UPPSALA
UNIVERSITET

Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1608

Robotized Production Methods for Special Electric Machines

ERIK HULTMAN

ACTA
UNIVERSITATIS
UPSALIENSIS
UPPSALA
2018

ISSN 1651-6214
ISBN 978-91-513-0177-8
urn:nbn:se:uu:diva-335504

Dissertation presented at Uppsala University to be publicly examined in Polhemsalen, Lägerhyddsvägen 1, Uppsala, Friday, 2 February 2018 at 13:00 for the degree of Doctor of Philosophy. The examination will be conducted in English. Faculty examiner: Professor Jörg Franke (Friedrich-Alexander-University of Erlangen-Nuremberg).

Abstract

Hultman, E. 2018. Robotized Production Methods for Special Electric Machines. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1608. 82 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-513-0177-8.

A research project on renewable energy conversion from ocean waves to electricity was started at the Division of Electricity at Uppsala University (UU) in 2001. The Wave Energy Converter (WEC) unit developed in this project is intended to be used in large offshore WEC farms and has therefore been designed with large-scale production in mind. The concept has now also been commercialized by the spin-off company Seabased Industry AB.

An essential part of the UU WEC is the linear direct-drive generator. This thesis presents the pilot work on developing robotized production methods for this special electric machine. The generator design is here investigated and four different backbreaking, monotone, potentially hazardous and time consuming manual production tasks are selected for automation. A robot cell with special automation equipment is then developed and constructed for each task. Simplicity, reliability and flexibility are prioritized and older model pre-owned industrial robots are used throughout the work. The robot cells are evaluated both analytically and experimentally, with focus on full scale experiments. It is likely that the developed production methods can be applied also for other similar electric machines.

The main focus in the thesis is on robotized stator cable winding. The here presented robot cell is, to the knowledge of the author, the first fully automated stator cable winding setup. Fully automated winding with high and consistent quality and high flexibility is demonstrated. Significant potential cost savings compared to manual winding are also indicated. The robot cell is well prepared for production, but further work is required to improve its reliability.

The other three developed robot cells are used for stator stacking, surface mounting of permanent magnets on translators and machining of rubber discs. All robot cell concepts are experimentally validated and considerable potential cost savings compared to manual production are indicated. Further work is however required with regards to autonomy and reliability.

Finally, the thesis presents a pedagogical development work connected to the research on robotized production methods. A first cycle course on automation and robot engineering is here completely reworked, as it is structured around three real-world group project tasks. The new course is evaluated from the examination results, the students' course evaluations and the feedback from the teachers during six years. The students greatly appreciated the new course. It is indicated that the developed teaching approach is effective in teaching both classical and modern engineering skills.

Keywords: Industrial robotics, Assembly automation, Large-scale production, Cable winding, Linear generator, Wave energy converter, Wave power, Engineering education

Erik Hultman, Department of Engineering Sciences, Electricity, Box 534, Uppsala University, SE-75121 Uppsala, Sweden.

ISSN 1651-6214
ISBN 978-91-513-0177-8
urn:nbn:se:uu:diva-335504 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-335504)

Till Ebba och Tage

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I **Erik Hultman**, Boel Ekergård, and Mats Leijon. Electromagnetic, mechanical and manufacturing properties for cable wound direct-drive PM linear generators for offshore environments. *Proceedings of the 31st International Conference on Ocean, Offshore and Arctic Engineering*, Rio de Janeiro, Brazil, July 2012.

II Yue Hong, **Erik Hultman**, Valeria Castellucci, Boel Ekergård, Linnea Sjökvist, Deepak Elamalayil Soman, Remya Krishna, Kalle Haikonen, Antoine Baudoin, Liselotte Lindblad, Erik Lejerskog, Daniel Käller, Magnus Rahm, Erland Strömstedt, Cecilia Boström, Rafael Waters, and Mats Leijon. Status update of the wave energy research at Uppsala University. *Proceedings of the 9th European Wave and Tidal Energy Conference*, Aalborg, Denmark, September 2013.

III **Erik Hultman**, Boel Ekergård, Tobias Kamf, Dana Salar, and Mats Leijon. Preparing the Uppsala University wave energy converter generator for large-scale production. *Proceedings of the 5th International Conference on Ocean Energy*, Halifax, Canada, November 2014.

IV **Erik Hultman**, and Mats Leijon. Utilizing cable winding and industrial robots to facilitate the manufacturing of electric machines. *Elsevier Robotics and Computer-Integrated Manufacturing* 2013; 29(1):246-256.

V **Erik Hultman**, and Mats Leijon. Six-degrees-of-freedom (6-DOF) work object positional calibration using a robot-held proximity sensor. *MDPI Machines* 2013; 1:63-80.

VI **Erik Hultman**, and Mats Leijon. A cable feeder tool for robotized cable winding. *Elsevier Robotics and Computer-Integrated Manufacturing* 2014; 30(6):577-588.

VII **Erik Hultman**, and Mats Leijon. Automated cable preparation for robotized stator cable winding. *MDPI Machines* 2017; 5(2):14.

VIII **Erik Hultman**, and Mats Leijon. An updated cable feeder tool design for robotized stator cable winding. Under review at *Elsevier Mechatronics*, June 2017.

IX **Erik Hultman**, and Mats Leijon. Robotized stator cable winding. Under review at *Elsevier Robotics and Computer-Integrated Manufacturing*, October 2017.

X **Erik Hultman**, Marcus Linder, and Mats Leijon. Robotized stacking of the Uppsala University wave energy converter generator stator. *Proceedings of the 33rd International Conference on Ocean, Offshore and Arctic Engineering*, San Francisco, USA, June 2014.

XI **Erik Hultman**, Dana Salar, and Mats Leijon. Robotized surface mounting of permanent magnets. *MDPI Machines* 2014; 2:219-232.

XII **Erik Hultman**, Dana Salar, Emil Åberg, and Mats Leijon. Robotized manufacturing of rubber components for commercialization of the Uppsala University wave energy converter concept. *Proceedings of the 2nd International Conference on Offshore Renewable Energy*, Glasgow, UK, September 2016.

XIII **Erik Hultman**, and Mats Leijon. Integration of real-world project tasks in a course on automation and robot engineering. Under review at *Taylor & Francis SEFI European Journal of Engineering Education*, November 2017.

Contents

Nomenclature

Symbol	Unit	Description
α	°	z-angle of Tait-Bryan z-y'-x''
β	°	y'-angle of Tait-Bryan z-y'-x''
γ	°	x''-angle of Tait-Bryan z-y'-x''
C_t	EUR	Net cash flow at time t
i	%	Discount rate
l_{feed}	m	Total cable feed length
n	years	Economical lifetime of the investment
NPV	EUR	Net present value
η_s	%	Gripping force transmission efficiency
η_w	%	Feed force transmission efficiency
p_s	m	Positional adjustment screw pitch
r_f	m	Feed wheel radius
$_{\boldsymbol{R}}\boldsymbol{R}_{\boldsymbol{W}}$	-	Rotational matrix from the RBCS to the WOCS
T	years	Payback period
t	years	Time after commissioning
T_f	Nm	Cable feed motor torque
T_n	Nm	Positional adjustment screw torque
t_{pos}	s	Total pure robot positioning process cycle time
t_{tot}	s	Total winding process cycle time
μ_s	-	Static frictional coefficient
v_{feed}	m/s	Average cable feed velocity
$^{U}\boldsymbol{X}_{\boldsymbol{R}}$	-	x-axis unit vector for the WOCS in the RBCS
$^{U}\boldsymbol{X}_{\boldsymbol{R0}}$	-	x-axis unit vector for the RBCS in the RBCS
$^{U}\boldsymbol{Y}_{\boldsymbol{R}}$	-	y-axis unit vector for the WOCS in the RBCS
$^{U}\boldsymbol{Y}_{\boldsymbol{R0}}$	-	y-axis unit vector for the RBCS in the RBCS
$^{U}\boldsymbol{Z}_{\boldsymbol{R}}$	-	z-axis unit vector for the WOCS in the RBCS
$^{U}\boldsymbol{Z}_{\boldsymbol{R0}}$	-	z-axis unit vector for the RBCS in the RBCS

Abbreviations

Abbreviation	**Description**
##:A-C	Stator reference designs
3D	Three-Dimensional
6-DOF	Six-Degrees-Of-Freedom
AIO	Analog Input/Output
CAD	Computer-Aided Design
CAM	Computer Aided Manufacturing
CNC	Computer Numerical Control
D1-3:#	Robot winding development scenarios
DIO	Digital Input/Output
EPDM	Ethylene Propylene Diene Monomer
G1-3	UU WEC design generations
GUI	Graphical User Interface
HIPS	High Impact Polystyrene
HMI	Human-Machine Interface
L1-12	UU WEC prototype devices
LCOE	Levelized Cost of Electricity
$Nd_2Fe_{14}B$	Neodymium Iron Boron
NPV	Net Present Value
P2P	Point-to-Point
PBP	Payback Period
PC	Personal Computer
PhD	Doctor of Philosophy
PLC	Programmable Logic Controller
PM	Permanent Magnet
POM-H	Polyoxymethylene Homopolymer
PR:#	The present winding method
PVC	Polyvinyl Chloride
RBCS	Robot Base Coordinate System
SMEs	Small and Medium-sized Enterprises
TCP	Tool Center Point
UU	Uppsala University
WEC	Wave Energy Converter
WOCS	Work Object Coordinate System

1. Introduction

Our society is critically dependent on the supply and conversion of energy, and we still rely heavily on fossil fuels. From playing more of a role in the margin, the interest in renewable energy sources has increased rapidly during the recent decades. Three important reasons to this are the increased environmental concerns regarding pollutions and global warming [1], the increasing global demand for energy [2] and the geographically limited access to and finite nature of fossil fuels [3]. To overcome the intermittency often being characteristic to renewable energy sources, a mix of different energy sources is regarded as favorable. Some renewable energy conversion technologies, such as hydropower, wind power and solar photovoltaics, are today well-established in energy systems worldwide. Others, such as wave power, are currently in the commercialization phase or in the early introduction phase.

Electric energy conversion through motors and generators plays an essential role in the modern society. With the promotion of renewable energy sources, a further increased use of distributed electric energy generation systems is expected [4]. Many medium and large sized generators will likely be needed for these systems. For new renewable energy technologies to be competitive, a low average total cost for the electricity delivered to the grid—often referred to as the Levelized Cost of Electricity (LCOE)—is essential. With zero fuel costs, the investment cost of the conversion unit is likely to be crucial for these technologies. Manufacturing automation can thus play an important role here. To enable local large-scale production on a global and rapidly changing market, advanced, adaptable and flexible automation systems are required [5-6]. New renewable energy conversion technologies are however often developed and commercialized by Small and Medium-Sized Enterprises (SMEs) with limited investment capital and little competence in automation technology. Hence, the development of affordable but flexible automated production methods for medium and large sized electric machines could serve as an enabler for additional renewable energy conversion technologies. With the steadily increased electrification of our society, such developments are likely to have further applications as well.

Advances in industrial automation technology during the past decades have enabled automation of more and more tasks, including the assembly of mainly smaller electric machines. The digitalization and the evolution of industrial robots, controllers, sensors and communication technology offers a huge potential for new automation applications with high flexibility at declining investment costs. However, the system complexity rises accordingly, reliability is crucial, connectivity is increasingly emphasized and the evolution is rapid [7]. The worldwide supply of industrial robots has steadily increased during the past years and is expected to continue so [8]. Since complete industrial production lines regularly are replaced when the production is changed or upgraded, there is a considerable amount of pre-owned older model industrial robots available on the market at lower costs. Such robots are of course always worn to some extent. However, older robot models are often rigidly designed and can provide similar programming, simulation and communication possibilities as new robots. Combining older robots with modern automation technology can thus open up for advanced robot applications with high flexibility at lower costs.

The Toyota production system is often referred to as a model for successful production planning [9]. Two basic elements in this production system are just-in-time production and respect-for-human. The latter is achieved among other things by striving for full use of the workers' capabilities.

1.1 Wave power

Wave power is so far a commercially almost unutilized renewable energy source. With positive attributes such as a huge global potential [10], a high utilization factor, a high energy density and a good predictability, many have put much effort in developing Wave Energy Converter (WEC) devices. A large number of different such devices have been developed and tested worldwide [11]. The sea environment is however a harsh opponent and starting up a new industry requires much effort, huge investments and patience. For example, the Pelamis Wave Power Ltd was until recently regarded as the market leader in wave power with their attenuating WEC. Pelamis Wave Power Ltd was however taken into administration in 2014, after failing to secure additional funding.

1.2 The Lysekil project

The Lysekil project on wave power research started in 2001 at the Division of Electricity at the Department of Engineering Sciences at Uppsala University (UU). Within this project, the UU WEC concept has been developed. A holistic perspective of wave power is strived for in the research, including work on wave climates, wave energy absorption, the WEC generator design, a marine substation for grid connection, a tidal compensation system, offshore WEC experiments, modelling of the WEC system, WEC farm performance, manufacturing, deployment and environmental effects. Mechanical simplicity, functionality and scalability are prioritized for the WEC concept. The UU WEC is categorized as an oscillating body with a point absorbing buoy, see Figure 1.1. A line connects the buoy to a direct drive linear generator, which is placed on a concrete foundation on the seabed. As ocean waves passes the buoy, the moving part of the generator—the translator—is thus moved vertically inside the fixed stator. To achieve a simple, durable and efficient generator design, Permanent Magnets (PMs) are used on the translator and the stator is wound with cables. Since the power output from a single WEC is much fluctuating, multiple WECs are intended to be deployed together—in farms of up to 1000 units—and connected to common marine substations. The first full-scale UU WEC prototype was deployed at the Lysekil research site on the west coast of Sweden in 2006. Since then, twelve full-scale UU WEC prototypes (L1-L12) have been constructed. These WECs can be divided into three design generations (G1-G3), where the G2 starts with the L9 and the G3 starts with the L12. Focus with the G1 was to demonstrate and validate the concept, while the G2 focused on performance optimization and the G3 focused on preparing the WEC for commercialization. The work presented in this thesis begins with the G2 and continues with the G3.

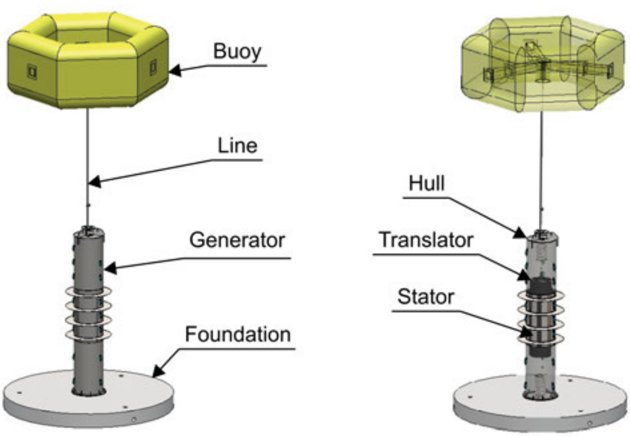

Figure 1.1. The mechanical design of the G3 of the UU WEC unit.

In parallel with the research at UU, the UU WEC concept has been commercialized by the spin-off company Seabased Industry AB. Here, extensive experience from the manufacturing of 55 WECs has been gained, see Figure 1.2. The UU WEC concept has from the beginning been designed with large-scale production in mind and the WEC design has continuously been adjusted to facilitate production. The Toyota production system and the highly robotized large-scale production achieved in the automotive industry have inspired this work. To achieve efficient production development and ensure the quality while minimizing the throughput time and the production costs, in-house production has been prioritized during the commercialization. Both the

UU WEC generator and the current production line at Seabased Industry AB are thus well prepared for integration of automated production equipment.

Research on robotized production methods for special electric machines, with focus on the UU WEC generator, was initiated by the author in 2010 at the Division of Electricity. By that, the robotics and manufacturing group was born. Much work has since then been put in to develop and run the research and the education in the field. This work include constructing nine general experimental robot cells with in total ten different industrial robots, two Doctor of Philosophy (PhD) student positions, multiple scientific publications—presented in this thesis and in [12]—, developing and running an introduction course on automation and robot engineering, running robot lab exercises on other courses, supervising and subject reviewing of ten diploma works, establishing industrial collaboration and having multiple project and summer workers, see Figure 1.3.

Figure 1.2. WEC generators manufactured by Seabased Industry AB, loaded on a pram before deployment.

Figure 1.3. Examples from research and education activities within robotized production methods at the Division of Electricity at UU.

1.3 Previous work

Until now, 28 PhDs have graduated from the wave power research at UU.

In 2006, Dr Thorburn defended her PhD thesis on electric energy conversion and transmission for wave power and hydropower [13].

In 2006, Dr Danielsson defended his PhD thesis on simulations and experiments with a linear synchronous PM WEC generator [14].

In 2007, Dr Eriksson defended his PhD thesis on modeling of a WEC generator in operation with experimental verification [15].

In 2008, Dr Waters defended his PhD thesis on full-scale experimental verification of the UU WEC [16].

In 2009, Dr Langhamer defended her PhD thesis on marine environment studies at the Lysekil research site [17].

In 2010, Dr Rahm defended his PhD thesis on the design of a marine substation for connection of several UU WEC generators [18].

In 2011, Dr Boström defended her PhD thesis on electrical damping of the UU WEC generator [19].

In 2011, Dr Engström defended his PhD thesis on the energy transfer from the ocean waves to the UU WEC generator [20].

In 2011, Dr Lindroth defended his PhD thesis on motion interaction studies for wave, buoy and generator for the UU WEC [21].

In 2012, Dr Savin defended his PhD thesis on measurements of the forces acting on the UU WEC generator hull during operation [22].

In 2012, Dr Strömstedt defended his PhD thesis on the submerged transmission system in the UU WEC [23].

In 2012, Dr Svensson defended his PhD thesis on control and sensor systems for offshore experiments with the UU WEC [24].

In 2013, Dr Ekergård defended her PhD thesis on using Neodymium Iron Boron ($Nd_2Fe_{14}B$) PMs in the UU WEC generator translator [25].
In 2014, Dr Krishna defended her PhD thesis on a three-level power converter system for the UU WEC [26].
In 2014, Dr Gravråkmo defended is PhD thesis on hydrodynamic studies for point absorbing WEC buoys [27].
In 2014, Dr Haikoen defended his PhD thesis on environmental effects of underwater noise from point-absorbing WECs [28].
In 2014, Dr Ekström defended his PhD thesis on a marine substation for grid connection of multiple UU WECs [29].
In 2015, Dr Hai defended her PhD thesis on using equivalent circuit theory to model the UU WEC system [30].
In 2016, Dr Lejerskog defended his PhD thesis on theoretical and experimental studies of the UU WEC stator and translator designs [31].
In 2016, Dr Hong defended her PhD thesis on numerical modelling and mechanical studies for the UU WEC [32].
In 2016, Dr Li defended his PhD thesis on numerical modelling of the UU WEC and statistical analysis of wave climates [33].
In 2016, Dr Castellucci defended her PhD thesis on active sea level compensation for the UU WEC [34].
In 2017, Dr Baudoin defended his PhD thesis on cooling strategies for the substation used in the UU WEC concept [35].
In 2017, Dr Wang defended his PhD thesis on control strategies for fully coupled UU WECs [36].
In 2017, Dr Sjökvist defended her PhD thesis on the behavior and peak forces for the UU WEC in extreme waves [37].
In 2017, Dr Ulvgård defended her PhD thesis on offshore measurement systems, onshore testing and deployments for the UU WEC [38].
In 2017, Dr Kamf defended his PhD thesis on automated production technologies for assembling the UU WEC translator [12].
In 2017, Dr Elamalayil Soman defended his PhD thesis on smart control of the power converter system for the UU WEC [39].

1.4 Research aim and thesis outline

The main aim of the research presented in this thesis is to investigate how industrial robots can be used to achieve flexible automated production methods for special electric machines. Focus is on enabling large-scale production of the generator used in the UU WEC device. Developing a fully automated stator cable winding method is prioritized, but other production tasks are investigated as well. The ambition is to achieve a low automation entry level for SMEs by striving for simplicity, reliability, flexibility and scalability combined with a low investment cost. A parallel aim is to strengthen the education in automation and robot engineering at the Department of Engineering Sciences at UU, by integrating the research on robotized production methods in the engineering education.

In the rest of the thesis, the methods used in the presented research are summarized in Section 2. The developed stator cable winding robot cell is presented and discussed in Section 3, while the three additional developed robot cells are presented in Section 4. In Section 5, the parallel pedagogical development work is presented and discussed. The main conclusions from the presented work are then presented in Section 6 and suggestions on future work are given in Section 7. Finally, all the research papers included in the thesis are shortly summarized in Section 8 and a summary in Swedish of the thesis is given in Section 9.

2. Method

In the presented research, the complete production of the UU WEC device has been investigated. The work has to some extent followed the evolution of the UU WEC design. To begin with, the G2 UU WEC generator design was compared to conventional electric machines in Paper I. The generator's suitability for automated production was also investigated. To enable effective production development with respect-for-human in focus, backbreaking, monotone, potentially hazardous and time consuming manual production tasks were identified. Three key assembly tasks were pointed out as particularly suitable for automation: stator stacking, stator winding and surface mounting of PMs on the translator. Research projects on these three tasks were thus initially prioritized, see Papers IV-VI and X-XI. In Paper II, the work on automated production methods was related to the general progress of the wave power research at UU. At this point, the UU WEC concept reached the G3. In Paper III, an updated evaluation regarding design and suitability for automated production was performed for the G3 UU WEC. It was here highlighted that the WEC cost had been much reduced for the G3 compared to the G2, and it was argued that production automation could reduce the production cost further. Additional production tasks were also identified to be suitable for automation. The research project on automated stator cable winding was now further developed as it was adjusted for the G3 stator design, see Papers VII-IX. A research project on automated production of rubber components was also conducted, see Paper XII.

In all four research projects on automated production, prototype equipment was designed, constructed and evaluated. To achieve high flexibility, scalability and reliability in a clear production flow with just-in-time production, industrial robots were used throughout the work. Focus was on proof of concept through experimental validation and evaluation of the constructed robot cells. In parallel with this work, the research on robotized production methods was also integrated in the engineering education through a research project on pedagogical development, see Paper XIII.

In the rest of this section, the methods used for designing and evaluating the robot cells are presented in Sections 2.1-2. Finally, the methods used in the pedagogical development work are presented in Section 2.3.

2.1 Designing a robot cell

Designing a new robot cell is often an iterative and sometimes complex task where a multidisciplinary approach is required. High requirements on performance, durability, compactness, reliability, control, supervision and flexibility are typically put on the equipment used in the robot cell. It is therefore usually necessary to develop task-specific special equipment. The major components in the robot cells developed in this work can be categorized as:

- Industrial robot
- Robot tool
- Side equipment
- Process controller
- Safety equipment
- User interface
- Communication interface

The actual development process varied for the different robot cells presented here, but it followed the same general pattern. To begin with, the corresponding manual production was studied in detail and relevant reference works were investigated from the literature. Detailed specifications and performance requirements for the robot cell were then defined. This included identifying all sub-processes in the production, any critical sub-processes, the flow of components, the final product quality, any product variations and the desired production pace as well as estimating the process forces. A preliminary robot cell design was developed using this information and with simplicity prioritized. Special equipment was designed in the Three-Dimensional Computer-Aided Design (3D-CAD) software SolidWorks and the complete robot cell was simulated in the industrial robot simulation and offline programming software ABB Robotstudio. Experiments with prototype equipment were also performed as needed. To optimize the production flow, several connected robot cells were simulated together as well, see Figure 2.1.

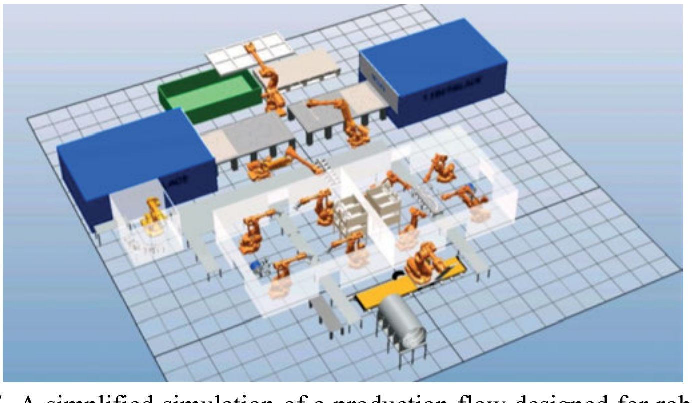

Figure 2.1. A simplified simulation of a production flow designed for robotized assembly of the G2 UU WEC generator stator.

As a satisfying theoretical robot cell design was achieved, the first full-scale robot cell prototype was constructed. Robot programming was here transferred between the robot cell simulations—which were performed on a separate Personal Computer (PC)—and the robot controllers. Older model pre-owned industrial robots were used to keep down the investment cost and industrial safety equipment was used to ensure that industrial safety standards were followed. All assembly, programming and evaluation of the developed equipment were performed in-house and standard industrial components were used as far as possible. To reduce the investment cost and the idea-to-prototype time, some components were machined in-house from Polyoxymethylene Homopolymer (POM-H) sheets or 3D-printed in-house with High Impact Polystyrene (HIPS). Components with higher requirements were custom made in high-strength aluminum or construction steel. The main objectives with the constructed robot cell were to validate the theoretical concept and to re-evaluate its performance. This work required numerous repeated experiments, with focus on reliability and performance.

The final step in the development process was to use the so far gained experience to further develop the robot cell and to construct an updated prototype robot cell accordingly. Focus was now on performance, reliability and autonomy. Higher flexibility, an improved user interface and preparation for industrial integration were also targeted. All assembly, programming and evaluation were again performed in-house. More durable standard industrial components with higher performance were used when motivated. In-house machining in POM-H was combined with custom-made components in high-strength aluminum and steel from external mechanical workshops. As before, the new robot cell and the equipment were validated and evaluated through numerous repeated experiments.

2.2 Robot cell evaluation

While robot cell simulations are easy to repeat, edit and analyze step by step, practical robot cell experiments are usually needed to handle challenges in the physical world which are hard to simulate. Such experiments can require considerable manual preparation before start-up as well as significant amounts of consumables, while having long process cycle times. In the presented work, video recordings were therefore used to streamline the extensive robot cell experiments. Another helpful evaluation method was to log essential equipment and process parameters during the experiments. Such logging was performed both with the robot cell process controllers and with separate measurement systems. External measurements were also performed, using for example a stopwatch, a caliper, a ruler or a dynamometer.

Manual supervision and inspection of repeated experiments were often required to evaluate the experiments. Logged parameters were also analyzed together in detail. When applicable, the experimental results were analyzed using normal or Kernel distributions and standard mean deviations were calculated. Since complete experimental processes often were not possible, process cycle times were then calculated through theoretical estimations or extrapolation based on the available experimental results. Another important part of the evaluation was to compare the developed robot cell with the corresponding manual production. Some aspects in such a comparison are more straightforward to estimate, such as the equipment investment cost and the process cycle time for a given scenario. Other essential aspects are harder to quantify or estimate, such as the manual work environment, in-house competence, costs related to commissioning and to downtime, effects on the overall production line, product quality and future developments. A rough economical evaluation can nevertheless provide a worthwhile indication of the economic potential for the robot cell. In the presented work, the Net Present Value (NPV) method was used to estimate the economic potentials for the developed robot cells. These evaluations assumed a base case with manual production in large-scale, according to manufacturing experience from UU and Seabased Industry AB. Full details of the parameters used in and the results from the respective economical evaluations are given in the papers included in this thesis. The NPV is defined in Equation 2.1,

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \tag{2.1}$$

where n is the economical lifetime of the investment, C_t is the net cash flow at time t and i is the discount rate. When evaluating the economic potentials for the developed robot cells, some height was taken for unexpected costs by either assuming investment in new industrial robots or by doubling the robot cell investment cost estimation with pre-owned robots. A parameter related to the NPV is the Payback Period (PBP), which here was used to estimate the payback period for the robot cell investment scenario used in the above described economic potential estimation. The PBP is defined in Equation 2.2,

$$\sum_{t=0}^{T} C_t = 0 \tag{2.2}$$

where T is the PBP.

2.3 Pedagogical development work

The pedagogical development work presented in this thesis focuses on a first cycle introduction course on automation and robot engineering, which is given for the Bachelor Program in Mechanical Engineering by the Department of Engineering Sciences at UU. Based on research on engineering education, a new teaching approach was developed and implemented on the course. In this work, the complete course was reworked and restructured around three group project tasks on robotics. These tasks were all taken from the UU research on robotized production methods. The developed lab exercises were also used in other courses at UU.

During 2012-2016, the results from extended individual anonymous student course evaluations, the students' examination results and the experience gained by the teachers were collected for the new course. These results were evaluated and compared to the corresponding results from the previous course in 2011, which was taught in a more traditional way. The student course evaluation result for new course was also briefly compared to all other courses given by the Department of Engineering Sciences during the school year 2016/17.

3. Robotized stator cable winding

The UU research project on robotized stator cable winding started in 2010 and has been run by the author since then. During this time, a robotized winding method has been developed. A delimitation is here made towards connection of the wound cables, which is not considered in this work. In the rest of this section, the background to the project is summarized in Section 3.1, the main results are presented in Section 3.2 and the results are discussed in Section 3.3.

3.1 Background

Stator winding was early identified as a critical assembly in the UU WEC production, due to the size of the generator and to the lack of industrial experience from using cable winding in large-scale production. To achieve an almost round linear stator, the UU WEC stator is divided into several angled or straight sections, see Figures 3.1-2. During winding, the cables are pushed and pulled back and forth through the slot holes in the stator sections in a predefined winding pattern. To maximize the active area of the stator, the end windings—i.e. the cable parts sticking out between two slot holes at the stator section side after winding—are kept short. The number of winding cables used depends on the winding pattern and on the number of slot hole levels in the stator section. The length of the cables depends on the winding pattern, on the number of slots in the stator section and on the width of the stator section.

As the UU WEC prototypes were constructed, it became clear that manual stator cable winding is a very time consuming, labor intense, exhausting and tiresome task. Over the years, different stator designs, winding patterns and winding cables have been tested and the manual winding process has been optimized, see Figure 3.3. Manual cable feeder tools have been tested as well. Stator winding is nevertheless still a critical task in the UU WEC production and automated winding is still the most requested production development among the production personnel. The vision about automated cable winding has however been met with skepticism from within the industry.

Further arguments for automating the stator winding were the possibility to achieve reduced production costs, an increased production capacity and a higher and more consistent quality. A lack of existing flexible and fully automated winding methods for larger sized electric machines was also identified.

Figure 3.1. Cable wound stators mounted inside the UU WEC generator hull: an eight-sided G2 stator with four single-angled stator sections (left) and a nine-sided G3 stator with three double-angled stator sections (right).

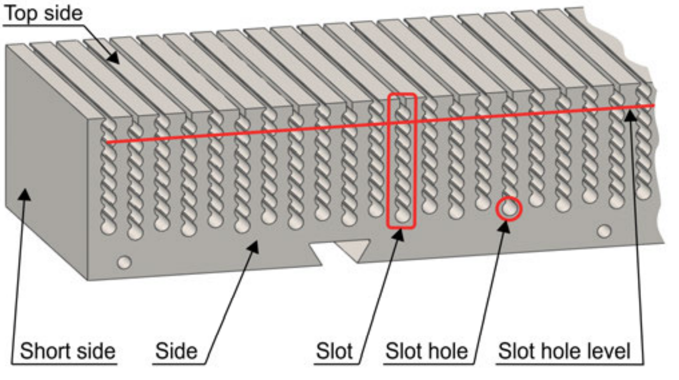

Figure 3.2. A 3D-CAD model explaining terms related to the stator section.

Figure 3.3. Manual stator cable winding of UU WEC generator stator sections: the G2 stator wound at UU (left) and the G3 stator wound at Seabased Industry AB (right).

3.1.1 Conventional stator winding

Traditionally, smaller electric machines are wound with strands of induction wire. These windings are usually either wound directly inside the stator slots or prepared outside and inserted into the slots. Split or sectional stator designs have also been developed, where the stator teeth are wound separately before the stator is put together. Larger electric machines, on the other hand, are often wound with rectangular inductor bars. These bars are then pre-formed and insulated before being inserted into the stator. With conventional stator winding concepts, fixation and connection of the windings are also often required. Automated technologies for stator winding with strands of induction wire have been available for long [40-45]. Recent developments in this field are focused on achieving simplified, more flexible and more efficient winding methods [46-51]. Automated technologies for winding with inductor bars are less common. Equipment for pre-forming and insulation of the inductor bars are available, but the stator insertion, the fixation and the winding connections are typically performed manually [41].

3.1.2 Cable winding

The cable winding concept was developed at ABB about two decades ago for medium and large sized generators, motors and transformers in particular [52-56]. Among the potential benefits with this winding concept are higher efficiency and a high durability. Cable winding also includes fewer assembly steps compared to conventional winding concepts. Especially, the cables are already insulated, the stator slots can be designed to fixate the inserted cables, no end winding fixation is typically needed and fewer winding connections are required. Until now, cable winding has been used for example in offshore motor installations [57], motors for electric vehicle propulsion systems [58] and in generators for hydropower [59], thermal energy [60], wind energy [61] and hydrokinetic [62] power plants.

3.1.3 Challenges and reference work

A major challenge with using industrial robots for stator cable winding is the flexible nature of the winding cable. During a cable winding process, winding cables are fetched from a cable drum, cut to the desired lengths, formed at the cut ends, pushed and pulled through the stator fetched, gripped and dropped numerous times. All this must be done with high accuracy and high reliability, while avoiding twisting and tangling of the cable. If cable twisting is not avoided, torsional forces on the cable can lead to the formation of cable loops. If a cable loop does not pop-out completely when the end winding is pulled, this can damage the cable and disturb the winding process. This phenomena is referred to as cable kinking or hockling in the literature, and it has been shown that such problems are more likely with torsional-stiff and easy-to-bend cables [63-66]. Methods and sensor implementations for automated localization, manipulation, shape prediction and routing of flexible objects, such as loose cables, have been demonstrated elsewhere [67-72]. However, these technologies can likely not fulfil the reliability, productivity and accuracy required for automated cable winding. Detecting and adjusting for arising cable twisting in particular, is a complicated task. A passive cable handling method, where cable twisting is avoided in the first place, is therefore preferred.

Another major challenge for the winding automation is to achieve high positioning accuracy relative the stator section. It must then also be considered that the stator section side is not completely uneven, since the stator sections are held together by threaded rods and bolts in the bottom. High accuracy Six-Degrees-Of-Freedom (6-DOF) positional calibration of the stator section and sufficient robot absolute positioning accuracy are thus required for the winding application. The exact position of work objects is usually measured using machine vision, but force feedback sensors, touch probes, laser sensors or proximity sensors can also be used [73-78]. Industrial robots generally provides high positioning repeatability, but less precise absolute positioning. Robot absolute accuracy calibration or positioning feedback and compensation systems can however significantly improve the absolute accuracy [79-80].

Additional important challenges to the work are to achieve a clear and user friendly but yet reliable and flexible control system for the complex winding process and to design powerful, reliable, precise and durable equipment with small dimensions. The long winding process cycle time, the cable consumption and the decision to use older model pre-owned robots added further complexity to the development work. By winding the cable through on slot hole at the time, considerable feed lengths are quickly reached. For example, winding a three phase winding pattern in a G2 UU WEC stator section, as shown in Figures 3.1 and 3.3, requires in total 24 cables each being about 25 m long. The total feeding length performed during manual winding of this stator section is however about 5000 m.

To the knowledge of the author, there is no other existing method for automated stator cable winding. Manual stator cable winding has however previously been performed using manual cable feeder tools [59]. Existing technologies with similarities to robotized stator cable winding are filament winding, winding of superconductive coils, tape winding, fiber optic winding, wire harness assembling and cable laying [81-93].

3.2 Results

The development of robotized stator cable winding was performed in three main steps. A robotized winding method was first developed and preliminary evaluated. This method was adapted for the G2 UU WEC generator stator and is described in detail in Paper IV. A full-scale prototype version of the stator cable winding robot cell was thereafter constructed and evaluated. This robot cell is described in detail in Papers V-VI. Finally, the prototype robot cell was significantly improved and adapted for industrial production of the G3 UU WEC, as described in detail in Papers VII-IX. All the here constructed prototype robot cells were installed and evaluated in lab facilities at UU in Uppsala.

The basic conceptual idea for automated stator cable winding used in this work is to wind the cable into a stator section using industrial robots, in a similar manner as during manual winding. Hence, one robot is placed on each side of the stator section and the robots feed the cable between each other. The robots are equipped with special cable feeder tools, which are used to handle the cable. A specialized Work Object Coordinate System (WOCS) positional calibration method is used to measure the position of the stator section and a special side equipment is used to prepare the cable for winding.

In the rest of this section, the cable feeder tool is presented in Section 3.2.1, the WOCS positional calibration method is presented in Section 3.2.2 and the cable preparation equipment is presented in Section 3.2.3. The results from robotized stator cable winding are described in Section 3.2.4.

3.2.1 Cable feeder tool

The robot cable feeder tool is the most critical equipment in the robotized cable winding concept. A general cable feeder tool design, with the following main components, was used during the complete research project:

- A cable guiding system
- A cable gripping mechanism
- A cable feed mechanism

In the cable guiding system, the winding cable was guided through the tool inside two tubes. The cable was here received from one end, guided through the fed mechanism between the two tubes and fed out from the other end. In the cable gripping mechanism, the cable was squeezed between two gripping wheels. A positional adjustment screw was used to adjust the radial distance between the two wheels, and power springs were used to dampen variations in the cable gripping force. One or both of the cable gripping wheels were designed with a concave high friction surface and used also as feed wheels in the cable feed mechanism. An electric motor was used to drive the feed wheels, and thereby feed the cable through the tool with adjustable velocity.

With this tool design and the above described winding method, the winding cable was always held by at least one cable feeder tool and cable localization was limited to finding the cable end and supervising the cable fed distance. A passive cable handling method was thus achieved. To optimize the tool performance, the minimum positional adjustment screw torque, T_n, required for achieving a sufficient cable gripping force with regards to the cable feed motor torque, T_f, was estimated using Equation 3.1,

$$T_n = \frac{T_f \; p_s \; \eta_w}{2\pi \, r_f \; \mu_s \; \eta_s} \tag{3.1}$$

where p_s is the positional adjustment screw pitch, η_w is the feed force transmission efficiency, r_f is the radius of the feed wheel, μ_s is the static frictional coefficient between the cable surface and the feed wheel surface and η_s is the gripping force transmission efficiency.

The first constructed cable feeder tool prototype was manually controlled, see Figure 3.4. A single cable feed wheel with a high-friction rubber surface was used in this tool, and the cable feed mechanism was driven by a step motor. The tool housing was made in construction steel and welded together. Through experiments with a G2 UU WEC stator section, the tool was demonstrated to push and pull cable through slot holes in the stator section without buckling the cable. The power spring damping of the lower cable gripping wheel enabled more precise setting of the cable gripping force and compensated for variations in the cable diameter. It was also noticed that well-defined cable feed velocities reduced the cable wear compared to manual winding.

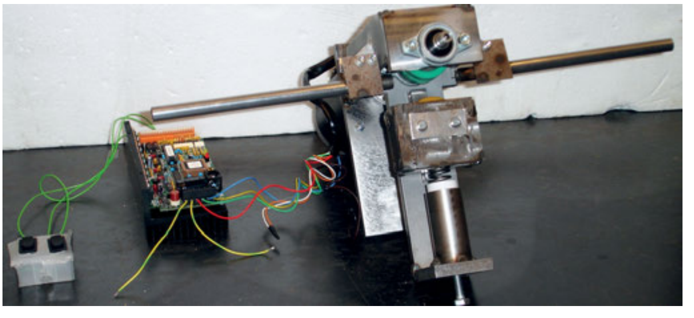

Figure 3.4. The first constructed prototype version of the cable feeder tool.

An updated cable feeder tool was then designed and constructed, see Figure 3.5. This tool was adapted for robotized winding of the G2 UU WEC generator stator and it was much improved compared to the previous tool. To begin with, a step motor was now used to drive the cable gripping mechanism. Cable dropping was also enabled, by splitting the cable guiding system tubes lengthwise and connecting the lower parts to the lower cable gripping wheel. Two optical fork sensors were used for cable presence supervision inside the cable guiding system and a proximity sensor was used to take external positional measurements. Feed slip supervision was achieved as well, by mounting incremental rotational sensors on the cable gripping wheel axes and comparing their outputs in a separate Programmable Logic Controller (PLC), see Figure 3.6. Furthermore, the feed wheel design was reinforced and the tool housing was now screwed together from mainly flat parts made in high-strength aluminum. More durable mechanical components were also used.

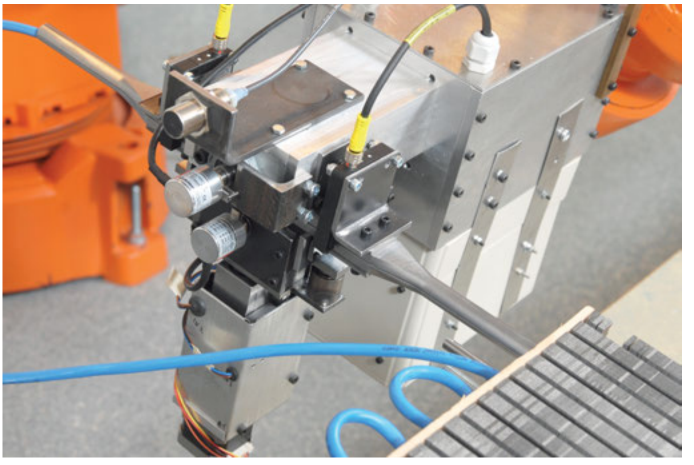

Figure 3.5. The second constructed prototype version of the cable feeder tool.

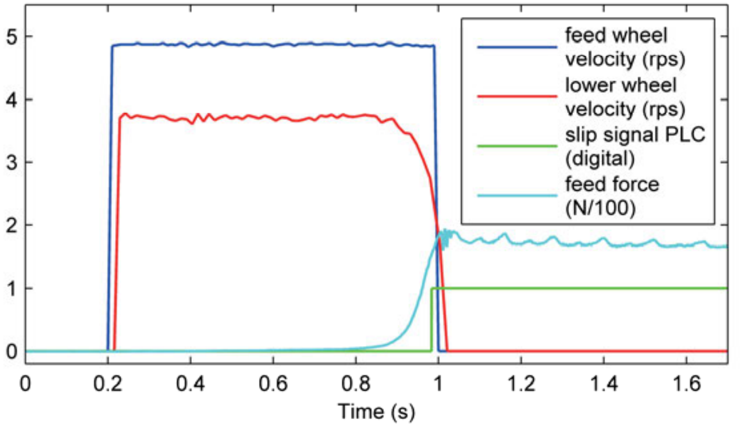

Figure 3.6. The behavior of the feed slip supervision function used in the second constructed prototype version of the cable feeder tool, while the tool is used to pull a cable which is attached through a tension spring to a fixed load cell. The cable feeding is started at T=0.20 s. The cable feed force, measured by the load cell, then rises as the spring is tensioned, until the feeding is stopped by the PLC slip supervision function at T=0.98 s.

The updated cable feeder tool was connected to and fully controlled by a robot controller, using Point-to-Point (P2P) Digital Input/Output (DIO) signals. To facilitate robot positioning, three different Tool Center Points (TCPs) were precisely defined on the two ends of the cable guiding system and in front of the proximity sensor on the tool. It was experimentally validated that the cable feeder tool was able to receive a cable from a slot hole, to grip a cable, to push a cable through a slot hole, to pull a cable through a slot hole, to react on feed slippage and to drop a cable.

Finally, a third cable feeder tool prototype was designed and constructed, see Figures 3.7-9. This tool was adapted for the G3 UU WEC generator stator and significantly updated compared to the previous tool. Powerful industrial servo motors, servo motor drives and gears were now used for the feed and gripping mechanisms. To achieve a more effective cable feed mechanism, the two cable gripping wheels were connected through cog wheels and thereby driven together when closed. The feed wheel design was also more durable, with a sand-blasted and grooved surface in high-strength aluminum. Absolute rotational sensors were used to supervise the feed wheels rotations and a special miniature cable fed distance measuring system was developed and integrated in the cable guiding system. Furthermore, a linear pneumatic cylinder was now used to position the lower part of the cable guiding system separately from the cable gripping mechanism. The tool was connected to and fully controlled by a powerful industrial PLC, using P2P DIO and Analog Input/Output (AIO) signals combined with industrial fieldbus communication.

Figure 3.7. The third constructed prototype version of the cable feeder tool.

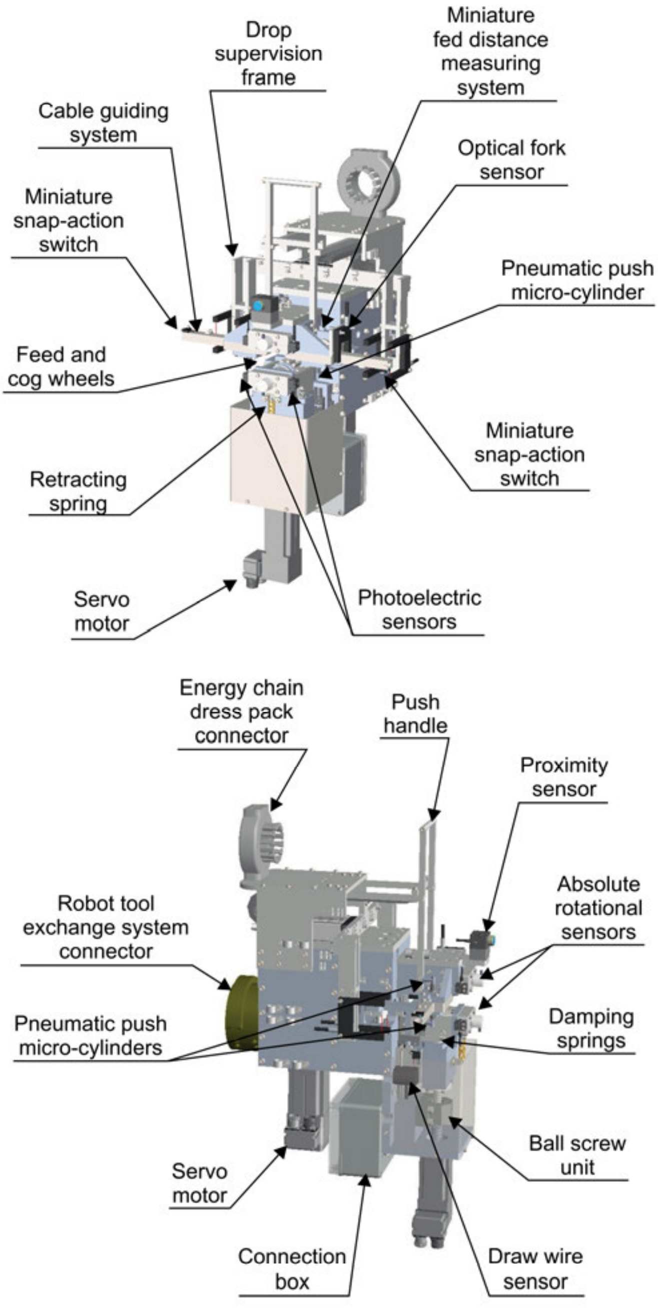

Figure 3.8. A 3D-CAD model explaining the main components of the third constructed prototype version of the cable feeder tool.

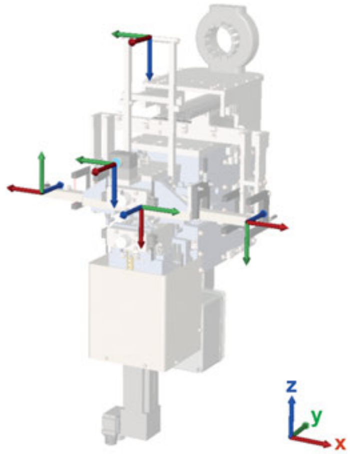

Figure 3.9. A 3D-CAD model displaying the placement of the five TCPs defined on the third constructed prototype version of the cable feeder tool.

In the new tool, the cable gripping force was supervised by measuring the compression of the damping springs in the cable gripping mechanism, using a miniature draw wire sensor. To supervise the cable feed force, the idle feed force needed to be subtracted from the total feed force. The total feed force was easily calculated from the feed motor current, a value which was provided by the servo motor drive. The idle force, on the other hand, was observed to depend mainly on the cable gripping force and feed velocity. These dependencies were estimated experimentally.

During feeding, the risk for cable slippage was continuously estimated by comparing the current cable gripping force to the current cable feed force, see Figure 3.10. Hence, the feeding could be stopped before slip occurred, avoiding unnecessary wear of both the cable and the feed wheels. To enable flexible, effective and powerful performance, different operation-specific cable gripping and feed functions were integrated in the PLC control system of the tool. This included to adjust the cable gripping force, to feed an absolute distance, to feed in synchronization with robot movements and with other cable feeder tools, to find and adjust to the cable end position, and to fit the cog wheels angularly to each other, see Figures 3.11-12. Automatic tool calibration functions for the relative angular mounting of the cog wheels and for the ball screw nut home position were also integrated in the control system. These functions were intended to be used at commissioning or after service.

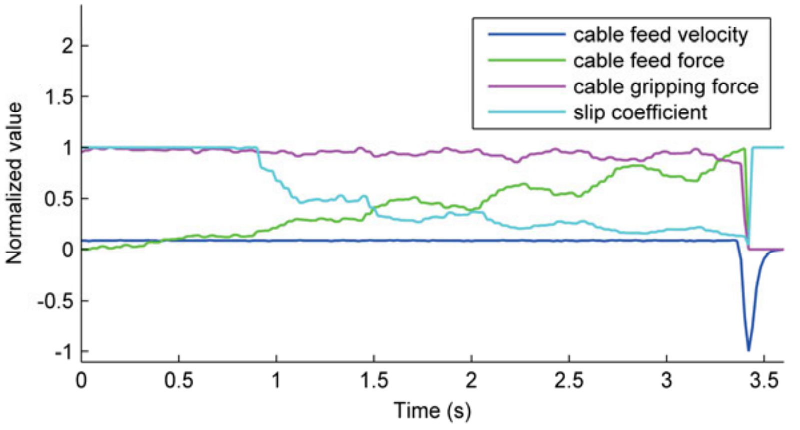

Figure 3.10. The behavior of the feed slip risk estimation function, used in the third constructed prototype version of the cable feeder tool, while slowly pulling a cable which is attached through a tension spring to a fixed table. The feeding is stopped at T=3.4 s and the displayed values are normalized. For reference, the actual maximum absolute values shown in the figure are 228 mm/s, 405 N and slip coefficient 10.

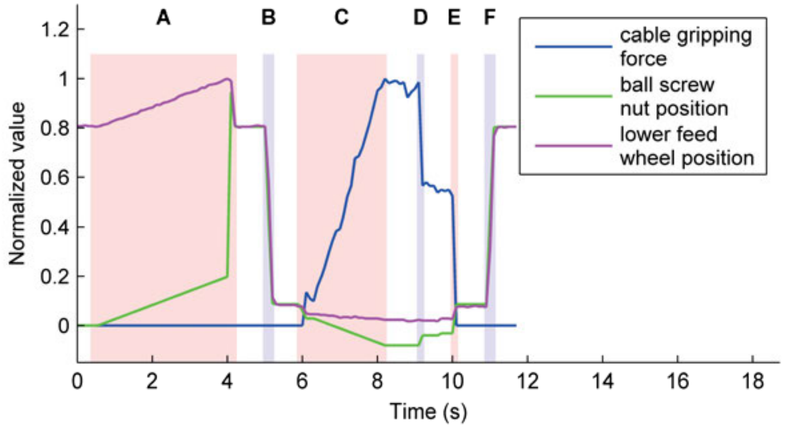

Figure 3.11. The behavior of the cable gripping mechanism, used in the third constructed prototype version of the cable feeder tool, during typical cable gripping operations. Zone A highlights a ball screw nut homing operation, Zone B highlights a wheel half-close operation, Zone C highlights a cable gripping operation, Zone D highlights a cable gripping force adjustment operation, Zone E highlights another wheel half-open operation and Zone F highlights a wheel open operation. The displayed values are normalized and the position values refers to the radial distance between the cable gripping wheels. For reference, the actual maximum values shown in the figure are 495 N and 348 mm.

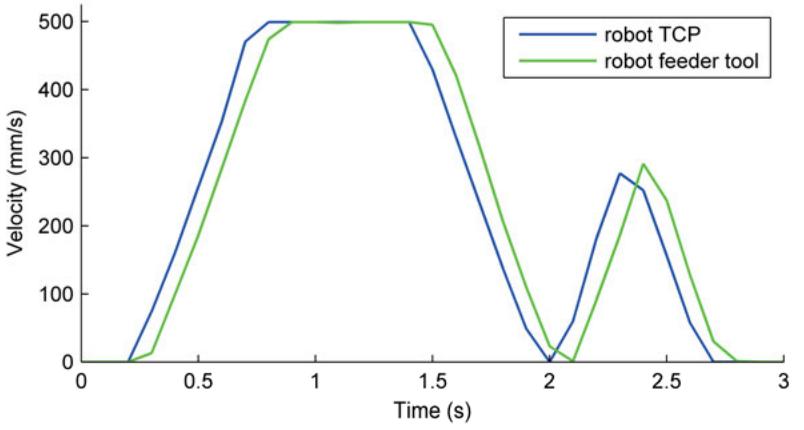

Figure 3.12. The robot absolute TCP positioning velocity and the cable feed mechanism feed velocity, while feeding cable in synchronization with robot movements and using the third constructed prototype version of the cable feeder tool.

To enable higher winding autonomy, a cable drop supervision system was developed for the new tool. Four optical fork sensors were here mounted on a common frame, which was pushed out over the cable guiding system using a linear pneumatic cylinder. Two through-beam photoelectric sensors were also mounted on the tool housing, close to the feed wheels. To drop the cable, the feed wheels and the cable guiding system were opened with the tool facing downwards. A successful cable drop was thus registered by all six drop supervision sensors. Cable dropping was also assisted by ejecting the cable from the cable guiding system, using three micro push cylinders.

To enable higher tool positioning accuracy relative the uneven stator section side, miniature snap-action switches were mounted at the cable guiding system ends. A push handle was mounted on the top of the tool as well. This handle was used for holding down the end windings while being pulled, thus preventing cable kinking. The handle was also used to pack together the end windings after being pulled, by pressing them down. Finally, an energy chain dress packs was used to protect and guide the tool cabling on the robot arm.

It was experimentally validated that the new cable feeder tool was able to feed cable with higher accuracy and with higher feed forces, compared to the previous tool prototype. Higher and more precise cable gripping forces, the function of the push handle and the cable drop supervision method were validated as well. Furthermore, the experiments validated that the new tool was able to react on unexpectedly high process forces and to detect cable feed slippage.

3.2.2 WOCS positional calibration

The specialized 6-DOF stator section WOCS positional calibration method enabled high robot positioning accuracy relative the stator section during winding. The calibration started from a standard WOCS definition in the Robot Base Coordinate System (RBCS) and was performed individually by the winding robots, using the proximity sensor mounted on their cable feeder tools. Several measurements were taken on the stator section and the WOCS definition was calibrated gradually, see Figures 3.13-14.

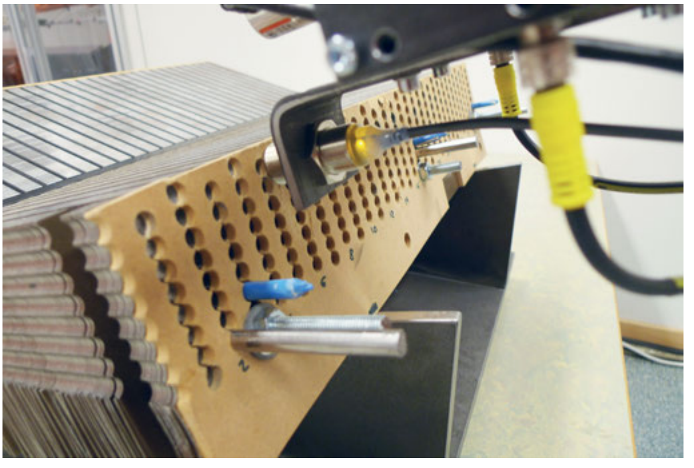

Figure 3.13. A positional calibration measurement is taken on a G2 UU WEC stator section part, using the second constructed prototype version of the cable feeder tool.

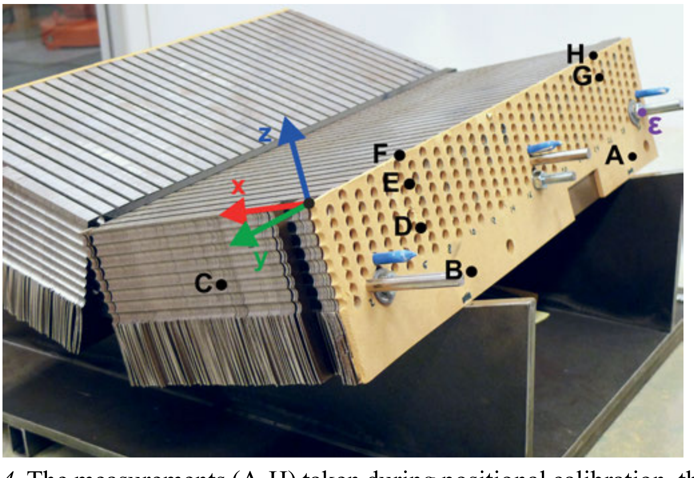

Figure 3.14. The measurements (A-H) taken during positional calibration, the farthest away slot hole to wind (ε) and the placement of the WOCS, displayed on the G2 UU WEC stator section part used in the first constructed prototype version of the stator cable winding robot cell.

Using the positional calibration measurements, a normal vector to the stator section side surface and a vector following the edge between the side and top side of the stator section were calculated. These vectors defined the WOCS rotation. The WOCS position was then defined from single measurements taken on the side, on the short side and on the edge between the side and the top side of the stator section. To transform measurements taken in the RBCS to WOCS coordinates, the rotational matrix from the RBCS to the WOCS, $\boldsymbol{{}_{R}R_{W}}$, was calculated using Equation 3.2,

$$\overline{\overline{{}_{R}R_{W}}} = \begin{pmatrix} \overline{{}^{U}X_{R}} \cdot \overline{{}^{U}X_{R0}} & \overline{{}^{U}Y_{R}} \cdot \overline{{}^{U}X_{R0}} & \overline{{}^{U}Z_{R}} \cdot \overline{{}^{U}X_{R0}} \\ \overline{{}^{U}X_{R}} \cdot \overline{{}^{U}Y_{R0}} & \overline{{}^{U}Y_{R}} \cdot \overline{{}^{U}Y_{R0}} & \overline{{}^{U}Z_{R}} \cdot \overline{{}^{U}Y_{R0}} \\ \overline{{}^{U}X_{R}} \cdot \overline{{}^{U}Z_{R0}} & \overline{{}^{U}Y_{R}} \cdot \overline{{}^{U}Z_{R0}} & \overline{{}^{U}Z_{R}} \cdot \overline{{}^{U}Z_{R0}} \end{pmatrix} \tag{3.2}$$

where $\boldsymbol{{}^{U}X_{R}}$, $\boldsymbol{{}^{U}Y_{R}}$ and $\boldsymbol{{}^{U}Z_{R}}$ are unit vectors describing the orientation of the WOCS in the RBCS and $\boldsymbol{{}^{U}X_{R0}}$, $\boldsymbol{{}^{U}Y_{R0}}$ and $\boldsymbol{{}^{U}Z_{R0}}$ are unit vectors describing the orientation of the RBCS in the RBCS. In the robot controllers, a WOCS orientation is described relative the RBCS using the Tait-Bryan z-y'-x'' angles α, β and γ. These angles were here calculated using Equations 3.3-5,

$$\beta = A\tan 2\left(-\overline{\overline{{}_{R}R_{W}^{31}}}, \sqrt{\left(\overline{\overline{{}_{R}R_{W}^{11}}}\right)^{2} + \left(\overline{\overline{{}_{R}R_{W}^{21}}}\right)^{2}} \right) \tag{3.3}$$

$$\alpha = A\tan 2\left(\frac{\overline{\overline{{}_{R}R_{W}^{21}}}}{\cos(\beta)}, \frac{\overline{\overline{{}_{R}R_{W}^{11}}}}{\cos(\beta)} \right) \tag{3.4}$$

$$\gamma = A\tan 2\left(\frac{\overline{\overline{{}_{R}R_{W}^{32}}}}{\cos(\beta)}, \frac{\overline{\overline{{}_{R}R_{W}^{33}}}}{\cos(\beta)} \right) \tag{3.5}$$

Additional measurements were taken on the stator section side to compensate for dimensional variations in the x-axis direction of the WOCS. With the second constructed prototype version of the cable feeder tool, these measurements were taken using the proximity sensor during the positional calibration. With the third constructed prototype version of the cable feeder tool, the measurements were instead taken on the fly during winding, using the miniature switches on the ends of the cable guiding system. To improve the positioning accuracy further, robot- and TCP-specific absolute positioning compensation matrixes were defined over the stator section side surface. These matrixes were calibrated by positioning the robot tool at predefined targets close to the stator section side and taking manual measurements of the deviation from perfect accuracy relative a perfect stator section.

Through 400 WOCS calibrations with a 500 mm long G2 UU WEC stator section part, it was validated that the developed positional calibration method provided sufficient accuracy and reliability for the winding task, see Figure 3.15. From these measurements, the standard mean deviation for the positional deviation, originating from the positional calibration, was calculated to 0.20 mm in the yz-plane at the farthest away slot hole to wind relative the WOCS origin. The positional calibration method was successfully implemented both for the G2 and for the G3 UU WEC generator stator design. To use the different robot cable feeder tool TCPs with the calibrated WOCS was validated to much facilitate robot positioning relative the stator section.

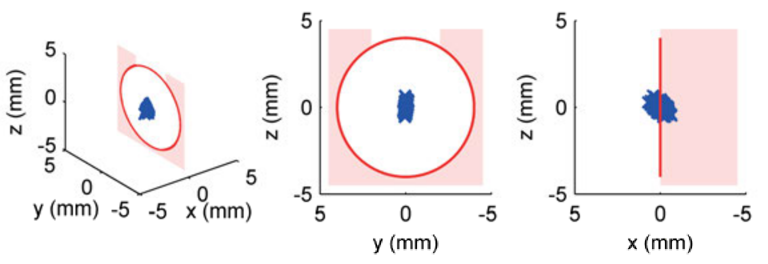

Figure 3.15. Calculated positional deviations at the farthest away slot hole to wind relative the WOCS origin, originating from 400 WOCS calibrations with the G2 UU WEC stator section part.

3.2.3 Cable preparation equipment

To fully automate the stator cable winding robot cell requires special equipment that automatically deliver winding cables to the robots, form the cable ends to tips—to prevent the cable from getting stuck when being fed through the slot holes in the stator section—and cut the cables to desired lengths.

In the first constructed prototype version of the cable preparation equipment, winding cable was pulled from a small cable drum using a drum cable feeder tool, see Figure 3.16. A modified version of the first constructed prototype version of the cable feeder tool was here used as drum cable feeder tool and the cable drum was mounted vertically on sliding bearings. Four guiding rollers guided the cable between the drum and the feeder tool, while a circular air blow nozzle blew off dirt from the cable. The equipment was connected to and fully controlled by a robot controller, using P2P DIO signals.

A significantly improved second prototype version of the cable delivery equipment was then designed and constructed, see Figures 3.17-18. A drum cable feeder tool with higher performance—a simplified version of the third constructed prototype version of the cable feeder tool—enabled the use of larger cable drums which were mounted horizontally on ball bearings. To prevent the cable drum from spinning faster than the cable was pulled off, a drum brake with adjustable brake force was developed. A special miniature rotation measurement system was used to supervise the drum rotation and the amount of cable left on the drum was continuously estimated as cable was fed off. A cable cutting equipment was also mounted after the drum cable feeder tool.

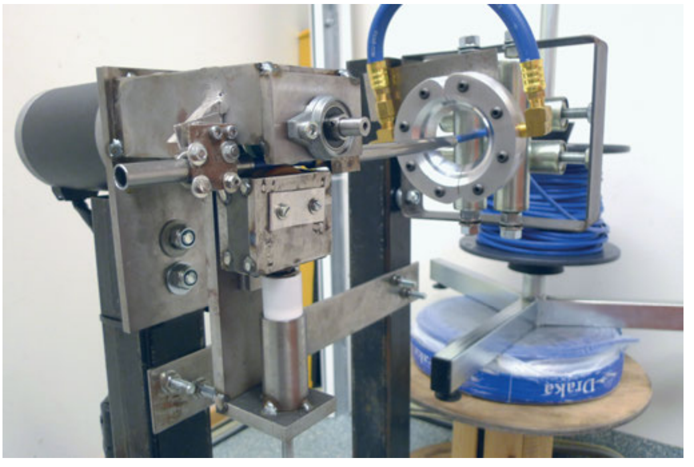

Figure 3.16. The first constructed prototype version of the cable delivery equipment.

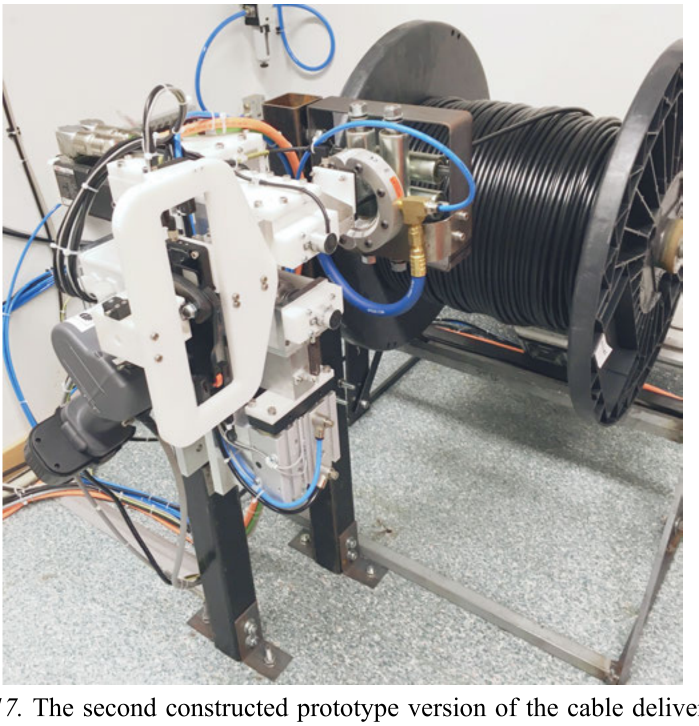

Figure 3.17. The second constructed prototype version of the cable delivery equipment.

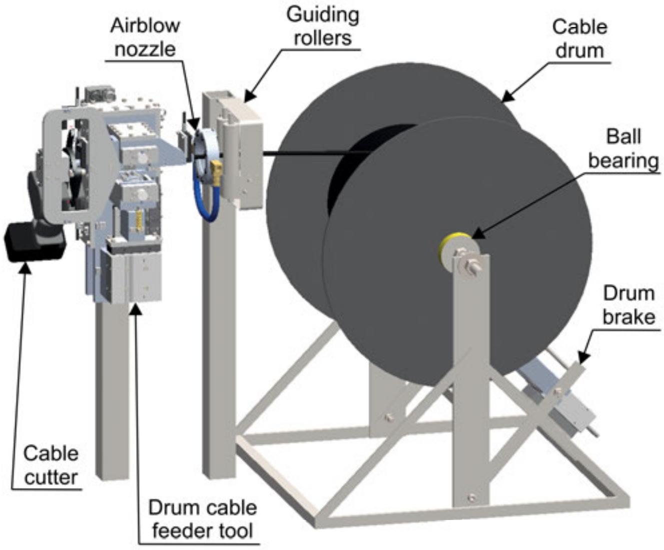

Figure 3.18. A 3D-CAD model explaining the main components of second constructed prototype version of the cable delivery equipment.

The new cable preparation equipment also included a separate cable end preparation equipment, see Figures 3.19-20. A cable end was here positioned inside the equipment by a winding robot. To begin with, the cable insulation was heated up about 50 mm from the end, stretched out over the cable end threads and cooled down in a special insulation pull-out equipment. A three-finger chuck with teethed gripper clutches was used to grip the cable end, a heat gun with an attached reflector nozzle was used to heat up the cable, a pyrometer was used to measure the cable surface temperature and a cold gun with double nozzles was used to cool down the cable.

The pulled out end insulation length was then controlled in a special insulation pull-out length control equipment. Cable ends which did not fulfill the specified accuracy requirements were removed to ensure high quality of the final prepared cable end. The control was performed by measuring the distance between the cable end insulation and the cable end threads, while slowly feeding the cable through an optical fork sensor and past a proximity sensor.

Finally, the stretched out cable end insulation was heated up, formed to a tip and cooled down inside a special cable end forming equipment. The tip forming was achieved by pushing the cable into a cast. Identical models of the heat gun, the pyrometer and the cold gun as in the insulation pull-out equipment were used.

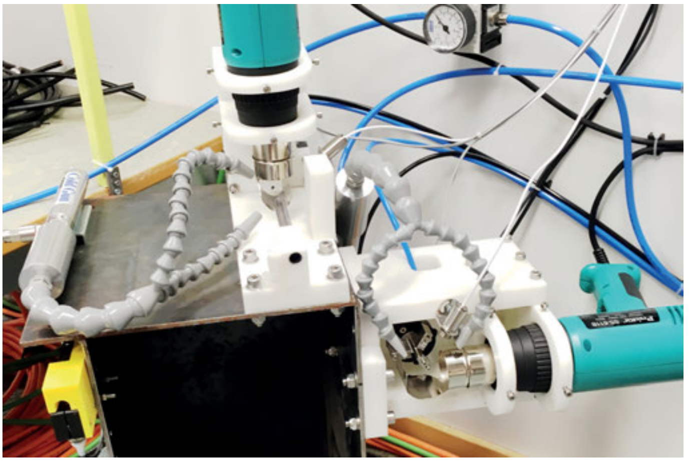

Figure 3.19. The constructed cable end preparation prototype equipment.

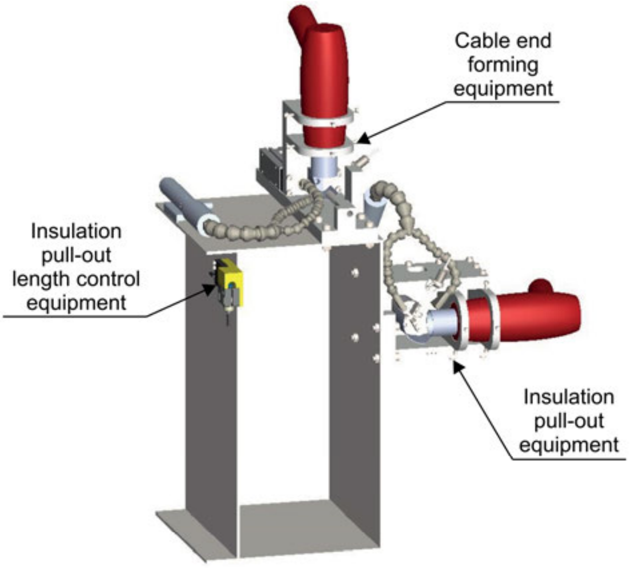

Figure 3.20. A 3D-CAD model explaining the main components of the constructed cable end preparation prototype equipment.

The new cable preparation prototype equipment was connected to and fully controlled by a powerful industrial PLC, using P2P DIO and AIO signals combined with industrial fieldbus communication. The constructed equipment was experimentally validated to be able to deliver winding cable from a drum to a robot cable feeder tool, to prepare cable ends with high quality and to cut off cables to specified lengths, see Figures 3.21-22. The standard mean deviations for the pulled insulation lengths and for the cable insulation pull-out measurements were estimated from in total 400 measurements on 20 pulled cable ends to 0.61 mm and 0.054 mm respectively.

Figure 3.21. A cable end after being cut (left), after being pulled out (middle) and after being formed (right) in the constructed cable preparation equipment.

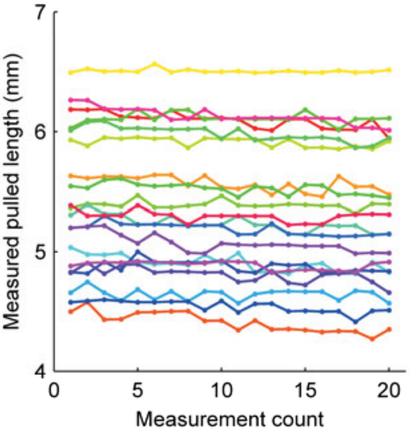

Figure 3.22. Actual values of the 400 cable insulation pull-out measurements performed on 20 pulled cable ends, sorted per cable end.

3.2.4 Robotized stator cable winding

In the first development step for the research project on robotized stator cable winding, the developed winding method was preliminary validated in theory through robot cell simulations with simulated equipment, see Figure 3.23. By combining these simulations with the experimental results from the first constructed prototype version of the cable feeder tool, the total winding process cycle time, t_{tot}, could be preliminary estimated using Equation 3.6,

$$t_{tot} = \frac{l_{feed}}{v_{feed}} + t_{pos} \tag{3.6}$$

where l_{feed} is the total cable feed length, v_{feed} is the average cable feed velocity and t_{pos} is the total pure robot positioning process cycle time. The process cycle time for winding a three phase winding pattern in a complete G2 UU WEC stator with four angled stator section was thus estimated to about 14 h. From experience at UU, the corresponding manual winding cycle time was estimated to about 80 h with four personnel. The robot cell investment cost was estimated to about 300 000 EUR with new robots. These results were also used in a rough preliminary economic analysis of the robot cell against manual winding. Using Equations 2.1-2 and assuming 4000 h yearly production time and five years investment economical lifetime, the NPV and the PBP were here estimated to about 7 000 000 EUR and two months respectively.

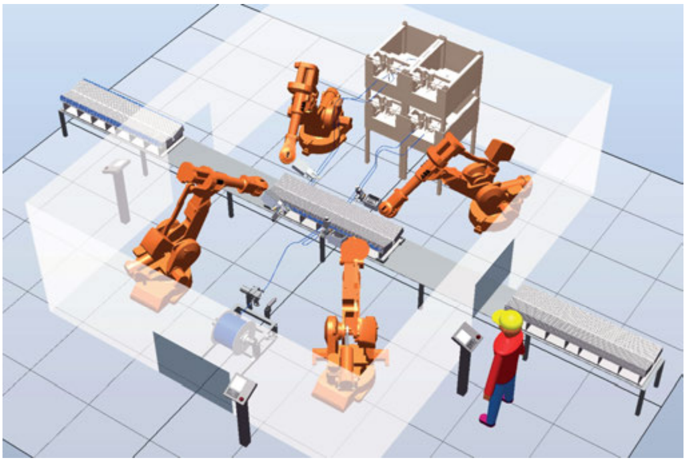

Figure 3.23. The first simulated version of the stator cable winding robot cell.

In the second development step for the robot winding project, the first prototype version of the stator cable winding robot cell was constructed. Cable feeder tools of the second constructed prototype version were here mounted on two pre-owned ABB IRB4400/60kg S4C+ M2000 industrial robots and the first constructed prototype version of the cable preparation equipment was used. All equipment was connected to and fully controlled by the robot controllers. The two robot controllers communicated through P2P DIO signals and were used together as main process controllers. A simple user interface was developed on the robot controllers teach pendants. Winding experiments were performed on a single-angled about 0.5 m wide G2 UU WEC stator section part, using 16 mm^2 multi-thread standard installation cable with Polyvinyl Chloride (PVC) insulation. With this setup, the developed robotized stator cable winding concept was experimentally validated, see Figures 3.24-25. Cable twisting was kept at a minimum by facing the robot cable feeder tools downwards and following the desired winding pattern when positioning the cable. Good correlation with the previous theoretical winding process results and reduced cable wear compared to manual winding were indicated. Extensive manual supervision was however required during the winding process. It was concluded that further equipment improvements were needed to achieve satisfying winding autonomy, reliability and performance.

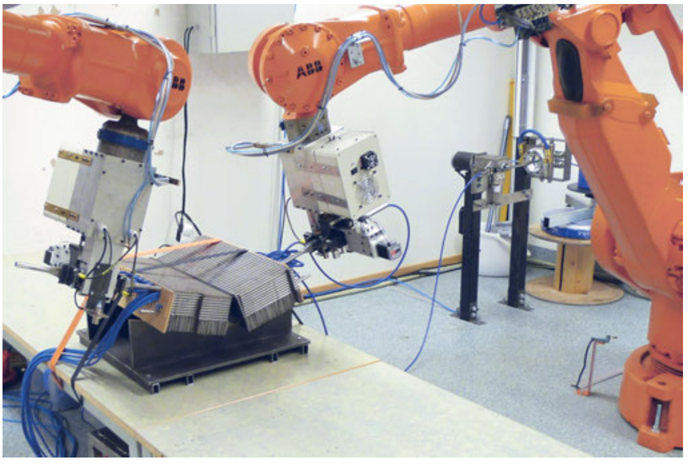

Figure 3.24. The first constructed prototype version of the stator cable winding robot cell.

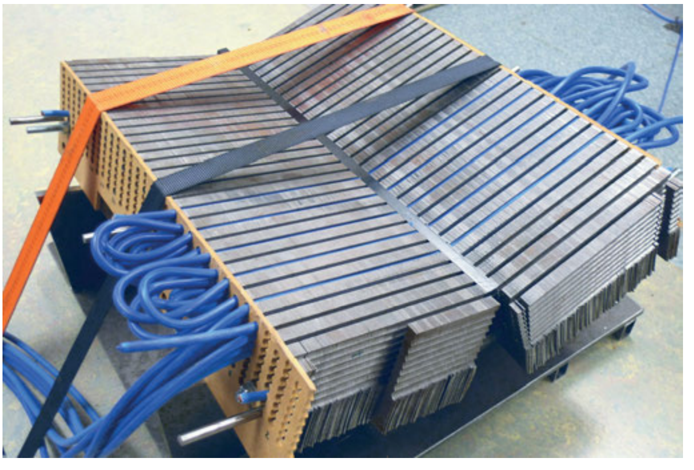

Figure 3.25. Stator cable winding performed on a G2 UU WEC stator section part, using the first constructed prototype version of the stator cable winding robot cell.

In the third robot winding project development step, the constructed stator cable winding robot cell was significantly improved, see Figures 3.26-28. The same industrial robots as in the first constructed robot cell were used, but now with the third constructed prototype versions of the cable feeder tools and the second constructed prototype version of the cable preparation equipment. A powerful ABB AC500 industrial PLC—the same PLC that control the winding equipment—was used as main process controller, industrial fieldbus communication was used between the equipment and an extensive Graphical User Interface (GUI) was developed for and integrated on an ABB CP675 15” Human-Machine Interface (HMI) touch panel, see Figure 3.29. Winding experiments were performed on a straight 0.5 m wide G3 UU WEC stator section part, using custom-made 25 mm^2 PVC-insulated multi-thread winding cable.

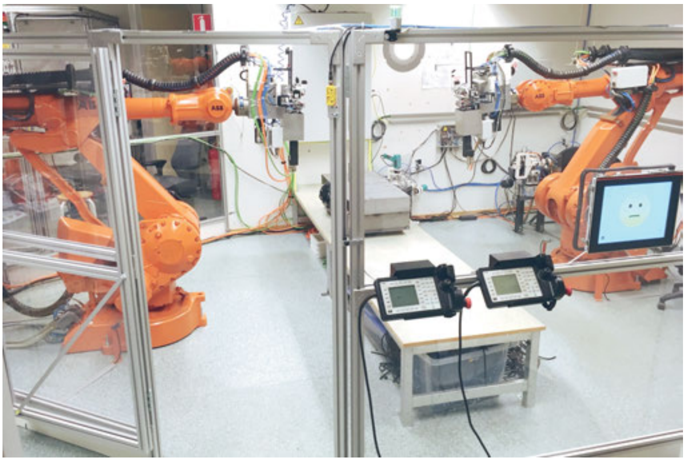

Figure 3.26. The second constructed prototype version of the stator cable winding robot cell.

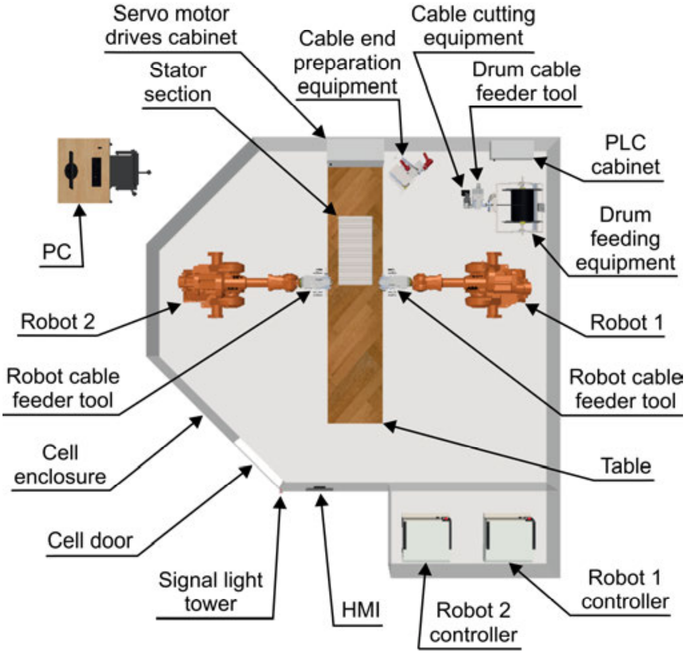

Figure 3.27. A 3D-CAD model explaining the main components of the second constructed prototype version of the stator cable winding robot cell.

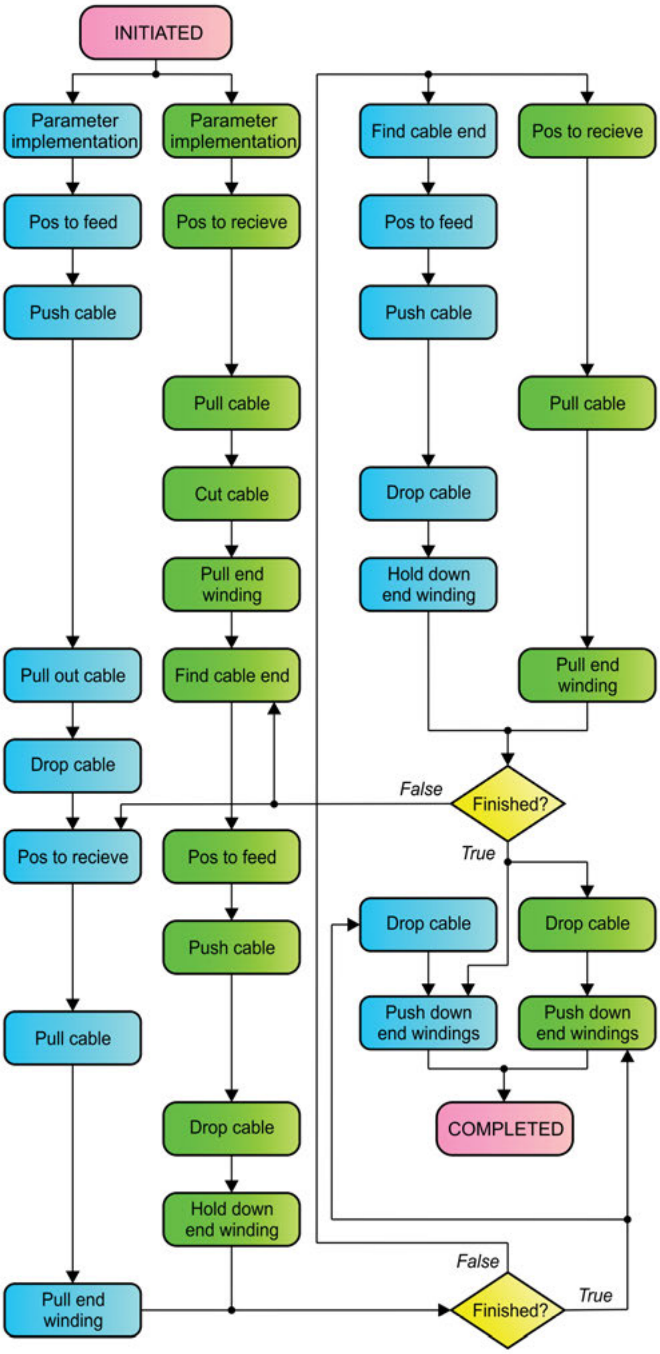

Figure 3.28. A simplified illustration of the part of the winding control system used to wind one cable into the stator section. This winding sub-process is started after the cable has been fetched from the cable delivery equipment and prepared in the cable end preparation equipment. The blue and the green boxes represents actions performed by the two winding robots respectively.

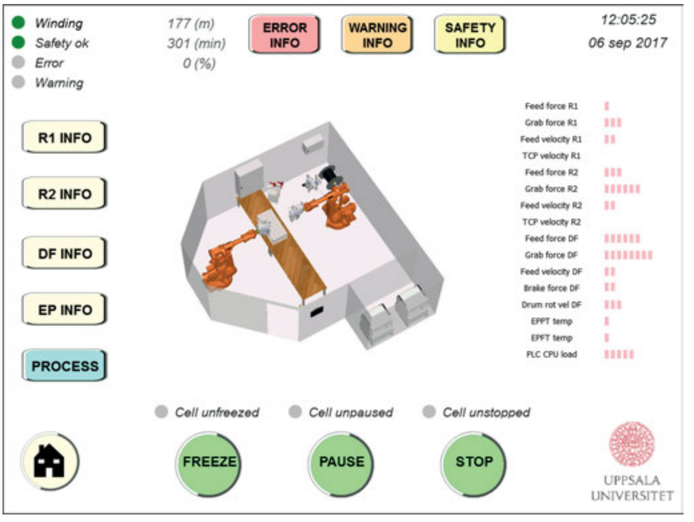

Figure 3.29. A screenshot from the GUI on the HMI used to control and supervise the second constructed prototype version of the stator cable winding robot cell.

The new robot cell was experimentally validated for high quality, durable, highly flexible and user friendly stator cable winding, see Figure 3.30. Cable tangling was kept at a minimum by always pulling the cable from the top layer after being fed out on the floor. Winding with four different winding patterns was demonstrated, see Figure 3.31, and the winding process was analyzed in detail, see Figure 3.32. The need for manual supervision was almost eliminated. It was however concluded that further measures are required to fully prevent cable kinking as the end windings are pulled, see Figure 3.33.

To extend the analysis of the robot cell concept, four different theoretical winding development scenarios were used: the present winding scenario (PR:#), a moderately developed winding scenario (D1:#), a fully developed winding scenario (D2:#) and an extended fully developed winding scenario (D3:#). Three different G3 UU WEC stator reference designs were also assumed: a nine-sided stator with nine straight sections (##:A), a six-sided stator with six straight sections (##:B) and a six-sided stator with three angled sections (##:C). The experimental winding cycle time results were now analytically extrapolated, see Figures 3.34-35. This resulted in a process cycle time estimation of about 23-30 h for winding a two phase winding pattern in a complete G3 UU WEC stator, assuming robotized winding scenarios D2:C and D3:C. The investment costs for these scenarios were estimated to about 450 000-700 000 EUR per robot cell with new robots. Manual winding of a corresponding stator with six straight sections was estimated from experience at Seabased Industry AB to about 24 h with four personnel. The rough preliminary NPV and PBP estimations were now be updated to about 300 000-700 000 EUR and about 3-4 years respectively, using Equations 2.1-2 and assuming a production pace of one UU WEC per day.

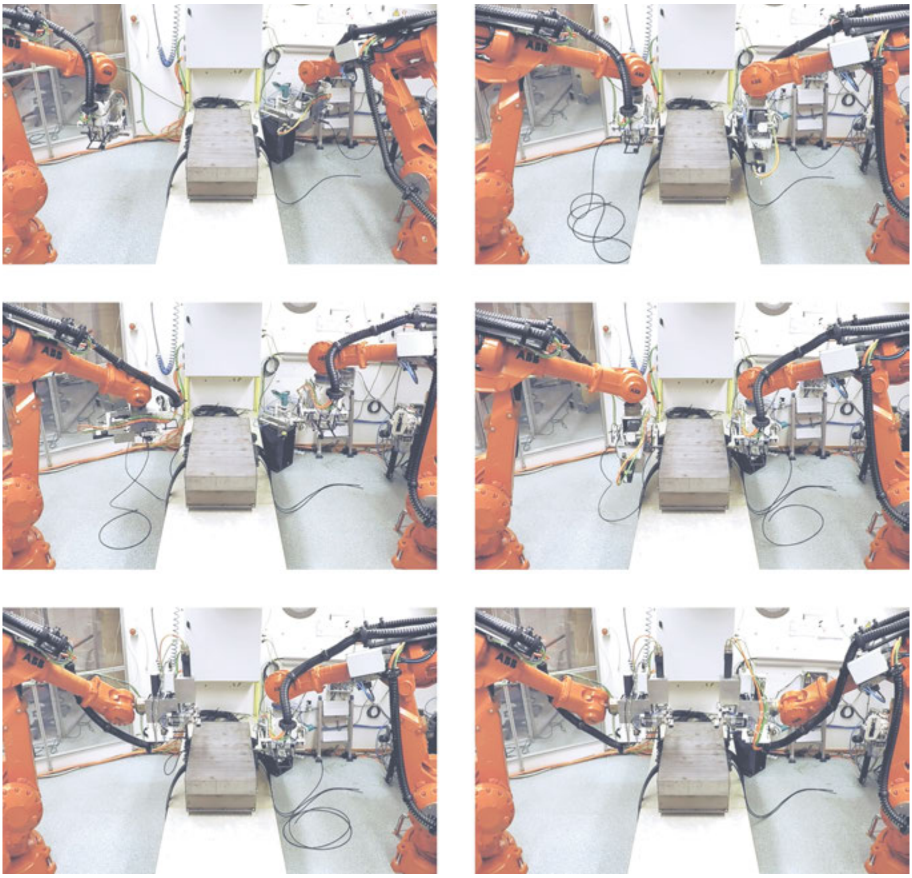

Figure 3.30. Photos of the second constructed prototype version of the stator cable winding robot cell during the winding experiments.

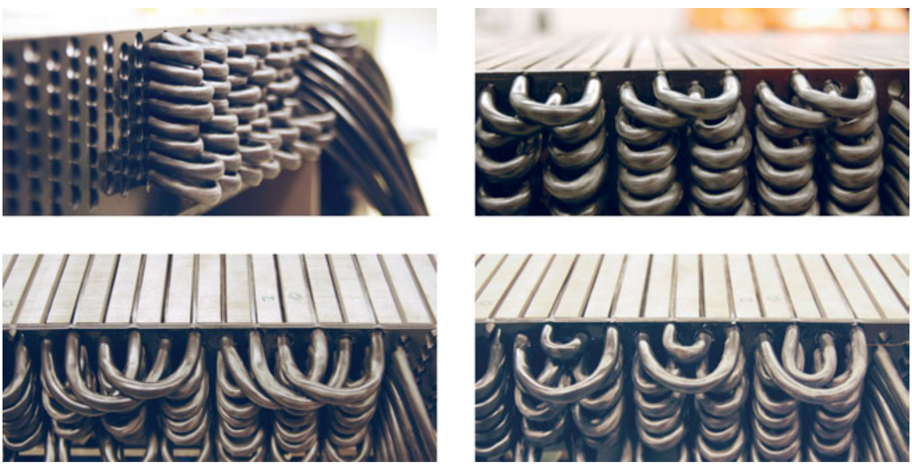

Figure 3.31. Four different winding patterns wound on a G3 UU WEC stator section, using the second constructed prototype version of the stator cable winding robot cell.

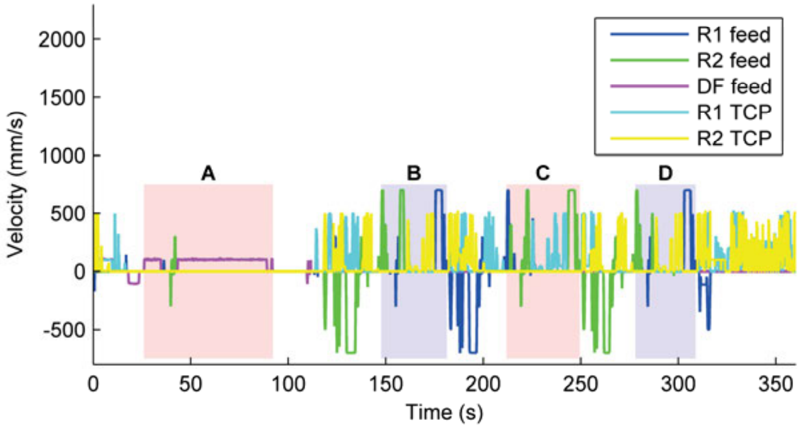

Figure 3.32. The cable feed velocities and the industrial robots absolute TCP positioning velocities during winding of one cable in a three phase winding pattern over 12 slot holes, using the second constructed prototype version of the stator cable winding robot cell. R1, R2 and DF represents the robot and drum cable feeder tools. Zones A, B, C and D highlights the parts of the winding process when the cable is fed through a slot hole.

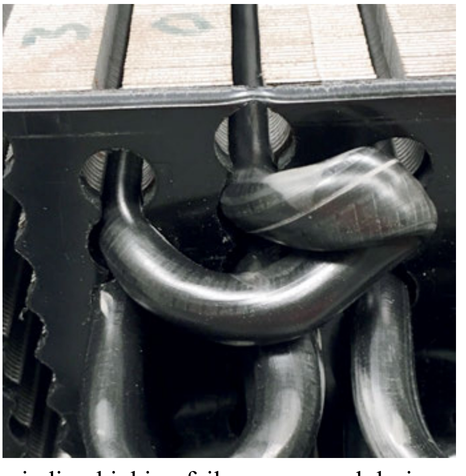

Figure 3.33. An end winding kinking failure, occurred during winding in the second constructed prototype version of the stator cable winding robot cell.

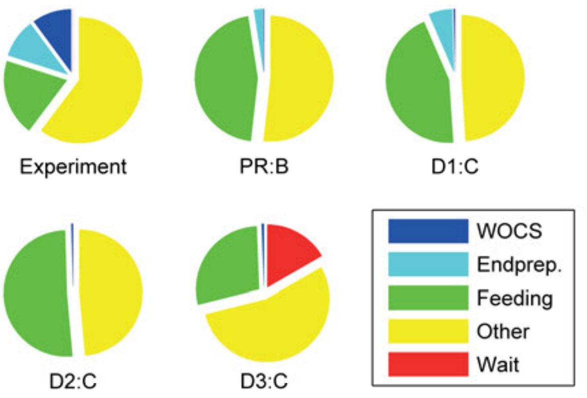

Figure 3.34. Winding process cycle time shares for selected robot winding scenarios, extrapolated from the experimental results with the second constructed prototype version of the stator cable winding robot cell. The experiment scenario refers to the actual experimental setup and the winding method used in the experiments and a one phase winding pattern over 16 slots.

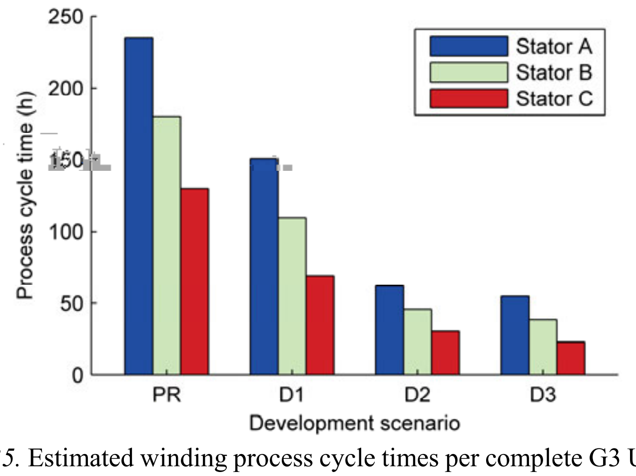

Figure 3.35. Estimated winding process cycle times per complete G3 UU WEC stator for the different robot winding scenarios, extrapolated from the experimental results with the second constructed prototype version of the stator cable winding robot cell.

3.3 Discussion

While stator cable winding includes few assembly steps, robotized stator cable winding is a complicated task. Much work has been put in to achieve a fully automated stator cable winding robot cell. The main challenges experienced during the work were related to the flexible nature of the winding cable and to the long winding process cycle time. To tackle these challenges, the development was performed step by step. In the end, durable and high performance industrial components were needed for the winding equipment. Detailed control and supervision, both of the winding equipment and of the winding process, was required to achieve high performance. It was however possible to use older model pre-owned industrial robots and simpler sensor systems, thus the equipment investment cost was kept down.

A simple feed wheel concept was used in the developed cable feeder tool prototypes throughout the work. The main reasons for not choosing feed belts, which are often used in commercially available cable feed equipment, were that the feed wheel concept was simpler, more compact and facilitated cable guiding. It was however noticed from the experiments that repeated feeding with very high feed forces—considerably higher forces than used during the winding experiments—over the same cable part could damage the cable insulation. If higher cable feed forces are required for future winding applications, the feed wheel mechanism might hence then need to be reconsidered. The static frictional coefficient between the feed wheel and the winding cable was higher with the rubber surface wheel design than with the aluminum surface wheel design. The rubber also distributed the cable gripping force more evenly over the cable. Considerable wear and aging of the rubber was however noticed, as well as a decrease in the achieved cable feed velocity with increased feed forces due to stretching of the rubber. These drawbacks were effectively overcame with the aluminum feed wheel design and the double feed wheel concept. The performance of the developed cable feeder tool can of course still be further enhanced. For example, the reliability of the cable drop supervision system could be improved by adding drop direction sensitivity and the cable gripping operation could be sped up.

The developed stator section positional calibration method provided sufficient reliability and performance for the winding task at a minimal cost. To implement it on pre-owned industrial robots did however require some extra work, compared to using absolute calibrated robots. In relation to the total winding process cycle time, the contribution from the WOCS calibration subprocess was very small. To take measurements on the stator section side on the fly during winding required more time. The later time contribution could however be significantly decreased, by reducing the number of measurements.

While high autonomy and reliability were demonstrated for the developed cable preparation equipment, further significant performance improvements are possible. For example, cable feeding with higher velocities from larger cable drums could be achieved, equipment for tensing and straightening of the cable could be integrated and automatic shape inspection of the formed cable end tip could be implemented.

Regardless of how powerful an automation technology is, an extensive and complicated control system can be a critical obstacle to production integration. Extra effort was therefore put in to make the extensive winding control system well-structured, flexible and user friendly. Parameter based programming with task-specific sub-procedures and special functions were used in the winding control system. For example, a task-specific sub-procedure was used for dropping the cable from the robot cable feeder tool and a special function was used to automatically define a robot positioning target relative a slot hole. Extra effort was also put in to achieve a simple but powerful GUI which was prepared for actual production. For example, the developed GUI provided functions to specify the desired winding parameters, to start the winding process from any desired point, to pause the winding process and to perform equipment service. Automatic process logging and statistical analysis of the production were also implemented. To make the GUI user-friendly, it was structured in different operator levels. In the simpler operator levels, high-level process information was provided together with basic cell control and supervision functions, thus requiring minimal prior knowledge. The more advanced operator levels, on the other hand, provided detailed process information together with detailed cell control and supervision functions, intended for a trained operator. The here described programming approach and extensive GUI were much helpful during the development and evaluation of the stator cable winding robot cell. Furthermore, the use of industrial fieldbus communication and a PLC as the main process controller improved the robot cell significantly with regards to performance, flexibility and structure.

The performance of the stator cable winding robot cell was steadily improved during the project, culminating in full winding autonomy with very high flexibility and high assembly quality. Most of the occurring winding failures were eliminated through repeated experiments and improvements, but further reliability improvements are still needed. End winding kinking in particular, was not completely avoided. During manual winding, cable kinking is prevented by untwisting of the cable while the end winding is pulled. To mimic this approach and automatically detect and adjust for cable twisting with the robot cable feeder tools, would however require advanced sensor and cable handling equipment. Simpler alternative measures that could be investigated first are to test other winding cables, to lay the cable in eights when being fed out on the floor and to improve the mechanical solution used to hold down the end windings while being pulled. When winding with longer cables than in the experiments, another potential problem is cable tangling. If so, tangling could likely be prevented by laying the cable in eights on the floor or by using temporary cable storages for the cable during winding.

A comparison between the initial theoretical robot cell and the final constructed robot cell, shows that the estimated total winding process cycle time was significantly higher for the final robot cell. The main reasons to this difference are that the time contributions from robot positioning and tooling operations were underestimated in the beginning and that the performance of the constructed robot cell has not yet been fully optimized. The estimated robot cell investment cost did also increase significantly during the project, mainly because more advanced equipment and additional robots were used in the end. Furthermore, the estimated manual winding cycle time was much reduced from the G2 to the G3 UU WEC. All these aspects influenced the rough economic analyses as well, where a much higher economic potential was indicated initially.

In the final winding experiments, the performance of the robot cell was evaluated over 15 full slots. The reason why winding over additional slots was not prioritized was to limit the cable consumption, the process cycle time and the risk for cable kinking failures during the extensive experiments. A complete evaluation of the reliability of the robotized stator cable winding concept would thus require further long-term experiments with different complete stator sections in a further developed robot cell. The main focus in the presented work was on autonomy and reliability. Hence, significant further optimizations of the developed winding procedure are possible. With a long and very repetitive winding procedure, even minor process adjustments can impact the total process cycle time significantly. New industrial robots with integrated tool cabling would likely reduce the winding cycle time significantly as well, by enabling faster robot positioning. Using new robots would also reduce the need for maintenance. Furthermore, adding more robots—dedicated to specific sub-tasks—to the robot cell could be motivated from an economic point of view. An example of a suitable sub-task is to prepare the cable ends.

It is clear that robotized stator cable winding is much awaited for large-scale production of the UU WEC generators. While the production cost savings might not be as high as first expected, unmanned production, a better work environment, high and consistent quality, high flexibility, high scalability and improved traceability are factors in favor for robotized winding. The demonstrated ability to wind angled stator sections is particularly favorable for the UU WEC generator, since this enables a stator design with a larger active area compared to using the straight stator sections which are preferred in manual winding. It is much likely that the developed robot cell can be adapted also for other electric machine designs where cable winding is used. With the demonstrated ability to handle different winding patterns and stator designs without equipment adjustments, considerable product variations could likely be handled as well. The scalability of the robot cell enables a smaller initial investment cost, which is likely to be particularly interesting for SMEs. Fully developed robotized stator cable winding could thus also serve as an enabler for a broader use of the cable winding technology. Furthermore, some parts of the here developed robot cell could possibly be adapted for other applications as well, such as in cable laying, cable manufacturing, high precision component handling or for positional calibration of other objects.

4. Other robot cells

The UU research projects on stator stacking, translator PM surface mounting and rubber disc machining were performed by the robotics and manufacturing group, with the author as the main responsible. All robot cells developed in these projects used P2P DIO signal communication, a robot controller as the main process controller and a robot controller teach pendant as user interface. Where nothing else is specified, the robot cell were installed and evaluated in the lab facilities at UU in Uppsala. Summaries of the projects are given in the rest of this section, in Sections 4.1-3 respectively. Further details can be found in Papers X-XII.

4.1 Stator stacking

A laminated stator design, where the stator is assembled from numerous thin sheets, reduces the Eddy current losses in electric machines. Stacking a laminated stator is a very repetitive task, requiring high precision, gentle handling and large reach. It is thus likely suitable for robotized assembly. The stator sheets used in the UU WEC generator are one mm thick, lacquered on one side and fixated by threaded rods and bolts after being stacked, see Figure 4.1. Alternative fixation methods are welding or cleating, while fixtures and bayonet pins can be used to achieve high stacking precision [94]. Fully automated stacking assembly solutions are available mainly for smaller machines [95].

Figure 4.1. The G2 UU WEC stator sheet design. Figure taken from Paper X.

In the UU research project on robotized stator stacking, a robot cell concept for stacking the G2 UU WEC generator stator was developed and constructed, see Figure 4.2. A special robot tool was here mounted on a pre-owned ABB IRB1400/5kg S4C M98 industrial robot. The robot tool was equipped with proximity sensors and electromagnets for positional measurements and for lifting of the stator sheets respectively. The power supply to the electromagnets was controlled so that an adjustable lifting force was achieved. Hence, it was possible adjust to the exact stator sheet position and to pick up exactly two stator sheets together from a pile of stator sheets. To achieve high precision stacking, a special mounting fixture was also used. The prototype robot cell was experimentally validated for high precision and flexible stacking, see Figure 4.3. The total process cycle time for robotized stacking of a stator section with 230 stator sheets was estimated to about 30 min, including manual fixation and transportation of the stacked stator section. From experience at UU, the corresponding cycle time for manual assembly was estimated to about four hours with two personnel. The investment cost for the robot cell concept was estimated to about 70 000 EUR with a new robot. A high economic potential compared to manual stacking was roughly indicated, but further developments with regards to durability and reliability were required.

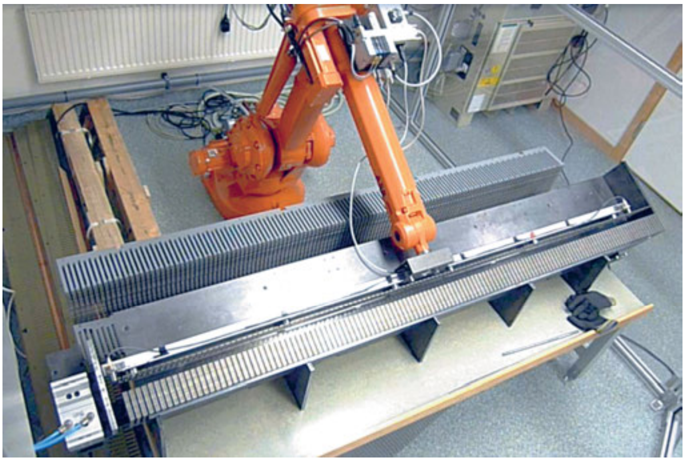

Figure 4.2. The first constructed prototype version of the stator stacking robot cell. Figure taken from Paper X.

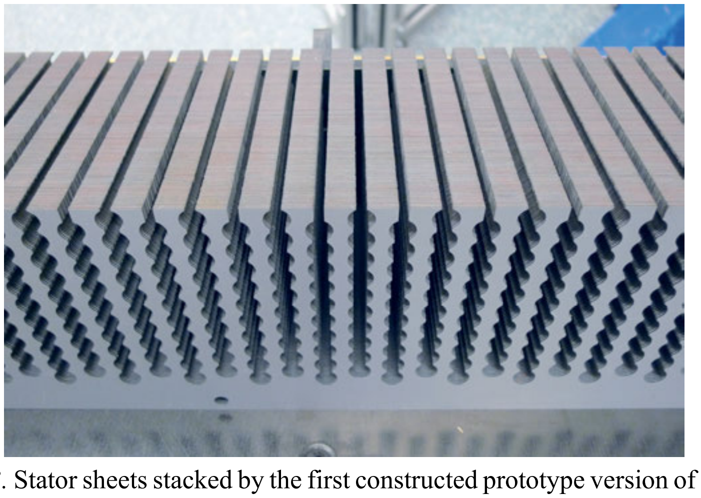

Figure 4.3. Stator sheets stacked by the first constructed prototype version of the stator stacking robot cell. Figure taken from Paper X.

Based on the experience from the first constructed stator stacking robot cell, further—previously unpublished—work was performed on constructing an updated prototype robot cell which was adapted for the G3 UU WEC, see Figure 4.4. This robot cell was installed and evaluated in the production facilities of Seabased Industry AB in Lysekil. A more durable special robot tool was here mounted on an older model pre-owned ABB IRB6000/150kg S3 M91A industrial robot and a custom-made pallet frame was used for delivery of the stator sheets. The pallet frame ensured that the stator sheets were placed in uniform piles, thus facilitating the stacking process. Using an older model industrial robot did however increase the programming complexity and limit the connectivity, compared to the previous robot used.

A flexible and precise stator stacking method was achieved. Further work is however needed to improve the reliability of the robot cell. To achieve full assembly autonomy, the development of equipment for automated fixation of the stacked stator section is needed as well. Furthermore, the use of self-sensing electromagnets—as demonstrated in [96]—could improve the reliability of the robot cell, by confirming full contact with several stator sheets during lifting. It is likely that the developed robotized stacking method can be adapted for other stator designs as well, and also as for picking stator sheets directly from for example a punching machine or a laser cutter machine.

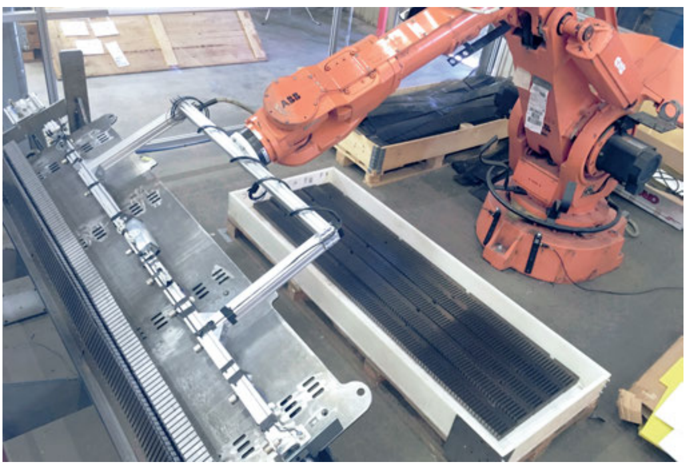

Figure 4.4. The second constructed prototype version of the stator stacking robot cell.

4.2. PM surface mounting

PMs are often used instead of rotor windings in electric machine rotors. The main advantage with PM machines are a simplified design, reduced wear, eliminated excitation losses and a high power density, but the control possibility of the rotor magnetization is lost [97-98]. Mounting strong PMs on large electric machines is a very repetitive and potentially hazardous task, requiring gentle handling of the PMs as well as high positioning precision with large reach. The assembly is thus likely suitable for robot automation. The G2 UU WEC generator translator is magnetized with surface mounted $Nd_2Fe_{14}B$ PMs, see Figure 4.5. The PMs are mounted, and thereby fixed, in machined slots. Alternative methods for fixing PMs on rotors are to use gluing or clamping [99-100]. PM assembly on larger rotors is often manual, but there are automated solutions [101-103].

A conceptual robot cell, adapted for the G2 UU WEC generator translator design, was developed in the UU research project on robotized PM surface mounting, see Figure 4.6. Two ABB IRB6650S/125kg IRC5 M2004 robots were here equipped with special robot tools and used together with four special PM delivery stations to mount the PMs on the translator. A prototype robot cell was also constructed for experiments. In this setup, a pre-owned ABB IRB4400/60kg S4C+ M2000 industrial robot was equipped with a special robot tool and used together with a special PM delivery station and a G2 UU WEC translator plate part. The PMs were passively picked up one by one with the robot tool, using small steel ball transfer units mounted inside the tool. A step motor driven linear slide was mounted inside the tool and used to push the PMs off the tool and onto the translator. The prototype robot cell was validated to be able to mount the PMs into the translator slots with high precision and high flexibility, see Figure 4.7. The total process cycle time for PM surface mounting on one complete G2 UU WEC translator, including manual loading of the PM delivery stations and transportation of the translator, was estimated to about 160 min for the developed robot concept. From experience at UU, the corresponding cycle time for manual assembly was estimated to about 20 h with four personnel. The investment cost for the robot cell concept was estimated to about 200 000 EUR with new robots. A rough economic analysis of the robot cell concept indicated very high potential cost savings compared to manual assembly.

A simple and durable robot tool design with high reliability was achieved. Further work is however needed to achieve high positioning accuracy for the robot tool against the complete translator and to increase the capacity of the PM delivery stations. The developed robotized PM surface mounting method is likely to be adaptable for other PM rotor designs as well. As the UU WEC concept reached the G3, the translator design with surface mounted $Nd_2Fe_{14}B$ PMs was abandoned for a new translator design with pole shoes and ferrite PMs. The development of the PM surface mounting robot cell was then paused, while a new separate UU research project on robotized assembly of the new translator was initiated [12].

Figure 4.5. The G2 UU WEC generator translator, with surface mounted $Nd2Fe_{14}B$ PMs.

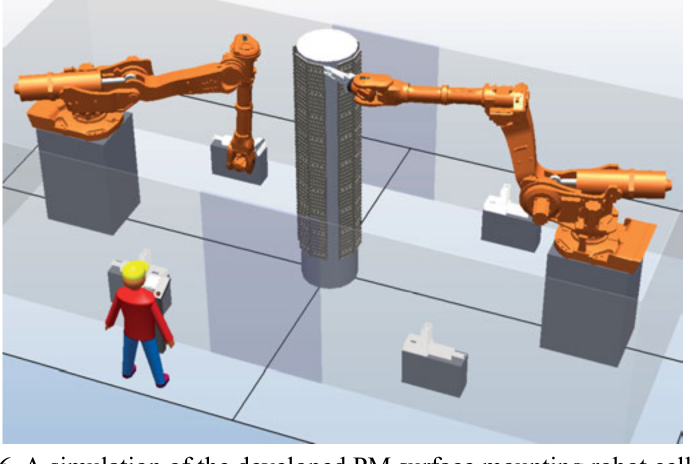

Figure 4.6. A simulation of the developed PM surface mounting robot cell concept.

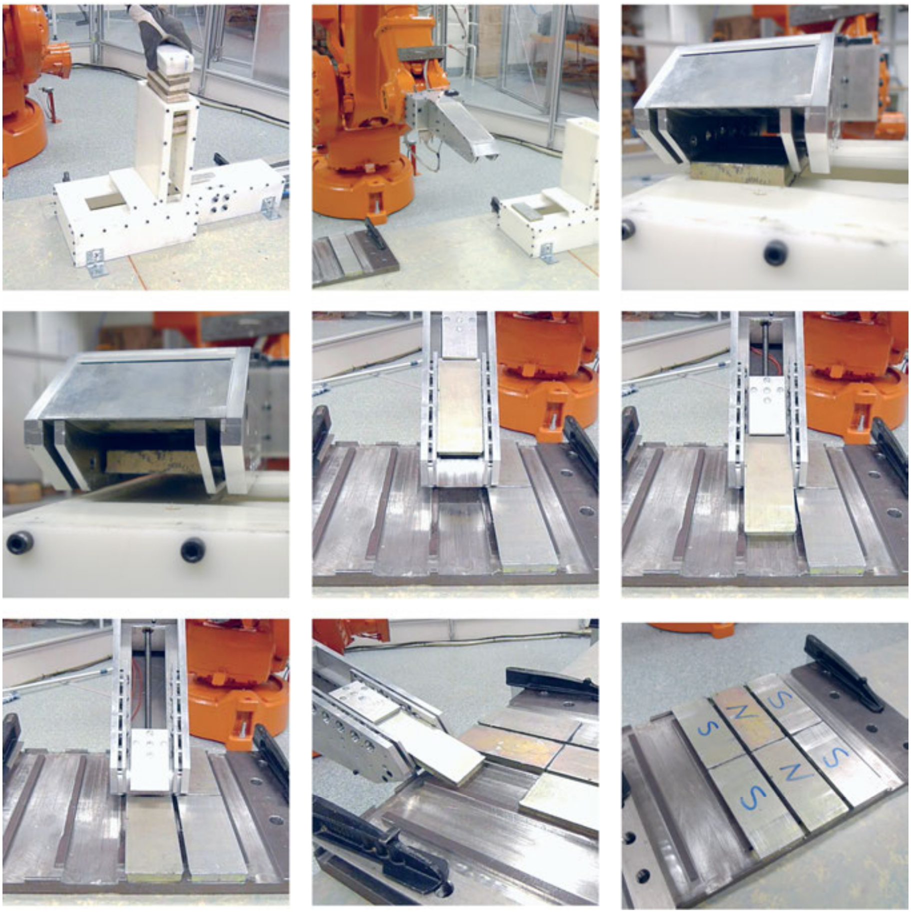

Figure 4.7. Photos of the constructed prototype version of the PM surface mounting robot cell, while assembling PMs on a G2 UU WEC translator plate part.

4.3. Rubber disc machining

About 60 Ethylene Propylene Diene Monomer (EPDM) rubber discs are used for absorption and smoothening of snap loads and end-stop loads, occurring with larger ocean waves, in the G3 UU WEC device. These discs are about 25 mm thick, about 250 mm wide and come in three different versions. In manual production the discs are cut out using a mechanical press, a very repetitive task. Since both the required dimensional accuracy and the desired production pace are low, the discs could however likely be machined by an industrial robot instead. In general, a mechanical press is superior to machining with regards to productivity, but does not provide the same flexibility. Compared to traditional Computer Numerical Control (CNC) machines, robotized machining provide higher flexibility but lower accuracy and more complex programming. Recent work in the field suggests mechanical improvements as well as improved robot motion control and programming tools—including specialized Computer Aided Manufacturing (CAM) software—to overcome the challenges with robotized machining [104-108].

In the UU research project on robotized rubber disc machining, a robot cell concept for producing rubber discs for the UU WEC device was developed and constructed, see Figure 4.8. The final version of this robot cell was installed and evaluated in the production facilities of Seabased Industry AB in Lysekil. A pre-owned ABB IRB6000/150kg S3 M91A industrial robot was here equipped with a special robot tool. A spindle motor was mounted on the robot tool and an end mill was used for machining discs from a large EPDM rubber sheet. An industrial vacuum cleaner nozzle and vacuum suction cups were also mounted on the tool. This equipment was used to remove the rubber chips waste and to plunder the machined discs. The prototype robot cell was validated be able to cut and plunder rubber discs for the G3 UU WEC with sufficient accuracy and high flexibility, see Figures 4.9-10. The standard mean deviation for the outer diameter of the machined discs was estimated to 0.62 mm based on 120 measurements on 40 machined discs. The total cycle time for producing 20 discs from one rubber sheet, was estimated to about 45 min for the developed robot cell concept. The corresponding cycle time for manual production was estimated from experience at Seabased Industry AB to about 80 min with two personnel. The investment cost for the robot cell concept was estimated and then doubled to about 90 000 EUR with a less old pre-owned industrial robot. Significant potential cost savings compared to manual production were roughly indicated.

A flexible rubber disc machining method was achieved. Further work is however needed to improve the autonomy of the constructed robot cell. It has also been suggested to include the assembly of the snap load reducer unit in the robot cell. It is likely that the developed robotized rubber disc machining method can be adapted for other similar applications as well, given that the dimensional accuracy requirements are in the same range.

As expected, the developed robot machining method cannot compete in accuracy with CNC machines. In previously unpublished experimental work, it has been demonstrated that specialized CAM software can enable facilitated and improved path generation for robotized machining also with older model pre-owned industrial robots, see Figure 4.11. This programming method could however not be implemented with the older model industrial robot used in the constructed prototype version of the rubber disc machining robot cell. Furthermore, higher programming complexity, limited connectivity and limited spare part availability were experienced with the robot model used in the experiments, compared to using newer robots.

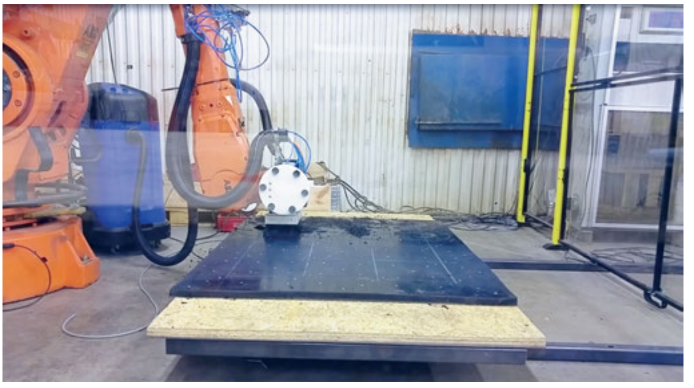

Figure 4.8. The constructed prototype version of the rubber disc machining robot cell.

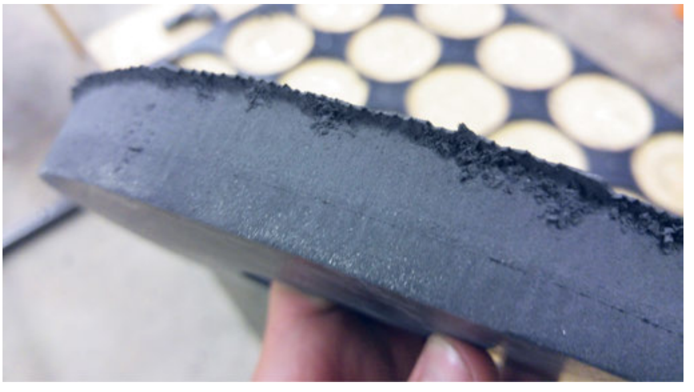

Figure 4.9. The surface of a rubber disc which has been machined in the constructed prototype version of the rubber disc machining robot cell.

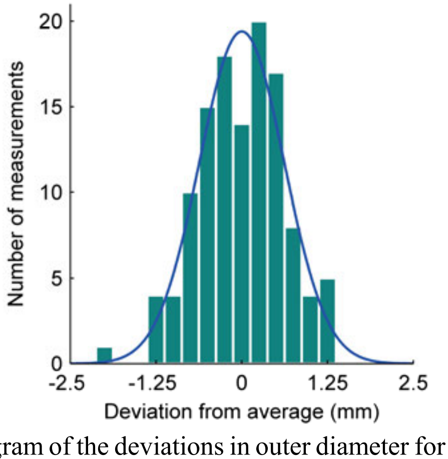

Figure 4.10. A histogram of the deviations in outer diameter for rubber discs produced in the constructed prototype version of the rubber disc machining robot cell, based on in total 120 measurements on 40 machined discs.

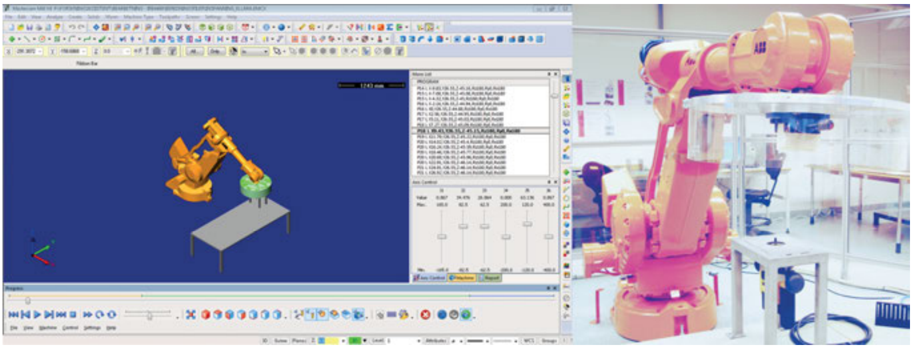

Figure 4.11. An experimental setup, where an ABB IRB4400/60kg S4C+ M2000 industrial robot is used together with a stationary spindle motor to machine in a piece of foam plastic. The robot programming was generated offline in the Robotmaster CAD/CAM robotic software (left), and then transferred to the physical robot (right).

5. Robotics in engineering education

The presented pedagogical development work for the education on automation and robot engineering was started by the author in 2011. In the rest of this section, the background to this work is summarized in Section 5.1 and the main results from the research are presented and discussed in Section 5.2.

5.1 Background

Like with the engineering society, the demands on the engineering profession are constantly developing. Classical engineering skills, such as a profound knowledge in fundamental physics and technology, analytical skills and problem-solving skills, remain essential. However, these skills should now preferably be combined with higher level skills in cooperation, communication, decision-making, life-long learning, multidisciplinary knowledge, creativity, social responsibility and sustainable development [109-114]. To fully utilize the potential with modern automation and robot technology puts high demands on the engineer as well, as different technical engineering competences often are combined in complex systems.

It has been recognized globally that the engineering education has not been adjusted according to the engineering profession [111-119]. Student-activating learning activities, cooperative learning, project-based learning, solving open-ended problems, authentic learning, using a holistic perspective and to establish relevance of the course material has been lifted up in the literature as effective methods for teaching modern engineering skills [117-124]. In education on robotics, the use of real-world projects and to establish a strong connection between theory and practice have shown to be effective teaching approaches [125-128].

5.2 Results and discussion

A new course planning was developed and first introduced in 2012 to an introduction course on automation and robot engineering given at UU. The course planning was then further developed, mainly until 2013. Focus in the work was to meet the emerging new demands put on the engineering profession, while keeping the depth of the classical engineering skills. To achieve this, all teaching activities—including lectures, classes, study visits, seminars and lab exercises—were connected to the three real-world project tasks. These tasks were all taken from the research on robotized production methods for the UU WEC generator: stator stacking as described in Paper X, translator PM surface mounting as described in Paper XI and ferrite translator assembling as described in [12]. At the beginning of the course, the students were divided into project groups of 3-6 students and each group was assigned with a project task. The project groups first performed a pre-study on their tasks, where they suggested a robot cell concept for fully automated assembly and compared this concept to manual assembly. The pre-study was based on the theory presented so far during the course, and the results of the study were presented at a seminar and in a project report. Next, the project groups performed a practical lab exercise on their project tasks, but with the equipment available at UU, see Figure 5.1. Using the experience gained at the lab exercise and the new presented course theory, the project groups then updated their pre-studies. The updated results were presented at another seminar and in another project report. Thereafter, the students performed a computer lab exercise, where they programmed and simulated their project tasks in the ABB Robotstudio software, see Figure 5.1. A case seminar on sustainable industrial development—connected to the project tasks as well—was also integrated in the course. Finally, an individual written examination was given.

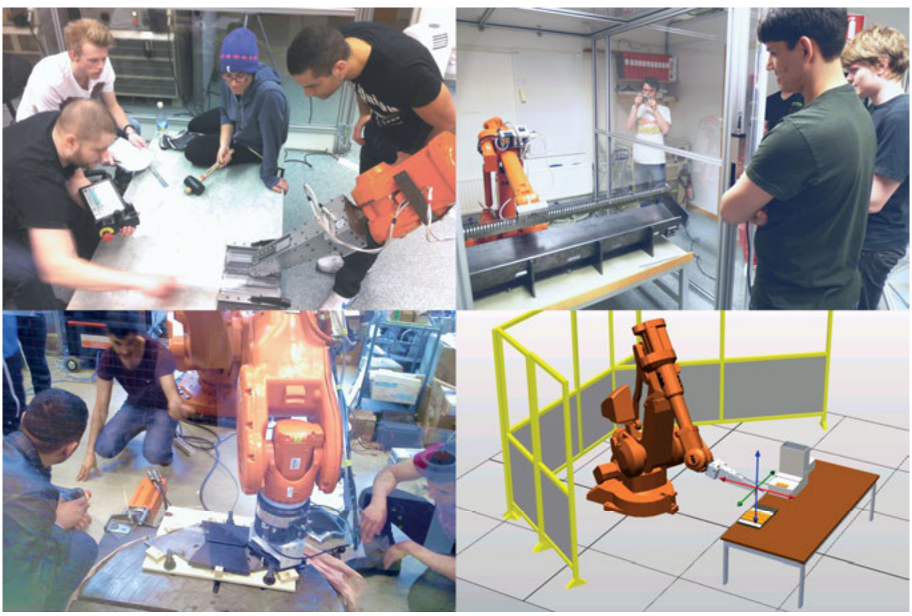

Figure 5.1. Three student project groups performing practical lab exercises on translator PM surface mounting (top left), stator stacking (top right) and ferrite translator assembly (bottom left), and a screenshot showing an ABB Robotstudio simulation of the stator stacking robot cell used in the computer lab exercise (bottom right), all during the new UU course on automation and robot engineering.

The new course structure received very positive feedback from the students, both during the course and in the course evaluations. Deriving explicit skills to specific learning activities can be difficult. However, based on the students' course evaluations and the teachers' experiences from teaching the course, there was a strong indication that the integration of real-world student group project tasks and the clear connection between the different teaching activities in the course were important for the students' learning. From the course examination results, it was indicated that the students had assimilated the widened course content well, with preserved theoretical depth. This was achieved without increasing the students' experienced work load. Evaluating the effect on teaching theoretical depth would however be easier with a higher level course. According to the teachers, the students' participation, activity and motivation were high during the course. A clear improvement in the students' examination results was noticed compared to the previous course. From the students' course evaluations, a significant improvement in the students' general opinion on the course was noticed as well. In a comparison of the student course evaluation results for all courses given by the Department of Engineering Sciences at UU during the school year 2016/17, the new automation and robot engineering course was ranked among the top ten courses in average result for the students' general course opinion. After excluding diploma works, pure project work courses and courses with less than 20 registered students, this comparison included about 140 different courses. To develop the project tasks and to teach on the new course required some time, but was both worthwhile and rewarding, according to the teachers. The developed lab exercises were also integrated standalone in courses on generator design, robot mechanics and wave power at UU, with very positive response. It is likely that the complete developed teaching approach can be adapted for other engineering courses as well.

6. Conclusions

Four robot cell concepts for automated large-scale production of the UU WEC device have been developed and experimentally validated through the presented work. High flexibility and the potential for unmanned production with high and consistent quality have been demonstrated for all four robot cells, while eliminating unwanted manual production tasks. Considerable potential cost savings compared to manual large-scale production have been indicated as well. It has thus been demonstrated that industrial robots can be used for large-scale production of the UU WEC device. It has also been strongly indicated that robotized large-scale production can reduce the LCOE for the UU WEC concept.

To keep down the investment cost and thus make the developed technology available for SMEs, simplicity was prioritized and older model pre-owned robots were used throughout the work. It has thus also been demonstrated that older model robots can be combined with modern automation technology to achieve advanced and highly flexible automated production methods at lower costs.

The presented production methods are likely to be applicable for other similar special electric machines as well.

6.1 Stator cable winding

The world-first, to the knowledge of the author, fully automated stator cable winding setup has been developed, constructed and experimentally validated. Much and dedicated work was required to carry out this complicated project. The developed advanced robot cell includes special equipment for cable preparation and winding, in particular a compact and high performance robot cable feeder tool. A specialized 6-DOF work object positional calibration method and a user-friendly but powerful GUI were also developed. It has been demonstrated that the robot cell is able to handle different winding patterns and stator designs without equipment adjustments. With linear stator designs similar to the one used in the UU WEC generator, the ability to wind angled stator sections enables a larger active stator area compared to using the straight stator sections which are preferred in manual winding. The robot cell is well prepared for production, but further work is required mainly to completely avoid cable kinking as the end windings are pulled.

6.2 Other robot cells

Robot cells for stator stacking, translator PM surface mounting and rubber disc machining have been developed, constructed and experimentally validated. Task-specific special automation equipment was developed for all robot cells. Further work is needed to improve the autonomy and reliability of the developed robot cells.

6.3. Robotics in engineering education

A first cycle course on automation and robot engineering has been completely reworked and restructured around three real-world student group project tasks. These tasks were taken from the research on robotized production methods for the UU WEC generator. The new course was greatly appreciated by the students. To focus the course planning around the project tasks was strongly indicated to be important for the students' learning. It was also indicated that the developed teaching approach was effective in combining learning of classical engineering skills with the new demands put on the engineering profession.

7. Future work

It has been strongly indicated that robotized production can enable large-scale production and reduce the LCOE for the UU WEC concept. It is therefore important to continue the work in this field. Especially, demanding assembly steps which are not straightforward to automate—such as the stator cable winding investigated in this thesis—should remain prioritized.

The developed stator cable winding robot cell concept needs to be improved with regards to reliability. Most importantly, cable kinking must be fully prevented. It would thereafter be interesting to perform additional winding experiments with different stator designs and also to integrate the robot cell concept in actual production. Performance optimizations, which can increase the productivity of the robot cell, are suggested as well.

Further work is needed to improve the autonomy and reliability of the developed stator stacking, PM surface mounting and rubber disc machining robot cells. The applicability of these robot cells for other similar electric machine designs could be further investigated as well.

Finally, it would be interesting to use the here presented teaching approach also in a higher level course. It would then be possible to better evaluate the students' learning with regards to theoretical depth. The developed teaching approach could be further sharpened as well, for example by further increasing the possibility for the students to design their own project tasks within the course.

8. Summary of papers

This section shortly presents the papers included in the thesis, including the author's contributions.

Paper I

Electromagnetic, mechanical and manufacturing properties for cable wound direct-drive PM linear generators for offshore environments

The paper presents the generator design used in the G2 UU WEC and compare it to conventional generators. The two main focuses in the paper are on implementation in an offshore environment and on manufacturing. Key assembly steps being particularly suitable for robotized production are also identified.

The author was the main responsible for the paper, wrote the manufacturing parts and put the paper together.

Presented by the author at the *31st International Conference on Ocean, Offshore and Arctic Engineering*, Rio de Janeiro, Brazil, July 2012.

Paper II

Status update of the wave energy research at Uppsala University

In this paper, a summary of the—at this time—current status of the wave power research at UU is given. Selected experimental results are presented and an outlook on future research within the project is also given.

The author wrote the manufacturing automation parts of the paper.

Presented at the *9th European Wave and Tidal Energy Conference*, Aalborg, Denmark, September 2013.

Paper III

Preparing the Uppsala University wave energy converter generator for large-scale production

This paper presents the G3 UU WEC design and compares it to the G2, with focus on manufacturing. It is highlighted that the cost for the WEC has been much reduced with the G3 design and it is argued that this cost can be further reduced with manufacturing automation. Large-scale production is also outlined and production steps being suitable for robot automation are identified.

The author was the main responsible for the paper, wrote most of the manufacturing parts and put the paper together.

Presented by the author at the *5th International Conference on Ocean Energy*, Halifax, Canada, November 2014.

Paper IV

Utilizing cable winding and industrial robots to facilitate the manufacturing of electric machines

The paper introduces the developed robotized stator cable winding concept. A conceptual cable winding robot cell is presented and compared to conventional stator winding methods and to manual stator cable winding. The robot cell concept is adapted for the G2 UU WEC stator and it is preliminary validated through experiments with prototype equipment—including the first constructed prototype version of the cable feeder tool—and simulations. Potential cost savings are indicated compared to manual winding, while eliminating a backbreaking, monotone, time consuming and labor intense manual task. Further work is however suggested for full validation of the robot cell concept.

The author performed all the work in this paper.

Published in *Elsevier Robotics and Computer-Integrated Manufacturing*, 29(1):246–256, 2013. The journal Impact Factor was 2.846 in 2016 and the paper was listed as the fourth most downloaded paper in the last 90 days in March 2013 on the journal homepage.

Paper V

Six-degrees-of-freedom (6-DOF) work object positional calibration using a robot-held proximity sensor

In this paper, a general 6-DOF work object positional calibration method for larger and medium complicated objects is presented and explained in detail. A simple robot-held proximity sensor is used to take the calibration measurements. The method is experimentally validated to provide sufficient accuracy and reliability for robotized winding of a G2 UU WEC stator section part.

The author performed all the work in this paper.

Published in *MDPI Machines*, 1:63-80, 2013. The paper was published in the Special Issue “Advances and Challenges in Manufacturing Automation” and it was listed as the in total second most viewed paper in the journal on the journal homepage in December 2017.

Paper VI

A cable feeder tool for robotized cable winding

This paper presents the design of the second constructed prototype version of the cable feeder tool and the first constructed prototype version of the stator cable winding robot cell. Robotized stator cable winding is demonstrated through full-scale experiments with a G2 UU WEC stator section part. Good correlation with the previous preliminary analytical results for the robot cell concept is also indicated. Further work is however suggested for preparing the robot cell for production.

The author performed all the work in this paper.

Published in *Elsevier Robotics and Computer-Integrated Manufacturing*, 30(6):577-588, 2014. The journal Impact Factor was 2.846 in 2016 and the paper was listed as the third most downloaded paper in the last 90 days in August 2014 on the journal homepage.

Paper VII

Automated cable preparation for robotized stator cable winding

The paper presents the second constructed prototype version of the cable preparation equipment. The equipment is developed for robotized stator cable winding of the G3 UU WEC and it is fully controlled and supervised through an industrial PLC. It is demonstrated through numerous full-scale experiments that the equipment can deliver cable from a drum, form the cable end to a tip and cut off cables from the drum. All operations are fully automated and validated to be performed with sufficient performance and high reliability.

The author performed all the work in this paper.

Published in *MDPI Machines*, 5(2):14, 2017. The paper was published as a Feature Paper.

Paper VIII

An updated cable feeder tool design for robotized stator cable winding

In this paper, the third constructed prototype version of the cable feeder tool is presented. The tool is developed for robotized stator cable winding of the G3 UU WEC and it is fully controlled and supervised through an industrial PLC. Through experiments, the new tool is validated to provide significantly higher performance, durability, reliability and autonomy compared to the previous tool. It is thus demonstrated to be better prepared for production.

The author performed all the work in this paper.

Under review at *Elsevier Mechatronics*, June 2017. The journal Impact Factor was 2.496 in 2016.

Paper IX

Robotized stator cable winding

This paper presents the second constructed prototype version of the stator cable winding robot cell in detail. The robot cell is fully controlled through an industrial PLC and operated through a separate HMI. Highly flexible robotized winding with consistent high quality is demonstrated through full-scale winding experiments with the G3 UU WEC generator stator. Potential cost savings compared to manual winding are also indicated. Further work is however suggested for fully preventing cable kinking during the winding process.

The author performed all the work in this paper.

Under review at *Elsevier Robotics and Computer-Integrated Manufacturing*, October 2017. The journal Impact Factor was 2.846 in 2016.

Paper X

Robotized stacking of the Uppsala University wave energy converter generator stator

The paper presents the first constructed prototype version of the stator stacking robot cell. High stacking precision and high flexibility are demonstrated through experiments with stator sheets from the G2 UU WEC. Potential cost savings are also indicated compared to manual stacking, while eliminating a monotone manual task. Further work is however suggested for improving the reliability of the robot cell.

The author was the main responsible for the robot cell design, supported the robot cell validation, analyzed the experimental data and wrote the paper.

Presented by the author at the *33rd International Conference on Ocean, Offshore and Arctic Engineering*, San Francisco, USA, June 2014.

Paper XI

Robotized surface mounting of permanent magnets

In this paper, a robot cell concept for surface mounting of PMs on the G2 UU WEC translator is presented. The robot cell concept is validated through simulations and full-scale experiments. Potential cost savings compared to manual assembly are also indicated, while eliminating a monotone, potentially hazardous and time consuming manual task. Further work is however suggested for preparing the robot cell for production.

The author supported the robot cell design, contributed to the robot cell validation, analyzed the experimental data and wrote the paper.

Published in *MDPI Machines*, 2:219-232, 2014. In the Special Issue “Advances and Challenges in Manufacturing Automation”.

Paper XII

Robotized manufacturing of rubber components for commercialization of the Uppsala University wave energy converter concept

This paper presents a robot cell for production of rubber discs. The robot cell is experimentally validated to be able to machine and to plunder rubber discs with sufficient quality for the G3 UU WEC device. Potential cost savings compared to manual production are indicated, while eliminating a monotone manual task. Further work is however suggested for improving the autonomy of the robot cell.

The author contributed to the design and to the validation of the robot cell, analyzed the experimental data and wrote the paper.

Presented by the author at the *2nd International Conference on Offshore Renewable Energy*, Glasgow, UK, September 2016.

Paper XIII

Integration of real-world project tasks in a course on automation and robot engineering

The paper presents how the research on robotized production methods for the UU WEC generator is used to strengthen the engineering education at UU. An introduction course on automation and robot engineering is restructured around real-world student group project tasks. The new course is evaluated during six years, using extended student course evaluations, the students' examination results and the teachers experience from teaching on the course. The results suggests that the developed teaching approach was important for the students' learning and effective in combining classical technical engineering skills with the new demands raised on the engineering profession.

The author did the majority of the work and wrote the paper.

Under review at *Taylor & Francis SEFI European Journal of Engineering Education*, November 2017. The journal Impact Factor was 0.501 in 2016.

9. Svensk sammanfattning

Elektriska maskiner spelar en mycket viktig roll i vårt moderna samhälle. Med det växande intresset för förnyelsebara energikällor i åtanke, är det sannolikt att behovet av mellanstora och stora elektriska maskiner kommer att öka ytterligare framöver. Ett exempel på en ny applikation där elektriska maskiner används, är i de vågkraftverk som utvecklats vid Uppsala universitet. Vågenergi är en än så länge sparsamt utnyttjad förnyelsebar energikälla. Mycket arbete har lagts ner runt om i världen för att utveckla teknik som kan omvandla den väldiga kraft som finns i havens vågor till elektrisk energi. Den marina miljön har dock visat sig svår att tämja, samtidigt som kraven på arbetsinsats, kapital och tålamod är höga när en ny industri ska byggas.

Vågkraftstekniken från Uppsala universitet ligger i framkant globalt sett och har nu även kommersialiserats av avknoppningsföretaget Seabased Industry AB. Tekniken bygger på enkelhet, funktionalitet och på skalbarhet. En direktdriven linjärgenerator placeras på havets botten och kopplas till en boj som flyter vid havets yta. När bojen rör sig vertikalt med de passerande vågorna absorberas vågenergi och omvandlas till elektrisk energi i generatorn. Generatorns två huvudkomponenter är den rörliga permanentmagnetiserade translatorn och den stationära kabellindade statorn. Ett stort antal vågkraftverk planeras kunna sjösättas tillsammans i marina parker och vågkraftverkens design har därför anpassats för storskalig produktion.

För att ny teknik inom förnyelsebar energi ska nå framgång måste den kunna konkurrera med etablerade energitekniker avseende totalkostnad för den till elnätet levererade energin. Då förnyelsebar energi inte har någon bränslekostnad, spelar energiomvandlingsutrustningens tillverkningskostnad en avgörande roll för den totala ekonomin. Ett sätt att minska denna kostnad är automatisera tillverkningen, vilket exempelvis kan ske med hjälp av industrirobotar.

Forskning inom robotiserade produktionsmetoder för speciella elektriska maskiner, med de vågkraftverk som utvecklats vid Uppsala universitet som tillämpning, inleddes år 2010 av författaren, ett pionjärarbete vars resultat presenteras i denna avhandling. Huvudsyftet med det presenterade arbetet har varit att undersöka hur industrirobotar kan användas för att möjliggöra storskalig produktion av Uppsala universitets vågkraftverk. Arbetet har innefattat utveckling och konstruktion av fyra olika robotceller, vilka ska kunna ersätta fyra speciellt slitsamma, repetitiva, riskfyllda och tidskrävande manuella tillverkningsmoment. Enkelhet, tillförlitlighet och flexibilitet har genomgående prioriterats för de nya robotcellerna och begagnade industrirobotar av äldre modell har använts för att hålla nere investeringskostnaderna. Stor vikt har lagts vid att konstruera fullskaliga robotceller, inklusive utveckling av specialutrustning, för experimentell utvärdering. Robotcellerna har även utvärderats analytiskt, med experimentella resultat och simuleringar som grund. Det är sannolikt att den utvecklade tekniken kan anpassas även till andra liknande elektriska maskiner.

Parallellt har också ett pedagogiskt utvecklingsarbete drivits, med syftet att stärka ingenjörsutbildningen vid Uppsala universitet. En grundkurs inom automatiserings- och robotteknik har här helt omarbetats, med utgångspunkt i pedagogisk forskning. Den nya kursen utvärderades utifrån studenternas kursutvärderingar, studenternas examinationsresultat och kursens lärares erfarenheter från sex kurstillfällen.

Det största arbetet i avhandlingen har lagts på att utveckla robotiserad kabellindning av statorer. En avancerad robotcell med specialbyggd lindningsutrustning, inklusive ett kompakt kabelmatarverktyg med hög prestanda, har här tagits fram. Utvecklingen har skett i flera steg och krävt ett omfattande och dedikerat arbete. Den slutligt uppförda robotcellen är, såvitt författaren vet, världens första helautomatiserade utrustning för kabellindning av statorer. Robotiserad lindning med hög och jämn kvalitet, samt hög anpassningsförmåga till variationer i lindningsmönster och statordesign, har demonstrerats. Signifikanta potentiella kostnadsbesparingar jämfört med manuell produktion har också indikerats. Robotcellen är väl förberedd för produktion, men ytterligare arbete krävs för att förbättra dess tillförlitlighet. Framförallt måste kinkning av lindningskabeln helt undvikas under lindningsprocessen.

De övriga tre utvecklade robotcellerna användes för stackning av statorplåtar, ytmontering av starka permanentmagneter på translatorer och fräsning av gummitrissor. Robotiserad produktion med tillräcklig kvalitet och hög flexibilitet har demonstrerats för samtliga tre moment. Betydande potentiella kostnadsbesparingar jämfört med manuell produktion har också indikerats. Ytterligare arbete krävs dock för att öka robotcellernas självständighet och tillförlitlighet.

Genom det pedagogiska utvecklingsarbetet integrerades forskningen inom robotiserade produktionsmetoder i ingenjörsutbildningen. Tre moment från tillverkningen av Uppsala universitets vågkraftverk valdes här ut som projektuppgifter och all undervisning i den omarbetade kursen relaterades till dessa projekt. Studenterna delades in i projektgrupper och fick under kursens gång arbeta med att utveckla robotceller anpassade för de olika tillverkningsmomenten. Den nya kursen var mycket uppskattad av studenterna. Det indikerades speciellt att centreringen kring projektuppgifter var viktig för studenternas lärande, men även att kursen uppnådde ett effektivt lärande inom klassiska ingenjörskunskaper kombinerat med de nya kunskaps- och färdighetskrav som dagens ingenjörer ställs inför.

Acknowledgements

To begin with, Mats Leijon, thank you for believing in me and for letting me work with much freedom. Thanks for inspiration, challenges and wise guidance. And for pushing me to achieve things that I did not expect to do.

A big thanks to present and former members of the robotics and manufacturing group: Dana Salar, Tobias Kamf and Marcus Linder. For our fun, challenging and rewarding collaborative work in building up the research on robotics. A special thanks to Dana for all the work you have put in to help me during the years, always helping out.

Thanks to all present and former colleagues at the Division of Electricity for support, discussions and all the fun times. Special thanks to Eduard, Valeria, Rickard, Wei, Foppa, Senad and Martin for great times around the world at different conferences, to Boel for our discussions and collaborative work all the way from Ångström to Seabased, to Ulf for all the help between the jokes, to Thomas for your technical support and to Gunnel, Maria, Elin, Anna, Emma, Lena, Ewa, Lena and Ingrid for your administrative support.

Thanks to all summer workers, project workers and students I have had the pleasure to work with. You have widened my perspective and deepened my knowledge while also contributing to the research.

Thanks to all friends in Uppsala for the great years and for making me forget about my research when outside Ångström. A special thanks to Svensäters for the much appreciated breakfasts and for providing a place to sleep when traveling to Uppsala during the past year. Thanks also to all friends in Rimforsa for welcoming us so warmly.

Finally, the biggest thank to my awesome and beloved family. Your loving support brought me here. My parents and sisters, thanks for being there and for cheering. Alexandra, thanks for all the love and for putting up with my late work nights. It is now finally time for the-life-after-the-thesis! Ebba och Tage, tack för att ni är världens bästa och mest underbara barn.

The author is thankful to Uppsala University, Vargöns Smältverk, the Swedish Research Council, ABB AB, Ångpanneföreningen's Foundation for Research and Development, C F Liljewalchs resestipendiefond and Seabased Industry AB for their support to this work.

References

1. Cox PM, Betts RA, Jones CD, Spall SA, and Totterdell IJ. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 2000; 408(6809):184-187.
2. International Energy Agency. World energy outlook 2016. Executive summary.
3. Aleklett K, Höök M, Jakobsson K, Lardelli M, and Snowden S. The peak of the oil age–analyzing the world oil production Reference Scenario in World Energy Outlook 2008. Energy Policy 2010; 38(3):1398-1414.
4. Pepermans G, Driesen J, Haeseldonckx D, Belmans R, and D'haeseleer W. Distributed generation: Definition, benefits and issues. Energy Policy 2005; 33:787-798.
5. ElMaraghy H, and ElMaraghy W. Smart adaptable assembly systems. Procedia CIRP 2016; 44:4-13.
6. Bogue R. Europe fights back with advanced manufacturing and assembly technologies. Assembly Automation 2012; 32(4):312-317.
7. Krüger J, Wang L, Verl A, Bauernhansl T, Carpanzano E, Makris S, Fleischer J, Reinhart G, Franke J, and Pelleginelli S. Innovative control of assembly systems and lines. CIRP Annuals 2017; 66(2):707-730.
8. International Federation of Robotics. World robotics 2017 industrial robots. Executive summary.
9. Sugimori Y, Kusunoki K, Cho F, and Uchikawa S. Toyota production system and Kanban system materialization of just-in-time and respect-for-human system. International Journal of Production Research 1977; 15:553-564.
10. Falnes J, and Løvseth J. Ocean wave energy. Energy Policy 1991 19(8):768-775.
11. Falcão AF de O. Wave energy utilization: a review of the technologies. Renewable and Sustainable Energy Reviews 2010; 14(3):899-918.
12. Kamf T. Automated production technologies and measurement systems for ferrite magnetized linear generators. PhD theses, Uppsala University, 2017.
13. Thorburn K. Electric energy conversion systems: wave energy and hydropower. PhD thesis, Uppsala University, 2006.
14. Danielsson O. Wave energy conversion: linear synchronous permanent magnet generator. PhD thesis, Uppsala University, 2006.
15. Eriksson M. Modelling and experimental verification of direct drive wave energy conversion: buoy-generator dynamics. PhD thesis, Uppsala University, 2007.
16. Waters R. Energy from ocean waves: full scale experimental verification of a wave energy converter. PhD thesis, Uppsala University, 2008.
17. Langhamer O. Wave energy conversion and the marine environment: colonization patterns and habitat dynamics. PhD thesis, Uppsala University, 2009.
18. Rahm M. Ocean Wave Energy: Underwater substation system for wave energy converters. PhD thesis, Uppsala University, 2010.
19. Boström C. Electrical systems for wave energy conversion. PhD thesis, Uppsala University, 2011.

20. Engström J. Hydrodynamic Modelling for a point absorbing wave energy converter. PhD thesis, Uppsala University, 2011.
21. Lindroth S. Buoy and generator interaction with ocean waves: studies of a wave energy conversion system. PhD thesis, Uppsala University, 2011.
22. Savin A. Experimental measurement of lateral force in a submerged single heaving buoy wave energy converter. PhD thesis, Uppsala University, 2012.
23. Strömstedt E. Submerged transmission in wave energy converters: full scale in-situ experimental measurements. PhD thesis, Uppsala University, 2012.
24. Svensson O. Experimental results from the Lysekil Wave Power Research Site. PhD thesis, Uppsala University, 2012.
25. Ekergård B. Full scale applications of permanent magnet electromagnetic energy converters: from $Nd_2Fe_{14}B$ to ferrite. PhD thesis, Uppsala University, 2013.
26. Krishna R. Grid connected three-level converters: studies for wave energy conversion. PhD thesis, Uppsala University, 2014.
27. Gravråkmo H. Buoy geometry, size and hydrodynamics for power take off device for point absorber linear wave energy converter. PhD thesis, Uppsala University, 2014.
28. Haikonen K. Underwater radiated noise from point absorbing wave energy converters: noise characteristics and possible environmental effects. PhD thesis, Uppsala University, 2014.
29. Ekström R. Offshore marine substation for grid-connection of wave power farms: an experimental approach. PhD thesis, Uppsala University, 2014.
30. Hai L. Modelling wave power by equivalent circuit theory. PhD thesis, Uppsala University, 2015.
31. Lejerskog E. Theoretical and experimental analysis of operational wave energy converters. PhD theses, Uppsala University, 2016.
32. Hong Y. Numerical modelling of positive electrical discharges in long air gaps. PhD thesis, Uppsala University, 2016.
33. Li W. Numerical modelling and statistical analysis of ocean wave energy converters and wave climates. PhD thesis, Uppsala University, 2016.
34. Castellucci V. Sea level compensation system for wave energy converters. PhD thesis, Uppsala University, 2016.
35. Baudoin A. Cooling strategies for wave power conversion systems. PhD thesis, Uppsala University, 2017.
36. Wang L. Modelling and advanced control of fully coupled wave energy converters subject to constraints: the wave-to-wire approach. PhD thesis, Uppsala University, 2017.
37. Sjökvist L. Wave loads and peak forces on moored wave energy devices in tsunamis and extreme waves. PhD theses, Uppsala University, 2017.
38. Ulvgård L. Wave energy converters - an experimental approach to onshore testing, deployments and offshore monitoring. PhD theses, Uppsala University, 2017.
39. Elamalayil Soman D. Multilevel power converters with smart control for wave energy conversion. PhD theses, Uppsala University, 2017.
40. Kirkhoff J. Automation in electric motor stator processing. Coil Winding International 1980; 4(2):4-9.
41. Müller R. Automation and flexible design of coil winding. Wire World International 1985; 27:22-25.
42. Leimbach WB, and Marshall JW. Automated stator and field winding. Electrical Manufacturing 1988; 2:13-14.
43. Pietropaoli L. How to evaluate, justify stator winding automation. Electronics 1987; 33:22-23.

44. Morrale P. Electric motor and generator manufacturing myths. In: Proceedings of the Electrical Insulation Conference and Electrical Manufacturing Expo. Nashville, USA; 2007, p. 413-417.
45. Kirkhoff J. Processes and design considerations for automatic assembly of electric motor stators. In: Proceedings of the Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Technology Conference. Indianapolis, USA; 2013, p. 79-88.
46. Akita H, Nakahara Y, Miyake N, Oikawa T. New core structure and manufacturing method for high efficiency of permanent magnet motors. In: Proceedings of the Industry Applications Conference. Salt Lake City, USA; 2003. p. 367-372.
47. Franke J, Dobroschke A. Robot-based winding-process for flexible coil production. In: Proceedings of the Electrical Manufacturing Technical Conference. Nashville, USA; 2009, p. 157-163.
48. Albrecht T, Konig W, Bickel B. Proceeding for wiring integrated winding of segmented stators of electric machines. In: Proceedings of the International Electric Drives Production Conference. Nuremberg, Germany; 2011. p. 132-138.
49. Brettschneider J, Spitzner R, Boehm R. Flexible mass production concept for segmented BLDC stators. In: Proceedings of the International Electric Drives Conference. Nuremberg, Germany; 2013.
50. Stenzel P, Dollinger P, Richnow J, Franke J. Innovative needle winding method using curved wire guide in order to significantly increase the copper fill factor. In: Proceedings of the International Conference on Electrical Machines and Systems. Hangzhou, China; 2014.
51. Kuehl A, Furlan S, Gutmann J, Meyer M, Franke J. Technologies and processes for the flexible robotic assembly of electric motor stators. In: Proceedings of the IEEE International Electric Machines and Drives Conference. Miami, USA; 2017.
52. Leijon M, Owman F, Sorqvist T, Parkegren C, Lindahl S, and Karlsson T. Powerformer(R): a giant step in power plant engineering. In: Proceedings of the IEEE International Electric Machines and Drives Conference, Seattle, USA; 1999. p. 830-832.
53. Leijon M, Dahlgren M, Walfridsson L, Ming Li, and Jaksts A. A recent development in the electrical insulation systems of generators and transformers. IEEE Electronical Insulation Magazine 2001; 17(3):10-15.
54. Leijon M, and Andersson T. High and dry [dryformer power transformer]. IEEE Review 2000; 46(4):9-15.
55. Eriksson, G. Motorformer – a new motor for direct HV connection. ABB Review 2001; 1:22-25.
56. Metwally IA, Radwan RM, and Abou-Elyazied AM. Powerformers: a breakthrough of high-voltage power generators. IEEE Potentials 2008; 27:37-44.
57. Lamell JO, Trumbo T, and Nestli T. Offshore platform powered with new electrical motor drive system. In: Proceedings of the Petroleum and Chemical Industry Conference. Denver, USA; 2005: 259-266.
58. Leijon M, Ekergård B, Apelfröjd S, de Santiago J, et.al. On a two pole motor for electric propulsion system. International Journal of Engineering Science and Innovative Technology 2013; 2(1):99-111.
59. Alfredson S, Harnnäs B, and Bergström H. Assembly of generators with rated voltage higher than 100kV. In: Proceedings of the International Conference on Power System Technology. Perth, Australia; 2000, p. 189-193.
60. Kjellberg M, Parkegen C, Sörqvist T, Karlsson AC, and Gundersen K. Powerformer chosen for Swedish combined heat and power plant. ABB Review 1999; 3:19-23.

61. Dahlgren M, Frank H, Leijon M, Owman F, and Walfridsson L. Windformer – wind power goes large-scale. ABB Review 2000; 3:31-37.
62. Grabbe M, Yuen K, Apelfröjd S, and Leijon M. Efficiency of a directly driven generator for hydrokinetic energy conversion. Advances in Mechanical Engineering 2013; 5:978140.
63. Yabuta T, Yoshizawa N, and Kojima N. Cable kink analysis: cable loop stability under tension. Journal of Applied Mechanics 1982; 49(3):584-588.
64. Coyne J. Analysis of the formation and elimination of loops in twisted cable. IEEE Journal of Oceanic Engineering 1990; 15(2):72-83.
65. Stump DM. The hockling of cables: a problem in shearable and extensible rods. International Journal of Solids and Structures 2000; 37(3):515-533.
66. Ermolaeva NS, Regelink J, and Krutzen MPM. Hockling behaviour of single- and multi-rope systems. Engineering Failure Analysis 2008; 15(1-2):142-153.
67. Zheng YF, Pei R, and Chen C. Strategies for automatic assembly of deformable objects. In: Proceedings of the IEEE International Conference on Robotics and Automation. Sacramento, USA; 1991.
68. Jiang X, Koo K, Kikuchi K, and Konno A, Uchiyama M. Robotized assembly of wire harness in car production line. In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems. Taipei, Taiwan; 2010. p. 490-495.
69. Tamada T, Yamakawa Y, Senoo T, and Ishikawa M. High-speed manipulation of cable connector using a high-speed robot hand. In: Proceedings of the IEEE International Conference on Robotics and Biomimetics. Shenzhen, China; 2013.
70. Jiang X, Nagaoka Y, Ishii K, Abiko S, and Tsujita T, Uchiyama M. Robotized recognition of a wire harness utilizing tracing operation. Robotics and Computer-Integrated Manufacturing 2015; 34:52-61.
71. Papacharalampopoulos A, Makris S, Bitzion A, and Chryssolouris G. Prediction of cabling shape during robotic manipulation. International Journal of Advanced Manufacturing Technology 2016: 82:123-132.
72. Hermansson T, Bohlin R, Carlson JS, and Söderberg R. Automatic routing of flexible 1D components with functional and manufacturing constraints. Computer-Aided Design 2016: 79:27-35.
73. Alkkiomäki O, Kyrki V, Liu Y, and Handroos H. Multi-modal force/vision sensor fusion in 6-DOF pose tracking. In: Proceedings of the International Conference on Advanced Robotics. Munich, Germany; 2009. p. 1-8.
74. Chen S, Li Y, and Ming KN. Active vision in robotic systems: A survey of recent developments. International Journal of Robot Research 2012; 30:1343-1377.
75. Kubota T, and Aiyama Y. Calibration of relative position between manipulator and work by point-to-face touching method. In: Proceedings of the 2009 IEEE International Symposium on Assembly and Manufacturing. Suwon, Korea; 2009. p. 286-290.
76. Lin ST, and Huang AK. Hierarchical fuzzy force control for industrial robots. IEEE Transactions on Industrial Electronics 1998; 45:646-653.
77. Liu W, Chen T, Wang P, and Qiao H. Pose estimation for 3D workpiece grasping in industrial environment based on evolutionary algorithm. Journal of Intelligent & Robotic Systems 2012; 68:293-306.
78. Maykol PA, Rocha LF, and Paulo MA. Object recognition using laser range finder and machine learning techniques. Robotics and Computer-Integrated Manufacturing 2013; 29:12-22.
79. Boochs F, Schutze R, Simon C, and Marzani, F. Increasing the accuracy of untaught robot positions by means of a multi-camera system. In: Proceedings of the International Conference on Indoor Positioning and Indoor Navigation. Zurich, Switzerland; 2010. p. 1-9.

80. Nubiola A, and Bonev IA. Absolute calibration of an ABB IRB 1600 robot using a laser tracker. Robotics and Computer-Integrated Manufacturing 2013; 29:236-245.
81. Skinner ML. Trends, advances and innovations in filament winding. Reinforced Plastics 2006; 50(2):28-33.
82. Markov L, and Cheng RMH. Conceptual design of robotic filament winding complexes. Mechatronics 1996; 6(8):881-896.
83. Minsch N, Herrmann FH, Gereke T, Nocke A, and Cherif C. Analysis of filament winding processes and potential equipment technologies. Procedia CERP 2017; 66:125-130.
84. Cazzaniga R, Valle N, and D'Urzo C. Winding machines for the manufacturing of superconductive coils of the main European fusion research machines. Fusion Engineering and Design 2005; 75-79:7-10.
85. Ghate M, Pradhan S, Patel M, Bhavsar D, and Vasava K. Design and fabrication of a special purpose winding machine for ELM control coils of JET. IEEE Transactions on Applied Superconductivity 2016; 26(4).
86. Scholliers J, Van Brussel H. Design and off-line programming of a robotic tape winding cell. Robotics and Computer-Integrated Manufacturing 1996; 12(1):93-98.
87. Sharon A, and Lin, S. Development of an automated fiber optic winding machine for gyroscope production. Robotics and Computer-Integrated Manufacturing 2001; 17(3):223-231.
88. Jiang X, Koo K, Kikuchi K, and Konno A. Robotized assembly of a wire harness in car production line. In: Proceedings of the IEEE International Conference on Intelligent Robots and Systems. Taipei, Taiwan; 2010. p. 490-495.
89. Griffioen W, Plutteaz G, and Nobach HG. Theory, software, testing and practice of cable in duct installation. In: Proceedings of the International Wire & Cable Symposium. Providence, USA; 2006. p. 357-365.
90. Mayhew AJ, and Stockton DJ. Cost-reduced cable delivery for the 21st century. BT Technology Journal 1998; 16(4):92-100.
91. Griffioen W, Gutberlet C, Mulder J, et.al. New approach to installation of offshore wind energy cables. In: Proceedings of the International Conference on Insulated Power Cables. Versailles, France; 2015.
92. Griffioen W, Gapany L, Grobéty S, et.al. Floating cable into duct: recent developments. In: Proceedings of the International Wire & Cable Symposium. Charlotte, USA; 2013. p. 11-20.
93. Griffioen W, Gutberlet C, Plumettaz G. New technique to install power cables into ducts. Journal of Energy and Power Engineering 2012; 6:1263-1275.
94. Libert F, and Soulard J. Manufacturing methods of stator cores with concentrated windings. In: Proceedings of the 3rd IET International Conference on Power Electronics, Machines and Drives. Dublin, Ireland; 2006 p. 676-680.
95. Kirkhoff, J. A new level of automation in fraction HP (kW) electric motor manufacturing. Assembly Automation 2004; 24(2):159-161.
96. Kamf T, and Abrahamsson J. Self-sensing electromagnets for robotic tooling systems: combining sensor and actuator. Machines 2016; 4(3):16.
97. Haring T, Forsman K, Huhtanen T, and Zawadzki M. Direct drive – opening a new era in many applications. In: Conference Record of the Annual Pulp and Paper Industry Technical Conference. Charleston, USA; 2003. p. 171-179.
98. Hsieh MF, Hsu YC, and Dorrell DG. Design of large-power surface-mounted permanent-magnet motors using post-assembly magnetization. IEEE Transactions on Industrial Electronics 2010; 57:3376-3384.

99. Aleksashkin A, and Mikkola A. Literature review on permanent magnet generators design and dynamic behavior. Research Report 77. Lappeenranta University of Technology: Lappeenranta, Finland, 2008.
100. Binder A, Schneider T, and Klohr M. Fixation of buried and surface-mounted magnets in high-speed permanent-magnet synchronous machines. IEEE Transactions on Industrial Applications 2006; 42:1031-1037.
101. Franke J, Tremel J, and Kühl A. Innovative developments for automated magnet handling and bonding of rare earth magnets. In: Proceedings of the IEEE International Symposium on Assembly and Manufacturing. Tampere, Finland; 2011. p. 1-5.
102. Joseph E, Tremel J, Hofmann B, Meyer A, Franke J, and Eschrich S. Automated magnet assembly for large PM synchronous machines with integrated permanent magnets. In: Proceedings of the 3rd International Electric Drives Production Conference. Nuremberg, Germany; 2013. p. 1-6.
103. Tremel J, Hofmann B, and Risch F. Handling and fixation of permanent magnets. Advanced Material Research 2013; 769:3-10.
104. Karim A, and Verl A. Challenges and obstacles in robot-machining. In: Proceedings of the 44th International Symposium on Robotics. Seoul, South Korea; 2013.
105. Sörnmo O, Olofsson B, Schneider U, Robertsson A, and Johansson R. Increasing the milling accuracy for industrial robots using a piezo-actuated high-dynamic micro manipulator. In: Proceedings of the International Conference on Advanced Intelligent Mechatronics. Kaohsiung, Taiwan; 2012.
106. Atmosudiro A, Keinert M, Karim A, Lechler A, Verl A, and Csizar A. Productivity increaser through joint space path planning for robot machining. In: Proceedings of the 8th European Modelling Symposium. Pisa, Italy; 2014.
107. Wang J, Zhang H, and Fuhlbrigge T. Improving machining accuracy with robot deformation compensation. In: Proceedings of the International Conference on Intelligent Robots and Systems. St. Louis, USA; 2009.
108. Domrös F, Rieger M, and Kuhlenkötter B. Towards autonomous robot machining. In: Proceedings of the 41st Int. Symposium on Robotics. Munich, Germany; 2014.
109. De Graaf E, and Ravensteijn W. Training complete engineers: global enterprise and engineering education. European Journal of Engineering Education 2010; 26(4):417-427.
110. Zhou C. Fostering creative engineers: a key to face the complexity of engineering practice. European Journal of Engineering Education 2012; 37(4):343-353.
111. Beder S. Beyond technicalities: Expanding engineering thinking. Journal of Professional Issues in Engineering Education and Practice 1999; 125(1):12-18.
112. Cruickshank HJ, and Fenner RA. The evolving role of engineers: towards sustainable development of the built environment. Journal of International Development 2007; 19:111-121.
113. Duderstadt JJ. Engineering for a changing world: a roadmap to the future of engineering practice, research and education. Ann Arbor: University of Michigan; 2008.
114. Rugarcia A, Felder RM, and Woods DR. The future of engineering education I: a vision for a new century. Chemical Engineering Education 2000; 34(1):16-25.
115. Azapagic A, Perdan S, and Shallcross D. How much do engineering students know about sustainable development?: findings of an international survey and possible implications for the engineering curriculum. European Journal of Engineering Education 2005; 30(1):1-19.

116. Hanning A, Priem Abelsson A, Lundqvist U, and Svanström M. Are we educating engineers for sustainability?: comparison between obtained competences and Swedish industry's needs. International Journal of Sustainability 2012; 13(3):305-320.
117. Felder RM, Woods DR, Stice JE, and Rugarcia A. The future of engineering education II: teaching methods that work. Chemical Engineering Education 2000; 34(1):26-39.
118. Grimson, J. Re-engineering the curriculum for the 21st century. European Journal of Engineering Education 2002; 27(1):31-37.
119. Mills JE, and Treagust DF. Engineering education: is problem-based or project-based learning the answer? Australasian Journal of Engineering Education online publication 2003-2004; 2003.
120. Blicblau AS, and Steiner JM. Fostering creativity through engineering projects. European Journal of Engineering Education 1998; 23(1):55-65.
121. Douglas EP, Koro-Ljungberg M, McNeill NJ, Malcolm ZT, and Therriault DJ. Moving beyond formulas and fixations: solving open-ended engineering problems. European Journal of Engineering Education 2012; 37(6):627-651.
122. Lehmann M, Christensen P, Du X, and Thrane M. Problem-oriented and project-based learning (POPBL) as an innovative learning strategy for sustainable development in engineering education. European Journal of Engineering Education 2008; 33(3):283-295.
123. Lombardi M. Authentic learning for the 21st century: an overview. Educause Learning Initiative 2007; 1:1-12.
124. Steiner G, and Posch A. Higher education for sustainability by means of transdisciplinary case studies: an innovative approach for solving complex, real-world problems. Journal of Cleaner Production 2006; 14:877-890.
125. Barakat N. Balanced integration of theory and applications in teaching robotics. International Journal of Mechanical Engineering Education 2011; 39(3):195-206.
126. Berenguel M, Rodríguez F, Moreno JC, Guzmán JL, and González R. Tools and methodologies for teaching robotics in computer science & engineering studies. Computer Applications in Engineering Education 2015; 24(2):202-214.
127. Esposito JM. The state of robotics education: proposed goals for positively transforming robotics education at postsecondary institutions. IEEE Robotics & Automation Magazine 2017; 24(3):157-164.
128. Pittí K, Curto B, Moreno V, and Blanco FJ. A new approach to robotics teaching at computer science engineering degree based on action-research. In: Proceedings of the 1st International Conference on Technological Ecosystem for Enhancing Multiculturality. Salamanca, Spain; 2013.

Acta Universitatis Upsaliensis

Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1608

Editor: The Dean of the Faculty of Science and Technology

A doctoral dissertation from the Faculty of Science and Technology, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology. (Prior to January, 2005, the series was published under the title "Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology".)

Distribution: publications.uu.se
urn:nbn:se:uu:diva-335504

ACTA
UNIVERSITATIS
UPSALIENSIS
UPPSALA
2018