top of the building. Photo by permission of SERBOT AG

2.8 Other types of robotic technology

Not all of the robotic devices identified in this thesis classify as the types of technology listed in the sections above. So in this section, other robotic technologies are listed.

Static robotic devices [54]

Statnett is working on a project for easier mounting and demounting of aerial markers. This will be a robotic device, hung under a helicopter, that surround the aerial marker while tightening and untightening the bolts that screw the marker sphere tight on to the ground wire. The device will also be able to carry the markers to and from the lines. This device will however not be able to move on the wires in the same way that the ROBHOT™ does.

Exoskeleton

External robotic skeleton used to increase strength, condition and support of humans. Many of the exoskeletons are made to help disabled walk or for use in the military industry [5]. However, Lockheed Martin is developing an exoskeleton for other markets [55]. Typical applications for exoskeletons are increase of lift support allowing more weight in a backpack when walking long distances, increased strength when lifting heavy boxes or equipment, as seen in Figure 2.16 and increased strength to support equipment during work [55, 56]. Most of the exoskeletons are under development, although some are already being used within other sectors then the transmission and distribution industry [57].

Figure 2.16: Lockheed Martins HULC exoskeleton with Lift Assist Device. Photo by permission from Lockheed Martin.

2.9 Summary

Many of the identified robotic devices are meant for other industries than the transmission and distribution (T&D) industry. Therefore, they might have a high technology readiness level (TRL) for that industry, but a lower one for the T&D industry. Table 2.2 show the different robotic technologies with their TRL level for use in the T&D industry. The reason why many of the technologies are listed on a wide span of TRL levels are because of the amount of identified devices in different stages of development or implementation, and the devices differences in applications. Some of the devices within a robotic technology are still under research or development, while other devices have been on the market for years. This thesis has focused on identifying technologies with a high TRL and that is why only a few technologies are listed in the research phase of the table.

Table 2.2: TRL for different robotic technologies for use in the T&D industry

Line suspended									
Fixed wing UAV									
Multirotor UAV									
Helicopter UAV									
ROV									
AUV									
De-icing vehicle									
Construction machinery									
Self-driving cars									
Substation robotics									
Snake-like robotics									
Window cleaner robots									
Static robotic devices									
Exoskeletons									
	TRL 1	**TRL 2**	**TRL 3**	**TRL 4**	**TRL 5**	**TRL 6**	**TRL 7**	**TRL 8**	**TRL 9**
	Competence building	**Research**		**Development**		**Demonstration**		**Implementation**	

Line suspended robotic devices
There are now a few line suspended robotic devices already on the market and some of them have been there for some years, like SkyWrap® first installed in 1982, shown in Figure 2.2, who wrap fibre optic cable around existing ground wires [58]. Most of the robotic devices are made for specific tasks like inspection or mechanical work as de-icing under live conditions. There are still devices like LineScout who can perform simple mechanical tasks including tightening of bolts and perform detailed inspection at the same time. Most of the robotic devices cannot cross towers yet, but the Transmission Line Inspection Robot from Transpower New Zealand is said to be able to cross dead end towers when it is commercially available [12]. Development of new line suspended robotic devices has a slow line of progress and there are not that many institutions working on this very specialized field of robotics.

UAV
UAVs evolve every year and have many applications that are useful for the power grid operators. Flight time, size, speed, operation method, etc. differ between models, hence some types of UAVs are more suitable for some tasks than other. Some UAVs are capable of hovering while others fly fast and long distances. Applications available include vegetation encroachment monitoring, survey, inspection of lines and towers, and obstacle avoidance. Furthermore, pulling of pilot lines has been field tested by Statnett [35].

Unmanned underwater vehicles
Statnett have already implemented ROVs in their underwater cable projects within inspection, survey, cabling, or trenching of the cable [37]. Still there are new technology to consider, like autonomous underwater vehicles (AUV) which operate without intervention of an operator.

Ground based robotic devices
Some of the more publicly known research areas within ground based robotic devices are self-driving cars, but there are plenty of other applications within the area [43]. There are trucks with remotely operated de-icing equipment mounted, remotely controlled vehicles for inspection of substations, and construction machinery rebuilt as remotely controlled [40, 41].

Climbing robotic devices
There are already robots for window cleaning, and snake-like robotics able to access locations that are otherwise impossible to use [53, 52].

Other types of robotic technology
There are many varieties of robotic technology and their applications are many. Statnett’s working on a robotic device to mount aerial markers, while Lockheed Martin are developing exoskeletons to increase humans lift capacity [54, 55].

3 Dangerous operations

3.1 Definition of dangerous operations

In this thesis risk is defined by Statnett´s definition “The probability that conditions or an incident may occur, and the consequences of that condition and incident occurring.” [59]

For the sake of this thesis the definition of a dangerous operation is an operation involving a high level of risk. Operations listed have already led to incidents or conditions that can and sometimes have caused consequences.

3.2 Method

Dangerous operations are identified through different sources. Numerous interviews and meetings over telephone, skype and in person with personnel at Statnett and Statnett´s entrepreneurs have led to discoveries of dangerous operations. There are also observations after a field trip to construction sites in Narvik, Norway, guided by personnel from both Statnett and the construction entrepreneur. Many dangerous operations are found from Statnett´s reporting system “Bedre”, where incidents or conditions that might lead to incidents are reported. Some of the operations are acquired as a result of a blog post on Statnett´s internal blog system. Where all employees were asked to report if they knew about any dangerous operations. Incidents and operation methods are further searched for in google, BIBSYS Brage, Oria and IEEE xplore.

Some of the discoveries found along the way do not suit the definitions of this thesis, but are listed in Appendix B as they might be useful for further work later.

3.3 Risk factors

Statnett with entrepreneurs are involved in many dangerous operations and accidents leading to deaths occurs from time to time [60]. The HSE department at Statnett have made a risk matrix that indicates which areas that involve high risk based on consequence and probability [61]. There are factors remarking themselves with higher risk than others, like helicopters, work in height, traffic, machines, electricity and stress. Even though these factors are listed separately, one specific operation can include several factors, leading to higher risk. Statnett´s risk matrix is restricted for Statnett employees. Even so, some of the information are allowed to use publicly and Figure 3.1 is based on Statnett´s matrix. In the figure, risk factors are plotted; presenting the amount of risk they involve.

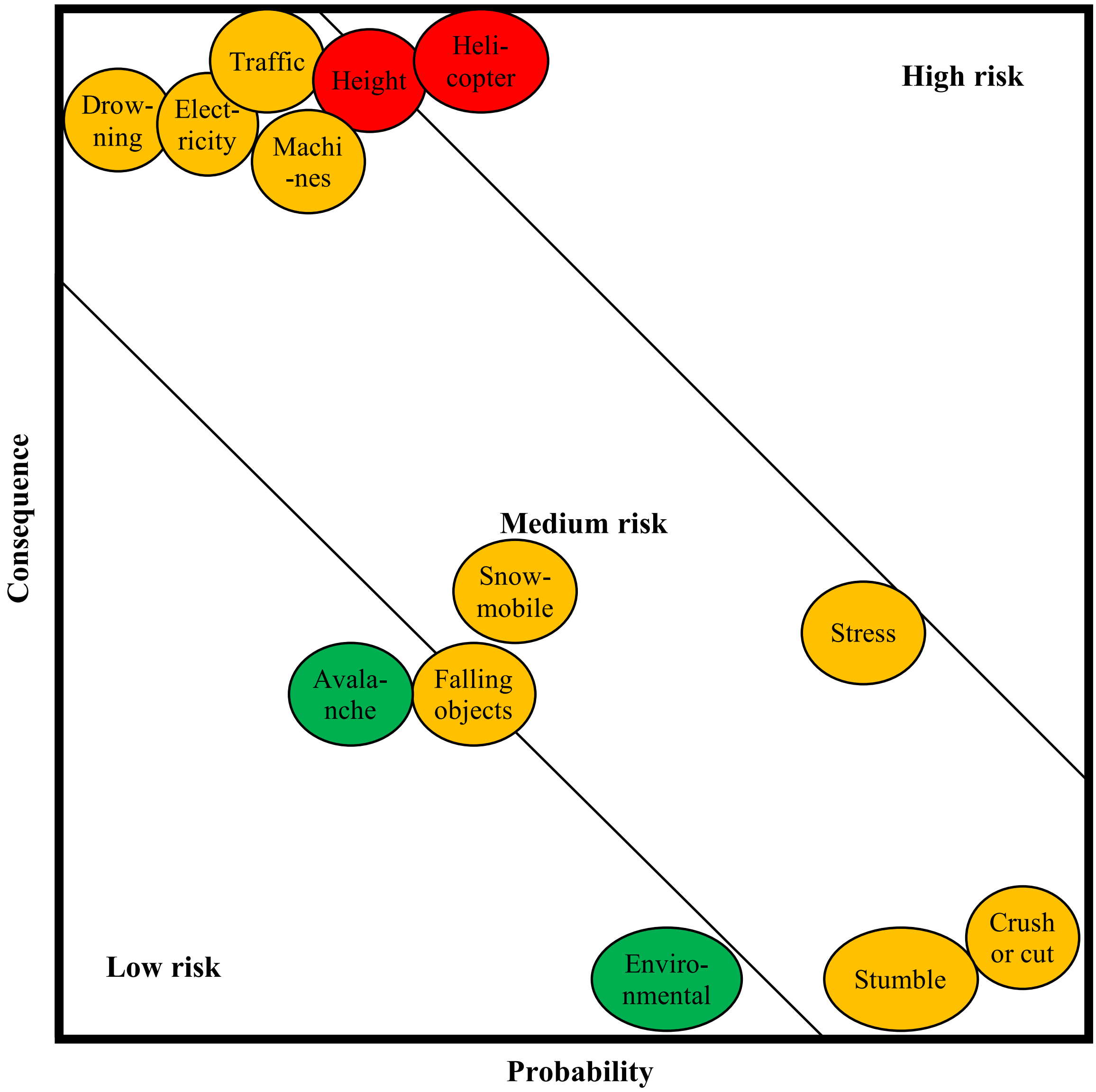

Figure 3.1: Risk plot. Presenting the amount of risk different factors involve. Red colour equal high risk, orange is medium risk while green is low risk.

3.4 General operations

Many of the identified operations are carried out in several of the categories listed below. Therefore, this section list some of the operations that covers several of the operations in the categories of construction and dismounting, maintenance and inspection.

Transportation with ground based vehicles

Transportation to/from work and during the working hours entails risk and there are plenty examples of situations that could and have gone wrong at Statnett´s registration system, Bedre [62, 63, 64, 65, 66, 67, 68, 69, 70, 71]. Sometimes animals like reindeers or wild boars crosses the road, causing dangerous situations [71, 66]. In my experience some of the contractors sometimes drive carelessly on dirt roads, too fast to stop if someone approach from around a corner and they do not always try to avoid or slow down before potholes [72]. This can cause extra risk to the driver, passengers, people and animals walking on the road, and in the end it can lead to more wear on the cars.

Snowmobiles as the one shown in Figure 3.2 are used in means of transport to remote areas. Incidents involving snowmobiles are overrepresented in the statistics at Bedre [73, 74, 75, 76, 77, 78]. Snowmobiles are able to drive on open snow terrain at high speed. It is therefore important to have good visibility of the path. Sometimes the conditions are similar to a light "white-out" and contours in the terrain becomes difficult to spot leading the snowmobile to overturn [77, 76]. Snowmobiles are quite different to drive than a car and it requires a special certificate [79]. There are also accidents related to mechanical failure on the snowmobile reported in Bedre [74, 75].

Figure 3.2: Snowmobile. Photo by Johan Wildhagen. © Statnett

Transportation in difficult weather

High voltage power lines are often placed on the highlands where the weather can change fast. Some of the places where Statnett builds are with restricted access and helicopter is used in means of transport [72]. Therefore, temporary cabins are installed as a security measure in case the workers are weather-bound [72]. During an inspection in the highland with snowmobiles, four men was caught off guard by bad weather and came apar [73]t. One man managed to find a road after five hours, two men dug themselves down for three hours before they found the way back to the starting point after ten hours out in the cold [73]. The fourth one stayed at the mountain for the whole night, with no other equipment than his clothes [73]. After this event GPS messengers with the ability to contact the rest of the team and emergency services where bought for the inspection crews [72]. Bad weather can also make driving difficult as described under the section Transportation with ground based vehicles.

Window washing

At Statnett´s head office in Nydalen, the windows are washed by a man in a cherry picker. This involves work in high heights and therefore the risk of falling down. The operation is shown in Figure 3.3.

Figure 3.3: Window washing at Statnett's head quarter in Nydalen, Oslo.

3.5 Construction and dismounting

Many operations are performed during construction and dismounting and this section describe some of the dangerous operations performed during these periods.

Land survey

The locations of the line and foundations are pinned after a survey [72]. This decision will decide how difficult and time consuming the laying of foundations and erection of towers will be [72]. The decision is based on premade maps together with surveys done by a helicopters or ground based personnel [80]. For the ground based personnel to to get to the locations, helicopters and ATVs are used [72]. The risk involved with helicopters are described in the section Helicopter transport. ATVs involve several risks like tilting in high speed or accidents due to bad road conditions [60].

Lift of heavy materials

To lift heavy materials cranes or other machines are used, sometimes with personnel at the ground to attach and detach the cargo [72]. Sometimes the cargo or lift equipment accidentally hit the personnel [81, 82, 83, 84]. In 2013 a man died in Kristiansand because a hydraulic pipe used to lift cargo snapped so that the lifting equipment felled down on a person’s head [84]. Communication can also be difficult as the operator of the lift often are placed inside the vehicle and the noise is too high to talk to the person who attach/detach the cargo [81]. In 2015 there was an incident where a 17-year old apprentice crushed his knee and broke his right leg on several places after a concrete element fell over him because of a misunderstanding in communication with the operator [81]. Figure 3.4 show a piece of a tower being lifted from the top of another tower piece with the use of helicopter.

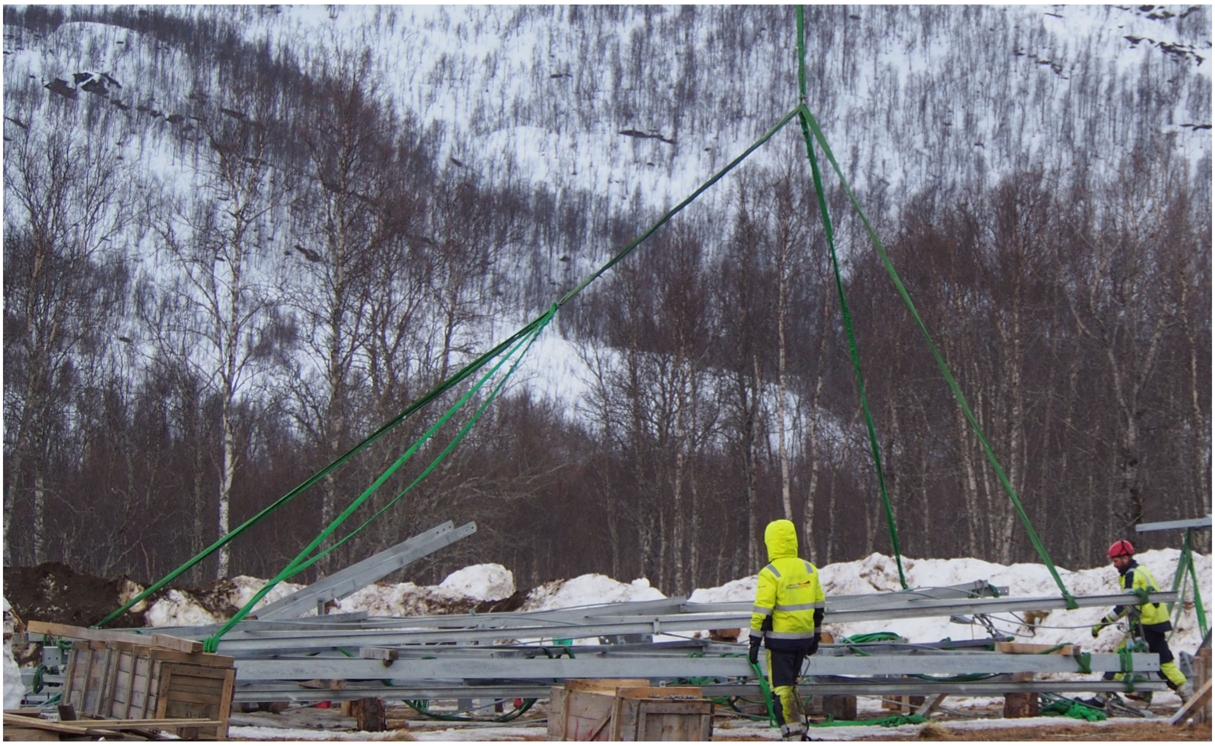

Figure 3.4: Tower-piece lifted from the top of another tower piece with the use of helicopter.

Helicopter transport

Because Statnett´s power lines are located on places with no other infrastructure, helicopter is a necessity. A study executed by Safetec Nordic AS for the Norwegian Ministry of Transport and Communications predicted that the total amount of accident for all helicopter operations in main-land Norway to be two in 2013, with at least 50 % probability of one death accident [85]. Note that this was only a prediction and that the amount of operations performed for Statnett are unknown. The same report does however estimate that around 40 % of the annual income of the 15 studied aerial work and personnel transport operators are from companies in the energy sector [85]. Further, the report write that in 2012 there where 17 accidents due to passenger transport and 23 accidents under transportation with underslung cargo [85]. Situations that might lead to accidents include weather conditions causing white out or simply that the pilot get tired and unfocused by flying the same transportation route over and over again [86].

There is also risk involved when cargo is getting attached to the helicopter. When the tower is stored in pieces on ground, the pieces lay on top of each other [72]. Because of their weight it is very important to fasten the pieces in the right way and on the right places so the helicopter do not lift two pieces at the same time [72]. Figure 3.4 show how a piece of a tower is lifted from the top of another tower-piece. During this procedure the communication between the pilot and the men on the ground are done by visual signs [72]. So the pilot need to have a good field of vision down to the men. There is also risk involved in reception of cargo. Often the cargo has a weight of around one ton and is received by men on the ground [72]. Therefore, the helicopters capacity to hover and make small movements are very important to make a safe delivery [72]. Under the section Tower erection risks involved in reception of cargo up in the towers are described and the left photo in Figure 3.8 show how it is done.

There have been cases where the helicopter have dropped its cargo during a flight as an result of an emergency manoeuvre to sustain the helicopters lift or as an failure [87, 88, 89, 90, 91]. It is also important to plan thoroughly where the helicopters fuel should be stored. There have been an incident where a flood caught the fuel barrels and left them out on a lake [86].

Under passenger transport some elements involving risks are related to communication due to limited line of sight and the fact that noise from the helicopter make vocal communication difficult [72]. It is also very important that all personnel on the ground bend down as the helicopter land or take off, and that persons moving towards or from a helicopter crawl, as seen in Figure 3.5 [72]. Sometimes the helicopters land on unstable ground like snow, which might fail to support the helicopter [80]. There might also be objects on ground that blow up because of the airstream from the rotors [72].

Figure 3.5: Personnel bending down as they walk out of a helicopter.

Foundation

Determination of the soil mechanics can be quite difficult and expensive, therefore every foundation is planned for two types of soil mechanics to prevent delay during the construction period [72, 86]. Laying of foundations also involves risk of falling from a height. The foundation is often buried down in a pit and homemade scaffolds made out of lumber are set up around [72]. To dig the pits, an all-terrain excavator, as shown in Figure 3.6 is used. Even though these excavators are made for steep terrain, there is always a risk of tilting and oil spillage [72].

Figure 3.6: All terrain excavator. Photo by Böhringer Friedrich, via Wikimedia Commons

The foundation can also be piled down in the bedrock, by manual labour and not by pile machinery due to the machine size and weight [72]. Liquid concrete used for the foundation is flown in by helicopter in buckets [72]. Because of the amount of concrete needed for the foundations the helicopter has to make many trips just for one foundation [72].

Foundation on steep hills

If the foundation is constructed on steep ground with difficult access, security measures must be made before the construction work begin [72]. This might include installing an iron path on the access trail as you can see in the left circle in Figure 3.7 [72]. In steep areas the need of extensive scaffolding as you can see in the right circle in Figure 3.7 will also be extra time consuming and risk full both to set up and during other work on the foundation, because of the limited space to move on [72].

Figure 3.7: Iron path in the left blue circle (edited for higher contrast) and scaffolds in the right circle for construction of foundation. The concrete columns are also elevated on each leg to resist avalanches.

Tower erection

There are many operations related to tower erection that involves risk and injuries do happen [92, 93, 94, 95]. In Statnett´s reporting system Bedre there are several examples of crush injuries related to tower erection [92, 93, 94, 95]. The towers are flown to site in pieces of around one ton by helicopters and mounted on top of each other [72]. The helicopter lift the piece close to where it shall be assembled and workers, climbed up in the unfinished tower, grab and guide the piece into place before it is fastened with nuts and bolts [72]. The left photo in Figure 3.8 show how a worker lean out from the unfinished tower to grab and guide the new piece into place. Crush injuries, typical on fingers or arms sometimes occur if the helicopter move a little bit resulting in movement of the cargo [92, 95]. This can typically be a result of difficult weather [94]. The right picture in Figure 3.8 show one man climbing up in a newly assembled tower piece right after it is mounted, the helicopters hook is still visual in the top of the photo. The author can only assume that the tower-piece was correctly assembled and fastened before the worker climbed up, but if it was not, then this operation involved higher risk than necessary.

To work in towers involves high risk of falling down and on the 15th of April 2016 there was a tragic accident where a man died after falling down from a transmission tower in Flekkefjord [96]. There is also risk involved in moving below a tower that is under construction or maintains. During the lowering of a torque wrench fastened in a rope, the torque wrench slipped out and hit a man on his helmet [97]. Fortunately, the impact only resulted in a few stings and the man was back at work later that day [97]. Work performed close to live lines can involve risk of flashover and problems due to induction. Particularly if cranes or other high reaching equipment is used. It is therefore important to keep the security distance.

*Figure 3.8:**Left:** An assembler reach out to grab the incoming cargo. This piece is then mounted on top of there the assembler is located.*
***Right:** An assembler climb up the newly attached piece. The helicopter hook is still visual in the top of the photo.*

Stringing

To perform stringing, there is need of a puller, break and feeder [72]. The break is often too heavy to fly in so there needs to be worked up an access road and a drum site [72]. To attach the line a helicopter pulls a thin, but strong rope called pilot line and places it in the tower using a needle as shown in the left photo of Figure 3.9. When the line is placed in the tower, it is only at a temporary position and needs to be clipped into the right place. This procedure involves high force and therefore risk due to the tension and weight of the wire [98]. During the whole process it is very important to protect the line, it is for example not supposed to lay or be dragged on the ground due to the damages that can be caused on the wire [72].

*Figure 3.9: **Left:** Helicopter placing a pilot line in a tower using a needle. Photo from Statnett **Right:** Dismantling of thick cable so that a dead end clamp can be fastened. Mounting ring is fastened on the outer layer by explosives.*

Explosives [72]

To join two cables and to connect the cables to dead end towers, explosives are sometimes used to gain enough force. To fasten dead end clamps on thick conductors like Hubro, three explosions are executed, the first one for a mounting ring fastened on the conductor (as seen in the right photo in Figure 3.9), the second for the steel wires and the third for the aluminium wires. The explosions are sometimes executed up in the towers and it is therefore very important for the workers to find shelter. Explosives are also used under dismantling of damaged towers due to the uncertainty of the force and tension in the towers. Under explosions it is difficult to predict how far fragments will fly and there is always the risk of misfire.

Dismantle [98]

Dismantling of towers are performed using explosives, by cutting the tower into pieces or by unscrewing every bolt. If the tower is damaged there might be unknown tension that is released during the procedure, possibly harming the workers. Therefore, explosives are commonly used so that the workers can stay at a safe distance. The left photo in Figure 3.10 shows a damaged tower and the right photo shows a man that has climbed up to place explosives in the tower.

*Figure 3.10: **Left:** Damaged tower. Photo by Egil Bjørgen © Statnett*
***Right:** A worker placing explosives in the damaged tower. Photo by Egil Bjørgen © Statnett*

3.6 Maintenance

Replacement of aerial markers [99]

Today the replacement of aerial markers demand disconnection of the line and are done using one out of three methods:

- Mount new marker on new wire during a replacement of ground wires.
- Crew in trolley out on phase conductors, as shown in Figure 3.11.
- Basket placed on the ground wire while the crew is secured by a helicopter.

Figure 3.11: Crew in a trolley working on an aerial marker. Photo ©: Trond Isaksen, Statnett

Replacement of spacers

In 2011 and 2016 there where death accidents during mounting of spacers using trolley [100, 101]. The 2011 accident happened as the trolley's breaks was not correctly attached on to the line so that the trolley started to slide down to the next tower [98]. An example of a trolley is shown in Figure 3.11. The 2016 accident are at the point of writing still under investigation.

Live work [98]

Statnett have for the last years performed some work under live conditions. This does of course involve a high level of risk, but there have been no accidents related to this type of work. This might be because of the high level of focus on the tasks and good planning in advance.

De-icing wires

Ice load can in worst case scenarios lead to destruction of towers [98]. Most of the time the ice builds up and falls down from the phase conductors after a while, but this is not always the case [98]. Methods that are used by transmission grid operators today are increasing the conductor's temperature by increasing the current or placing a stick below a helicopter to hit the conductors [98, 102].

3.7 Inspection

Vegetation encroachment monitoring [98]
Statnett monitor vegetation around the transmission lines by men on the ground, demanding a lot of manpower moving in difficult terrain, or by flying over with helicopter. Infrequently inspections might lead to problems where trees fall over the lines or flashovers due to the height of the trees.

Corrosion detection [98]
Statnett do not experience a lot of corrosion on lines, even though some of the lines are quite old. This might be because the conductors are coated with thick layers of aluminium around the steel core. Although some corrosion does occur on both lines and towers it is considerably less than one could expect. Even the lines near the coast do not experience that much corrosion. Today, inspection of corrosion is done using helicopters.

Tower and line inspections [24]
In Statnett different procedures are performed for inspection of lines and towers. Helicopters are used to inspect lines and towers using visual observation, thermal sensors and photography of some equipment like dead end connectors. Risk related to person transport in helicopters are described in the section Helicopter transport at page 25. Inspections are also performed from ground by two persons traveling by foot and ground based vehicles along the line using cameras and binoculars in addition to normal visual inspection and sometimes by climbing up the towers to perform a thorough inspection. Risk involved with ground based inspection come from e.g. the usage of ground based vehicles like snowmobiles, which is presented in the section Transportation with ground based vehicles on page 22. When the workers climb up the towers they are exposed for the risks of falling down and of flashover, if its performed under live conditions.

Extra ordinary inspection [24]
Inspection performed in addition to periodic inspection. Typically performed after a period of bad weather or power outage by ground based crews or by flying over the area with helicopter.

3.8 Summary

There are many dangerous operations identified in this thesis and they contain different factors of risk as listed in Table 3.1. Some of the risk factors have led to tragic accidents ending with death or serious illness [100, 101]. From the risk plot in Figure 3.1 and from the identified operations in this thesis the factors with the worst consequences and relatively high probability, making them the highest risk factors are: height, helicopter, traffic and machines.

Table 3.1: Risk factors for operations as they are performed today. The last column called highest risk level represent the risk level of the factor with the highest risk for each operation. Red colour equals high risk, orange is medium risk and green is low risk.

Risk factors / Operations	Helicopter	Height	Traffic	Machines	Electricity	Drowning	Crush or cut	Snow mobile	Falling objects	Avalanche	Environmental	Highest risk level
Personnel transport on public roads			Orange				Orange			Green	Green	Orange
Personnel Transport in terrain				Orange			Orange	Orange		Green	Green	Orange
Inspection of subsea cables						Orange						Orange
Lift of heavy materials				Orange	Orange		Orange		Orange		Green	Orange
Window washing		Red		Orange			Orange		Orange			Red
Land survey	Red			Orange			Orange			Green	Green	Red
Aerial Cargo transportation	Red				Orange		Orange		Orange		Green	Red
Foundation	Red	Red		Orange			Orange	Orange	Orange	Green	Green	Red
Foundation on steep hills	Red	Red		Orange			Orange	Orange	Orange	Green	Green	Red
Tower erection	Red	Red					Orange	Orange	Orange	Green	Green	Red
Stringing	Red	Red		Orange	Orange		Orange	Orange	Orange	Green		Red
Joining cables		Red					Orange	Orange	Orange	Green	Green	Red
Dismantle towers	Red	Red		Orange			Orange	Orange	Orange	Green	Green	Red
Replacement of Aerial markers	Red	Red		Orange			Orange	Orange	Orange	Green		Red
Replacement of spacers		Red		Orange			Orange	Orange	Orange	Green		Red
Live work		Red			Orange		Orange		Orange	Green		Red
De-icing wires	Red			Orange	Orange		Orange	Orange	Orange	Green	Green	Red
Vegetation monitoring	Red		Orange				Orange	Orange		Green	Green	Red
Corrosion detection	Red											Red
Tower and line inspection	Red	Red	Orange		Orange		Orange	Orange	Orange	Green	Green	Red
Extraordinary inspection	Red		Orange		Orange		Orange	Orange		Green	Green	Red

4 Implementing robotic technology

4.1 Method

This section lead to a ranking of what robotic technology that have the greatest potential to execute and reduce the risk of the dangerous operations. This is done through analysis and selection of the robotic technology and dangerous operations identified in the previous chapters.

First the robotic technologies suitability for the dangerous operations are determined. The next section ranks the identified robotic technologies potential to both execute the operation and reduce its risks. To make the analysis as reliable and objective as possible, only three classifications are used; high, medium and low.

4.2 Robotic technologies abilities to perform the operations

Table 4.1 lists the identified robotic technologies abilities to perform the identified dangerous operations. The table use colour marks to show the level of suitability. Dark blue colour represents high suitability, medium represents medium suitability, light blue is low suitability while white is unsuitable. The white "X" represent that a combination of the technologies might be preferable for greater risk reduction.

Table 4.1: Robotic technologies suitability to perform dangerous operations. Darker grade of blue equals higher suitability and no colour mean that the technology is not suitable. White X represent that a combination of the technologies might be preferable to perform the tasks and reduce the risks.

Robotic technology / Dangerous operations	Line suspended	UAV	Under-water	Ground based	Climbing	Static	Exosk-eletons
Personnel transport on public roads							
Personnel transport in terrain							
Window washing							
Land survey							
Lift of heavy materials							
Aerial Cargo transportation							
Foundation		X		X			X
Foundation on steep hills		X		X			X
Tower erection							
Stringing							
Joining cables							
Dismantle towers							
Replacement of Aerial markers							
Replacement of spacers							
Live work							
De-icing wires							
Vegetation monitoring							
Corrosion detection							
Tower and line inspection							
Extraordinary inspection							
Inspection of subsea cables							

4.3 Robotic technologies combined with dangerous operations

This section ranks the identified robotic technologies potential to execute a dangerous operation and reduce its risks. In Table 4.2 the dangerous operations are listed together with the robotic technologies that have the highest suitability to execute the operation and reduce it risks. Colours are used to determine the risk level of the operations risk factor with the highest risk level and the technologies suitability to execute the operation. Out of these two parameters the technology with the specific operation is ranked with colour to show the total potential. Dark green represent high potential to execute the operation and reduce risks. Medium graded green represents medium potential. The operation and technology is ranked as light green if it represents less potential to reduce the risks and/or if the technology do not have a high level of suitability.

Table 4.2: Ranking of the identified robotic technologies potential to execute and reduce the risk of the dangerous operations. Darker grade of green represents the higher potential. Risk level describes the risk level of the operations risk factor with the highest risk level.

Operation	Risk level	Robotic technology	Suita-bility	Ranking	Comment
Tower and line inspection		UAV			Different UAVs for different inspections
Window washing		Climbing			Window cleaner robot
Corrosion detection		UAV			Multirotor or helicopter
		Line suspended			
Replacement of aerial markers		Static			Device hung below helicopter
Extraordinary inspection		UAV			Fixed wing or large helicopter
Vegetation monitoring		UAV			Fixed wing
Stringing		UAV			Helicopter or multirotor
Land survey		UAV			Different types for different surveys
Replacement of spacers		Line suspended			With robotic arm
		Static			Device hung below helicopter
Live work		UAV			Only inspection
		Line suspended			Inspection and simple maintenance
Aerial cargo transportation		UAV			Large helicopters
De-icing wires		Line suspended			
		Ground based			De-icing vehicle
Dismantle towers		Climbing			Placing explosives
Lift of heavy materials		Ground based			Unmanned machines
Foundation and foundation on steep hills		UAV			Combination. Unmanned excavator as ground based and large helicopters or multirotor as UAV
		Ground based			
		Exoskeleton			
Tower erection		UAV			Large helicopters
		Ground based			Unmanned construction machines
Inspection of subsea cables		Under-water			AUV or high speed ROV
Personnel transport on public roads		Ground based			Fully-autonomous cars
Personnel transport in terrain		Exoskeleton			

Tower and line inspection with UAV

There are different UAVs already on the market able to perform tower and line inspection [31, 29, 30, 28]. Fixed wing UAV can fly beyond visual line of sight (BVLOS) and deliver an overview of a large area, but are not able to perform detailed inspection due to the lack of hovering. Helicopter UAVs come in large sizes that fly BVLOS and have the ability to hover, so they can perform detailed inspection of large areas. Multicopters are easy to manoeuvre and have the ability to hover, but have limited operation lengths and time. Multicopter can therefore perform very detailed inspection of smaller areas. Inspection with UAV can e.g. reduce the need of helicopters.

Window washing with climbing robotic device

Robots made for window washing on tall buildings are already in use [53]. The quality of the cleaning compared to manual washing is however unknown. The implementation of robots for window washing can reduce the risk of personnel falling from heights.

Corrosion detection with UAV or line suspended robotic device

Corrosion is said by personnel at Statnett, not to be a big problem in the Norwegian main grid [98]. There are however several multirotor UAVs, helicopter UAVs and line suspended robotic devices able to perform inspection of corrosion. The implementation of UAVs or line suspended robotic devices for corrosion detection can decrease the risk involved with the use of helicopters.

Replacement of aerial markers with static robotic technology

Statnett have recently implemented a new procedure for replacement of aerial markers that perform the replacement in less time than previous procedures [54]. However, this procedure involves helicopter and personnel hanging from grate height underneath the helicopter. A robotic device hung below a helicopter will reduce the risk involved with working in the height. The robotic device is under development and Statnett is already involved in the development process.

Extraordinary inspection with UAV

A fixed wing UAV or a large helicopter UAV can fly beyond visual line of sight to a place of interest and send photos and videos of the area back to the operator. Smaller multicopters can be used for more detailed inspection and to give an overview for the personnel at site. Use of UAV instead of helicopter can reduce risks that follows helicopters.

Vegetation encroachment monitoring with UAV

A fixed wing UAV can be used beyond visual line of sight to capture photos that a computer software analyses to give a recommendation on what vegetation that needs to be cut down [26]. The system is already available, and tested in France [26]. The implementation of UAV can e.g. reduce the use and risks of helicopters.

Stringing with UAV

Statnett have already tested Stringing with UAVs, nevertheless there are still need of further development for a seamless process [35]. The use of UAVs reduce the risks with helicopters.

Land survey with UAV
Multicopter UAVs can produce detailed surveys over large areas without the intervention of an operator, making it possible for the operator to move less around in the terrain. The use of UAV can also reduce the use and risks of helicopters.

Replacement of spacers with line suspended robotic devices or static robotic devices
Mounting and replacement of spacers are high risk operations. One of the reasons why there is such a high risk is that this work combines working in high heights with machines, and stress can come in as an outer factor, increasing the risk even further. In connection with mounting and replacing of spacers using cable car technology two persons have lost their lives during the last five years [101, 100]. Unfortunately, there is no robotic technology found during this study that is able to perform the task of mounting spacers today. It is however possible to imagine the development of a device based on the same concept as the device meant to mount aerial markers, hung below a helicopter, or on further development of a line suspended robotic device with robotic arms.

Live work with UAV or line suspended robotic devices
Small UAVs have the ability to fly closer to live lines and towers than helicopters. UAVs can be used for inspection of towers under live conditions, reducing the risks of height and electricity for the personnel who else would have climbed up the tower.
Some of the line suspended devices are made with the ability to perform inspections and uncomplicated maintenance on equipment within a short range to the line [13]. Nonetheless, today's technology cannot replace manual maintenance as the devices cannot move on towers. The use of line suspended robotic devices for these small tasks might still reduce the risk of height and electricity.

Aerial cargo transportation with UAV
Large helicopter UAVs can lift tens of kilograms, however a regular helicopter cargo today is about one ton [35]. Consequently, a UAV have to travel the distance more frequently and some of the cargo might be too heavy. There are unmanned full-size helicopters under development and testing that would be able to perform the same procedures as a manned helicopter while reducing the safety risks of a manned helicopter.

De-Icing wires with line suspended robotic devices or ground based robotic devices
There is one identified line suspended robotic device with the possibility to de-ice wires [11]. This device cannot cross dead-end towers, which makes it less suitable. There is also identified a remotely operated de-icing truck, but due to the location of Statnett´s grid the possible area this vehicle can operate on is limited [40]. However, the use of this technologies represent less risk then the use of helicopter.

Dismantle towers using climbing robotic device
A climbing robotic device, e.g. a snake-like robotic device might be able to climb damaged towers and place explosives on wanted locations. In this way the risk involved for a person to climb up in an unstable tower is removed.

Lift of heavy materials with ground based robotic devices
Unmanned construction machines have the same capabilities as manned construction machines, while keeping the operator at a safe distance. Therefore, large machines can be used at construction sites with well-developed access roads. Unmanned excavators might be flown in to constructions sites in more remote areas. The use of unmanned construction machines removes the operator from the machines together with the safety risks that machines cause to the operator. They can also reduce the risk of electricity during work close to live lines. Because lift of heavy materials with ground based robotic devices have the possibility to reduce two risk factors with one technology type, it is ranked above inspection of subsea cables with unmanned under-water vehicles.

Foundation and foundation on steep hills using UAVs, ground based robotic devices and exoskeletons
The operation of foundation involves many smaller operations and different robotic technologies can perform some of these smaller operations. UAVs might be able to transport materials to the sight, exoskeletons can assist personnel with lift of heavy materials and unmanned excavators can dig holes for the foundation and prepare the construction site. If all three technologies are used, there is potential for risk-reduction within the risks factors helicopters, machines, and crush or cut.

Tower erection usin UAV or ground based robotic devices
Tower erection involve the risks of both helicopter and height. A strong enough UAV to lift the tower pieces can remove the risks of the pilot. If unmanned construction machines are used to lift the pieces the risks involved with the use of helicopters will be removed, but there are few towers where construction machines have access due to remote locations.

Inspection of subsea cables with unmanned under-water vehicles
The risk of drowning during inspection of subsea cables are the general risk involved with traveling on the sea, since remotely operated under-water vehicles (ROV) are already in use. Automatic underwater vehicles (AUV) will still demand a vessel to follow it, so the risk of drowning is still present, but High speed ROVs or AUVs might reduce the time spent on sea.

Personnel transport on public roads with ground based robotic devices
Fully-autonomous cars have attracted much attention from the media the last years and they are expected to hit the market within a few years [44]. There are nevertheless challenges related to navigation. The roads need to be thoroughly mapped before self-driving cars can use them and Statnett use a numerous amount of deserted roads, including dirt roads without road marking. The use of new car technology might however reduce the risks of traffic.

Personnel transport in terrain with exoskeleton
Exoskeleton can assist personnel walking in the terrain. It can help personnel to carry more weight in backpacks or enhance the users strength to use heavier tools. Exoskeletons are still under development, and the decrease in risk is smaller than for many of the other technologies and applications in this thesis, leaving it down on the ranking list.

5 Discussion

Sources

The information used in this thesis is based on many sources with different credibility. Many of the robotic devices are referenced in research reports with high credibility, while some information are sourced from meetings, interviews, producer's fact sheets, etc. [24, 23, 85, 103] Because of the wide spread of sources, a lot of relevant information was obtained during a relatively short period of time, resulting in numerous identifications of operations and technologies. One downside is that some of the obtained information might not hold the same credibility as a research report does. The information used in this thesis is therefore read with a critical mind-set and other sources are used to verify the information as far as possible.

Robotic technology

There is a wide span of identified robotic technology in this thesis and the technology readiness level (TRL) differs largely both within a technology and between different types of technologies. It was difficult to determine the TRL of some technologies as the credibility of the specific devices sources differs. Some of the information are dated from a few years ago, resulting in large uncertainty of TRL classification [11, 13, 40]. It is therefore most correct to call the TRL-classification an estimation of TRL levels.

There might be other robotic technologies excluded from the definition and thesis that could be useful for Statnett. Some definitions of robots and robotic technologies include computer software. With Statnett´s huge amount of data, software to process this data might help Statnett to make better and perhaps, even safer decisions in the future. The definition excluded some of these technologies, but made it easier to draw the line of where to stop the research. There might also be robotic technology with potential in the transmission and distribution industry, fitting the definition, that is not listed in the thesis, as the time to research for new robotic technology was limited.

Dangerous operations

The dangerous operations listed in this thesis was widely based upon which operations the interviewees presented and which incidents that were reported in Statnett´s internal report system, Bedre. The reason why these sources are used instead of reading several reports and statistics are because of the amount of operations that are identified with this process. Since Statnett do not have a list covering their dangerous operations, a lot of reports would have to be analysed, resulting in a long research period. Because of limited time to research, the identified dangerous operations cannot be called a complete list. Even so it covers a wide spread of operations that qualified personnel thought was worth to mention plus reported incidents or near incidents. Some near accidents with only one person involved, like a car collision avoided in the last second, might not be reported in Bedre as the person might feel that it attracts unwanted attention for an accident that did not happened. It might therefore not be identified with the same risk as it actually contains. E.g. it can be discussed whether traffic is an even bigger risk factor than first thought.

The table in the summary-section of chapter 3, listing risk factors for operations as they are performed today, is made of the author with a brief examination by the supervisors. For future work, an idea is to involve a group of qualified personnel to verify this types of tables. Due to the high activity level at Statnett and limited time to fabricate the thesis, this was unfortunately not done for this thesis. The risk factors used in Table 3.1 are based on the risk plot in chapter 3.3. The risk plot is however based on a risk matrix made by Statnett in 2014 [61]. If Statnett where to make a new risk matrix, some of the factors might be placed differently. There have unfortunately been two tragic death accidents so far in 2016 [101, 100]. This would most likely change the estimated level of risk some of the factors have.

In addition to the factors used in Table 3.1, factors like stress and unexperienced personnel can increase the risk of all operations listed in this report. The reason why this was not analysed are because of the authors lack of competence to perform this analysis.

Implementing robotic technology

The tables of chapter 4 is based on the authors opinion as well. The authors supervisors have however, looked at them for a brief verification. The author will recommend the same procedure for this types of tables in the future as the one mentioned for Table 3.1. Some of the operations mentioned in Table 4.1 consist of many small tasks and the robotic technology might only be able to perform some of these tasks and not the whole operation. Furthermore, some of the devices are still in the development phase, so it is difficult to predict if it is actually able to perform the operation in a realistic environment.

Some of the information that forms the basis of the ranking contains uncertainty and the previous tables used for the ranking are an objective form to present subjective meanings. Therefore, only three classifications are used; high, medium and low. This represent a less quantitative presentation than numbers, while still being able to show which technologies and operations that represent the largest potential to execute the tasks and reduce risk. The downside of the method used to rank the results in this thesis is the amount of results in each category. There is no first, second and third choice, which might make it more difficult to choose what technology to move forward with.

Comparison of the results with other known results

It is difficult to compare the ranking of robotic technology with potential to execute operations and reduce the risk, as it is, as far as the author knows, the first of its kind. There are comprehensive reports listing robotic technology, and some reports and reporting systems with statistics over accidents [24, 23, 85, 103, 60]. The information from these reports are however used to identify the robotic technologies and dangerous operations in this thesis, in addition to operations and technologies acquired from other sources along the study. There are however some differences, e.g. other reports on robotic technology might focus more on the specific devices than the general abilities within the technologies [103, 23]. Other examples are reports on risk factors who focus on a bigger picture, e.g. how many accidents within the different sectors of construction, and do not look at the specific operations that leads to these accidents [85].

6 Conclusion and further work

This thesis is three parted. First robotic technologies with potential for use in Statnett that are under development with prospect for commercializing within five years and technologies already on the market are identified. Then dangerous operations performed by Statnett and their entrepreneurs are identified. At the end, the results of the robotic devices and the dangerous operations are compared and analysed to provide a ranking of the technologies potential to execute operations and reduce its risk.

Identified robotic technologies

There are many types of robotic technologies with potential use for Statnett identified, all with a high level of technology readiness (TRL), and they were categorized in the following categories.

- *Line suspended robotic devices* have already been used for years now and the ones under development have an estimated TRL level above 6. Most of the devices are limited to and made for specific tasks within inspection or mechanical work, even though the new development is in the direction of implementing multiple operations on one platform. Furthermore, the better part of the devices has problems crossing suspension towers and the Transmission Line Inspection Robot in development by Transpower New Zealand is the only one said to be able to cross dead end towers. Further development line suspended robotic devices has a slow line of progress and there are not that many institutions working on this small field within robotics.
- *UAV* have been implemented by other grid operators in their inspection procedures. There are large individual differences in operation time and -radius, device size, operation method, etc. between categories and similar devices. There is an increasing amount of application available and the technology is moving forward in a high pace.
- *Unmanned underwater vehicles* are already well-implemented in the form of ROVs in Statnett´s work with subsea cables. The technologies and abilities within ROVs are mature, even though there are room for improvements and the next one seem to be within autonomous operation.
- *Ground based robotic devices* have attracted much attention from the media the last years with the development of autonomous cars, there are however plenty of other applications within the area as well. Almost all ground based vehicles available today are possible to develop into remotely operation. The development within other sectors then the car industry are however slow and with low priority.
- *Other types of robotic technology* are the category for technology that do not fit into the other cathegories. It includes technology like exoskeletons to improve human strength, window cleaning robots and snake-like robotics with high movability.

Identified dangerous operations

There is no doubt that Statnett and their entrepreneurs are involved in dangerous operations. Many operations are identified in this thesis, but there are still reasons to believe that even more operations could be identified if a larger and more thorough study is launched. All of the identified operations contain different factors of risk. Some of the risk factors have led to tragic accidents ending with death or serious illness. The two biggest risk factors are helicopter and height.

Implementation of robotic technology

There are many robotic technologies with the abilities needed to perform the dangerous operations. The robotic technologies with highest suitability and the given operations are ranked against each other to show which ones that have the highest possibility to both execute the operation and reduce its risk. The general result is that there are several robotic technologies with the possibility to perform and reduce the risk of some of the dangerous operations identified in this thesis. The specific operations and robotic technologies with highest potential to both reduce risk and perform the operation are in an unranked list:

- Tower and line inspection with UAV
- Window washing with climbing robotic device
- Corrosion detection with either UAV or line suspended robotic device
- Replacement of aerial marker with static robotic devices
- Extraordinary inspection using UAV
- Vegetation monitoring with UAV
- Stringing with UAV
- Land survey with UAV
- Replacement of spacers with line suspended robotic devices or static robotic devices

Recommendation for further work

Based on the robotic technology with the highest potential to both execute and reduce risk of operations, the eleven technologies listed above are recommended for further research and development towards permanent implementation in the nine specific operations. It is the authors opinion that some of the technologies listed above could be developed for implementation across operations, e.g. an UAV for tower and line inspection could possibly perform corrosion detection just by equipping it with the right sensors.

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Appendix A

Appendix A lists other technologies found along the study that do not suit the definition used in the thesis. Since this technology might be useful later it is listed her.

Zipper truck for building of small tunnels [104]

Lock-Block Ltd. have made Zipper Truck, seen in Figure 0.1. A truck that supports concrete blocks under construction of small tunnels. The concrete blocks are made with a locking mechanism, similar to Lego. When the truck drives forward the support circumference on the trucks diminish and the blocks fall into place and lock each other.

Figure 0.1: Zipper truck for building of small tunnels. Photo by permission of Lock-Block

Divisible puller

To develop a divisible puller with small enough pieces to be flown in by helicopter may reduce logistic problems before and after stringing [105].

Figure 0.2: Photo of a puller for large cables like Hubro.

Pile machinery [105]
Make a demountable pile machinery that can be flown in by helicopter.

Tracking and storing of equipment [105]
Enterprise Resource Planning (ERP) might help contractors to know if all parts needed for construction are on its way or already in storage. There might also be difficult to keep track of all the equipment stored outside during periods of snow. Typical problems when storing equipment outside during snowy periods might be not to mix up parts for separated towers.

Appendix B

Appendix B list operations discovered along the study that do not necessarily include high risk.

Inspection, cleaning and pulling of cable in OPI channels [106]

OPI channels, shown in Figure 0.1 are used to protect cables in substations. When the cable is pulled through the channel it is very important that the channel is free from foreign matter to protect the outer coating from damages. Today there are no good methods for inspection and cleaning of the channels. Fish tape is used to pull the cables through the channels. The channels are 150-200 meters with inspection hatches along making it challenging to pull the fish tape through.

Figure 0.1: OPI channels. Photo by permission from OPI AS.

Avalanch, landsled and rockslide

Avalanches, landslides and rockslides are quite common due to the Norwegian topography [98]. This is often planed for by elevating the concrete foundation as the ones in Figure 3.7 or relocation of the foundation if possible [98]. It is also possible to make a plough out of car crash barriers and place it above the tower to lead the snow around [3].

Access roads [72]

When Statnett applies to the Norwegian Water Resources and Energy Directorate (NVE) for licence to build a new power line, they have to include which roads they plan to use for access to the construction areas. Sometimes this access roads look better on a map than in reality. Figure 0.2 show an access road to a construction site where the contractor planned to use ATVs, but was denied permission and had to acquire vehicles with tracks. Another problem might be that under a construction period or inspection the crew might use shortcuts or other roads in the area without permission from the NVE and cause disturbance of the public peace and order outside of the licenced areas. Sometimes access roads needs to be extra secured like the iron path made to secure the access trail of a tower in the left circle of Figure 3.7.

Figure 0.2: Two photos of the same access road to a construction site that required special vehicles.

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