NTNU
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From Copper to Composite Stator

Early Phase Product Development of Fiber Printing Techniques

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Abstract

Key insights from the making of two stators, and two complete electric motors, have laid the foundations for an improved production machinery based on the patent of Alva Motor Solutions. As resources are limited, an iterative product development process driven by probing and wayfaring was applied to meet the pressing milestones faced by the startup company.

As Alva through this research has become able to construct competitive electrical motors with semi-automated production equipment, the course towards industrialization is set, and further work suggested.

Samandrag

Erfaringar opparbeida gjennom utviklinga av to statorar og to komplette elektriske motorar, har lagt eit grunnlag for å forbetre produksjonsmaskineriet til Alva Motor Solutions, basert på deira patent. Ettersom ressursar er avgrensa, har ein iterativ produktutviklingsstrategi vore brukt. Dette har vore drive av eit søkande og Wayfaring-basert tankegods, for å kunne kome milepålane til oppstartsfirmaet i møte.

Alva har gjennom forskingsperioda blitt i stand til å konstruere konkurransedyktige elektriske motorar med semi-automatisk produksjonsutstyr. Kursen er staka ut for vidare industrialisering, og forslag til vidare arbeid er gjeve.

Dedication

This work is dedicated to my favorite bee.

Preface

This thesis concludes my studies at the Norwegian University of Science and Technology. It reflects my keenest interest; early phase concept validation. Searching for the unknown unknowns mapping out novel solutions to problems that matter, is at the core of my passion. The task at hand in this thesis have great potential if eventually resolved. If Alva Motor Solutions could make tailored, efficient, electric motors the industry standard, the consequences would be huge.

The thesis is to be read as a work log. The theory, results and discussion would be the best place to start in order to get the general idea. If the process itself, and the specific experiences leading from one prototype to another are of interest, the milestone descriptions in chapter 3 – Design loops - would be where to go.

- Halvard Berge

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1 Introduction

Alva Motor Solutions is a start-up originating from NTNU School of Entrepreneurship. The start-up is aiming to enter the electrical machinery market by proposing a better way of producing iron-less stators than the industry generally offers today. Alva Motor Solutions has a growing network, and are showing promising results regarding prototypes and progress.

There are several angles of attack when investigating business opportunities. In some instances, a problem or need is discovered, leaving a natural progression towards a profitable solution. In other cases, a certain basic and low-level technology is developed and its application becomes evident subsequently or later. In the case of Alva, the latter opportunity rings the truest.

1.1 The focal point

A rotating, electrical machine normally consists of at least five parts; shaft, housing, rotor, stack of electric sheets and stator (Kampker, Burggräf, and Nee 2012). In the stationary coil configuration, electromagnetic fields are sequentially induced to act on the rotating part – rotor. This stationary part is called a stator. According to Kampker, Buggräf, and Nee, the automated winding of iron teethed armature shown in the figure below constitute the largest investment in terms of production equipment, 5.4 million € to 6.6 million €. This equipment is to a large degree tailored for specific motor sizes, which limit the flexibility of production.

Figure 1 - Stator Coils of a Kawasaki Mule 3000

By exploiting the latest advancements in motor design, it is possible to make composite motors without the presupposition of having to apply the iron teeth in the stator. In consequence, new windows of opportunities have opened.

1.2 Problem description

This thesis aims to investigate how to go from copper wires to composite stators that are satisfactory for the design specifications of Alva Motor Solutions. Alva are setting ambitious goals concerning the performance of self-produced stators. I will consider how to technically realize such stators moving towards automated production answering two questions:

1. **Can stators of satisfactory quality be made within the pending patent of Alva Motor Solutions?**

2. **Which principles, in terms of automated production equipment, does a Wayfaring methodology approach point towards?**

1.3 Genesis

A previous idea, tracing back to the inventor of EMCM (Electromagnetic composite material) Martin Gudem, from the Institute of Product Development and Materials, NTNU, formed the basis of the Alva concept. The EMCM research of Gudem was, to the knowledge of the writer, undertaking the pioneering research, whilst Alva later developed the concept to fit a specific production method.

1.4 Concept

The basic concept of these stators concentrate on simplifying the rather complex and expensive stator in conventional production. Alva poses the idea of making two dimensional mats with certain patterns of copper and fibers. When such a mat is rolled up like a toilet paper roll, the copper pattern is to match up with the preceding layer to form definite slots.

When positioning and accuracy of the slots are satisfactory, the stator can be molded in order to maintain these while running. Summed up as in the patent pending:

Printed composite material –

A suitable configuration of copper wires and reinforcement fibers are arranged as warps and wefts to constitute a EMCM mat.

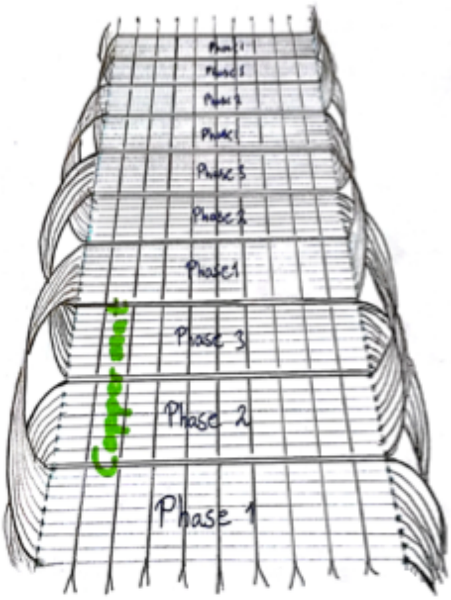


Figure 2 - Printed/Woven Composite Mat

Forming of the component –

The two-dimensional mat is rolled up to a cylinder. At this point the poles and phases must match up with the preceding layers.

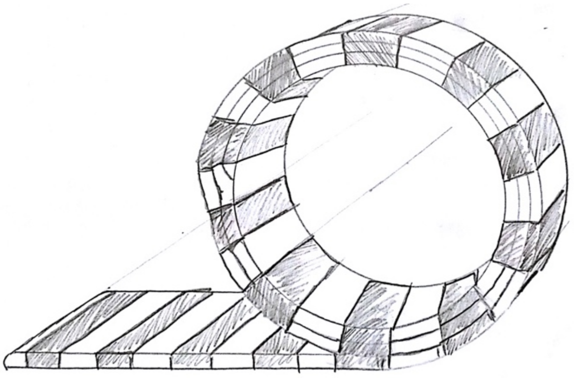


Figure 3 - Forming a Stator Mat

Casting in polymer –

The composite cylinder is casted in a potting. This could be any kind of matrix, given suitable properties with respect to structural integrity, heat conductivity, etc.

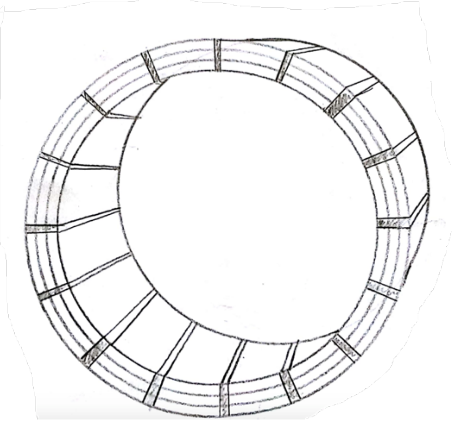


Figure 4 - Casted Stator

The explanatory imagery here shows a method of extreme simplicity which is still not easily developed. In process of realizing such stators, a wide variety of production equipment is to be materialized, and novel solutions will need to be discovered.

The detailed preliminary patent can be found in appendix C.

1.5 Traditional weaving

In order to easily convey the different aspects of fiber printing, the understanding and terminology of conventional weaving is key. As several of the constitutional concepts within both techniques are shared, many of the terms will be applied when inventions are discussed throughout this thesis. “Conventional weaving”, strictly speaking, is a rather wide field as machineries in the industry have been around for centuries. There are numerous patterns, materials, and vast possibilities in terms of robotics and textile. However, Alva is primarily basing its production equipment on the few basic principles depicted underneath, upon which all further expansion and innovation are built.

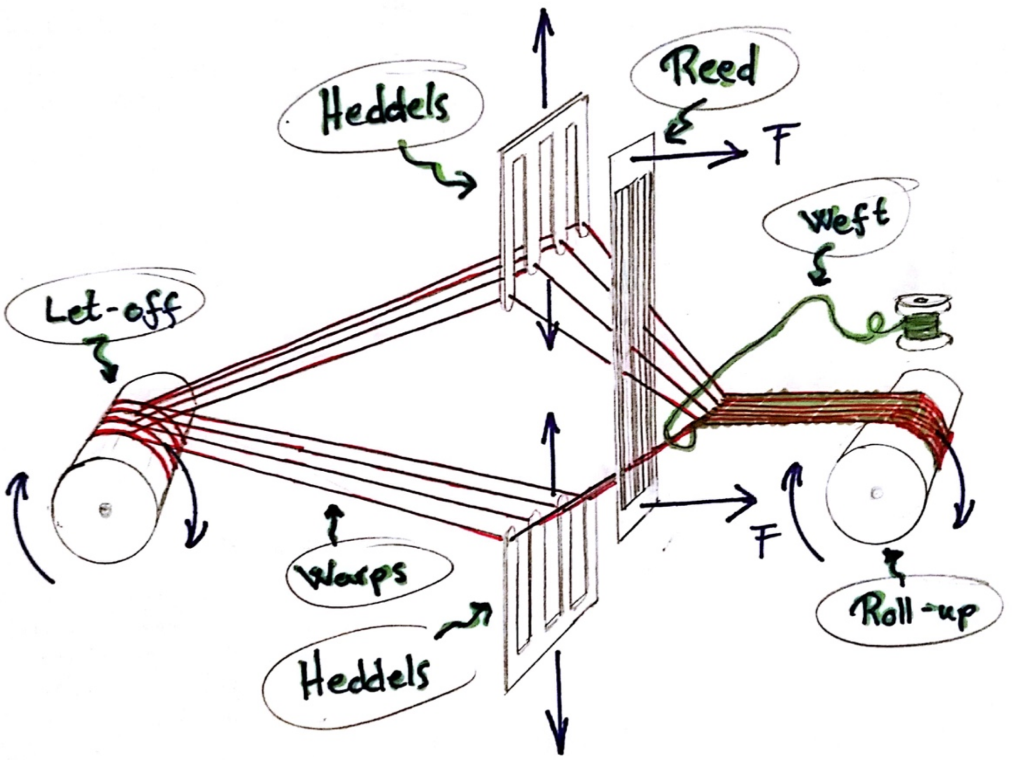


Figure 5 - Traditional Weaving Components

Let-off: This is a roll, or bobbin, on which the warps a kept. Whenever more of these longitudinal threads are needed in the production, they a fed by the let-off mechanism.

Warps: These are the harp of threads, or yearns, that are fed out from the let-off. They are the threads which constitute the longitudinal contribution in the cloth or mat.

Heddle: A looped wire, cord, or a stick, with a (heddle-)eye in the centre. Through this eye a warps yarn is passed before entering the reed. The heddle lifts or lower the warp yarn to form the shed.

Reed: Divide and guide the warp yarns before they integrated the mat or cloth. The reed is pushed towards the mat to achieve compression and alinement.

Weft: The threads introduced transversely in the mat through the shed. In Alva this would include copper wires.

Roll-up: Is where the cloth, or mat, is stored. As lengths are produced, the roll-up rotates to continually collect the cloth.

Plain weave:

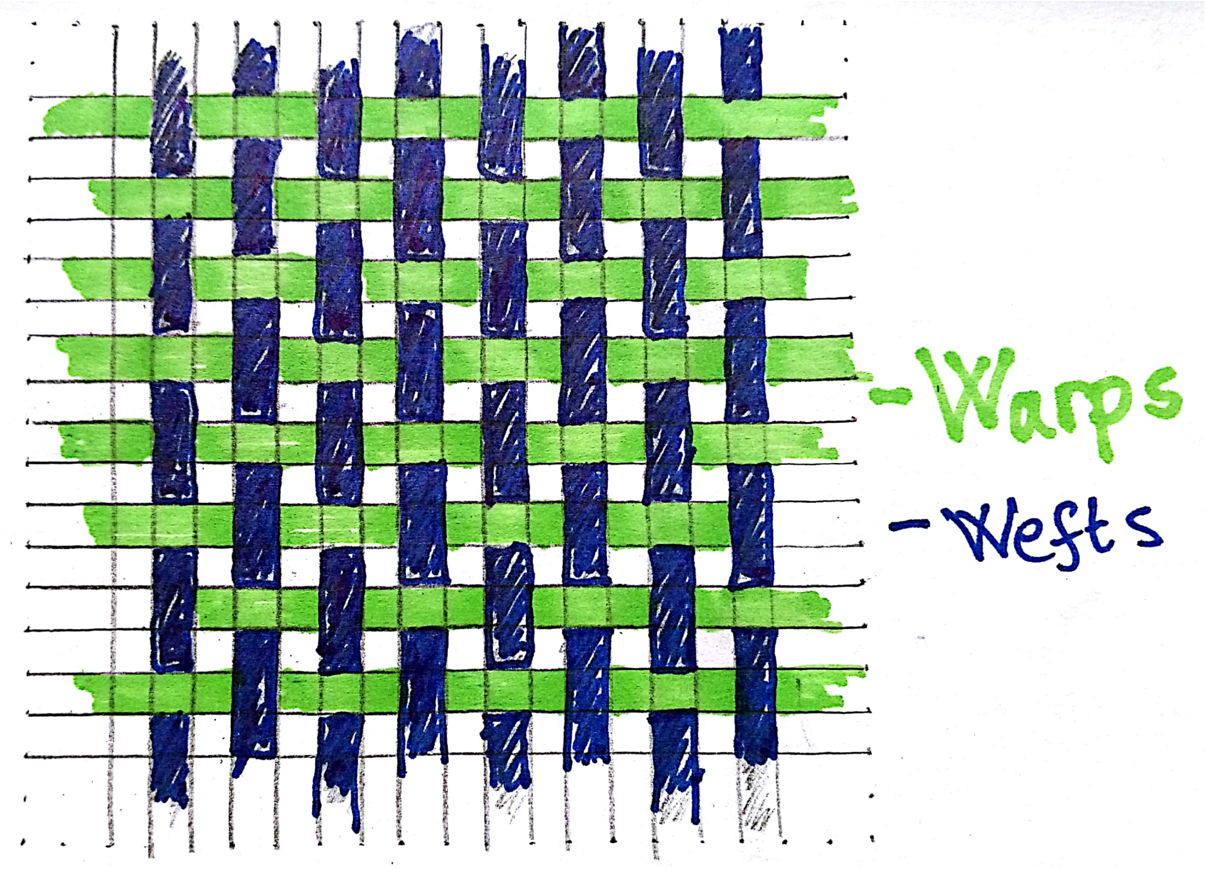


Figure 6 - Plain Weave Pattern

In weaving, there are myriads of patterns and combinations of warps and wefts that changes the product in slight, or large terms. Throughout this project period, however, only plain weave has been utilized, as this is the basic pattern, and a natural starting point.

1.6 Previous work by the author

Description of the project work of fall 2017 has been the included in this thesis. The project thesis discusses how the team dynamics changed and was influenced by the start-up environment. Many of the reflections on the prototypes from this period were omitted as they did not fully connect with the project topic. However, these are included in this thesis, as the development of both stators and machinery are interconnected. During the project period, Alva´s simple weaving machinery named Amelé 1.0 was completed. By utilizing this machinery, and rapid prototypes, stators for testing and validating different concepts were made. This testing indicated that a potential motor from Alva could compete with motors delivered by competitors in certain market segments. However, further improvements were needed to conclude the production method, which is specifically addressed this thesis.

1.7 Motivation

For Alva Motor Solutions, the long-term goal is to fully automate flexible production equipment to make satisfactory stators within their patent pending. This machinery could either led to in house production, or be licensed to motor manufacturers. In other words, the technology is the main value. Because of this, the information, know-how, and knowledge generated from prototyping and development runs are to be highly treasured. Logs, pictures, and documentation lay the foundation for good knowledge transfer between projects and employees. An unpublished article on the value of this kind of documentation is found in **Appendix D.** This thesis is aiming to provide a useful account of the development so far for Alva and a study for in-action Wayfaring methodology. The work has been done in collaboration with, and as a part of the research of TrollLabs.

1.8 Roles, Team work, and collaboration

Behind the work described in this account there lay more work hours than one individual could accomplish during the project period. The work described is executed and influenced by a technical team under the leadership of the author. This have been a great strength in terms of idea generating, time saving, and a broad range of practical competence, and engineering fields.

2 Theoretical foundations

Alva Motor Solutions is a start-up company in search for the most viable market opportunity. Changes in the business plan have throughout the project time propagated to the product, and therefore also to the milestones which have been the primary propulsion of the project. To follow the different turn of events, and meet the development need of Alva, the methodology for doing so had to be agile.

2.1 Product development strategy

As for conducting a product development run there are a thousand approaches. In this thesis, the Hunter-Gatherer model of Steinert and Leifer (Steinert and Leifer 2012) has been an important, inspirational source. Elements from other methodologies are also applied throughout the actual development period and will introduced shortly whenever needed for explanatory reasons. As for all transaction from theory to real applicability, the degree of practical implementation varies throughout the project timeline.

2.1.1 The Hunter-Gatherer model

Through their work, Martin Steinert and Larry Leifer (Steinert and Leifer 2012) from the Center for Design Research (CDR) at Stanford University, have constructed a methodology that "is of a transiting and subjective nature. It is not about fixed truth rather a personal, context dependent pathway alternative." This methodology brings us to the fuzzy front end of product development where the solution not really is in sight – at least the better solution. The process is depicted underneath. This mapped out process demonstrate a highly ambiguous route through the design process. As there is no way to tell in advance how the solution will unfold, the best way is somewhere new as getting somewhere teaches you things you did not know before. The process is, more so than methods like waterfall (Kasser 2002) and stage gate (Cooper 1990), highly agile. Alternatives are not abandoned until tested, and even then, the chance of revisiting a concept is relatively high as physical prototypes very well might be stored for further development down the line. Useful information may evolve from later experiments, deeming an old concept feasible, contrary to previous belief. Furthermore, the Hunter-Gatherer model keep the prey, the final solutions, open and movable. What appears to be the predicted outcome from any design process might change, or worse, do not sway from the predetermined and narrow solution space, leaving true novelty undiscovered. The ambiguity of moving targets, demand a conscious choice from the designers to stick to the rules and not jeopardize the process taking short cuts leaving feasible stones (or concepts) unturned. One of the most important rules is this, according to Steinert and Leifer; never go hunting alone. This is supported by Alan S. Blinder and John Morgan that suggest more informed decisions are made by groups, than by individuals if the starting point is the same in terms of available information ((Blinder and Morgan 2000). Furthermore, Blinder and Morgan found through empirical tests that, contrary to previous beliefs, there is no measurable difference in decision time, between an individual and a group. As the Hunter-gatherer model is based on continually choosing where to go next based on accumulated knowledge, this methodology is a team sport.

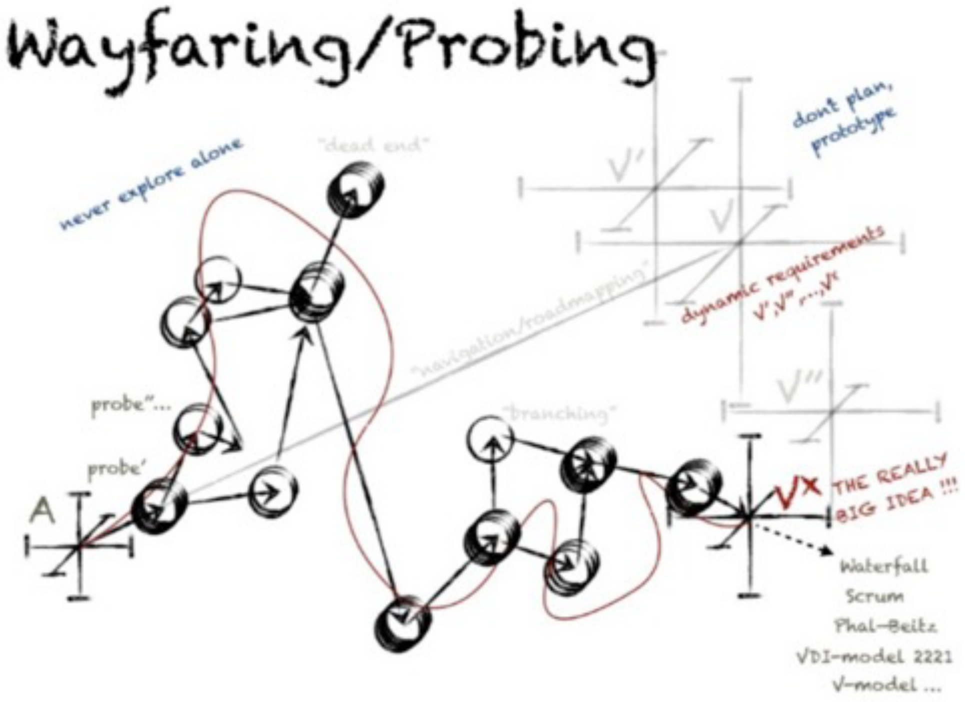


Figure 7 - Wayfaring (Steinert and Leifer 2012)

As the hunt for the innovative begins, one set out for the most promising course. Open-mindedly denying all possible hindering and critical functions that may well make it difficult to realize, you imagine where you need to get. Then you design and build a prototype in order to test uncertainties, and learn. Learning is key here. By engaging in abductive reasoning, one have a chance of discovering the unknown. That is, by allowing for the logical fallacies of inferring causes, one is freer to move in a given solution space. even though working hypothesis are wrong, one promote a bias towards action securing further learning rather than blind planning. If one does not have to work in a deductive manner to ensure the outcome by drawing safe conclusions, one are more prone to stumble over new information. The learning then serves as guidance for further course adjustments and information on what and which questions one need to answer through a next prototype.

The methodology, as depicted, includes four main aspects (Kittilsen Leikanger, Balters, and Steinert 2016):

1. Probing ideas - exploring opportunities, sometimes simultaneously by means of low resolution prototypes, to fail early and to enable abductive learning.
2. Merging multidisciplinarity - including all knowledge domains from the beginning, in
   order to uncover interdependencies and build interlaced knowledge.
3. Speed - planning based on short iteration timeframes, to maximize the number
   of iterations possible.
4. Agility - opportunistically choosing the next step and letting the development process
   shape the outcome, to make room for serendipity findings and innovative outcomes.

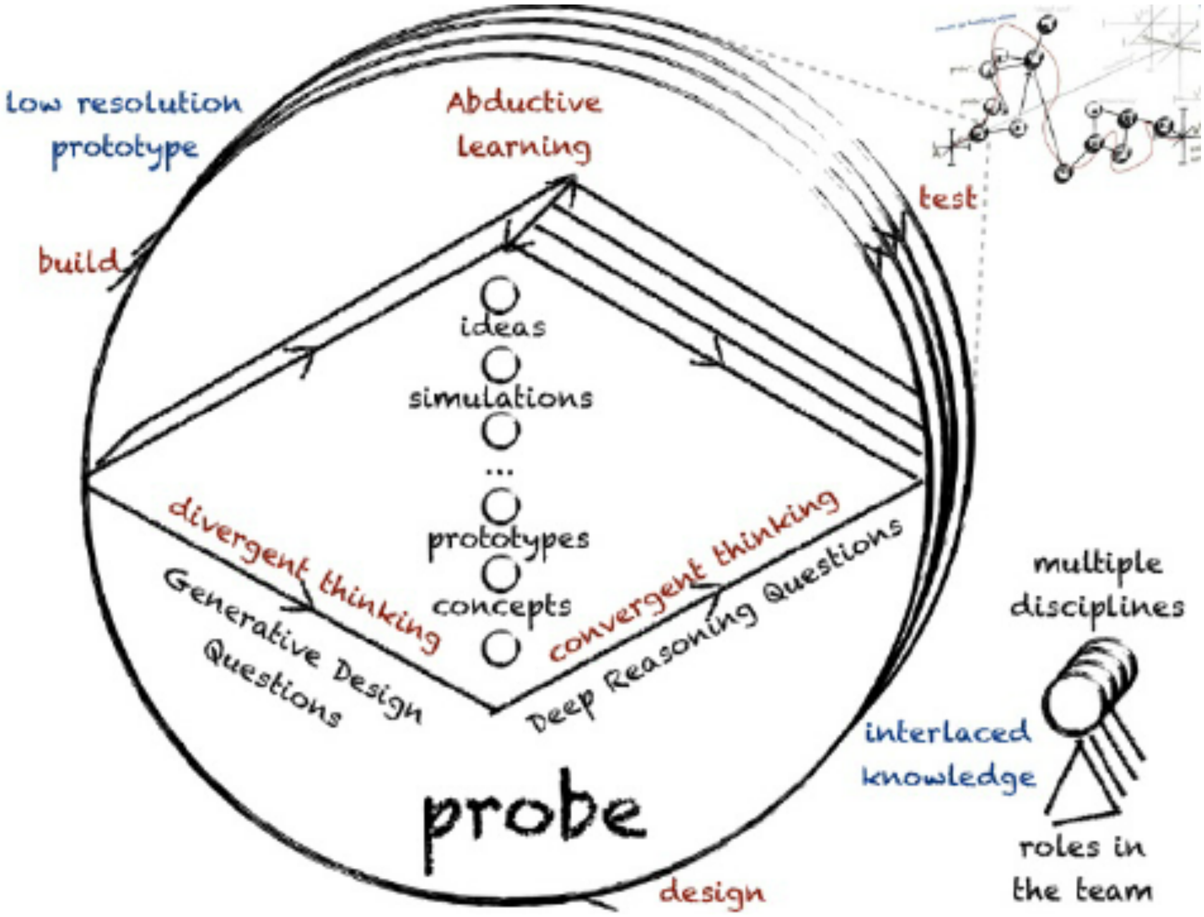


Figure 8 - Probing (Kittilsen Leikanger, Balters, and Steinert 2016)

When a sufficient number of iterations are conducted, a viable solution hopefully emerges. This solution in brought back “home” being subjected to more standard product development refinement and engineering. This is however a more “linear-thinking optimization steps” – as Steinert and Leifer put it – though crucial to real life deployment.

The Wayfaring model prove most suited for novel concepts, where interdependencies are not possible to foresee. However, experience is useful for constructing traditional contraptions which might be crucial for the environment or system you intend to test a concept in. This is where the more common realm of engineering subsidises the methodical product development challenge. As the developer is helpless without the competence- or partners of good engineering practise, both are mutually dependent traits. The difference lie in what on does and does not know in advance of solving a problem. Grestenberg refers to what Edward Snowden call the unknown unknowns (Gerstenberg et al. 2015). Furthermore, Grestenberg claim that such unknowns must be discovered through the probing of ideas, and that in most cases, probing translate to prototypes. As the core of idea probing is to let the idea speak for itself without imposing views before validated or not, the need for tangible results become clear. Further discussions on the importance and aim of prototypes are found in the next section. Building and testing prototypes have, if intentionally built, the power to generate new information that lie beyond our skills of anticipation, and expectations. Every probe in the figure from Gerstenberg represent a prototype influenced by everything from logic, gut feeling and doubt. The knowledge obtained often prove to revolve in the borderline of different fields of study. This generation of interlaced knowledge encourage further the engagement of interdisciplinary teams.

When a sufficient number of iterations are conducted, a viable solution hopefully emerges. This solution in brought back “home” being subjected to more standard product development refinement and engineering. This is however a more “linear-thinking optimization steps” – as Steinert and Leifer put it – though crucial to real life deployment.

When the solution does not emerge conveniently one are encouraged to invoke the rule of “never going home prematurely”. As the figure suggest your current path to a solution is stated as one of many. As the destination is “the big idea”, the targeted prey dynamically changes with the respective path chosen. It is all a matter of speed and number of iterations, so the better path quickly can be revealed. At some point, it is deemed probable the designers will introduce a major abduction, referred to as "**dark horse prototyping**" by Steinert and Leifer. This is where the team is allowed to pursue a brand-new concept. In this way room to free the team from previous "path dependencies and model blindness". A dark horse prototype may solve challenges that hinder previous prototypes from functioning, or solve the very problem. Either way, learnings extracted from these kinds of prototypes could be valuable contributions in the wayfaring towards the solution.

2.1.2 Prototyping

The back bone of innovation is prototyping. To launch any idea, some degree of prototyping will be involved – voluntarily or not. When producing, information will present itself and impose changes in a respective design – if everything runs smooth, good chance are one are not operating in the abductive, innovative realm. According to Beaudiouin-Lafon and Mackay, prototyping can be defined as concrete representation of a part of, or an entire interactive system (Beaudouin-Lafon and Mackay 2003). The most important attributes are that there is no need for interpretation, that it is not an abstract description, and is a tangible artifact. Tangible, as in; not abstract, include computer aided drawings and media in this instance. As stated by Lim, Stolterman, and Tenenberg, "prototypes are the means by which designers organically and evolutionarily learn, discover, generate, and refine designs" (Lim, Stolterman, and Tenenberg 2008). Furthermore, a prototype is said to be a design-thinking enabler. This imply that the role of tangible prototypes is not merely to prove success or failure in a concept, but also to spark further ideation. Being an idea generation effort in, and of, itself, a prototype does not have to be pretty to serve its purpose. As long as the purpose is served, the cheapest and fastest way, is the best. Therefore, all types of designers, technical staff, and people of other traits, can participate in creative ideation, and be builders. Beaudouin-Lafon and Mackay pose that collaboration on paper prototypes increase participation, and improve communication across disciplines (Beaudouin-Lafon and Mackay 2003). **Fundamental prototyping**, posed by Lim, Stolterman, and Tenenberg, is the distilled form of function demonstration. If one are to focus on exploring a design space, the importance of identifying, or satisfying requirements is in fact not the primary goal. One should, as far as it is possible, strive for "finding the manifestation that in its simplest form, filters the qualities in which designers are interested, without distorting the understanding of the whole".

2.1.3 Design Fixation

As Alva Motor Solutions is primarily basing their innovation partially on preexisting concepts. Intuitively, basing parts of a solution on existing technologies are a safer and quicker mean to reaching a success. The danger, however, is clearly shown through numerous studies on design fixation (Linsey et al. 2010). Being confronted with existing solutions, will reduce the design solutions generated by the developer, decreasing the degree of creativity. Such design fixations stick and influence, according to Youmans, even despite it would impair the performance of a novel design (Youmans 2011). On the contrary, if viable solutions exist, the shortest way to market would be the one that does not have to build first.

2.2 Stators

There are several attributes that constitute a well-made electric motor. For brushless permanent magnet motors, as are the motors Alva Motor Solutions are focusing their efforts around, predicting and controlling the magnetic field distribution is the key to good performance and design (Hanselman 2006).

These are the primary drivers in the case of Alva to realizing satisfactory stators:

Copper fill factor:

The higher the copper fill factor in a stator, the more current can the conducting slot carry. The more current is passing through the slot, the more powerful become the magnetic field.

Smaller airgaps are desirable:

Smaller airgap gives less reluctance path between magnet and coil. More flux cut the coil with less distance. According to Hanselman, the following model of permeance cover the basic behavior of permanent magnet-stator configurations.

Equation 1 - Simple Permeance With Straight Lines

$$P_g = \frac{\mu A}{g} \tag{1}$$

Where $\boldsymbol{P_g}$ is the permeance of the air gap, $\boldsymbol{\mu}$ is the permeability of the material, $\boldsymbol{A}$ the area of the magnet and $\boldsymbol{g}$ the length of the gap.

The reluctance is an inverse function of the permeance:

Equation 2 - Reluctance as an Inverse of Permeance

$$R = \frac{1}{P} = \frac{1}{\mu A} \tag{3}$$

R designate the reluctance in the gap.

Which decrease the magnetomotive force $\boldsymbol{F}$ exerted between the bodies, where $\boldsymbol{\phi}$ is the flux density:

Equation 2 - Magnetomotive Force

$$F = \phi R \tag{4}$$

This is means that high accuracy in terms of stator thickness and airgap control are of great importance.

3 Design loops of development

The scope of this chapter is to conduct a preliminary investigation of Alva’s stator production. This investigation is aiming to map out the functionalities and constraints the equipment a first-generation production line could be based on. Key to the process have been the validation of a concept within the patent of Alva Motor Solutions. Pending from October 2017, the freedom of adding and subtracting from the patent´s concept description has been present throughout the year. However, efforts have been made, and wishes have been expressed, to exhaust a wide a variety as possible under the envelope of the preliminary patent claim. This have, to a degree, steered the iteration cycles in favour of the patent throughout the process, whenever deemed feasible.

Alva Motor Solution split the project period from September 2017 to May 2018 into four main milestones. The aim of the investigative project period has been to deliver functional stators for these milestones. Each produced stator has been associated with different contraptions of production equipment. These rapid prototypes have served as simplistic support for realizing the stators and validating steps for production techniques. Throughout the project time, the process of making a stator naturally has emerged into four distinct production steps; fiber printing/weaving, forming, casting, and integration. This chapter run through the process for reaching each of the first three milestones, leaving the evolvment of the drone motor for later treatment as this is concidered the result of the project period. For each milestone the development of each production steps are accounted for. As for any product development endevor, the solution is is measured on its purpose, or stator aim found for every milestone. In the setting of Alva this translates into stator quality.

3.1 Test stator

The scope of this milestone was to simply get going, pursuing a bias towards action. The Department of Electric Power Engineering at NTNU were gracious enough to lend Alva access to the test laboratory with three phase rotors for interchangeable test stators like ours.

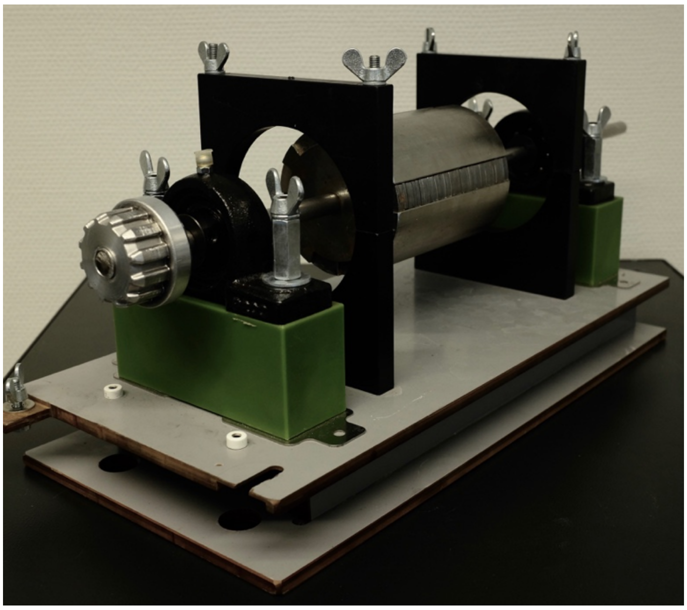


Figure 9 - Test Rotor

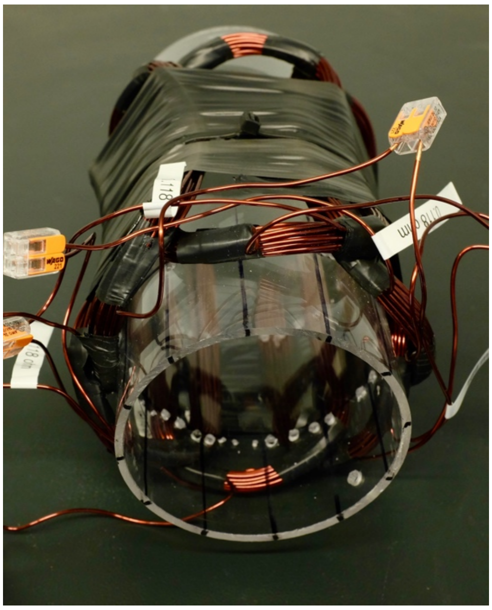


Figure 10 - Example Test Stator on Acrylic Tube

Stator aim:

Pole number:	4	
Motor:	In-runner	
Diameter:	100	*mm*
Axial length:	60	*mm*
Aimed Copper fill factor:		*%*

Table 1 - Test Stator Specs

From Alva’s perspective, this initiative would provide a suitable introduction to the electromotive realm for the technical team. Additionally, this would let every involved member feel and try to make a stator with the suggested method. In this way, every individual would get on board with what the company is trying to achieve. The first loom contraption could now be seen in action, being the very first prototype in the time span of the project period. Amelé 1.0, as the loom/fiber printer was named, had been prepared prior to the project start with only a few adjustments left before functional. This could further be built upon and laid the foundation for the machinery development.

Priority for the developer was to get something to spin, so to learn from something functional, however bad. To further gain confidence on building upon the production equipment, the knowledge on whether the product is in the ball park of what is demanded is important.

3.1.1 Fiber printing the test stator

The intention of this run was to shed light on what worked, and what did not in the first attempts of fiber printing. This learning was crucial in the subsequent development of the fiber printer. As a common name of all the fiber printers Alva develop, Amelé is used followed by a version number. The first version – Amelé 1.0.

A. Fiber printing with Amelé 1.0

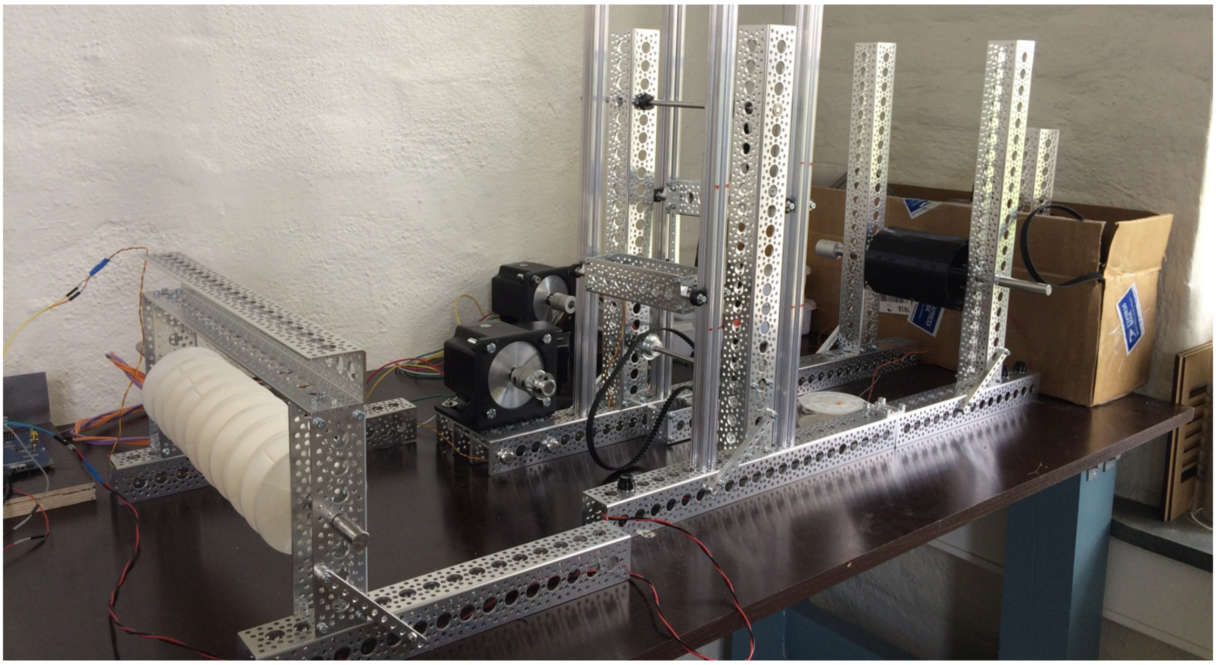


Figure 11 - Amelé 1.0, Photography by Simen Stenersen Pjaaten

Amelé 1.0 was the first test in the project period started. The start of evaluating whether the hypothesis of Alva, that elements from the textile industry can be applied when combining copper and fiber to a composite mat, is factual. Consisting of common loom parts like let-off, heddles, and roll-up, this machinery would enable the first efforts of semi-automatic fiber printing.

Let-off mechanism:

The tension was maintained by one common bobbin for all warp yarns. However, what quickly was discovered led to an immediate iteration on the solution. The warps came from different angles toward the heddles. This meant that as the diameter of the different let-off bobbins varied, the travel length of the thread was different with each rotation. Also, the degree of alinement through the center of the heddles play a role in how unevenly the warps are let of the common bobbin. Furthermore, as the warps had no elasticity, there was no chance of maintaining an evenly distributed tension throughout a mat.

The second iteration was a rapid prototype to get it all up and running quickly. By using a simple leaver with a limited allowed travel distance, a spring would maintain tension throughout the movement of the belonging heddle. Whenever the roll-up mechanism, or heddle, pulled more than the spring allowed in travel distance the bobbin on the spool attachment would yield in terms of friction and feed more warp as showed in the figure.

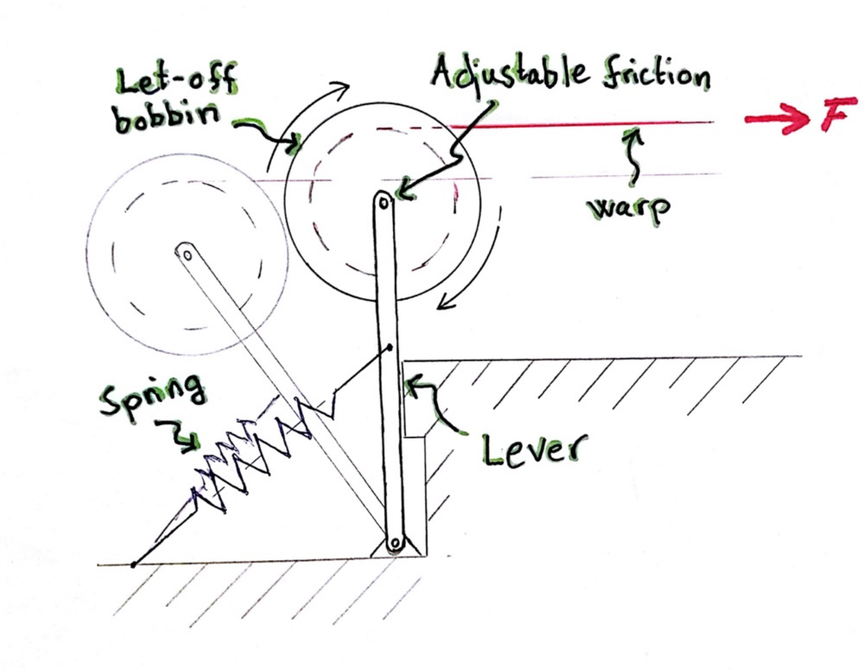


Figure 12 - Let-off Mechanism

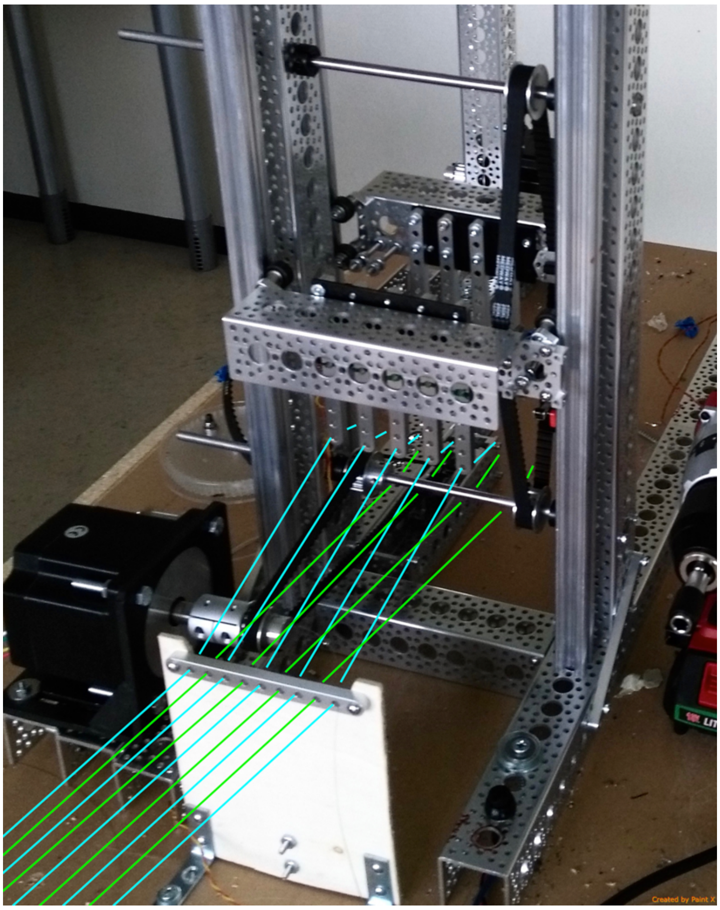


Figure 13 - Heddles of Amelé 1.0

Heddles:

The heddles on Amelé 1.0 were aluminum bars that were lifted and lowered to cross warps.

Roll-up mechanism:

This mechanism was merely a steel tumbler with screws for locking the PMMA tube made for the test-setup at the lab. The shaft on the contraption was rotated by a stepper motor with small-cogwheel belt.

Product produced

When the machinery was completed, the first few goes of fiber printing begun. With instruction from Alva´s motor designer, these tests were conducted with 1mm solid wires.

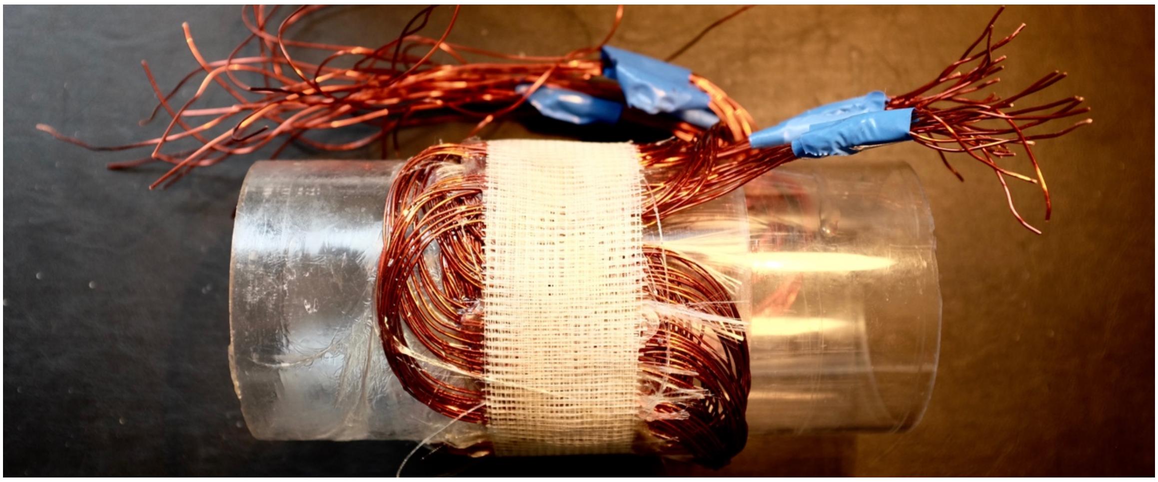


Figure 14 - Test Stator

The wires were inserted one at the time, with heddle exchange for each pass-over. In this attempt, a conventional plain weave mat. The end-windings were bent over in accordance with the desired asymmetric three phase pattern. Each wire was pushed towards the cloth, but showed a tendency of slipping away after pressure release. A natural workaround became to lock the wire in between the warps and the roll-up roll itself to increase friction. To maintain a proper distribution of slots and wires, glassfiber strands were applied as a woven cushion in between each phase.

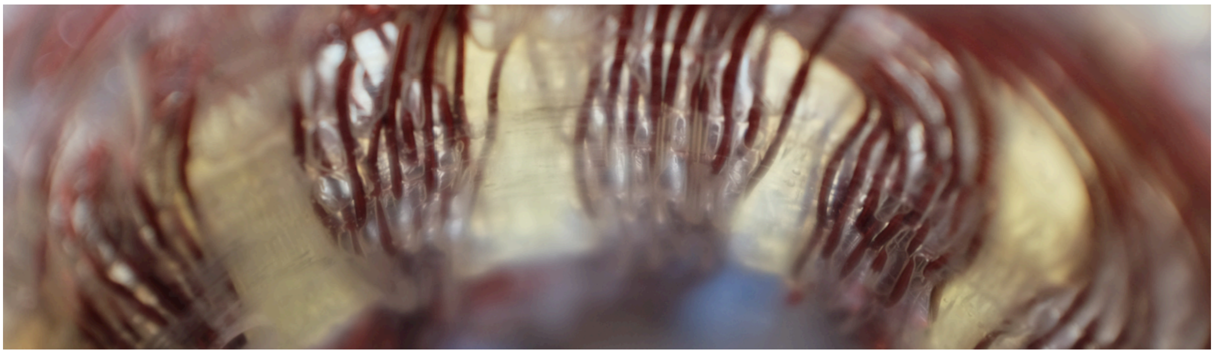


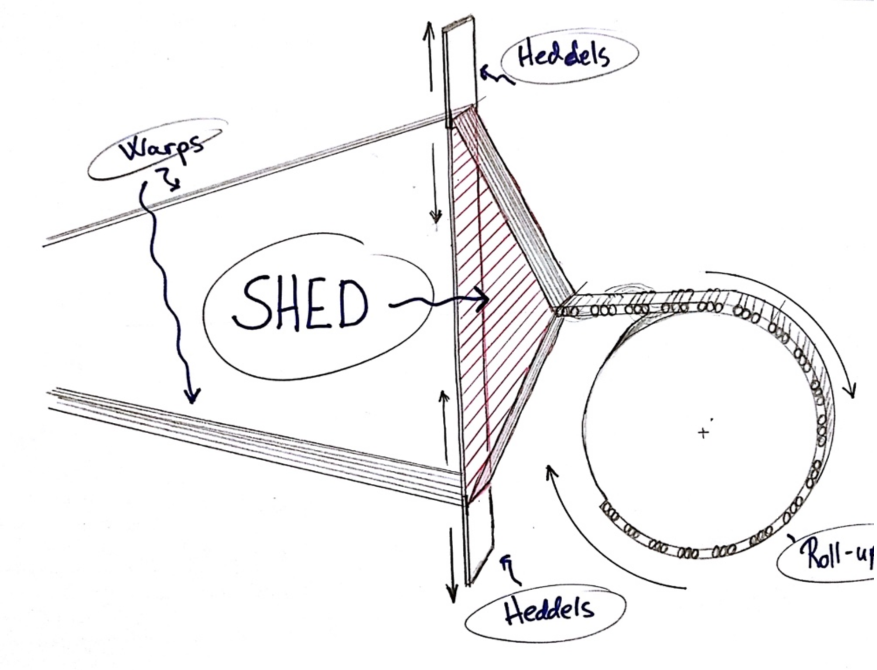
Figure 15 - Glassfiber Cushion

Learnings on fiber printing with Amelé 1.0

LET-OFF:

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The stepper motors and belonging code for controlling the motions was reliable. Individually controlled tension lever proved a good upgrade, as all warp yarns were tight. As bobbins was used for the let-off mechanism, the warps could be long enough to print tens of meters of stator mat without having to be reset.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION:	The spacing between the bobbins appeared too big. As the angle towards the heddles became large, the warps started to split and thin when forced back and forth with friction in its respective heddle eye. This happened despite a seemingly low friction in the eye itself. A limited space resulted in as few warps as six, distributed over 60mm axial length.

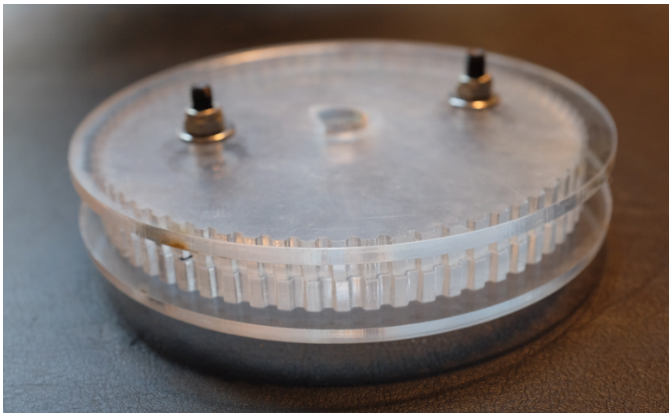
HEDDLES:

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The heddles arms were rigid, and withstood the high tension from the warps.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION:	Each of the heddle attachments ran on short rails limiting the shed. Limited shed space make it more challenging to pass wefts and wires, resulting in slower production pace. For heddles, the spacing between each warp were quite large, as was true for the let-off bobbins. In terms of the weaving, more warps might have made the cloth more rugged. Therefore, a slimmer design leaving more space for more warps would be preferable.  Figure 16 - Shed Space

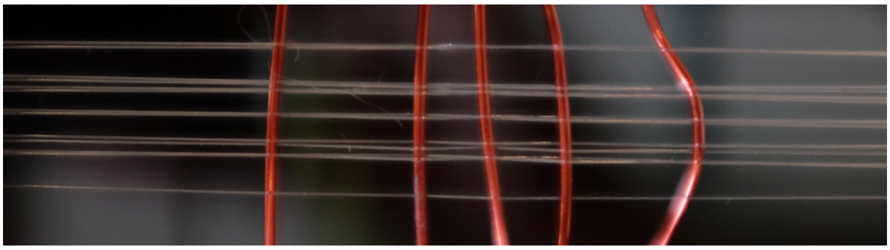
LET-OFF:

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The stepper motors and belonging code for controlling the motions was reliable. Individually controlled tension lever proved a good upgrade, as all warp yarns were tight.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION:	The spacing between the bobbins appeared too big. As the angle towards the heddles became large, the warps started to split and thin when forced back and forth with friction in its respective heddle eye. This happened despite a seemingly low friction in the eye itself. A limited space resulted in as few warps as six, distributed over 60mm axial length.

ROLL-UP:

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The stepper motors and belonging code for controlling the motions was reliable. Individually controlled tension lever proved a good upgrade, as all warp yarns were tight.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION:	The roll-up mechanism suffered an initial blow. The warp used in the final prototypes was nylon fishing thread – which have a rather high tensile strength of approximately 10,000 MPa and a diameter of 0.1mm, which allow for a tension of 8KG per warp. Combined, 6 warps of tension around 4KG. It turned out that 24KG, started to inflict yielding in the components of Amelé. Also, the roll-up stepper motor showed clear signs of struggle. With a 1:1 gear exchange from motor to shaft and with a roll of 100mm diameter the estimated dynamic torque will be in the ball park of 12Nm. A laser cut cogwheel served to balance out a more suitable gear exchange.  Figure 17 - Laser Cut Cogwheel The main take away was that as the warps multiply, and the combined tension will potentially be high. 40 warps of 4 KG yields easily 160 KG in the machinery.

STATOR**:**

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The stepper motors and belonging code for controlling the motions was reliable.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION:	Challenging to weave with thick wires. Any prior deformation in a straight wire causes it to vary throughout the active area. Such deflections remain permanent as there is no way to apply enough force by hand to straighten it.  **Figure 18 - Bent Wires in Grid** The end-winding curve, from exiting the mat to entering, is never perfect. A stress the deflection propagate into the active area, which proves a challenge to standardize. All wire wefts were parted by warps, which give every wire a small room for misalignments.

3.1.2 Forming the component

The scope of this section is to investigate choices, and conduct the development concerning the cylindrical placement of copper phases. Moving from a flat copper mat to a three-dimensional stator is the very core of utilizing the technology of Alva. Different techniques, and approaches in the fiber printing make this production step more, or less relevant.

Amelé roll-up

On Amelé 1.0 the mold itself was a part of the roll-up mechanism. The PMMA tubes belonging to the test rotor at the lab constituted both the roll-up roll and the mold. This means that when the stator mat was printed it had at the same time been positioned. The warps were originally fastened on the tube as the tube was permanently to be a part of the stator.

Roll-up of test stator

When assessing the accuracy of the stators, the angle between each slot is the most important. As a phase receive an electric pulse, the matchup between these determine how well the push is exerted on the rotor. To obtain this matchup glassfiber strands were inserted to fill the gap between each slot.

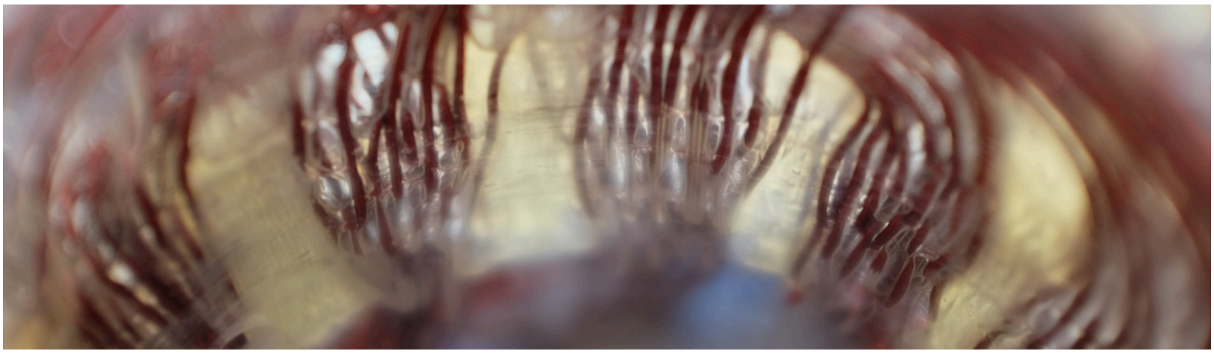


Figure 19 - Glassfiber Cushion

Learnings

ROLL-UP:

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The mechanism made it, if not in a pretty manner, possible to lock down the 1mm thick wires. As these wires have a wide elastic range before deformed, warps had to exert external force on the wires to keep them straight. After the cogwheel adjustments done with respect to the stepper drive, the warps were enabled to let-off despite the high tension.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION:	The stationary components of Amelé were clearly under stress, as the parts visibly deflected.

ROLLED-UP STATOR:

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	Running the roll-up mechanism, a couple of extra turns helped keep the copper on the tube. In this case, the outer diameter of the stator had no space restrictions, which gave way for such convenient wrapping.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION:	Clearly the end-result were not satisfactory. The spacing between the slots, and the matchup between phases were off. Estimated deviation of 6% means that some of the slots does not even match the corresponding magnets in the rotor. This appeared to a result of the fact that the glass woven in-between the slots was compressed when the elastic warps shrunk, due to decreasing tension.

3.1.3 Casting in polymer

The scope of this section is to provide a clear picture of how the polymer should are introduced in the windings. There are numerous possibilities applicable from vacuum infusion, to injection molding.

Brush and Glassfiber – Keeping It Simple

In the case of the test stator, the tube on the inside of the stator mat mad it all simple. As the tube was to stay; the inner diameter was already fixed. This enabled a simple approach of wrapping a couple of layers of glassfiber grid, and directly apply an epoxy with brush. At this point, the aim was merely to get going with casting, utilizing the chepest and quickest means available.

Stator result

The resulting stator was bulletproof in terms of ruggedness. It is however hard to determine any other value of the cast than the fact that is was done for the learning, as the PMMA tube was support structure enough alone. Furthermore, the airgap and precision of the stator was set by the tube as well, this was expected to become more of a challenge when no such support would be available.

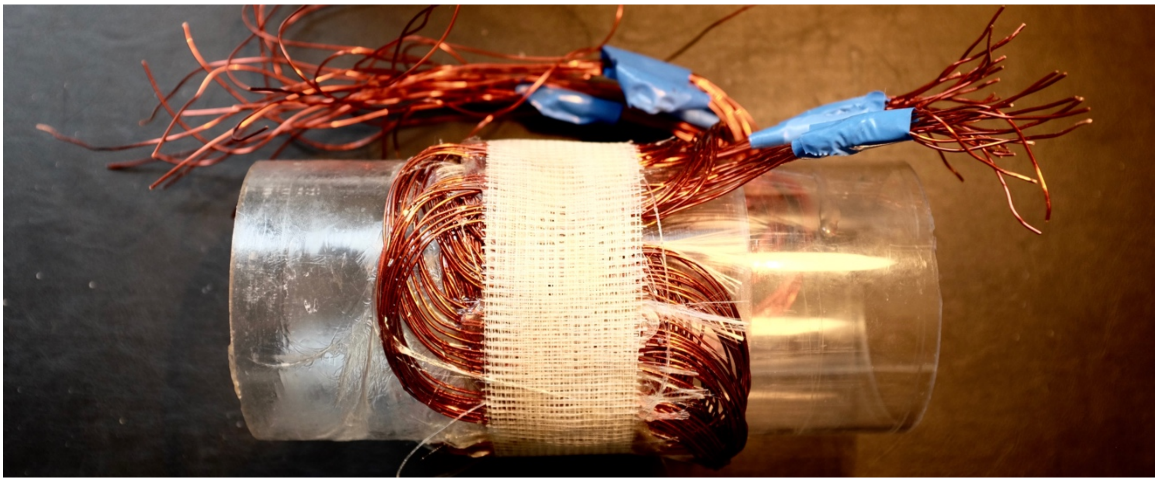


Figure 20 - Final Cast of Test Stator

Learnings

MOLDING PROCESS:	
WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The operation was made easy because of the PMMA tube. This luxury would subside when the work towards the next milestone begun. The glassfiber grid helped keep the copper mat close to tube, however, an even higher applied pressure could make the copper fill factor closer to the rotor higher.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION	The tube added as much as 3mm to the airgap (plastics are considered “air” because there are no electromagnetic losses associated with flux through these material, only the travelled length) between rotor and stator(referance). In conventional machines, less airgap between stator and rotor lead to less losses, if sufficient heat transport is sustained(refrence).

3.1.4 Product integration

Tube clamping

The test machinery at the Department of Electric Power Engineering is in in-runner. This mean that the stator is positioned on the outside of the rotor. The setup was equipped with clamps to lock down the stator tube. With everything pre-set, the wires naturally exited the stator in the axial direction. From here the terminals were connected, and the test rig good to go.

Base or contraption

No armature, base or flange was needed. Therefore, matters like attaching sensors and handling circuit boards for terminal connections was not encountered at this point.

3.2 Diverting

The wayfaring model describes “dark horse prototyping” as abduction introducing a new concept that represent a leap from previous path dependencies and model blindness. The experience with the poor test stator begged the question; what other ways could a desired stator mat be made? The disadvantages of weaving 1mm wire in a plain weave seemed obvious at the time:

- **The spacing between each slot, and subsequently the matchup internally for phase was hard to ensure.**
- **The right wire had to be introduced at the right place – with was a time-consuming process.**
- **Every time a wire was locked in place, a set of warps would keep a distance to the next wire – this appear somewhat counter intuitive as Alva was striving towards as high copper fractions as possible in the limited volume of every stator.**

With these factors in mind, a new approach emerged. Taking the liberty of defining a temporary aim; how to make stators fast and cheap? Still with the necessity of working under the main concept of Alva, where warp and weft were central constituents.

Machinery – Band weaving

In the previous go a total of 30 wires were managed and inserted at the right time. Each of these wires had to make the turn in the end-winding to be inserted further down the mat. To avoid the hassle of this, the prototype aimed to combine all wires within each phase ensuring that the proper order of wires. Additionally, the warps would only change for each slot, not single wires, so that the CFF improved from the test stator.

Rapidly made laser cut molds were laid out, hosting the exact amount of room for each phase. Casting the active area with polyurethane made the linear parts stiff whilst leaving the end-windings easily bent.

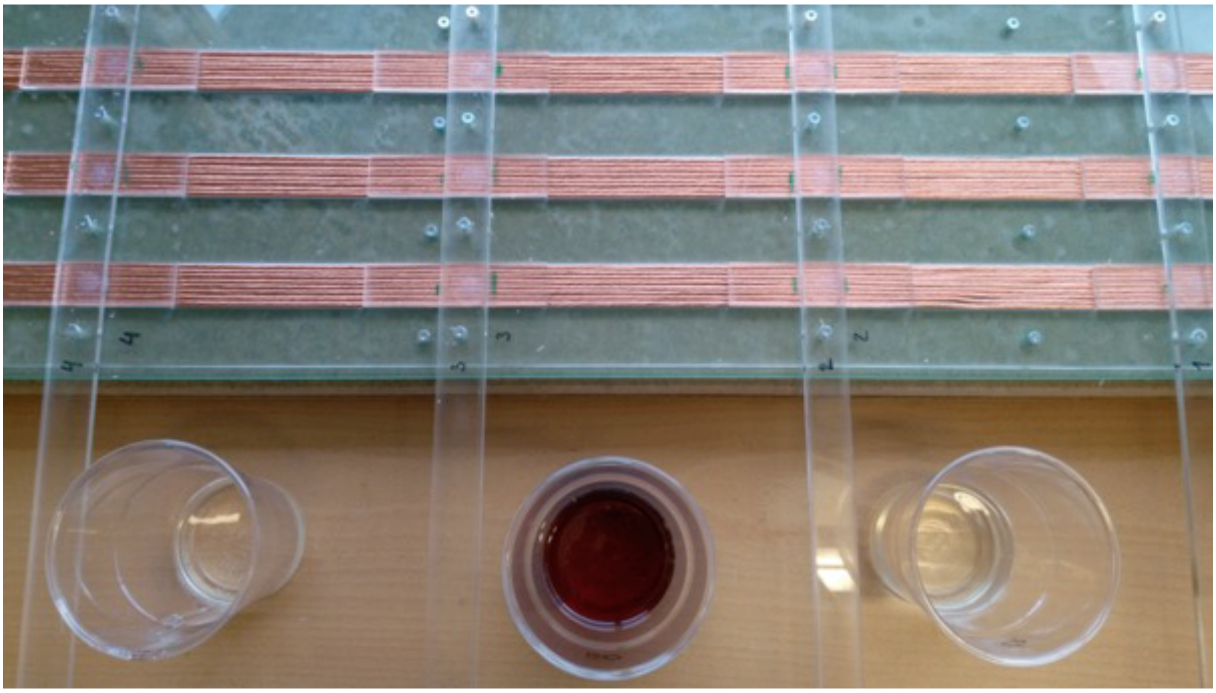


Figure 21 - Laser Cut Molds with Pooling of Active Area

Stator

The stator result had clear advantages in favor of the previous version. The spacing between slots and phases turned out well, with a worst deviation of 1%, which was a huge improvement from the first rounds. The concept was tested both with solid wires and litz wires.

Figure 22 - Casted Phase of Bare Wire

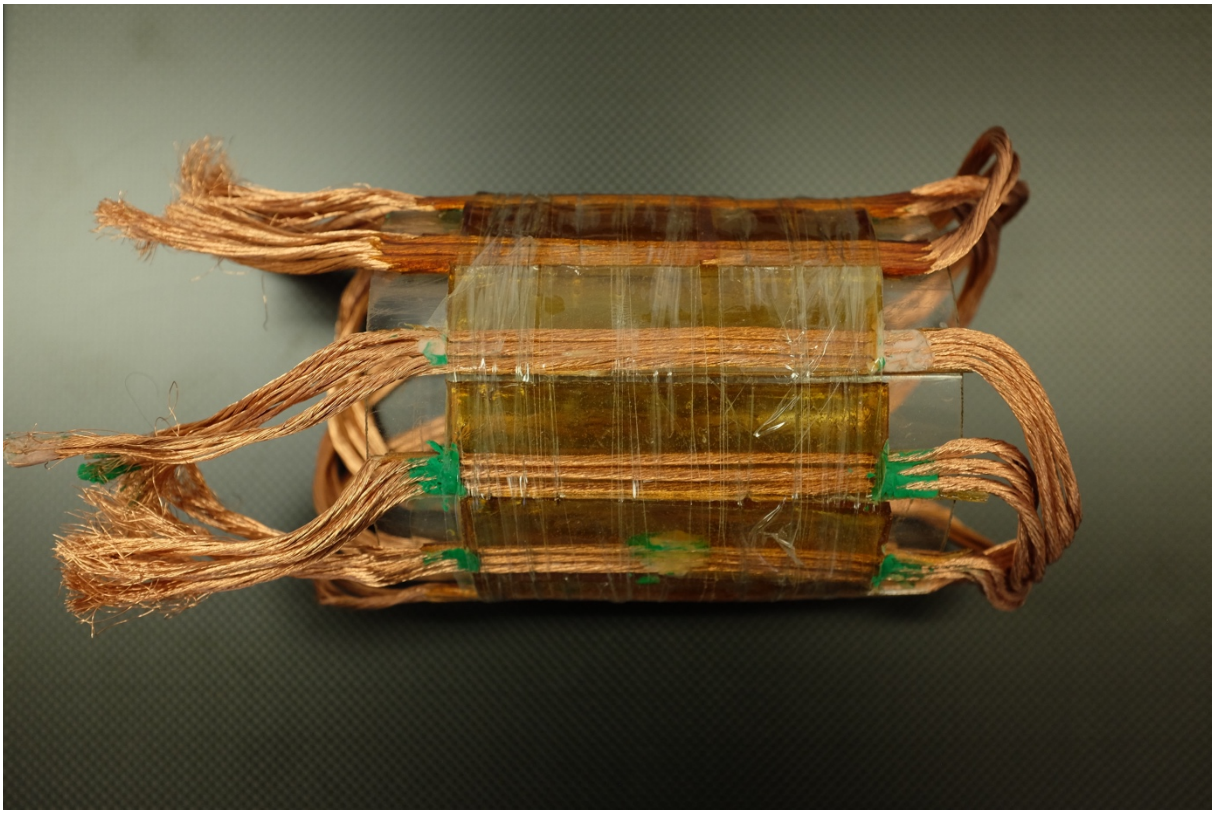


Figure 23 - Test Stator with Polyurethane Spacers

Learnings

MOLDING PROCESS:	
WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The main take away from the prototype was how simple the management of wires became after everything is pre-casted in the right configuration, as 30 wefts turned to 3. other properties were ensured like alinement, regularity in end-windings, and even distribution of poles. Copper fill factor increased drastically from the first goes on conventional plain weave. the phases experienced less yielding in contact with high-tension warps because of the added stiffness of 10 wires.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION	The mass production potential of the method was uncertain. Seemingly less of the operations could be adopted from the textile industry. The time for a serious diversion like this was too early for Alva, as the concept in conventional weaving not yet had been exhausted. The obtained production speed was an advantage when associated with manual labour. When potentially automated, both difference in production speed and flexibility was hard to predict at this point.

3.3 ThinGap™

ThinGap™ is an American electric motor manufacturer situated in California, United States, and is the self-proclaimed "world leader in high performance electromechanical conversion" - thingap.com. ThinGap™ design and produce composite stators, aiming to provide high power, and torque densities for their customers. To Alva, ThinGap™ seem like the most similar competitor. Both are aiming at composite stators to obtain motors with more flexibility in production, more lightweight, and with zero cogging torque. For this milestone, the TG305X from ThinGap™ was bought to test this in our own test bench. Furthermore, Alva wanted to replace their stator and run the motor on a self-made, retrofitted stator.

Figure 24 – TG71XX – Typical ThinGap™ Architecture

https://www.ThinGap.com/standard-products/

The main difference between this stator setup and the test stator, would be that the ThinGap™ stator need to have correct dimensions on both sides. As evident from the figure above, the rotor carry a back iron for the stator, something that means that accurate dimensions in both width, and axial height is crucial. The machine drawings on this particular model reveal an airgap on both sides of the stator of only 0.5mm.

3.3.1 Fiber printing

The scope of this part of development was to validate weather the current method could provide feasible results, compared to ThinGap™. Specifications for the stator mat was such:

STATOR AIM:

POLE NUMBER:	22	
MOTOR:	Out-runner	
POLE WIDTH:	6.3	**MM**
AXIAL LENGTH:	≥ 20	**MM**
AIMED COPPER FILL FACTOR:	< 22 (Benchmark by TG)	**%**
SPEED:	17000	**RPM**
POWER:	151	**KW**
TORQUE:	0.21	**NM**
CURRENT:	3.1	**A**
MINIMUM NUMBER OF WIRES PER PHASE:	6	

Table 2 - ThinGap™ Stator Retrofit Aim

Moving on to a new stator case with Amelé 1.0

At the first go around Amelé was tested as it were, in terms of let-off, heddles, and roll-up mechanisms. This led to a few iterations on both the heddles and the let-off, as the width of these was much too wide to produce the 20mm mat. On the test stator, the warp spacing was close to 8mm per warp, far too long to interlock the ThinGap™ mat.

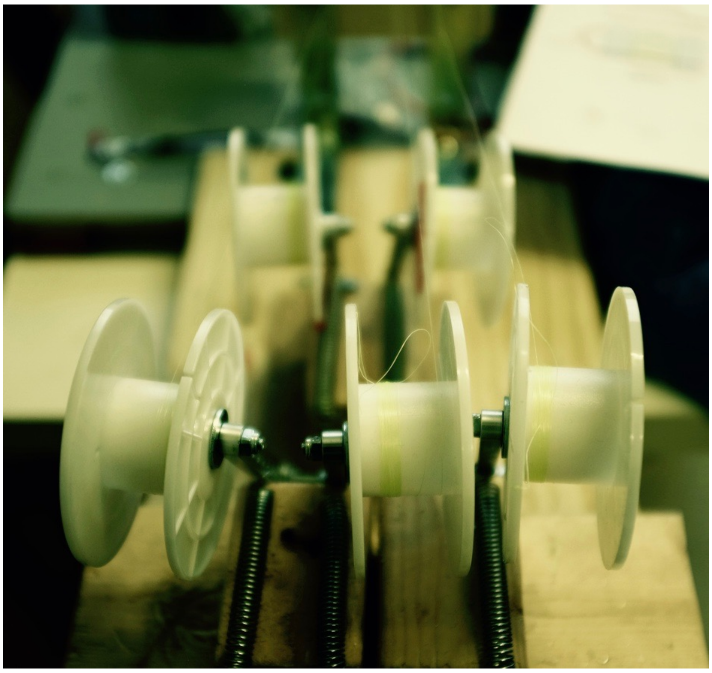


Figure 25 - Let-off Levers Amelé 2.0

As undesired movements and yielding parts interfered with weaving work, it was found necessary to remove one functionality at the time for Amelé 1.0. The troubleshoot became challenging when it all came down to a still-standing loom, still struggling to keep the system stabile, unyielding, and reliable.

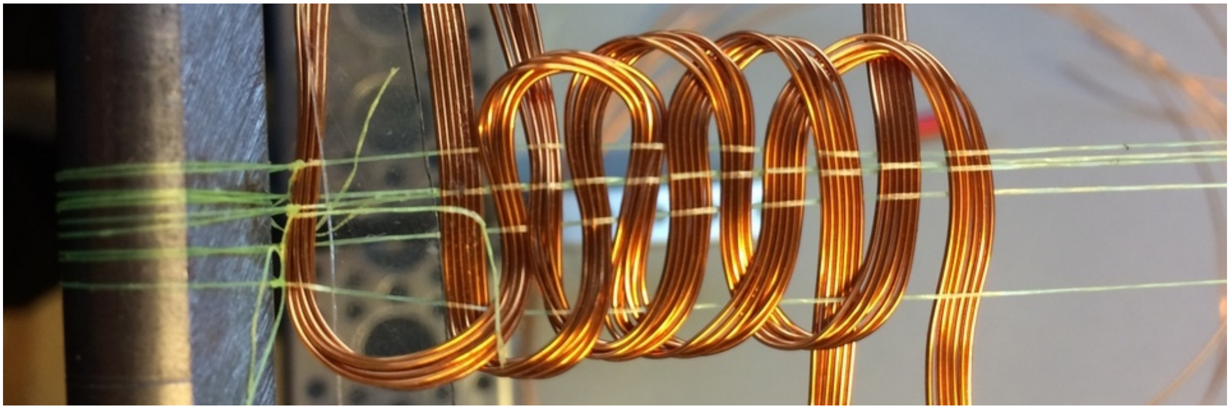


Figure 26 - Fiber Printing for ThinGap™ Try-out on Amelé 1.0

Stator mat

The try-outs were conducted with 0.6mm copper wire, inserting each by hand at its respective pass-over. Because of it being a severely time consuming process, fewer wires than what would fill each slot was used for testing. Furthermore, the first concept to be passed on to this milestone was the phase weaving that could up the fill factor.

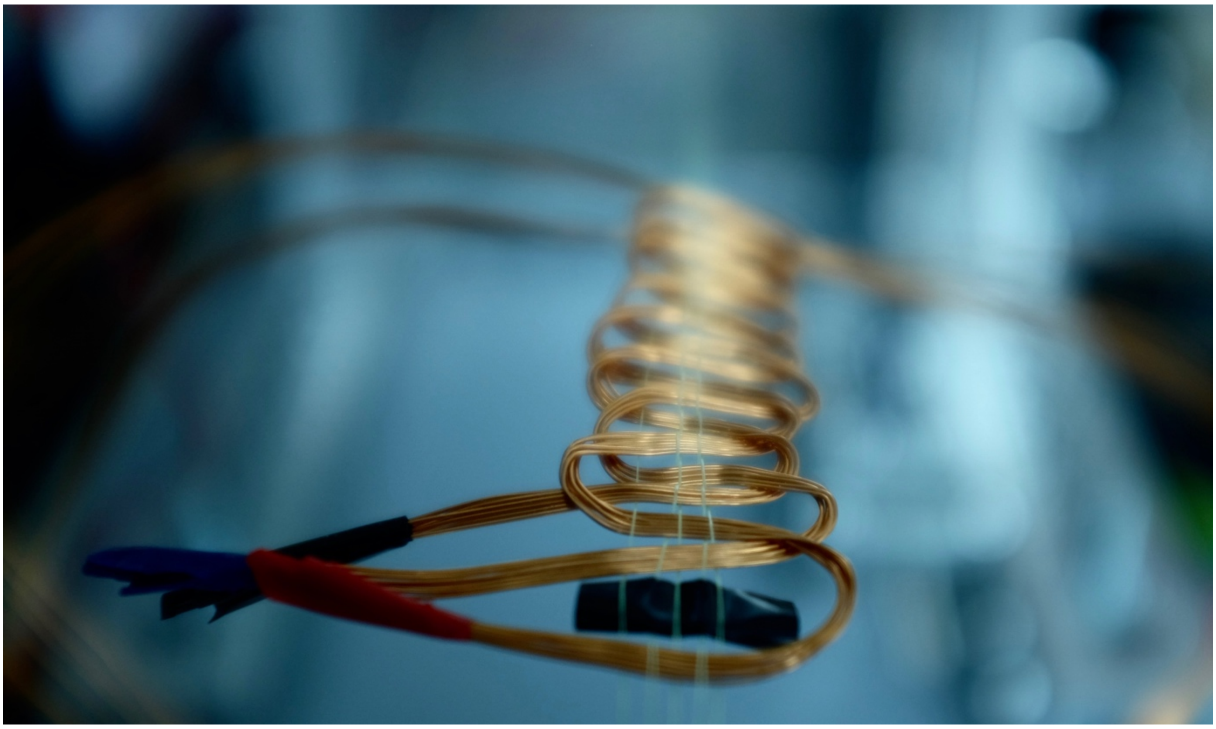


Figure 27 - Flimsy Stator Mat on Amelé 1.0

Learnings

AMELÉ 1.0

DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION:	The entire system of Amelé 1.0 added up to a flimsy contraption when the warps were gathered like a narrow band whilst still not the perceived need of high-tension warps could be met. There were simply too many uncertain, and half-functional components to figure out what worked or not.

Second go to fiber print a ThinGap™ retrofit

As the overview is lost, development could benefit from a time-out, and a change of direction. Amelé 1.0 was a dead end at this point, and the new diversion arose.

Quick harp construction

The aim of this prototype was to eliminate all complexity form the system. Preferably only the fiber printing concept, and method would remain. By constructing a simple mock-up, the conceived, important constituents were in place. To let the warps simply pass over the threads of two equal screws, the warps were spread out evenly over a narrow area. By using a needle to make the shed for weft insertion, and simultaneously using the needle as a reed, each slot was configured. Furthermore, the casting principle from the band weaving concept came in handy. Gluing the active area with rapidly curing superglue, locked each phase together, and added friction between the warps and wefts while weaving.

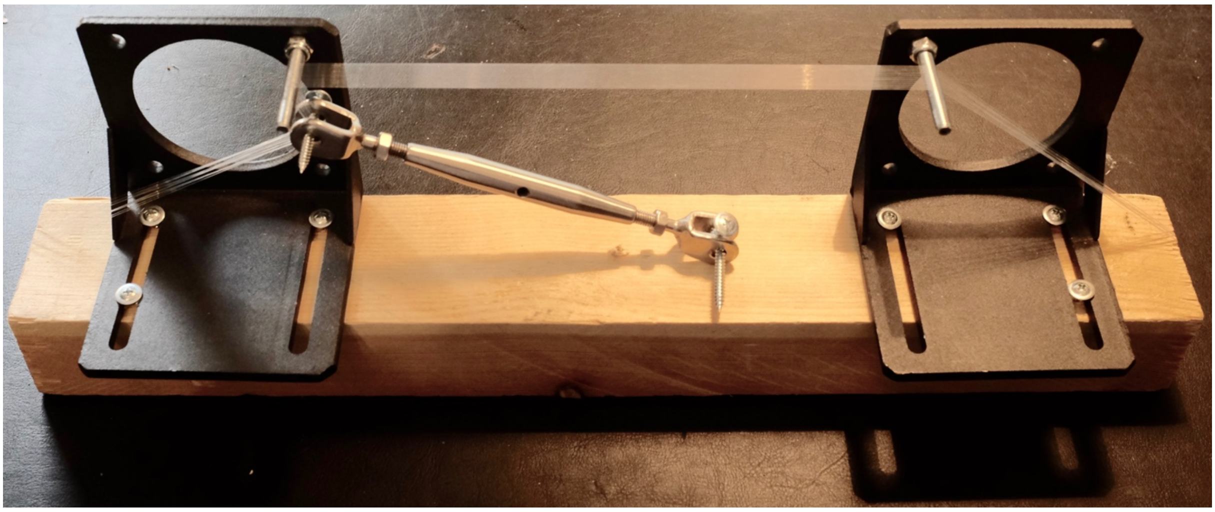


Figure 28 - Quick Harp with Simple Tension Control

With the harp an unlimited tension in the warps could be obtained, (within the tensile strength of the nylon thread) and the individual differences in tension were kept at minimum.

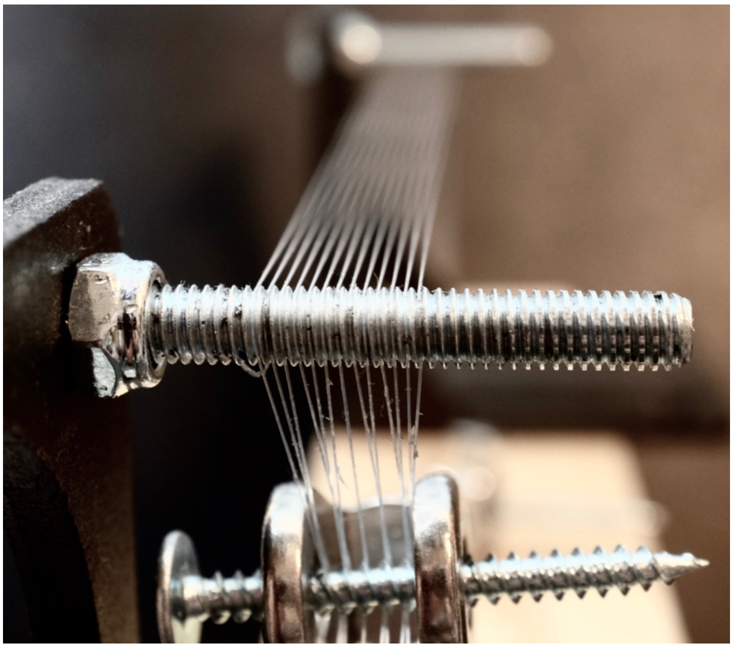


Figure 29 - Even and Stabile Warp Yarns of the Quick Harp

Three stator iterations

For each iteration, the copper fill factor increased, as the manual technique evolved. In the first test go, an attempt to only fill half the potential slots was conducted. By only filling half a slot, one save the time it would take to fill up all of it, and still obtain a feeling of how well it works. Results from a motor test with smaller phases would provide the information needed to predict how a fully saturated stator would perform. Evidently, such an approach was time saving, but the distribution of slots was harder to control when the copper voids were only air. Therefore, a fully copper-packed stator eventually would provide a better distribution, and became the final iteration.

Learnings

QUICK HARP

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The Quick harp had the ruggedness that was needed to start using proper force for placement. A shorter warp span gave less room for warps to bundle up in the middle, or at the sides of the mat. With more evenly distributed warps, the result turned out more uniform throughout its length. The needle reed helped straighten out the active area, however, not to an extent considered deviation free. the phases experienced less yielding in contact with high-tension warps because of the added stiffness of 10 wires.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION	Without any other way of lifting the warps than using a needle, the process became extremely tedious. On stator mat had a lead time of 12 hours. When the tension in the warps yarns were high, it was no longer possible to place the slots close.

The harp was a simple platform for testing, and helped focusing down on the product, which was the basis for the next loom.

3.3.2 Forming the component

At this point, the production step called “forming the component” is introduced as a separate operation for the first time. - Moving the mat from the loom machinery, to wrapping the stator correctly, and ensuring an even distribution of slots, leaving the electric pulses corresponding in the motor.

Roll-up as post-processing

The produced mats had very different stiffness, as the amount of copper in each mat varied. In the end, the mat with the thickest wires of 0.6mm where the entire slots were filled out, turned out to be the most stabile under roll up. The mats were rolled onto the cylindrical mold as shown below.

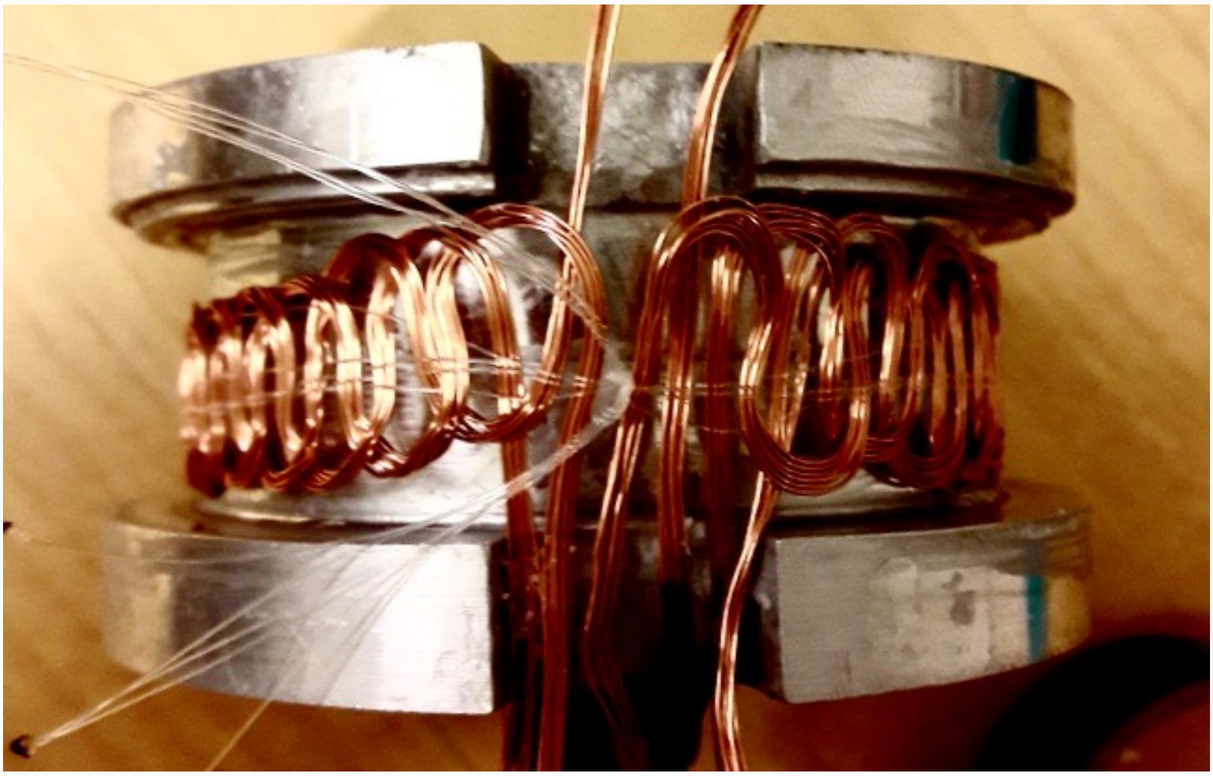


Figure 30 - Tying Mat for Roll-up

The rolled-up stators

In many cases of conventional weaving, the cloth is made without any other support than what is provided by the warps. These yawns were connected to let the stator stick to the mold. This is also what was achieved here, adapting the mat afterwards. Additionally, the mat was eventually supported by glassfiber cloth on both the outside, and the inside to sufficiently thigh it down before molding.

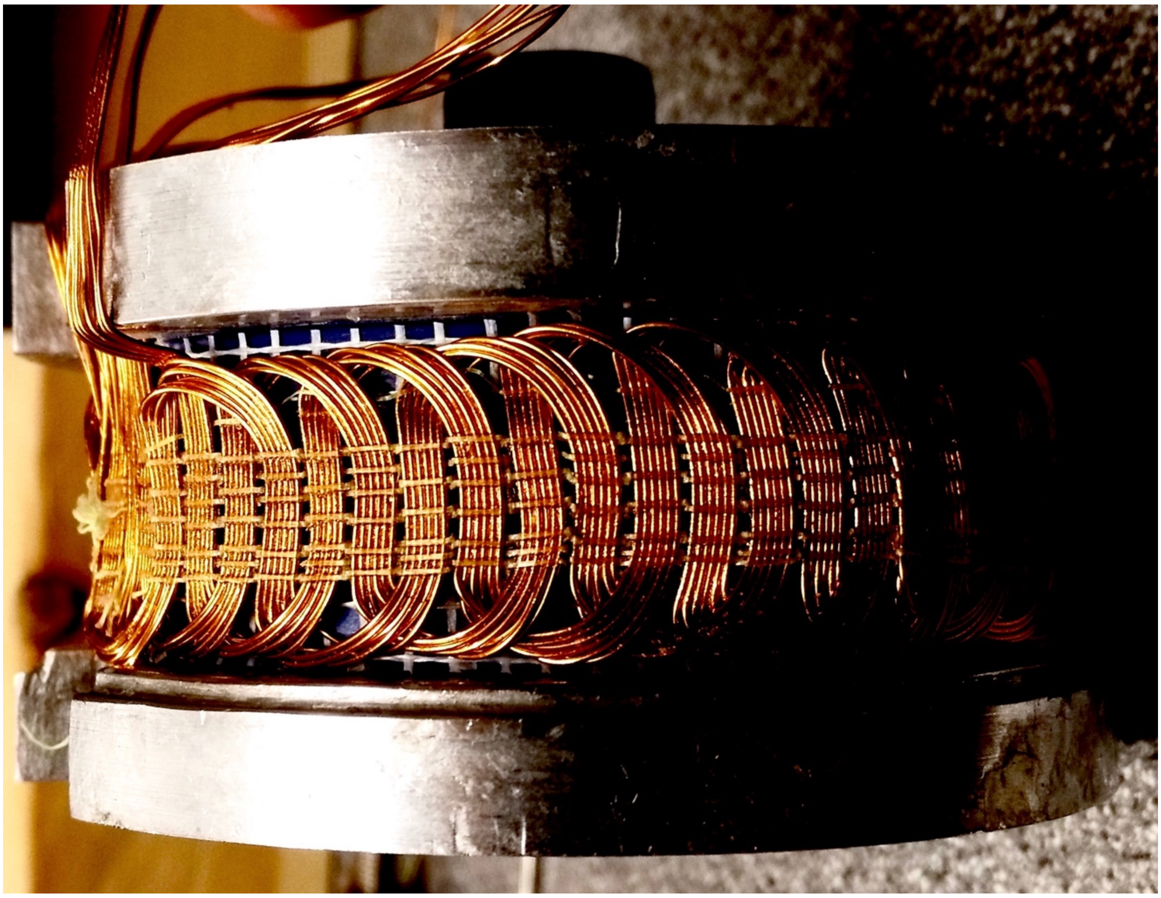


Figure 31 - Mat Placed on Mold with Fiber Reinforced Back

3.3.3 Casting in polymer

Closed aluminum mold

Production-wise, it was at this point clear that a proper mold was needed to obtain the desired dimensions and tolerances to fit the ThinGap™ rotor. This was milled in aluminum to the precise measurements.

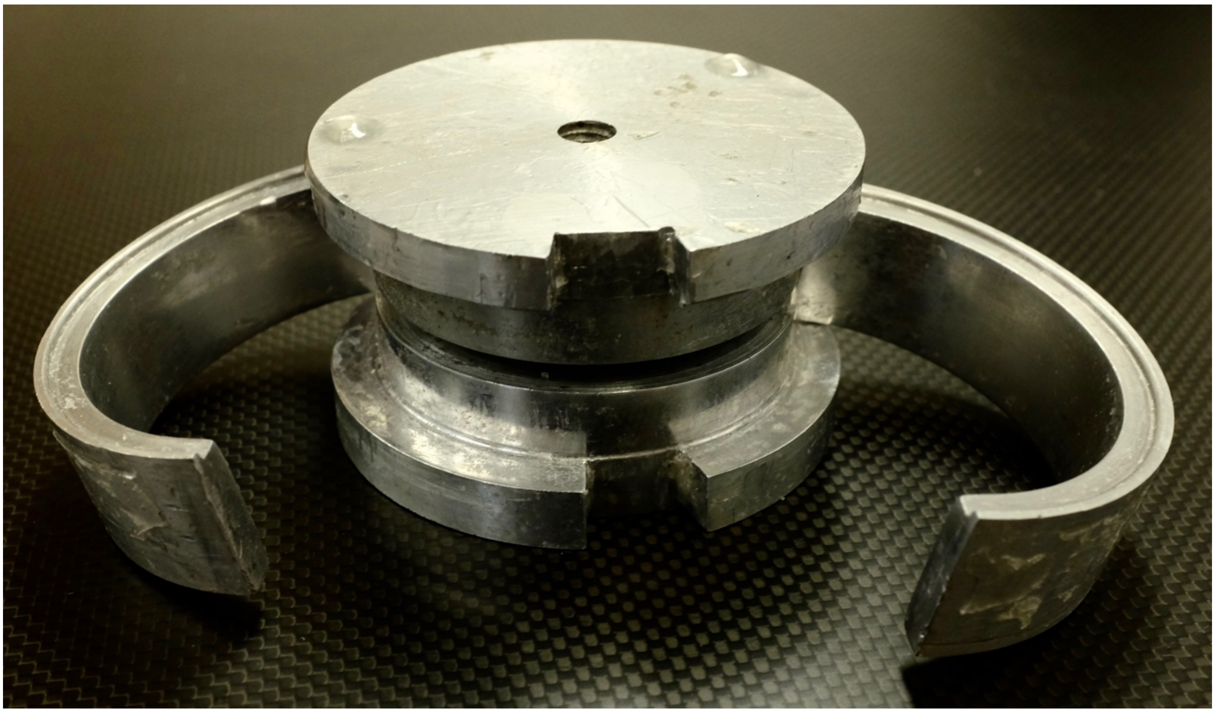


Figure 32 - Aluminium Mold for ThinGap™

The inner mold was constructed with slip angle of 0.5 degrees towards the middle for easy demolding. The parts were sanded and polished, and treated with release before molding. To maintain a proper outer pressure to compress, and ensure dimensions, the outer parts were clamped.

As each stator took around 18 hours to make, several test moldings were made to ensure that each try with real stators would suffer minimal risk of going to waste.

Figure 33 - Test Cast for ThinGap™

Casted stator

The three stators are listed in the order of succession, and iteration. The first one was made without any reinforcement, subsequently the latter two contain a increasing amount of glassfiber reinforcement to keep the stator circular.

Figure 34 - First Stator Iteration of ThinGap™ Retrofit

All of them were casted with a cheap, and easy to work with epoxy. Not in need of oven curing, this was a rapid solution. Also, a see-though epoxy was beneficial for visual inspection when demolded. The stators were brushed in epoxy, then encapsulated and compressed into the mold.

Learnings

MOLDS

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	Proper molds give proper results. The biggest take away from the molding process of the ThinGap™ retrofit stator was that polished and precise molds give polished and precise products. The stators were easy to demold because of the slip angle.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION	A slip angle make the outer section of the active area deviate further away from the rotor than the mid-region, which give less efficiency.

STATORS

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	As the amount of reinforcement increased the stator results became better. Its ability to remain circular when removed from the mold is key, because small airgaps give little room for deformation.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION	The copper fill factor in the stators became lower that what it could have been, because of the reinforcement. A harder potting could decrease the need for fiber insertion.

3.3.4 Product integration

The way ThinGap™ has done their terminal exit is through a circuit board that further give easy-access connections for motor control. Also, the entire stator appears molded simultaneously as, and into, the base.

Terminal and base strategy

In the mold, space for the terminals was cut, allowing an axial, easy exit. To make a quick and modifiable base, that worked, this was 3d-pinted, and the final stator was glued in a matching slit. Furthermore, the hall back sensors from the original ThinGap™ stator was integrated in the base for precise motor control.

Figure 35 - Typical Circutbord Connection for ThinGap™ Stators - https://www.thingap.com/standard-products/

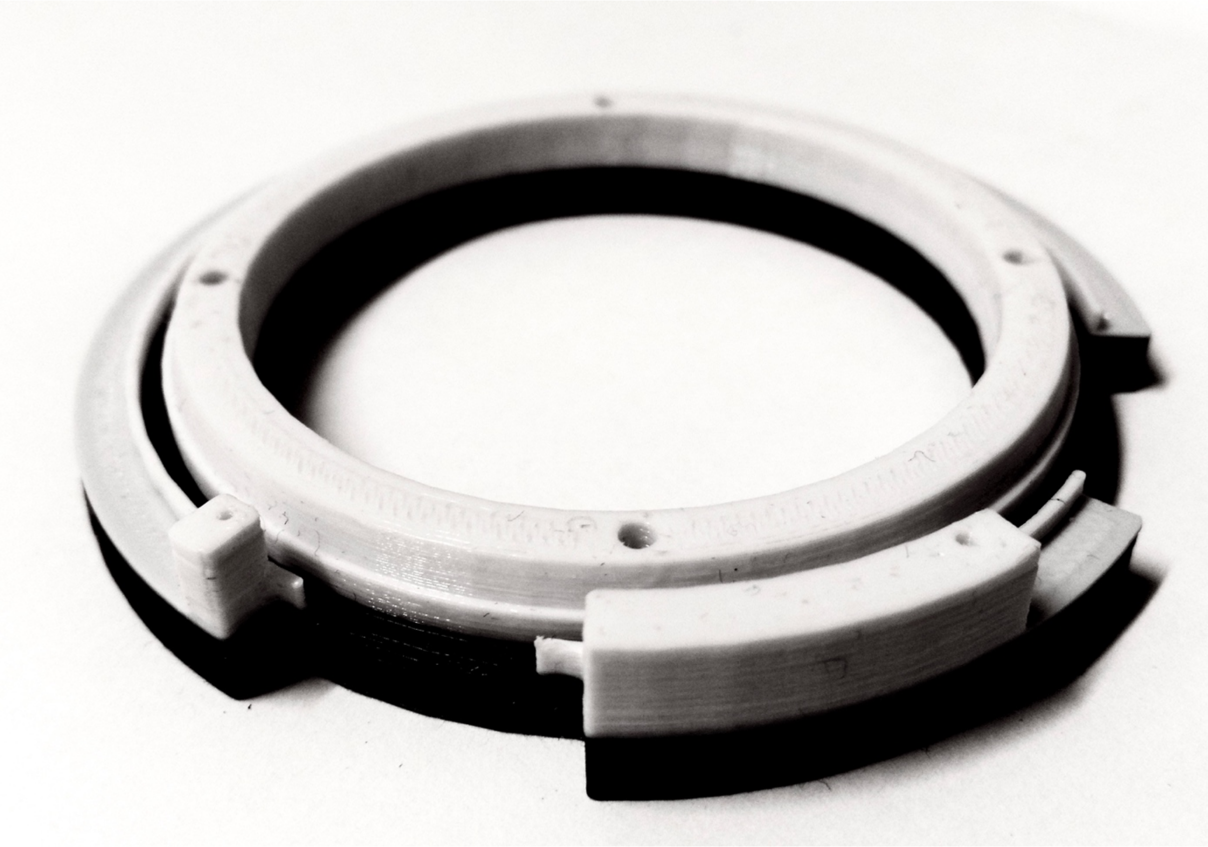


Figure 36 - 3d Printed Base for Fitting the TG305X

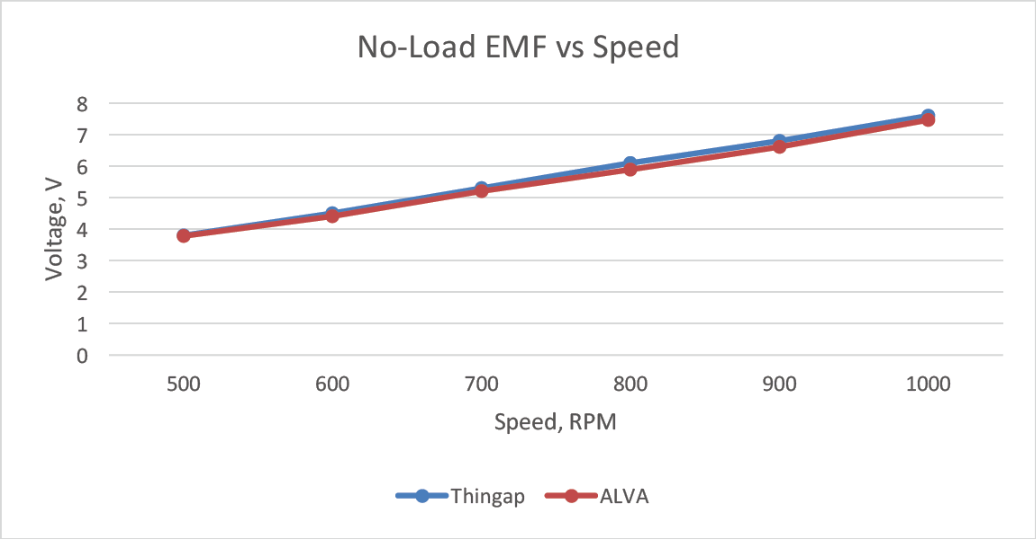
Learnings

INTEGRATION

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	At a test stage, a lot of time was saved not copying the molded circuit board slot from ThinGap™ , but choosing to let the wires directly through the base. For testing, the 3d-printed solution was fast and sufficient, remarking that the design needed several iterations to fit the motor properly. Direct terminal connections, was an easy and interchangeable way of testing the different stator iterations on shorter notice. Also, making the roundness of the stator improved when fitted in the stiffer base.

3.3.5 Test results

The final stator prototype proved to behave similar as the TG305X motor from ThinGap™ in terms of electromotive force versus speed. However, the copper fill factor of the retrofit stator measured around 40%, whereas the TG305X is 22%. This left the Alva retrofit with a near doubling of torque. The successful no-load test is depicted in the graph underneath. Further load testing is to be conducted, but the results so far are deemed conclusive.



Curve 1 - No-Load EMF versus Speed for TG305X Retrofit

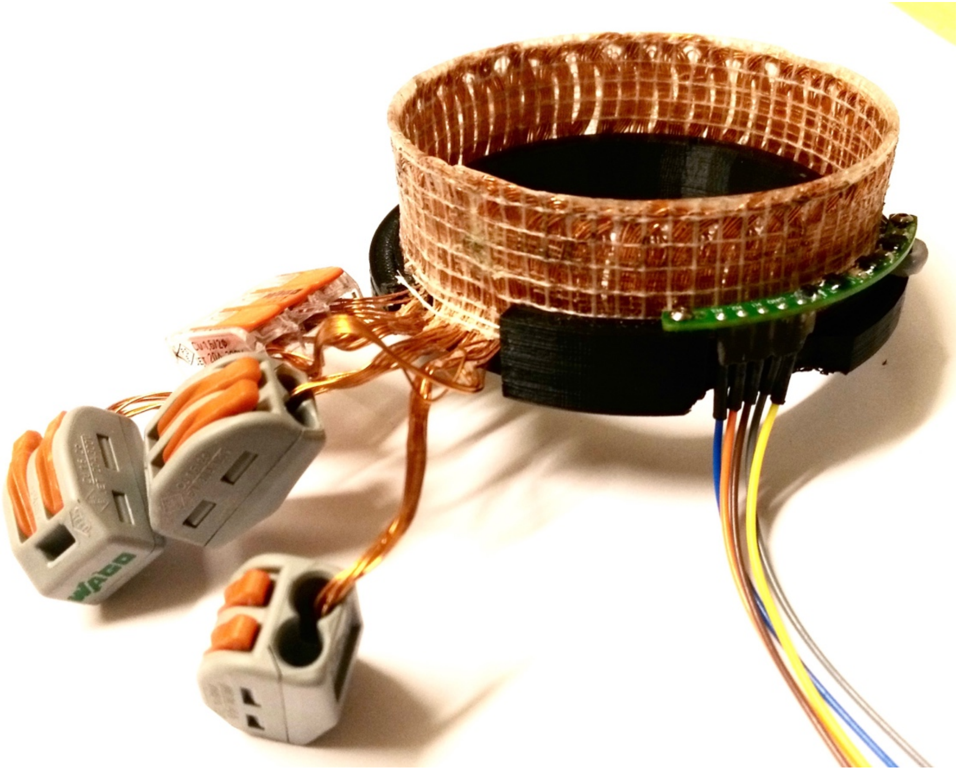


Figure 37 - Final Stator Iteration - With Integrated Hall-back Sensors

3.4 Demonstrator

The scope of the Demonstrator milestone was for Alva to increase the knowledge on the entire process of making an electric motor from scratch. Investigations of different markets indicated that supplying complete motor solutions might be a promising business model.

The Demonstrator motor was designed completely by Alva, and the Technical Team was to design and build it from scratch. As the dimensions was chosen for easy stator production, the diameter was the same as for the Test Stator. By letting the diameter remain relatively large compared to the ThinGap™ stator, but decrease the number of poles, one minimize the consequence of slot deviation.

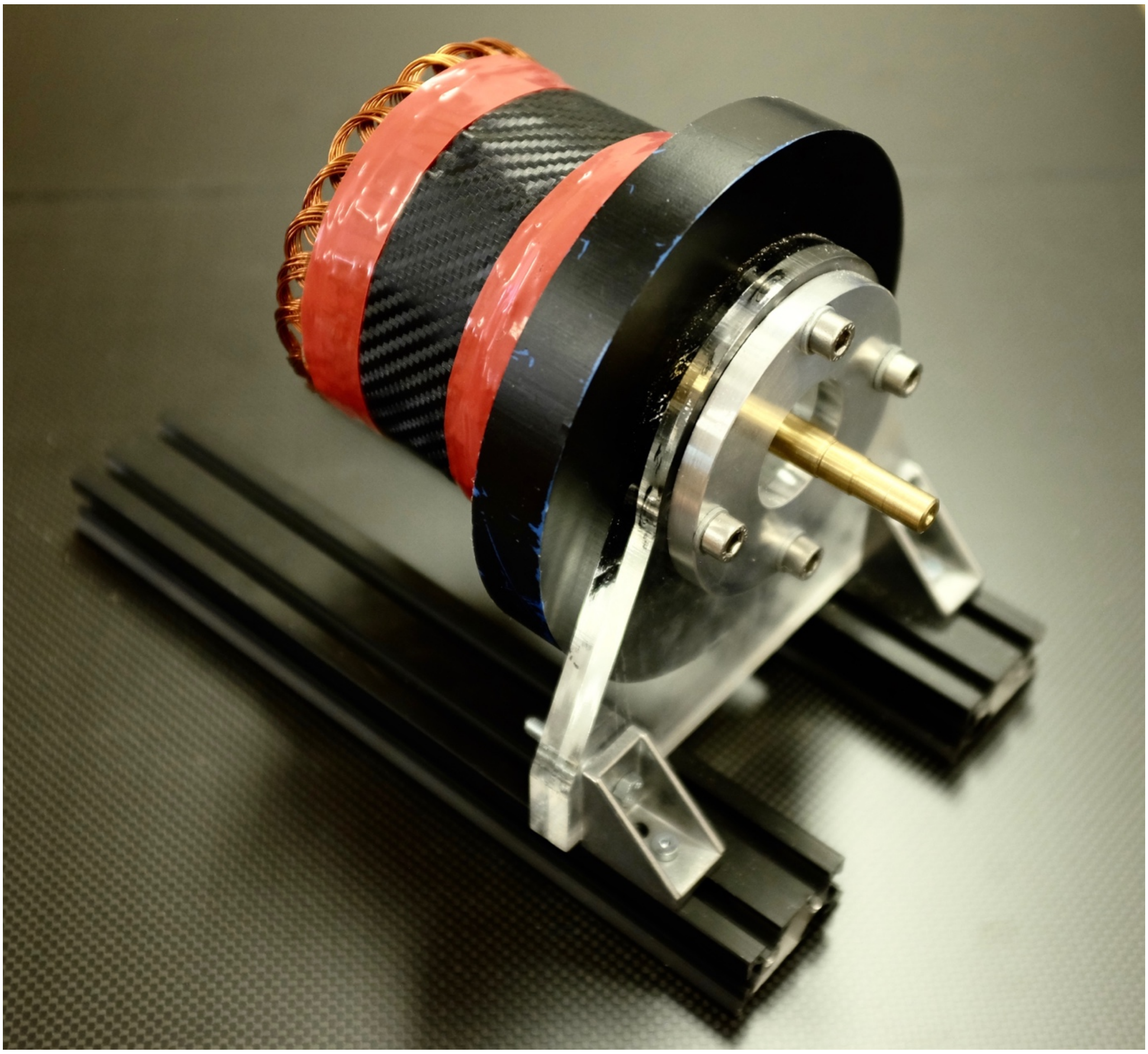


Figure 38 - Demonstrator Motor

Stator aim:

Pole number:	16	
Motor:	In-runner	
Pole width:	19.6	*mm*
Axial length:	40	*mm*
Aimed Copper fill factor:	60	*%*
Speed:	7000	*RPM*
Torque:	1.5	*Nm*
Power:	1.1	*kW*
Current:	15	*A*

Table 3 - Demonstrator Aim

3.4.1 Fiber printing

The collected learnings from the previous prototypes were applied when embarking on the new milestone. Wanting to make a new Amelé that could replicate the sturdy working environment that the Quick Harp had provided, the machinery needed to be built again.

Amelé 2.0

The scope was first and foremost to imitate the harp with a viable shed to insert wires easily, being able to provide a constant tension and work area.

Let-off mechanism

The let-off mechanism was a refined version of the let-off bobbins of Amelé 1.0. This time around with close to twenty warps. Instead of spreading them out in one plane, these were distributed in two planes, allowing for more warps per width.

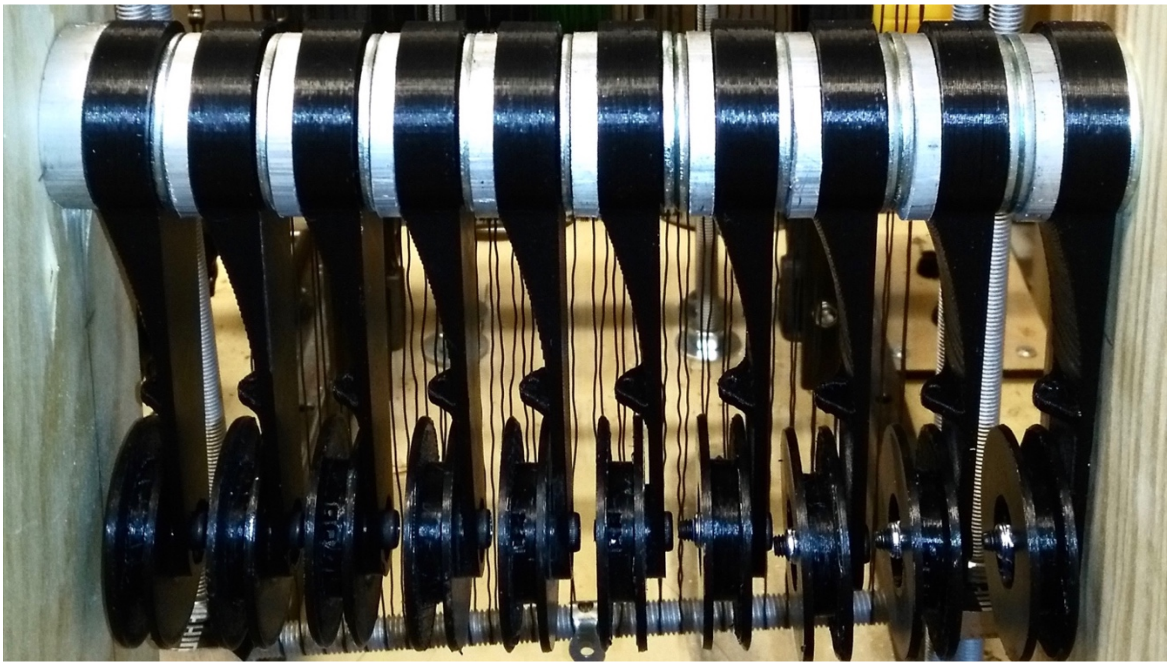


Figure 40 - Top Let-off Levers

Wire harp 1

As experienced on Amelé 1.0, the aggressive angles between let-off bobbins and heddle eyes, was straining for both the components and the yawn. To avoid this, a harp of wire was constructed to led the threads gently towards the heddles, reliving the let-off rolls of any unwanted, sideways strain.

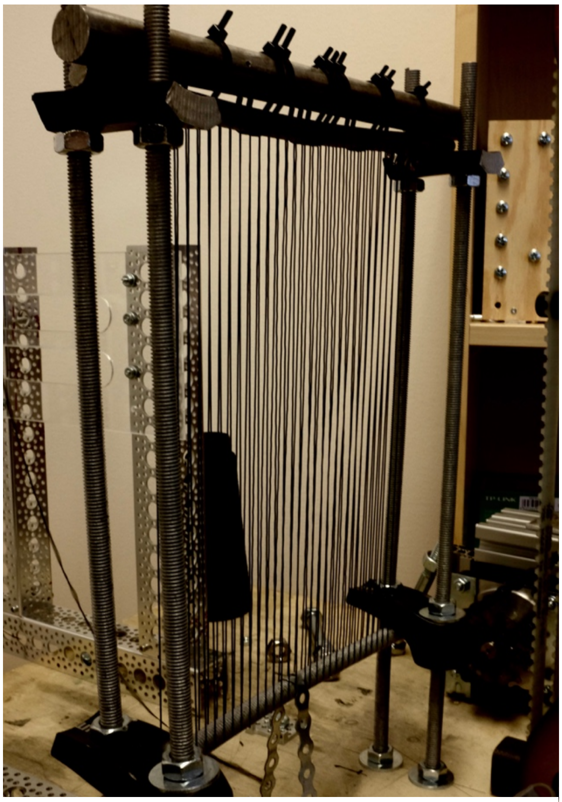


Figure 39 - Wire Harp 1

Wire harp 2

This harp was made to redirect the warps after exiting the heddle system in desired width.

Figure 41 - Wire Harp 2

Heddles

This time, the wire harps made sure the heddles would not have any other loads than what met in the linear movement for lifting and lowering warps. Also, need for little spacing between the heddles was unnecessary to achieve denser warps, as the harps redirected the yarns before entering the shed area. Inspired of other loom solutions, wires with heddle eyes was rolled on and off synchronous shafts. These shafts were coupled together with each other, and a controlling stepper motor by bicycle chains. As the travel distance of the wires was much longer than for Amelé 1.0, the shed became sufficiently large to work with.

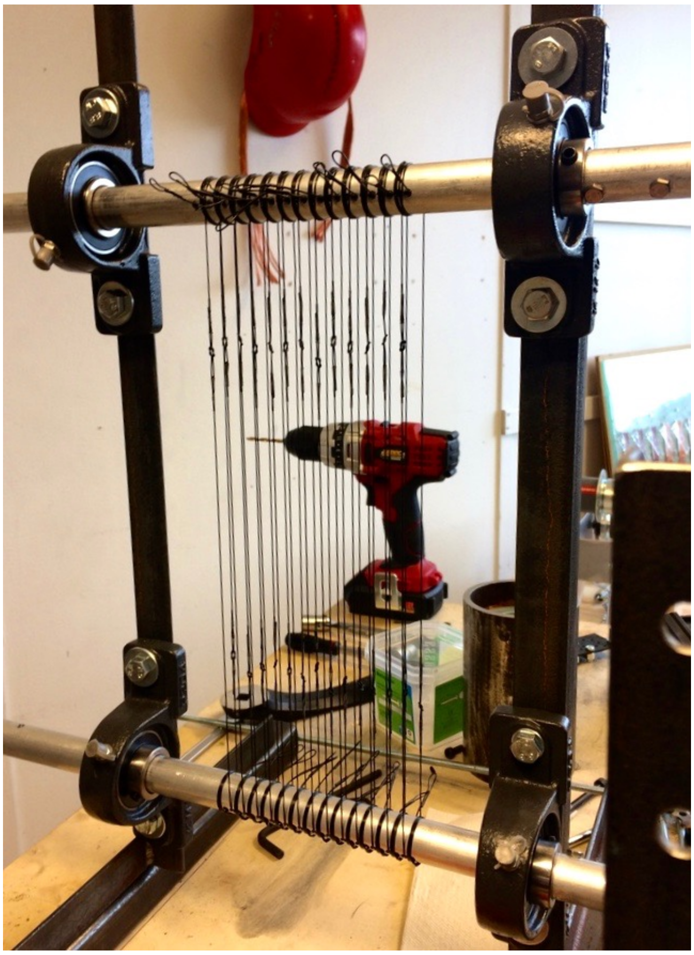


Figure 42 - First Heddles Iteration Amelé 2.0

Roll-up mechanism

The roll-up mechanism shared many of the same traits as for Amelé 1.0. However, this was made with an open end, for simple placement and removal of rolls and molds. Furthermore, an easier access for hands, when counting a manual assistance helped speed the fiber printing process. The overall design was made sturdier, and the gear exchange better.

The roll-up bobbin was milled in the exact dimension of the mat, with markings of active area, and size of end-windings.

Coil feeder

A specific challenge that stood out as time consuming when weaving both the Test Stator, and the ThinGap™ stator was the sorting of wires. In both cases between 18 and 30 wires had their special interval of insertion. An ideation round sparked the concept of feeding each phase simultaneously, if one had the chance of only changing warps for each slot, as done in ThinGap™ stator. A few tries with 3d-printed parts generated the Coil Feeder, which shorted the production time by 70%.

Figure 43 - Coil Feeder Prototype

Stator mat

These mats were filled in terms of slot width. With solid wire, the diameter and thickness of the warp were estimated to match the stator circumference. The active area of each phase was glued, or casted, after the Coil Feeder had passed through the shed, to prevent any overlap of wires. By using the level markings in the roll-up bobbin, the active area was more naturally defined while printing.

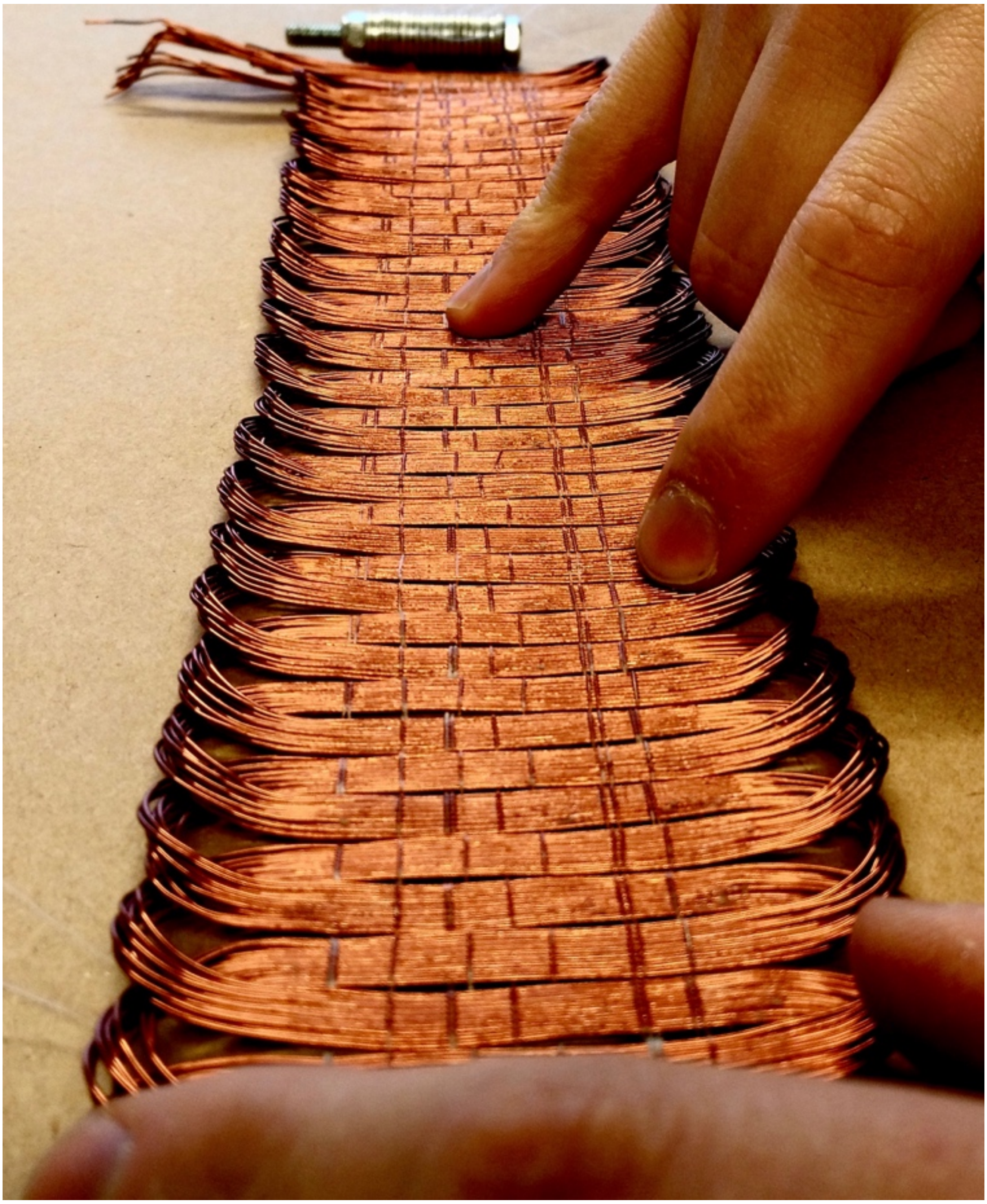


Figure 44 - Stator Mat for Demonstrator Motor

Learnings

AMELÉ 2.0

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The let-off system worked ok. However, the setup time was still significant, as the friction had to be carefully tuned on each roll. Also, every warp had to be wrapped on its respective bobbin. As bobbins also here was used for the let-off mechanism, the warps could be long enough to print tens of meters of stator mat without having to be reset. Heddles concept was promising as it was less afflicted by other components. However, several of the wires broke during the production, caused by poor attachments. Wire harps became a valuable attribute to the system increasing stability and uniformity in the cloth. The stators were easy to demold because of the slip angle. Coil feeder was the true game changer when dealing with high nubers of wires per phase, as in this instance. It gave a much better overview of wire configurations, and fed the wires in a straighter manner, than obtained by hand.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION	Though Wire Harp 2 limited the workspace by 5cm. After the coil feeder was introduced, this became a slightly tight fit.

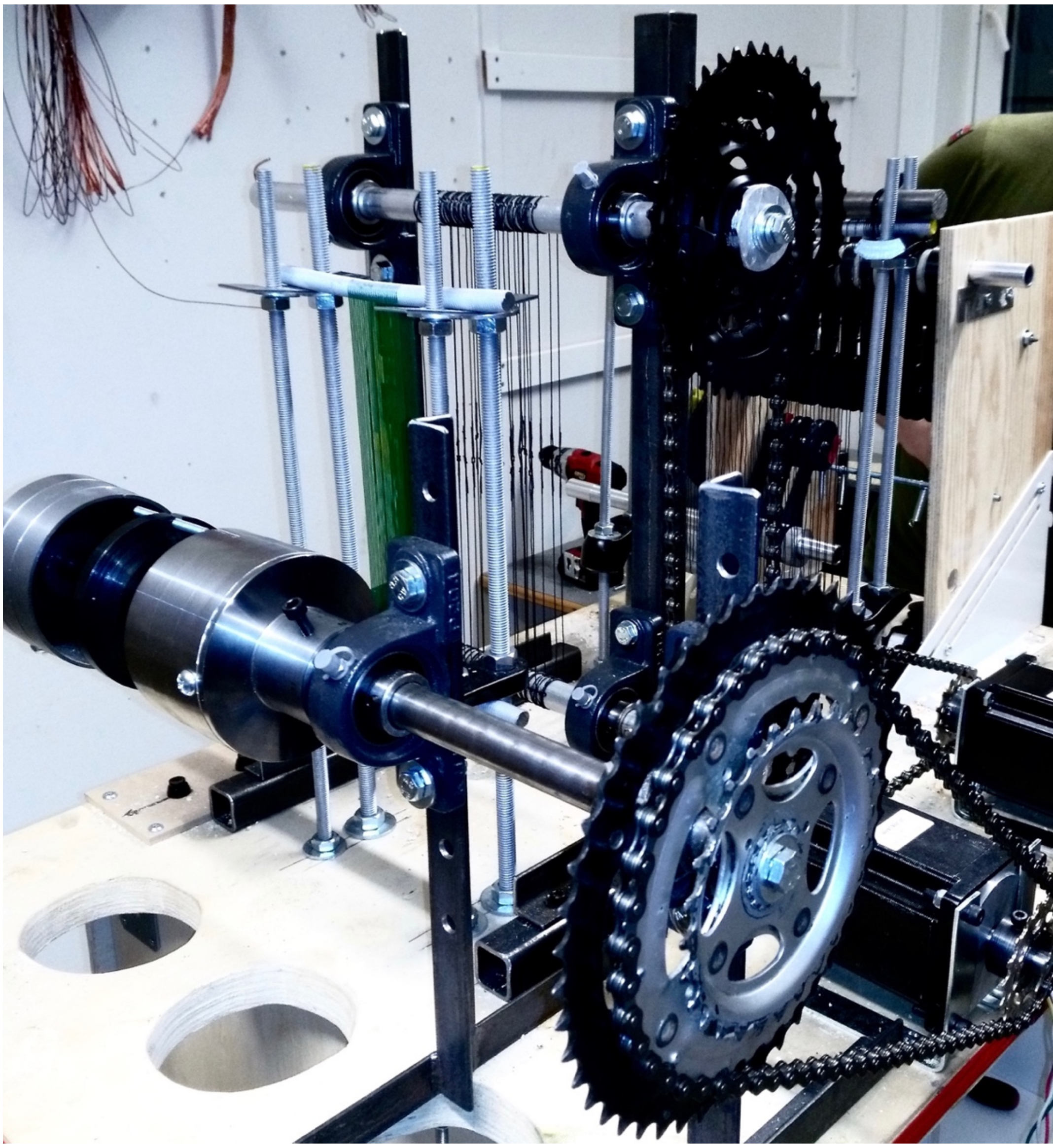


Figure 45 - Amelé 2.0

STATOR MAT

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	These stator mats benefitted from being made in a thicker wire. The mat remained stiff after detached from the roll-up bobbin.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION	The warps were thicker than ideal, as more space could have been saved.

3.4.2 Forming the component

In this section efforts were made to combine the learning from previous tests to achieve satisfactory results. How to practically match up slots in terms of width and active length.

Direct roll-up for matching

On the Demonstrator, the roll-up had the exact same dimensions as the mold. In this way, it could be reassured under production that all properties were satisfactory in terms of positioning.

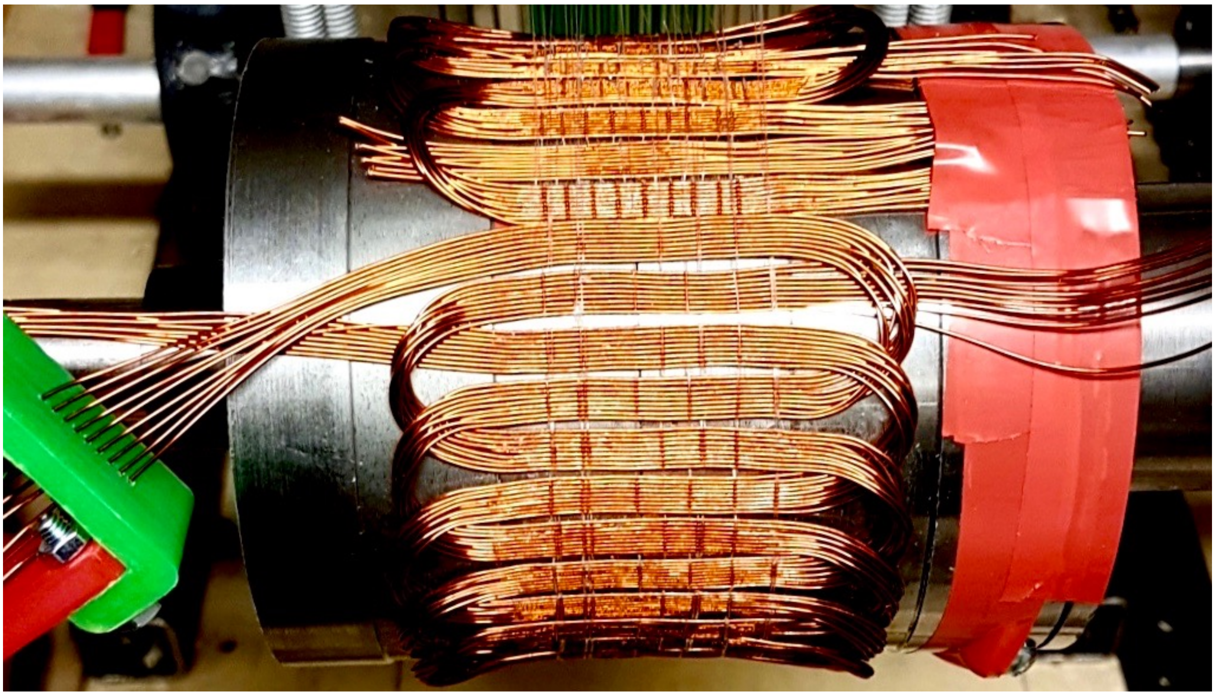


Figure 46 - Direct Roll-Up with Coil Feeding

Mat transfer

Transferring the mat to the mold was an easy maneuver. The mats sustained their shape because of the glue and longitudinal warps.

Learnings

ROLL-UP

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	It proved useful from the ThinGap™ test that the main challenge of post-process roll-up on a mold is dependent on a certain accuracy to match up the poles on the stator. The warps yarns were stretchy. This appeared challenging with respect to keeping the wires correctly configured. However, did this result in a shrinkage when the mat was removed from the roll. This caused all slots to pack closely, which made the internal phase correspondences add up nicely. A benefit from removing the mat from Amelé 2.0 and transferring it to a separate mold, was that a second go immediately could begin, while the previous stator was casted and cured.

3.4.3 Casting in polymer

Because the motor design for the Demonstrator was an in-runner with single rotor, the inner precision of the stator was in focus. From the ThinGap™ stator it was noted that a slip angle would decrease the efficiency of the motor, as this brings the rim-parts of the stators further away from the rotor than the mid-section of the stator. Therefore, the next iterations explored the possibility of collapsible molds with zero degree slip angles.

Collapsible mold

Allowing for 0 degrease slip angles, a collapsible mold was developed for the stators. To make this happen fast, 3d-printed parts were produced, assembled, and sanded to fit the desired measurements.

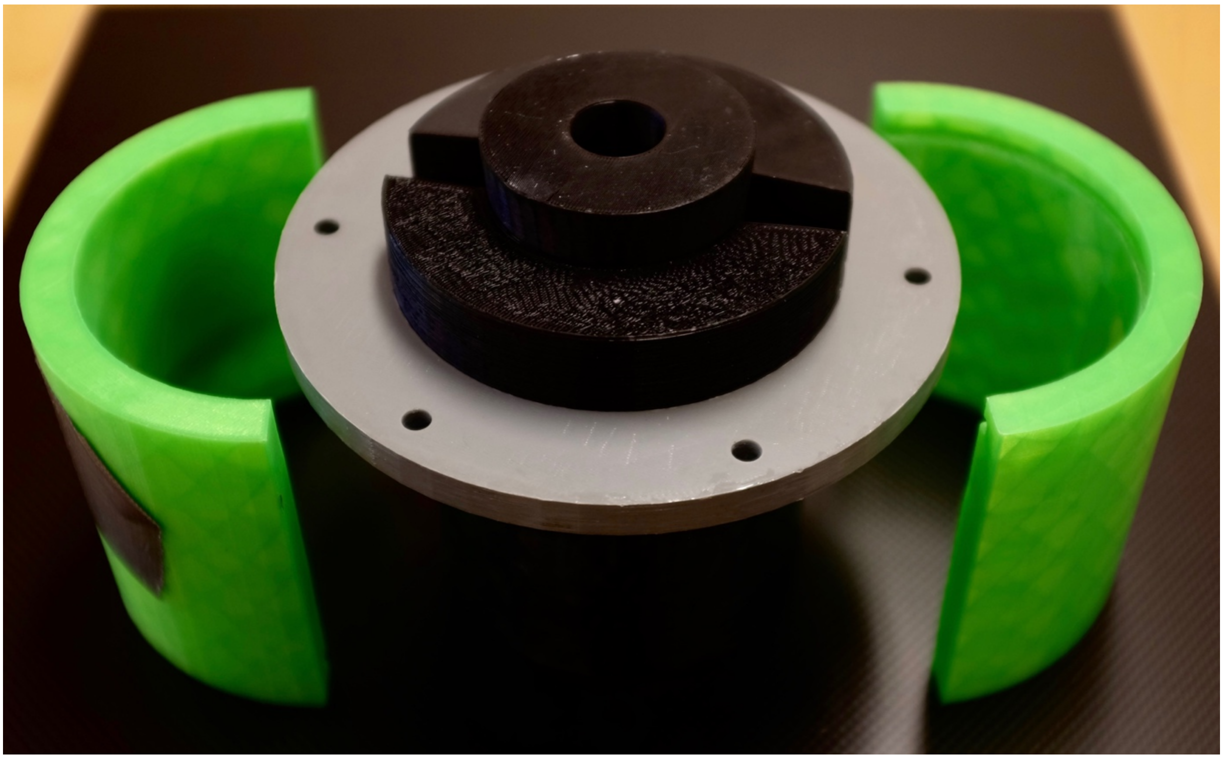


Figure 47 - 3d-print - Collapsible Inner Mold and Demountable Outer Mold

A PET-tape, tailored for being oil-repelling, was wrapped on the outside of the mold. This was further treated with release agent before molding. The mold was mounted on the roll-up mechanism of Amelé 2.0 to slowly spin the mold, distributing the applied epoxy. Glassfiber reinforcement was wrapped on the outside of the stator, enhancing the integrity as learned from the previous prototypes.

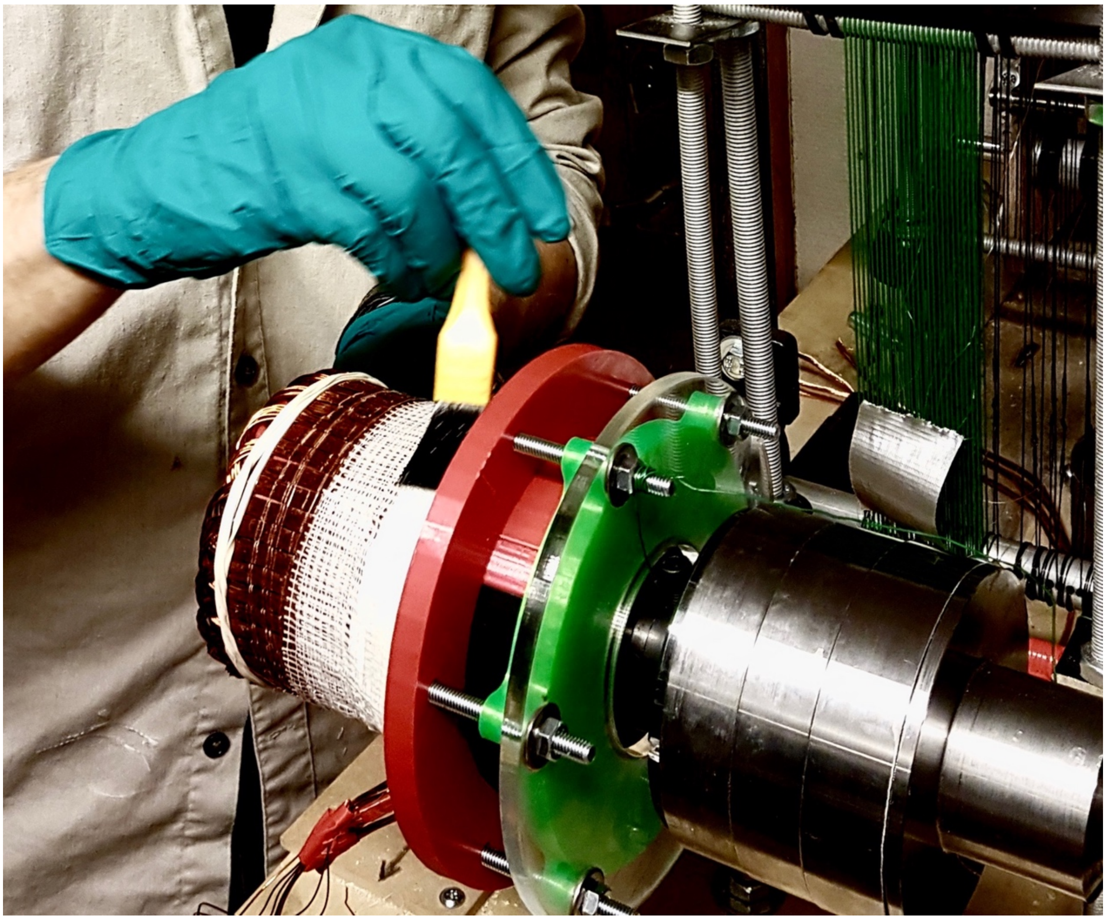


Figure 48 - Brush Based Casting Demonstrator

Stator

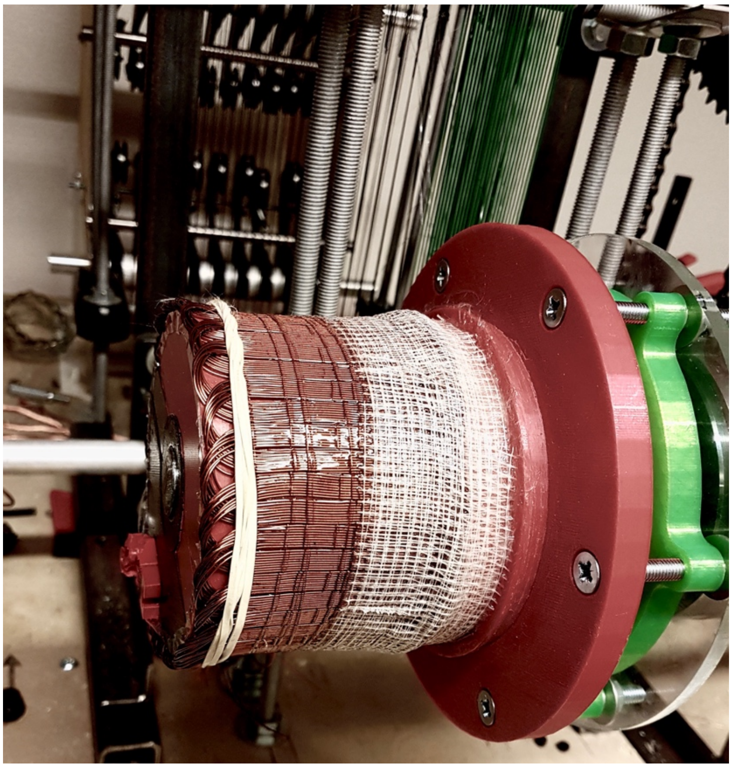


Figure 49 - Casted Stator for Demonstrator

The stator had a good of molding precision, as the airgap was precise in terms of both roundness and 0 degree angles.

Learnings

COLLAPSIBLE MOLD

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The mold was easy to collapse, reassemble and reuse. This technique is also used when injection mold bottle corks. An extremely efficient manner of producing demanding inner geometries that appear pursuable in further development of a production line.

STATOR

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	When soaking the copper mat in epoxy before, while, and after placing the fiber reinforcement, the chances for air voids and uncured spots decrease.
	When only an inner mold is needed, it is easy to adjust an correct amll misalignments etc.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION	Further advancement would be needed if the motor design incorporated double rotor, with both inside and outside precision on the stator, as for ThinGap™ .

3.4.4 Product integration

Re-fitting of terminals in the grid

The method from the ThinGap™ retrofit was adopted for the Demonstrator as well. After placed on the mold, the dummy slot was removed and the proper slot was layed on top of the warps. Than the yawns wrapped the stator a couple of times to pack it, and lock it before molding. The terminals exited the stator in a straight line, receiving simple connectors.

Base construction

The base for the stators was milled out from a block of POM. Having a matching diameter of the stator, both ensuring support, alinement with the rotor, and roundness. The stator and the base related to three screws to prevent relative torsion.

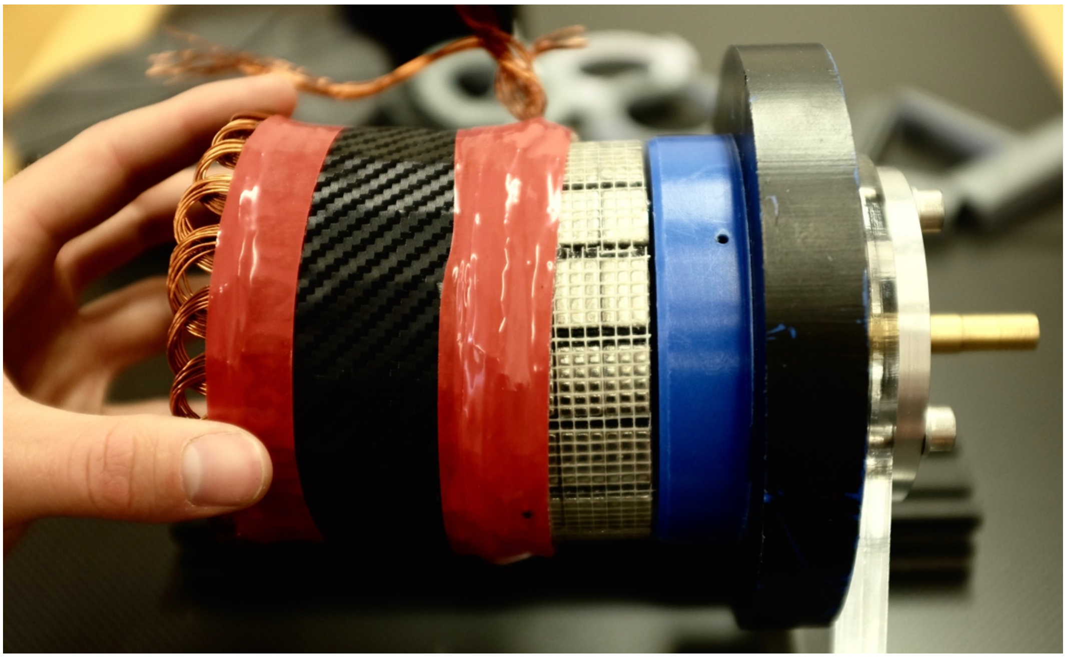


Figure 50 - Fitting Stator on Demonstrator Base

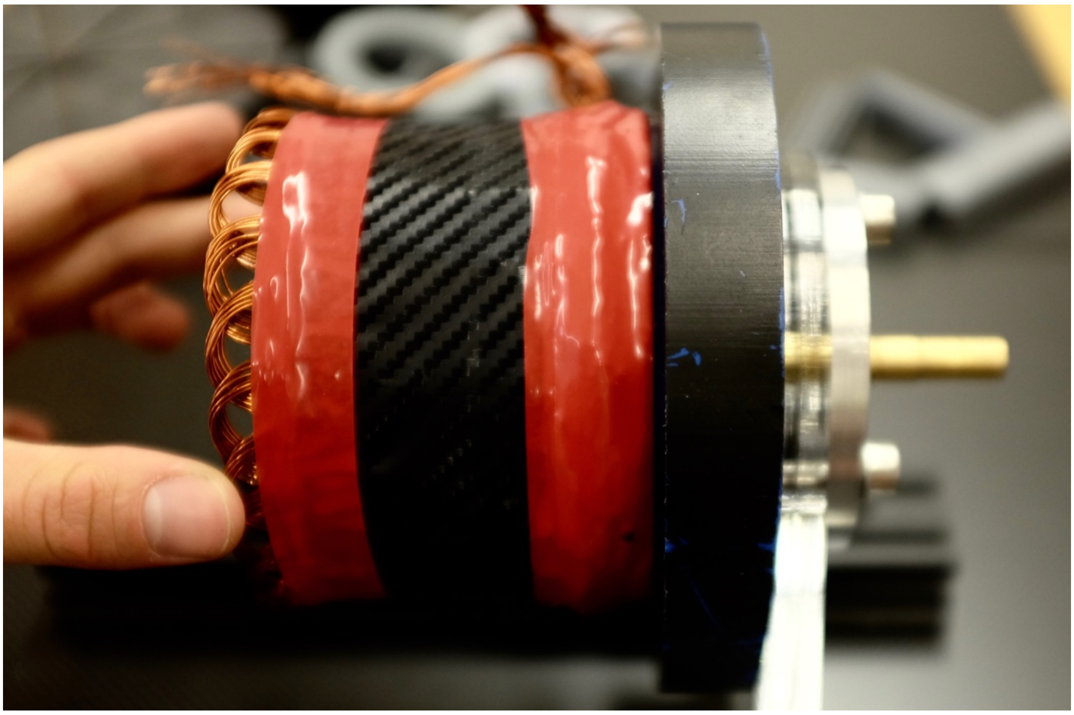


Figure 51 - Stator in Aligned and in Place

Learnings

BASE CONSTRUCTION	
WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The base provided good alinement, as it was a milled piece. It was easy to remove and replace the stator.

4 Results – converging the Drone case

This section run through the resulting prototype on the semiautomatic machinery and the most recent stator. These results are considered the last building block before the process is taken closer to automation by Alva. Though the drone motor and its production machinery are considered the result of this thesis, it will naturally not conclude the broader task at hand for Alva. Therefore, learnings are included in the result for further refinement of stators and machinery. The production time today is estimated to about 25 hours of work with semi-automated production equipment, from copper wires to functional stator. The goal of Alva Motor Solutions is still to automate the production line to a more flexible and profitable extent.

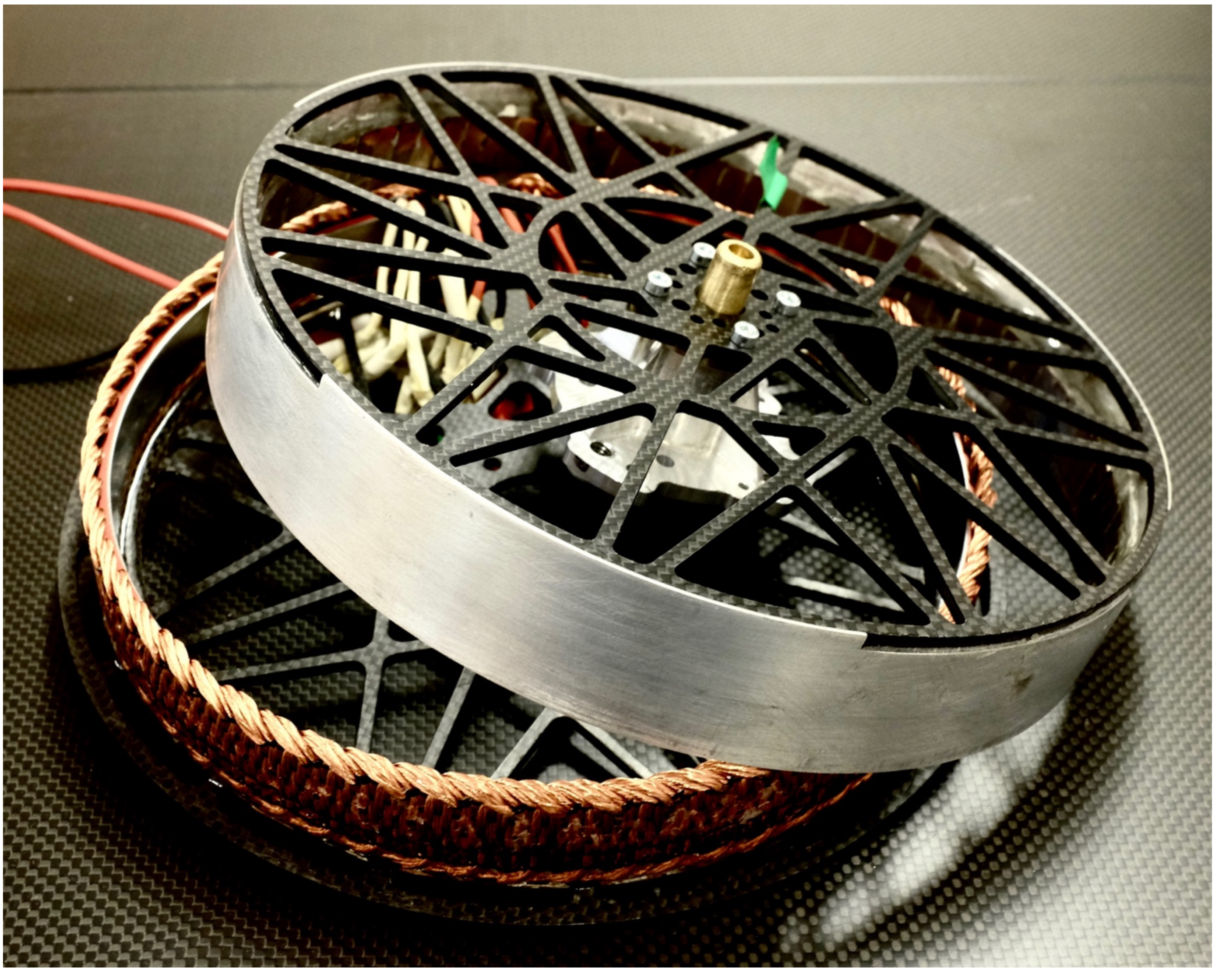


Figure 52 - Functional Version of the Drone Motor – Built from Scratch

Stator aim:

Pole number:	42	
Motor:	Out-runner	
Inner pole width:	13.82	*mm*
Outer pole width:	15	*mm*
Axial length:	≥ 15	*mm*
Aimed Copper fill factor:	60	*%*
Speed:	5300	*RPM*
Power:	4.5	*kW*
Torque: *(with forced air cooling)*	8.1	*Nm*
Minimum number of wires per phase with three layers of mat:	3	

Table 4 - Stator Aim - Drone Motor

4.1.1 Fiber printing

The drone motor had a very high number of poles, 42. This meaning that the circumference would be split into 126 slots equally spaced.

Amelé 3.0

Several improvements were made to the weaving techniques and the stator construction.

Let-off

For the let-off systems of Amelé 1.0, and 2.0, the levers had worked well. However, as stated in the learnings sections for fiber printing, it was hard to adjust the individual tensions. With even smaller slots than before, the need for uniformity across the active area proved increasingly important. Therefore, a simple implementation of hanging weights in the end of each yearn was done, resulting in a simplified solution.

Figure 53 - Warp Yarns with Weight Tension

Heddles

The experience with the previous prototype indicated a fragile design. As a result, the shaft diameter was increased to bring the warps all the way up and down without relying on several turns. The wires were changed with rugged belts. Finally, 3d-printed guides were inserted to shield the warp yarns from friction fatigue.

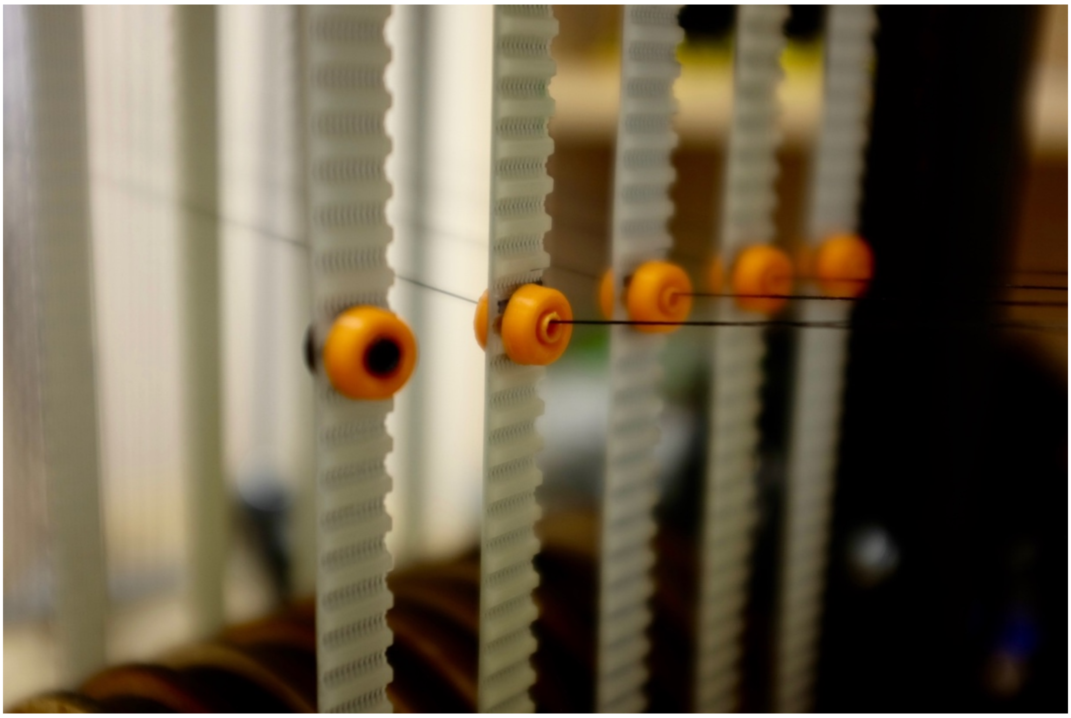


Figure 54 - Heddles Belts with 3d-printed Guides

Roll-up

The largest roll-up disk so far was needed to place the stator. With a diameter ranging from 185mm to 191mm, and with a slot number of 126, a safe way of ensuring the positioning and accuracy emerged. The resulting solution for keeping the slots in their respective area, turned out to be the use of pins. The roll-up was laser cut and stacked to a sandwich with pin holes.

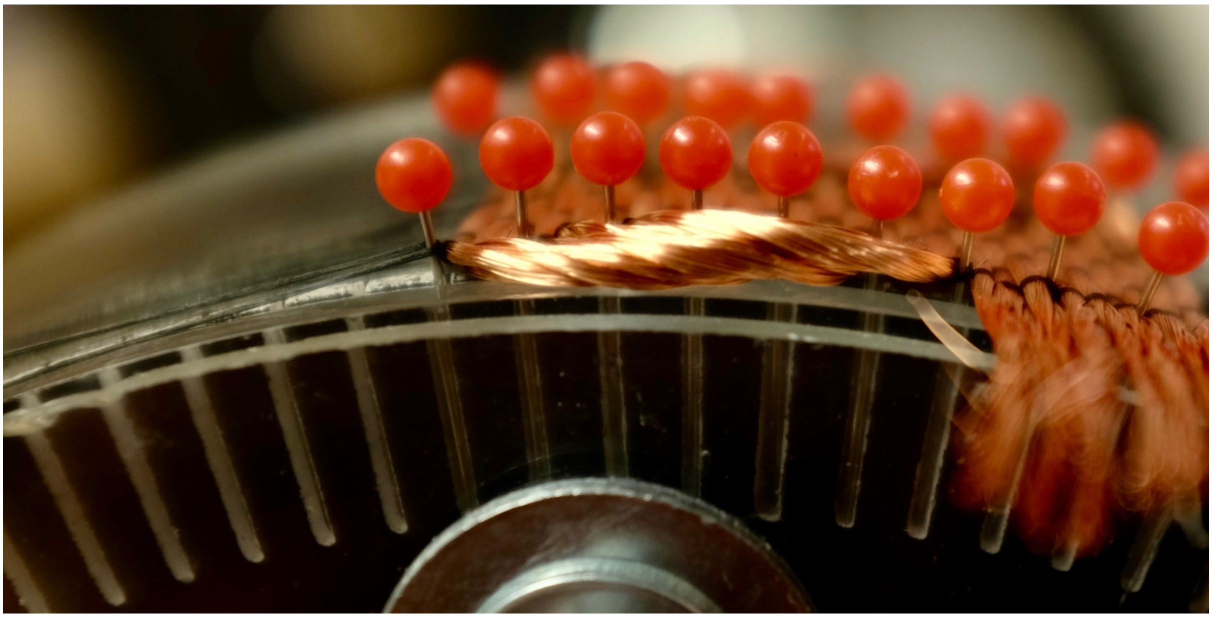


Figure 55 - Pins for Slot Spacing

Back iron

Back iron was introduced in the stator to guide the electro-magnetic field. When weaving, this was made an integrated part of the roll-up, placing the pins on each side of the back iron.

Stator

Several of the challenges met in the prior prototypes, stemmed from difficult handling of bare wire. In this design, this was substituted with litz wire, a multistrand wire softer than bare wire. Despite a somewhat lower internal fill factor than solid wire, the advantages in terms of handling made it worthwhile.

Learnings

AMELÉ 3.0

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	Weights were an easy way to regain control for the tension in each individual warp yarn. The pins ensured the slot positioning on the mat.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION	By using weights for tension control, the length of the warp yarn was somewhat limited. This made it a challenge to do more than three layers of stator mat. The heddles still do occupy more space than necessary, as an even higher number of warps would be desirable.

STATOR MAT

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The litz wires made the weaving a whole other ball game. As the stator volume one was filling with copper, was long and wide, it deemed easier to compress thicker litz wires, than to introduce a higher number of thinner bare wires. With lower number of wires, including more flexible once, the lead time went down. However, with a circumference ranging from 580 – 600mm, several layers of mat were needed. A three layers version about 20 hours to do.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION	With the back iron steel ring in the middle of the roll-up disk, there was no natural way of attaching the warps to the disk. When the wefts are softer, they are more prone to crimp.

4.1.2 Forming the component

The final way of forming sum up the learnings from the earlier prototypes. The stator mat was made and rolled up directly in the loom. When removed, it still had the structural support in the form of back iron, making it easy to place in the mold. In this way, the developed technique barrow principles from the test stator, thin gap, and demonstrator.

From two to three dimensions

The back iron became encapsulated by the larger end-windings. When the pins and the mat itself was removed from the roll-up mechanism, the stator kept its form because of the back iron.

Stator

The tightly packed stator remained intact after removal. Neither height, nor positioning of slots seemed to change.

Figure 56 - Three Layer Rolled-up Stator

Learnings

FROM TWO TO THREE DIMENTIONS	
WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The back iron solved much of the previous hassles. All further transfer from Amelé 3.0 to molds was made easy as the structural support was not removed. The milled back iron had a completely smooth surface. This gave better conditions for making the outside smooth and even, as well.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION	With the back iron steel ring in the middle of the roll-up disk, there was no natural way of attaching the warps to the disk. When the wefts are softer, they are more prone to crimp. When dealing with several layers, the transaction from one layer to the next could give some challenges in terms of height difference.

4.1.3 Casting in polymer

The most important result of the drone stator mold was smooth and precise outside. After several prototypes for the mold, an acryl version gave way to a final aluminum mold.

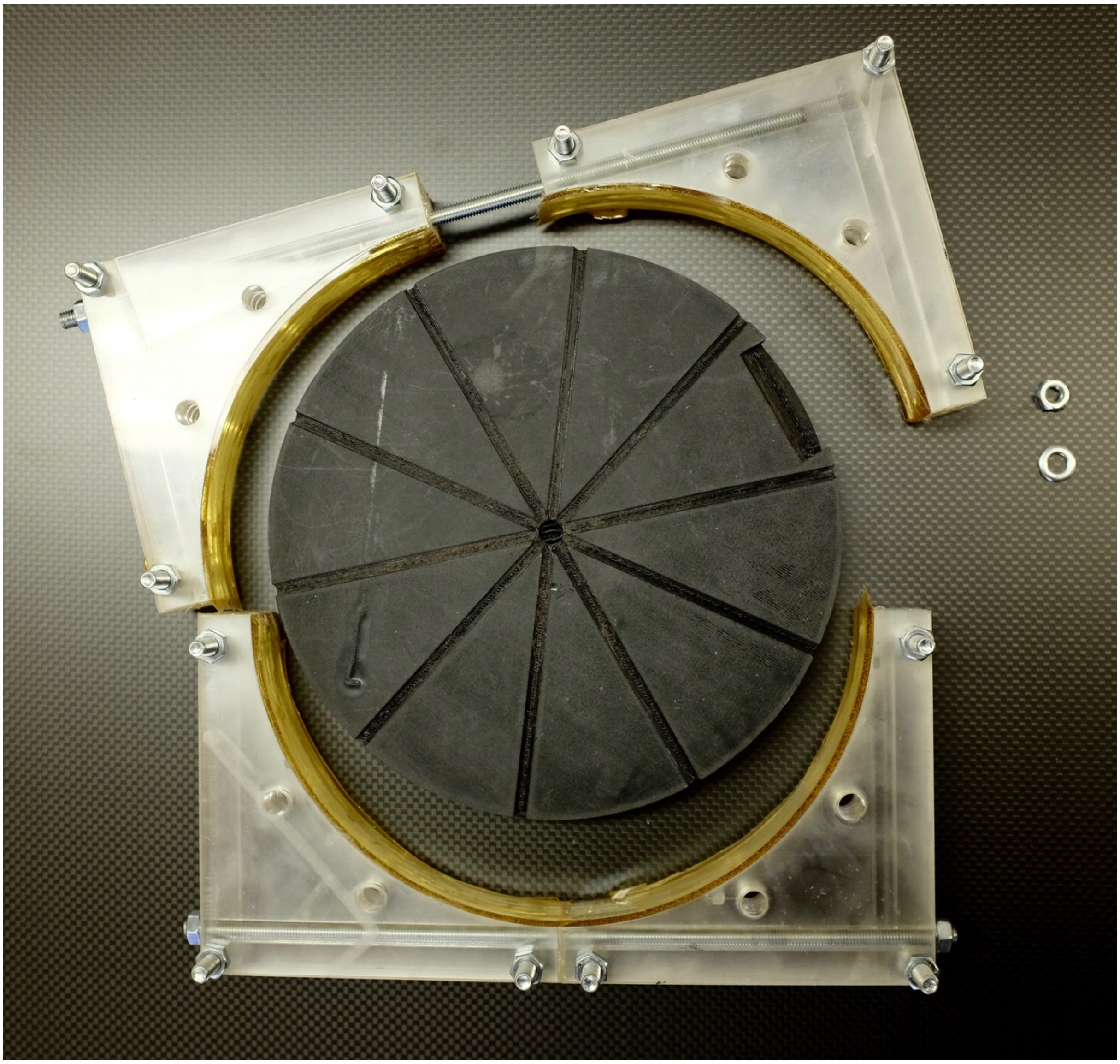


Figure 57 - Acrylic Prototype of Mold

As the outer mold from ThinGap™ showed, this part should consist of more than two pieces if there is a need to apply pressure to close the mold. The point where mold pieces meet, can damage the wires, and squeeze spill epoxy in between the pieces. Such flanges create a greater diameter for the stator, and hence decrease accuracy. Because of this learning, four parts were applied with plastic shielding between stator and gap as demonstrated in the figure below. Also, since the weft was litz, the resulting ability the mold had to compress the coils with as much as four different pieces, was crucial.

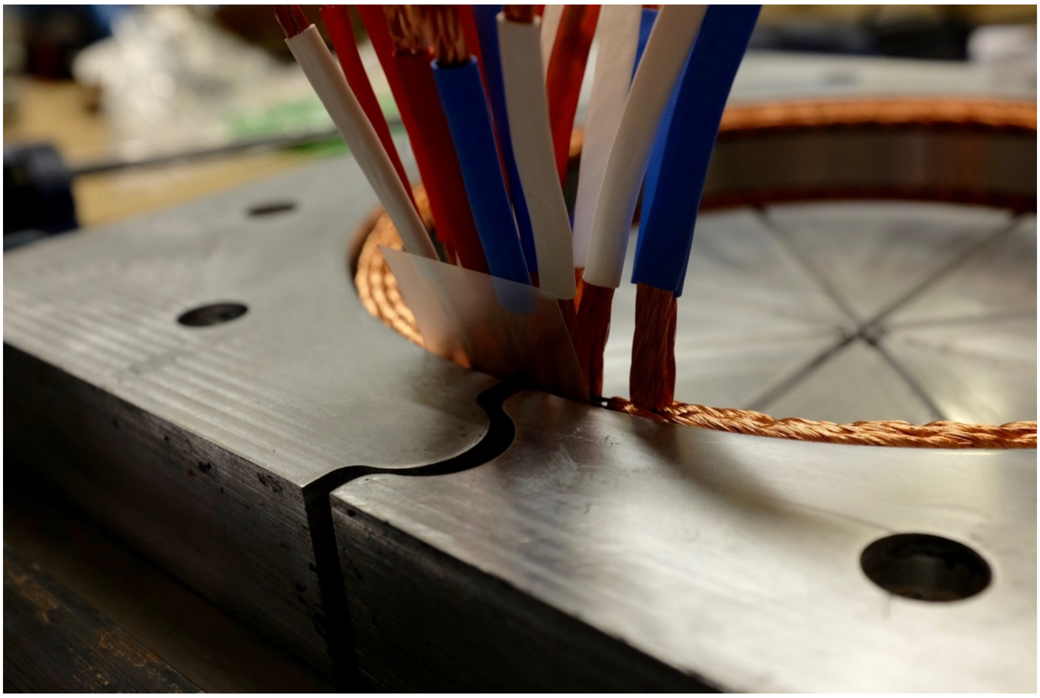


Figure 58 - Plastic Shielding While Closing the Mold

Mold

The final version was milled out to match up relative to each other and the holes in the base.

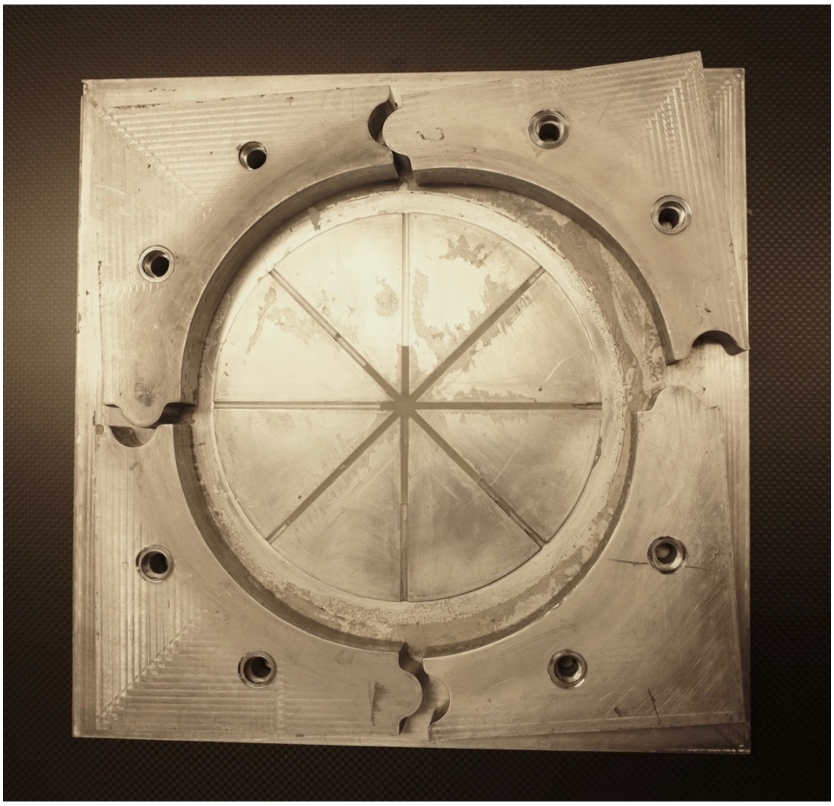


Figure 59 - Final Aluminium Mold

The inner mold was eventually made as a 3d-printed plug, because tolerances were not an issue for the inner diameter. Furthermore, the back-iron steel ring would be the counterforce as the outer mold was pushed together. The resulting plug was made with slip angles, as for the ThinGap™ iteration.

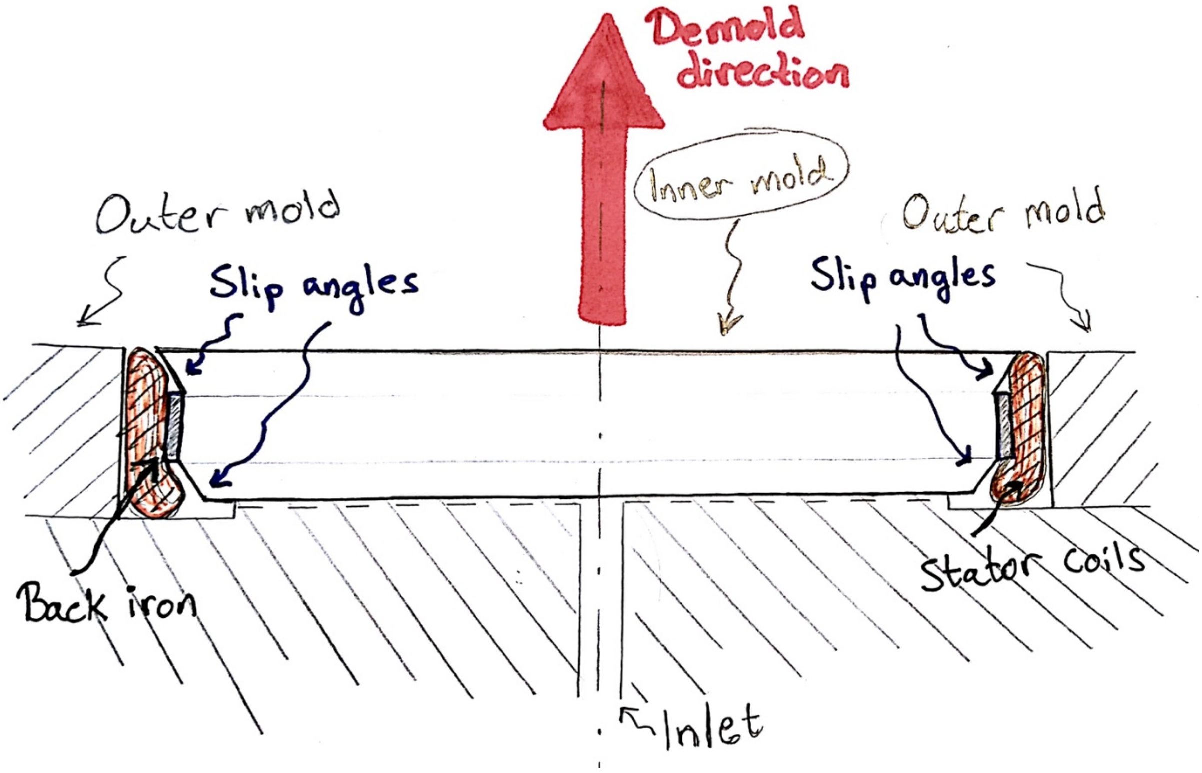


Figure 60 - The Mold Construction with Inner Mold Slip Angles

The previous use of brush resulted in an iterated final method of vacuum infusing the stators through closed mold. Both inlets and outlets were made for the epoxy. These were branched into several channels to distribute the epoxy through all the stator coils. The inlet was milled in the aluminum floor as shown in the drawing above. The outlets were made a part of the 3d-print, with an acrylic lid as shown in the picture below.

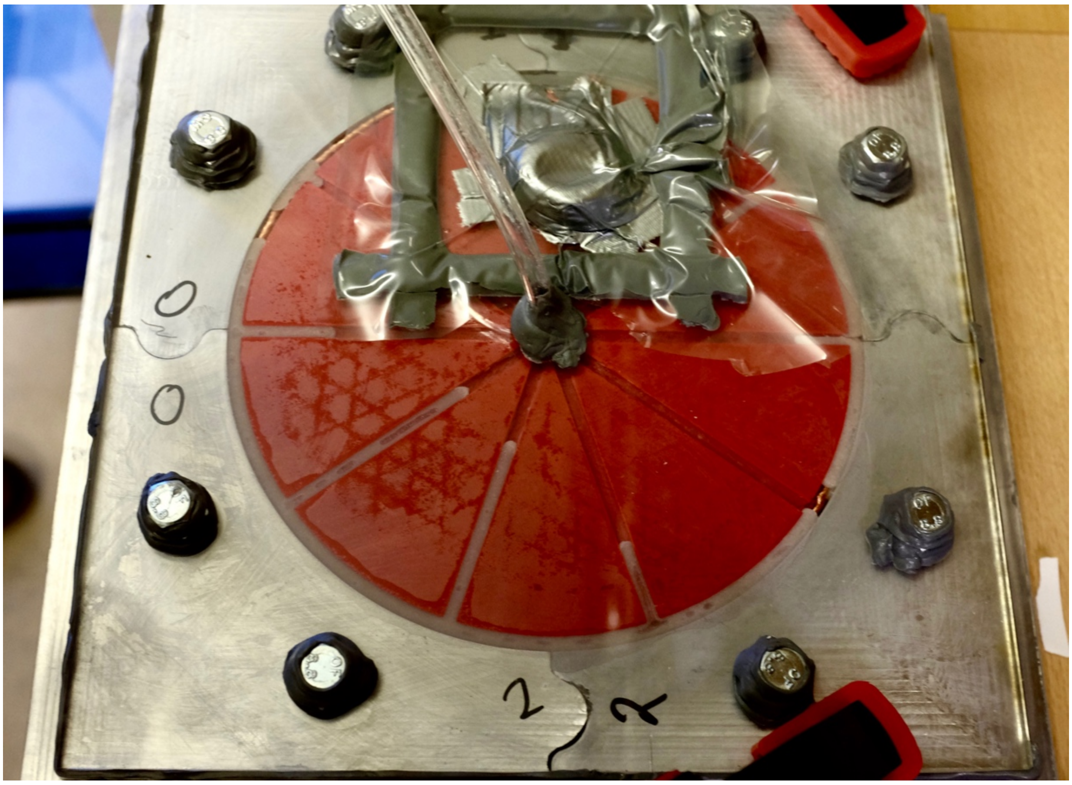


Figure 61 - Vacuum Infusion of Stator Prototype – Sealed Mold

Several iterations were done in order to completely seal the mold. In picture above, an attempt of sealing the mold with sticky tape. Below, a picture of the final iteration; complete bagging.

Figure 62 - Vacuum Infusion Prototype with Bagging for Sealing

Casted stators

Several functional prototypes were produced, and several are in production.

Figure 63 - Two Layer Vacuum Infused Stator

Figure 64 - Three Layer Vacuum Infused Stator

Learnings

MOLDS

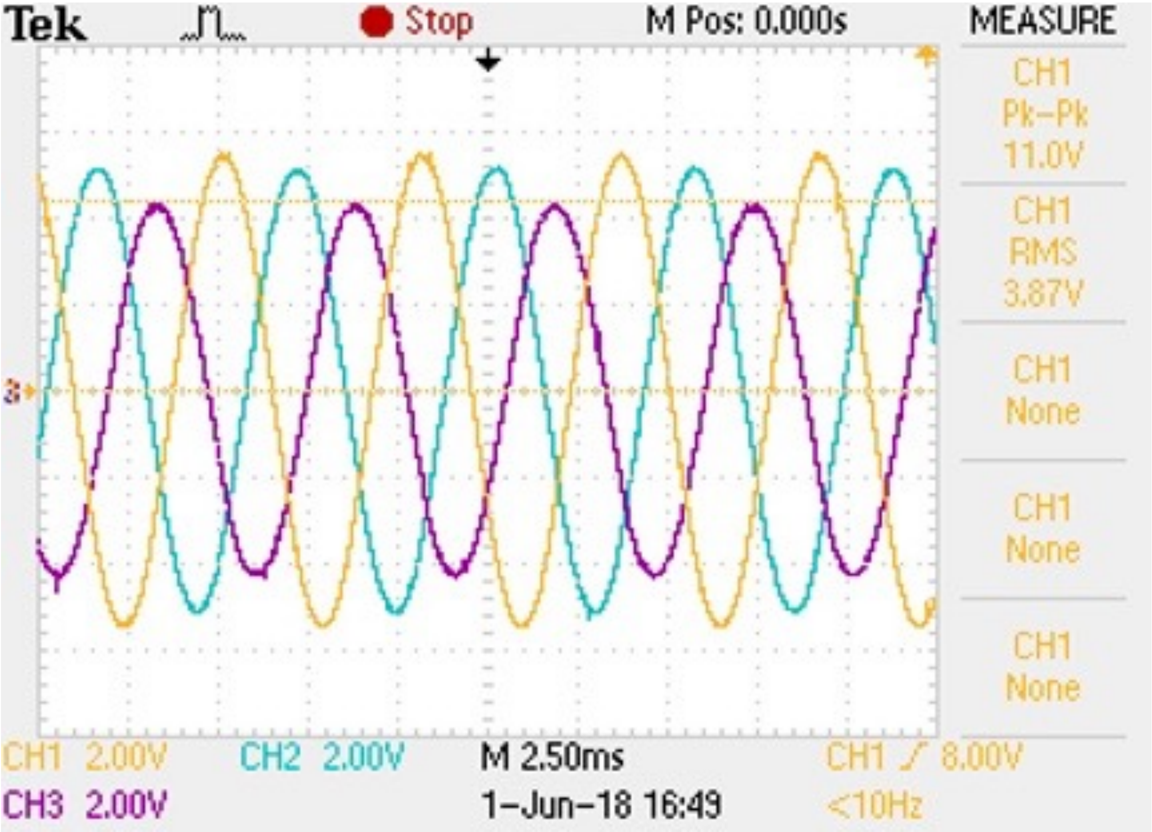
WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The molds ensured proper dimensions to the stators. Given that the were completely closed.
	Having more than two pieces on the outer mold shielded the stator towards flange development in the meeting points.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION	The inner mold did not work as planned, and the demolding turned out challenging. This is probably due to a rough surface, where sanding and painting was not done sufficiently.
	It was difficult to infuse the stator properly. More research on epoxies with lower viscosity should be done.

STATORS

WELL-FUNCTIONING OR/AND WITH POTENTIAL:	The development of the stators were of an iterative nature. First stator number three was usable, as the other stators short circuited or came out with the wrong dimensions.
	For the final iteration, brush in combination with outer mold only, was applied. This gave a better result, though with less potting and support, as all the coils were covered in epoxy.
DYSFUNCTIONAL OR/AND IN NEED OF ATTENTION	Not all the stator were infused during the vacuum infusion.

4.1.4 Test results

For initial testing one can see from the oscilloscope voltage tracking picture below from underneath that the phases behave a bit differently. Different amplitudes can stem from variance in magnet positioning in the rotor or higher resistance in some of the wires. As the curve is from a no-load test, broken strands should not influence the voltage peaks, as this is the same in all phases despite differences in operative wires.



Curve 2 - Voltage Tracking of Drone Motor

However, the motor runs smoothly. Further investigations on short circuiting and mechanical unbalance will be conducted to maximize the motor outcome.

4.2 Conclusion

This thesis aims to investigate how to go from copper wires to composite stators that are satisfactory for the design specifications of Alva Motor Solutions. Alva are setting ambitious goals concerning the performance of self-produced stators. I will consider how to technically realize such stators moving towards automated production answering two questions:

1. **Can satisfactory stators be made within the pending patent of Alva Motor Solutions?**

The patent pending of Alva Motor Solutions is quite wide. Though the confining limits lie in the production of a mat filled with copper and fiber. This mat is to be rolled up and casted in a polymer. "Sufficient" is measured in leading competitors in viable markets. As for this project, this translates into the milestones of retrofitting the ThinGap™ motor, and aiming for the drone motor design specifications.

The answer in retrospect is yes, because of the copper fill factor achieved in the ThinGap™ stator. However, it is possible that the drone motor specifications can be reached, but this is not validated yet. The method of weaving that have evolved throughout the project period, can in other words already be deemed advantages in the market shared by ThinGap™. However, the following points are still ways of further improving the applicability of the method:

a) When weaving the stators, copper fill factor is a pressing matter. Warp yarns that separate the wefts need to be minimized, if they cannot be omitted due to the patent.
b) The warp yarns could be implemented as reinforcement. Up until this point, the motors investigated have not been within the torque ranges demanding any ability to withstand considerable shear forces in the stator. As motors without armature teeth need a higher diameter to function, the shear stresses might never reach the levels where the reinforcement is needed.
c) If thermal expansions turn out to be a challenge, including closing the airgap, adhesive breakage etc., the reinforcement might be used to limit such expansions.

d) Working with motor designs demanding more than one layer mean that alignment of slots become critical. Also, it is more challenging to compress the layers enough to ensure a competitive CFF.

1. **Which principles, in terms of automated production equipment, do a Wayfaring methodology approach point towards?**

The principles that are deemed the most successful throughout the development run are the following:

a) Weaving entire phases in each shed when bare wire is used

b) Using coil feeders when sorting and positioning wires

c) Using glue or other adhesives to stiffen, and freeze the active area. This could be done both before, and while printing

d) Weaving clean plain weave pattern with litz wire wefts whenever possible

e) While manually investigating the process, beat-up (the reed function) has been done by hand. This is vital to the process, and should be included.

f) Utilizing back iron for direct roll up from the fiber printer proved to simplify the process greatly in terms of transaction from printer to mold.

g) The most important tolerances are the ones that determine air gap, and leveling of the stators. A stator is placed in a double rotor, or a rotor with opposite back iron like ThinGap™, calls for the casting molds to have a collapsible inner mold, and demountable outer mold in three, or more pieces. If there is only a single rotor, where the rotor only face the stator in one side, the rotor side is the only side to be considered in terms of tolerances.

h) Vacuum infusion would not necessarily be the easiest way to go about when casting the stators. The geometry is rather complicated to distribute the matrix in, and the highly compact copper demand low viscosity potting to become fully saturated, and is not yet managed.

5 Discussion

Wayfaring trough the last eight months have been a journey of successes and failures. And in my experience, you need both to orient. If all seemingly work, you are probably not doing something novel, if things go wrong you receive these as corrective guidelines. Within the team of Alva, there have been opposing views on where to go, or probe next. Never go hunting alone. If blindly following the directions pointed out by the latest prototype you may run the risk of exhausting your resources, and the most precious resource is time. Following leads in prototyping is the very core of wayfaring, but with strict deadlines, you must put a boot in the ground at some point.

5.1.1 Directions - taking wayfaring, recourses, and risk into account

A certain tension presents itself. Through the project period, a clearer picture of what an end-result may look like has emerged. When further wanting to automate the production of such stators, where do you go?

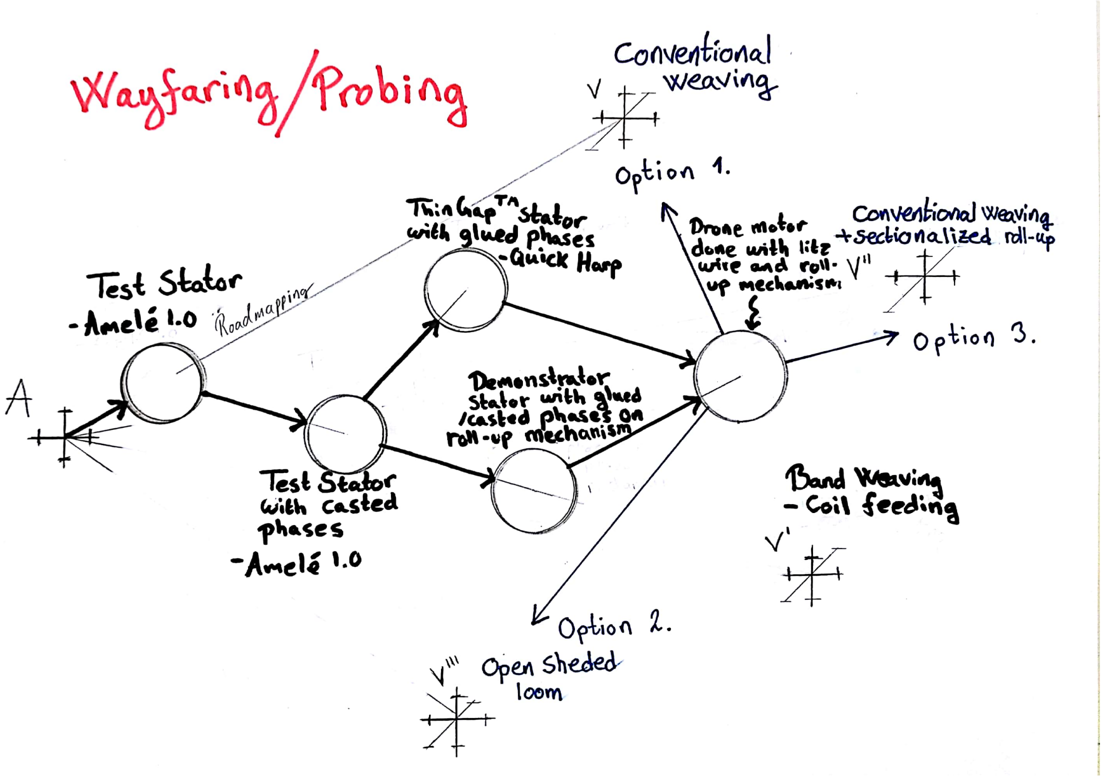


Figure 65 - The Alva Wayfaring Journey

Option 1: On one hand the textile industry have massive amounts of knowledge in industrialization of looms and processes. Alva have received preliminary designs on machinery from a research cluster in Manchester, led by professor Prasad Potluri. This cluster is recognized as world leaders on loom machinery design, which should make them the perfect fit for the task at hand. Initiating a comprehensive project aiming to build and develop the machinery design from research cluster might drain Alva for its resources in shear cost, and time consumption, promoting rather high fidelity prototypes.

Option 2: At the same time, the operations needed for making stators as demonstrated in this thesis could potentially be found in more simplified systems. Weather these systems are a faster way to market, than to realize, test, and iterate the designs from Manchester is hard to decide upon. On the other hand, there are clear elements of risk in solely running the wayfaring approach for all key concepts promising ready-made equipment within a specific time frame.

Option 3: For this option, pursuing the success of weaving stators on sectionalized roll-up mechanism. The further development of this would focus on cutting man hours, and to a greater extent automate Amelé 3.0.

Considering in the map (Figure 66), the time for more traditional engineering approaches like waterfall, stage gate etc. are closing in depending on where Alva chose to go next. In the case of this run, this golden nugget does not seem to have appeared yet. Some gold dust here and there, on more local issues that have yet not accumulated to stand out as **the solution**.

5.2 Team work

The technical team have worked closely throughout the project period. Leading the team have given me the chance to consider all aspects of the development up until date. Weekly meetings have been a collective endeavor keeping team members on the same page, and tracking progress.

The more challenging aspect of leading the team is that it is constituted by volunteers. That is, shares are given for the effort put in by individuals, but the amount of contribution and time spent at the facilities are regulated by the individual’s schedule. It was still possible to delegate and agree upon responsibilities, but logistic challenge of engaging seven or eight people in smaller tasks adapting to weekly variance have been severe.

5.3 Working in a Company Setting

There are clear differences between writing a master’s thesis with a company, and merely with project through university. In the case of this period I had the option of focusing on one smaller component, or pain point in the production machinery of Alva, or to lead the technical team through broader development runs. I chose the latter, being able to go hunt with others, which was a great pleasure. However, this also limited my ability to control the directions in the process. Giving way for influence by employees caused this thesis to head for the milestones posed by Alva. The milestones were naturally created from a strategic business perspective, leaving some unnatural dead ends in the wayfaring. Even though some leads and directions were cut prematurely, learnings from these lived on and reappeared later in development, like phase weaving and casting of active area. Considering reporting peers from research and development divisions in industry, tendencies like these are highly common.

5.4 Prototyping

While working towards the four milestones, the prototypes have held a relatively low fidelity. However, with deadlines closing in, the fidelity has in my opinion risen somewhat prematurely, leaving learnings costly from a product development perspective. One pretty prototype might very well materialize several functional prototypes in terms of resource consumption. For Alva however, the more refined prototypes may still have proved valuable facing investors and stakeholders.

5.5 Prototypes

Throughout the period, massive amounts of prototypes have been produced. Prototyping all parts of the production line of Alva have been rewarding, and have provided perspective on where pain points are found. However, the range of steps needed to realize stators of industrial quality are many and specialized. In this respect, I imagine the outcomes to be less innovative then what they could have been if the same amount of effort was exerted on one particular challenge. But then again, smaller scopes of focus might just be the next, correct move. In my opinion, the degree of ambiguity that existed with respect to the production method embarking on this endeavor, was too high to point out pain points with confidence. In retrospect, the wayfaring mindset seem a sensible development method to apply on the process as a whole.

Build, test, and see what works – the concept makes sense;

- *now let´s assign the engineering tasks.*

6 Further Work

The technical team Alva is employing this fall have a great potential. Strengthening the team with four to five full time engaged engineers, will truly accelerate the development. Alva is also closing its first seed round these days, funding further research in the year to come. Further cooperation with TrollLabs, and other divisions at NTNU would be valuable both for low risk innovation and further recruitment.

6.1 Methodology

In terms of development, there seem to be different types of engineering tasks ahead. Some pure in the sense that know-how from industry is to be translated into the Alva production line, and some of a more ambiguous nature, deeming wayfaring mentality valuable to uncover the unknown unknowns. For continuation of developing the production equipment, the practical applicability of probing will still be relevant if building on traditional weaving concepts. Local innovations will be needed to fill in for needs in the machinery. Information storage is key, as new ideas will be sparked while working on the production line. Low-fidelity validations live well alongside more high-fidelity development runs, leaving prototype opportunities in between larger milestones.

6.2 Conventional weaving – Option 1 (Figure 66)

Alva is now aiming to pursue the designs Manchester in a probing manner, simply to investigate whether this is a short cut to market, or not. In this endeavor, the current solutions within the textile industry should be exhausted through the expert team, and further developed in a wayfaring spirit. For sure, the learnings will be great, despite uncertain outcomes.

6.3 Suggestion for automation – Option 3 (Figure 62)

As a contribution on site, an idea sparked by an evident pain point emerged during the development. In wayfaring terms, this would qualify as a dark horse prototype 2.1.1.

Throughout the time dealing with the semi-automated equipment, the least accessible part of the machinery has been the shed, where the wires are passed through in their respective order. Furthermore, this is considered a challenging aspect to automate when weft numbers are high.

A draft for an open shed solution was iterated in October. By utilizing scattered time windows through the period, a limited probe of the concept is ongoing. The idea is to eliminate the need for passing the wires through the shed, let go, and subsequently tighten the weft. By passing the warps vertically up and down, full access and flexibility are achieved for insertion of wefts, as depicted below.

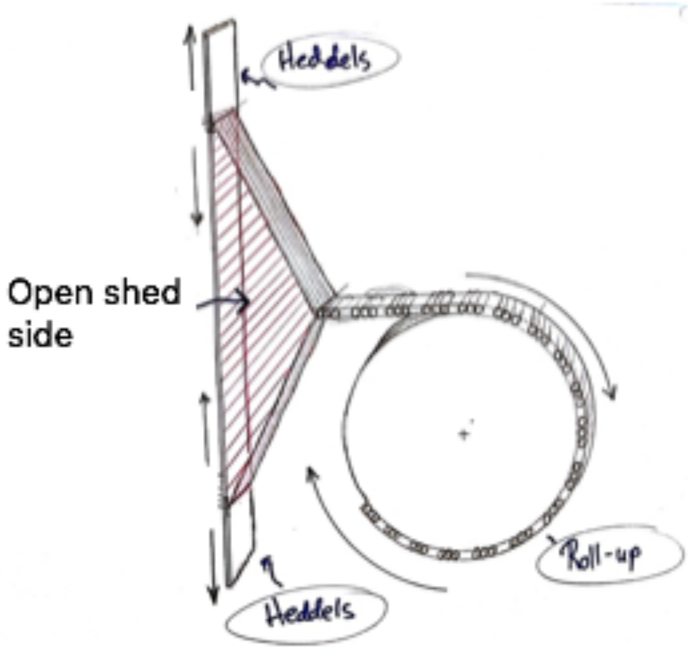


Figure 66 - Open shed solution

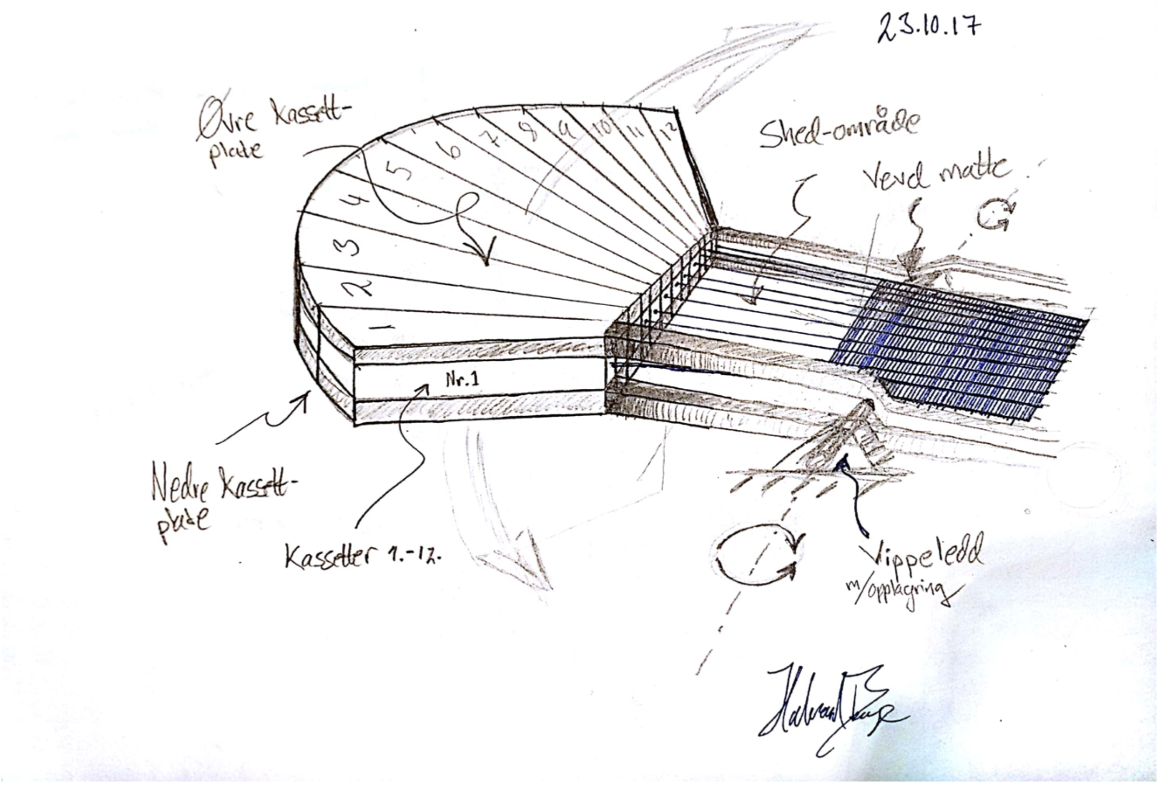


Figure 67 - Open Shed - Concept drawing

Each cassette will bring its respective warp yarn up- or down. In this manner the mat will be fully exposed for copper insertion in less complicated manners.

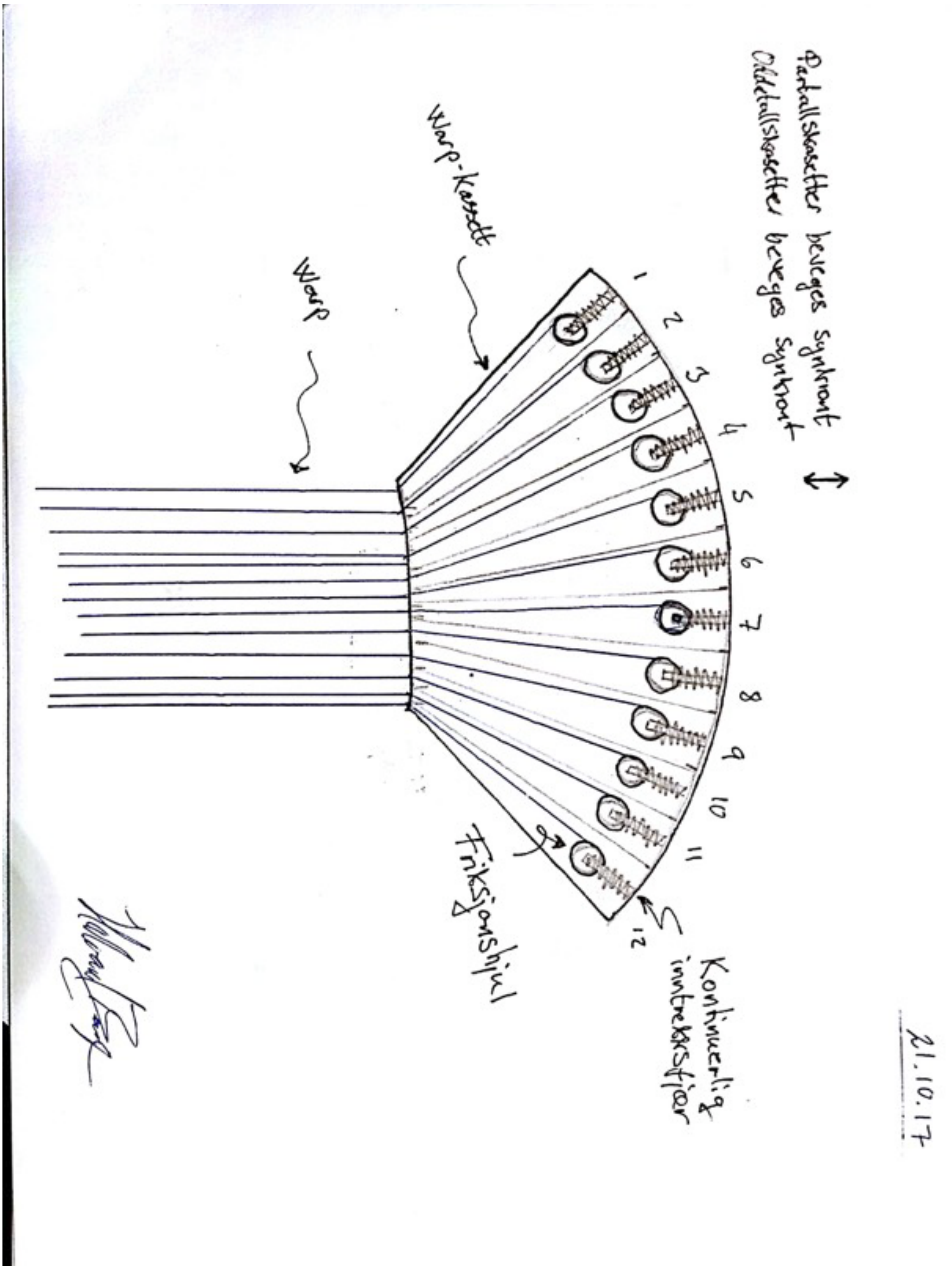


Figure 68 - Open Shed - Warp yarn levers

The lever idea from Amelé 2.0 has been adopted in order to maintain tension through the warps motions.

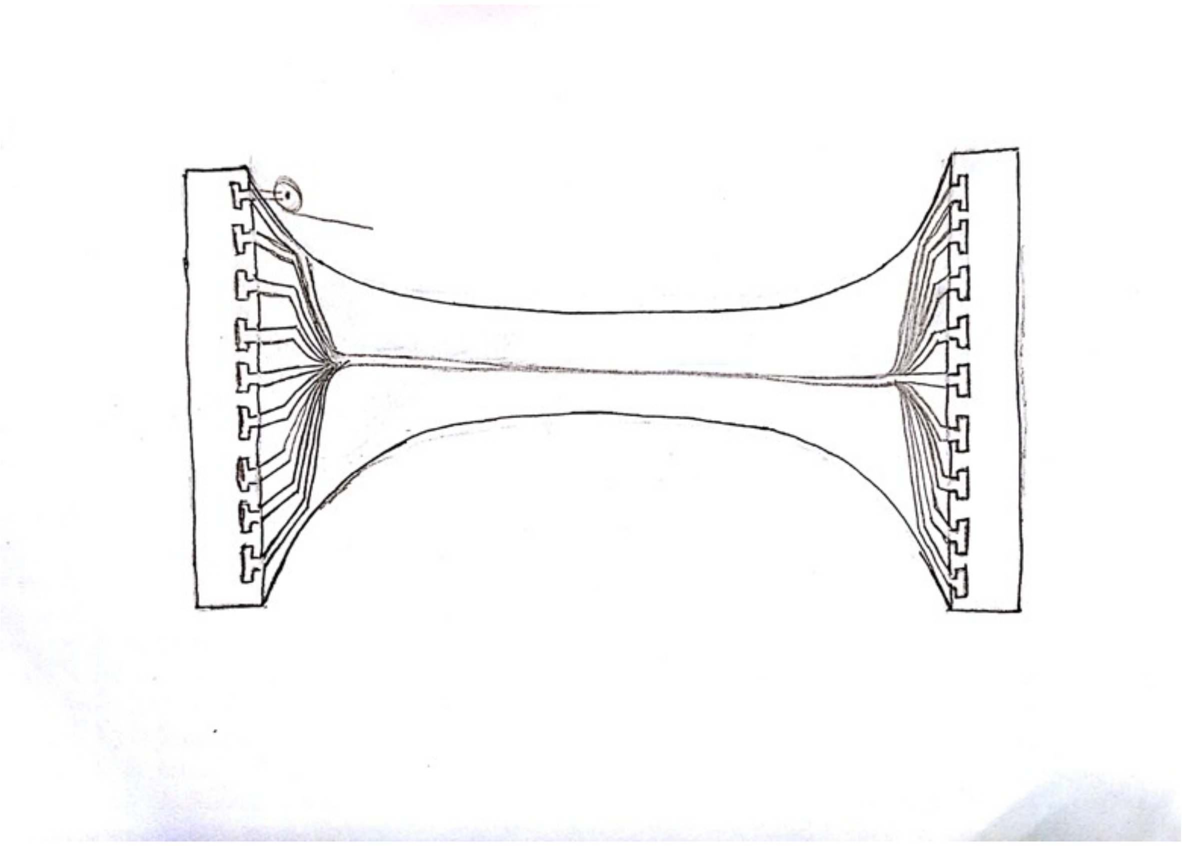


Figure 69 - Open Shed - rails for placing copper

By running each bobbin in a half circle around the shed, every wire can be placed in the predicted order, between every heddle change.

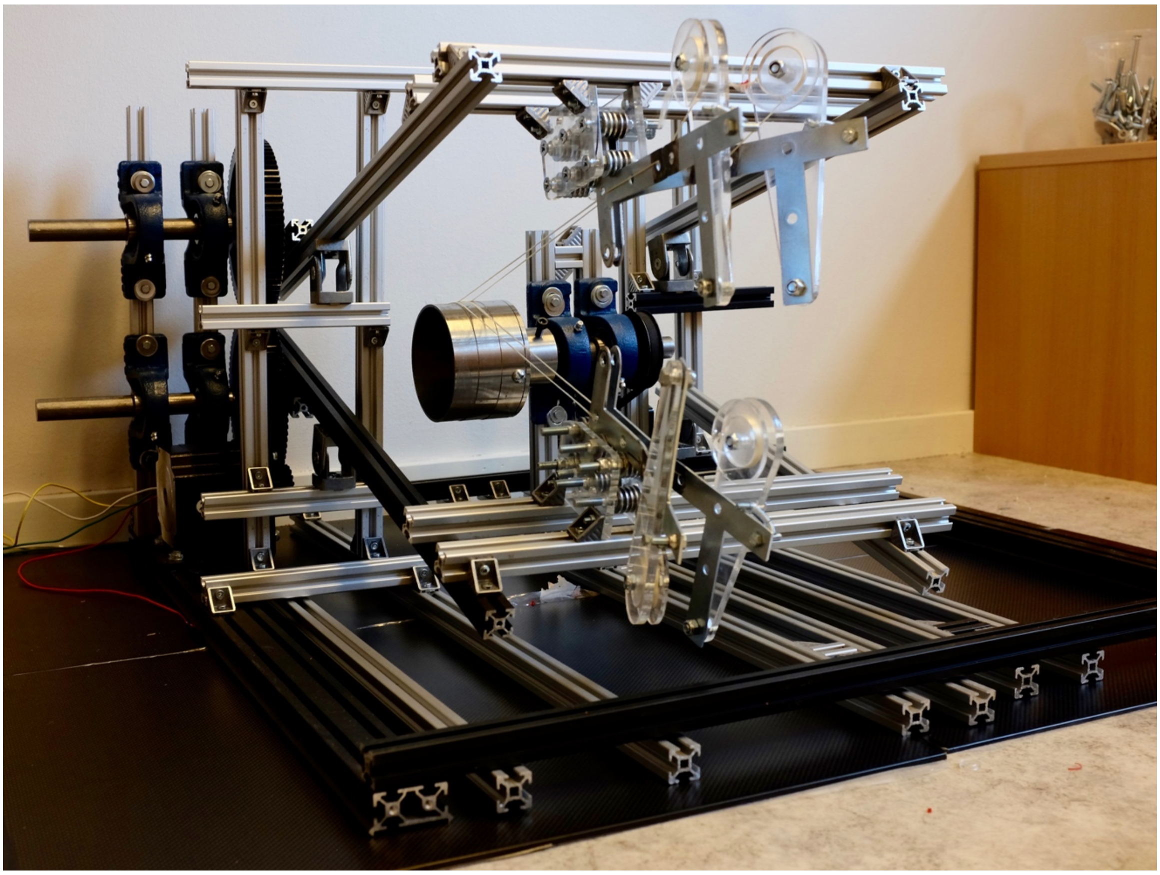


Figure 70 - Modular open shed prototype assembled in cooperation with Ole Christian Hermansen

It is recommended to exhaust this concept, learn, and potentially implement viable solutions in combination with other ideas in the time to come.

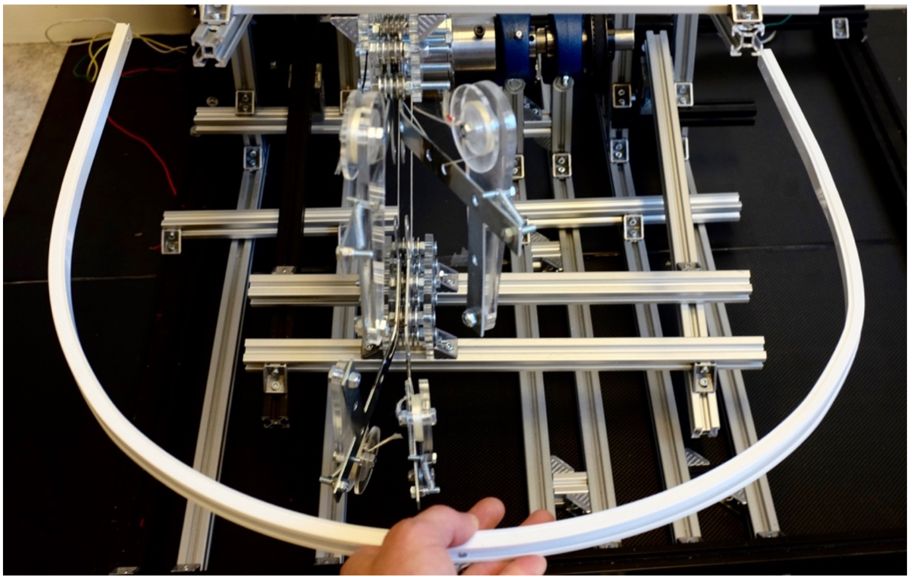


Figure 71 - Open shed solution under construction

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Acknowledgments

I would like to thank my supervisors Martin Steinert and Kristoffer Bjørnerud Slåttsveen for support and advice through the development process.

Homage is due to the team of Alva Motor Solutions:

To the tech team; thank you for going the distance with me, and all contributions that helped evolve Alva further through this period.

- **Sampsa Matias Ilmari Kohtala**
- **Marcus Kolberg**
- **Lars-Endre Johannessen**
- **Magnus Becker**
- **Arild Stenset**
- **David Flem**
- **Sondre Johannessen**
- **Ali Tabeshian**
- **Ole Christian Hermanrud**
- **Martin Henriksen Dahl**
- **David Flem**

Jørgen Pac Selnes - Thank you for all ideation, resistance, faith in me, and support.

Knut Nielsen – Thank you for helping hands, and managing development resources.

Mikael Vedvik – Thank you for challenging me, and putting in the hours to get things done.

Ravindra Babu Ummaneni – Thank you for all help, and for sticking out with the mechanical limitations I provide your motor designs.

I would like to thank my closest for supporting me:

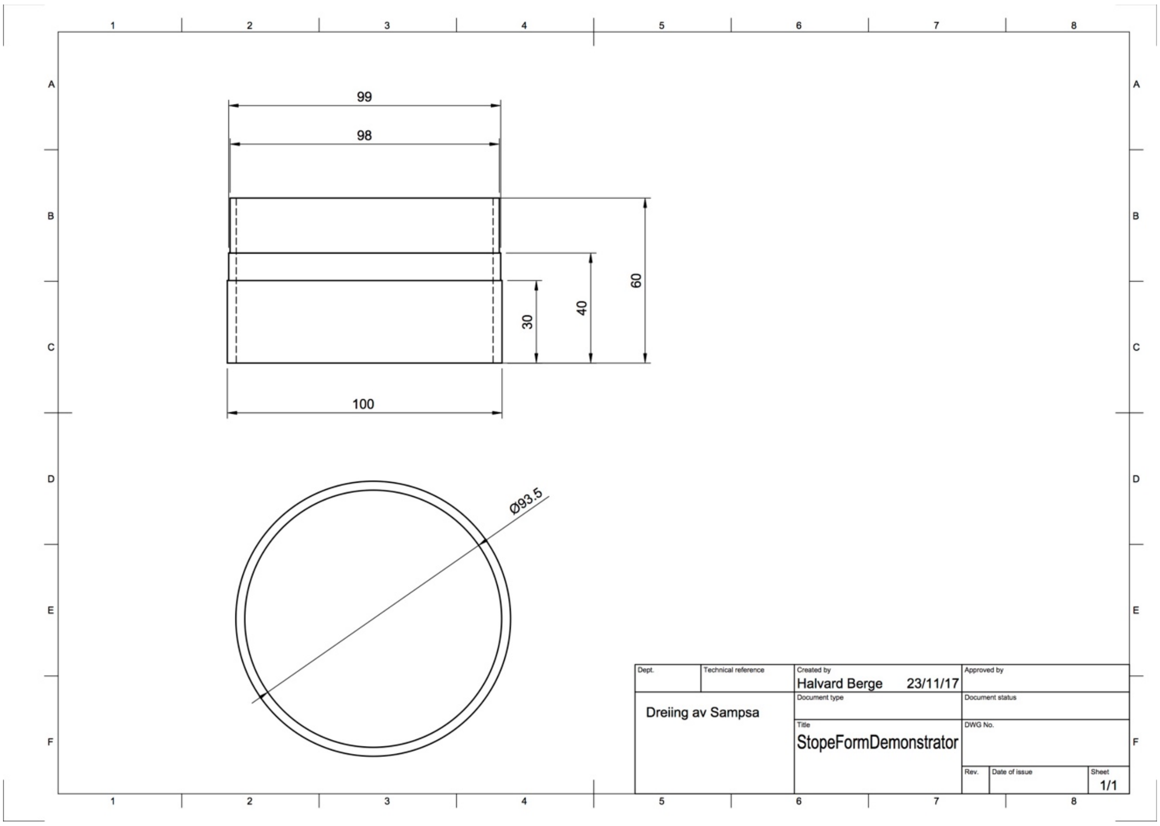
Mom and dad; **Grethe-Inger** and **Reidar Berge**
My brother for advice on thesis segments; **Arngeir Berge**
My girlfriend for all heartfelt prayers; **Ingjerd Langegard Nakken**

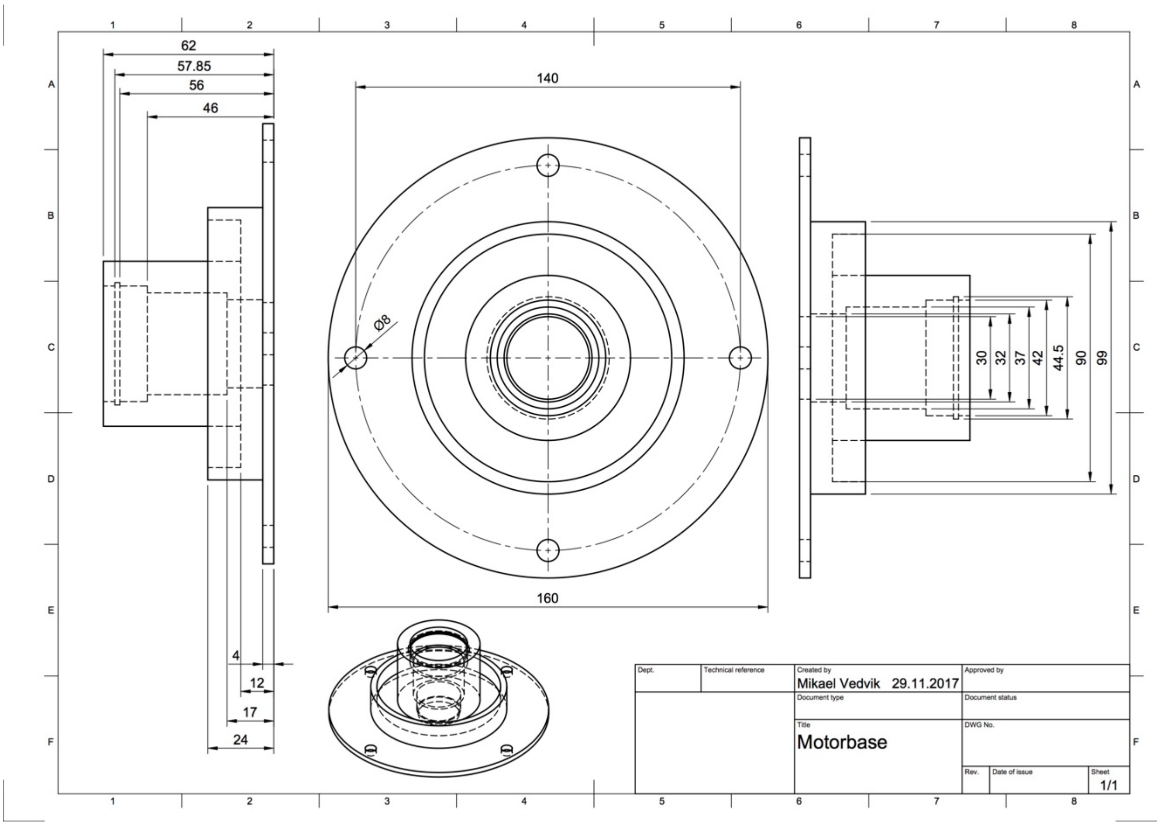
Thanks to **Jørgen Erichsen** for providing the suitable template used for this thesis.

APPENDIX A: Motor Construction

Demonstrator Design

The demonstrator was merely a mean to an end, being a motor to make stators for while being able to show to potential customers. However, to be able to control weather the stators performed or not, the motor had to be built.

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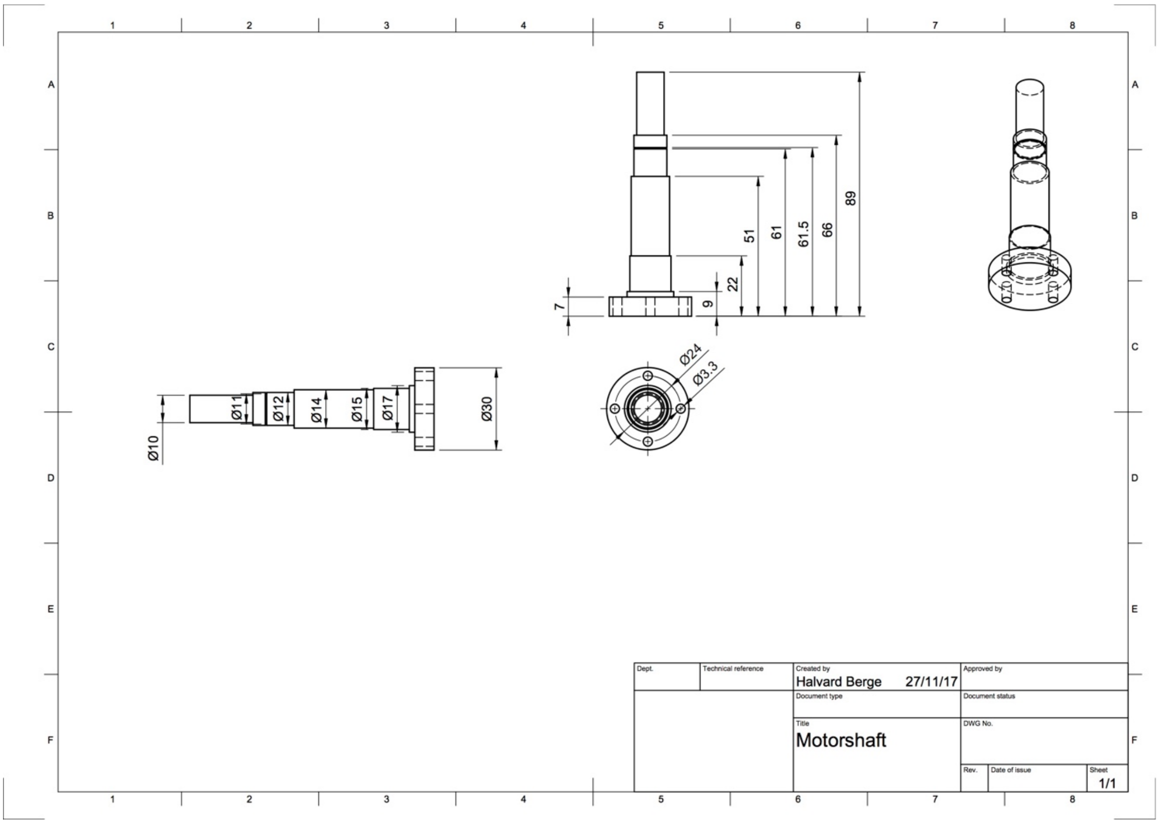
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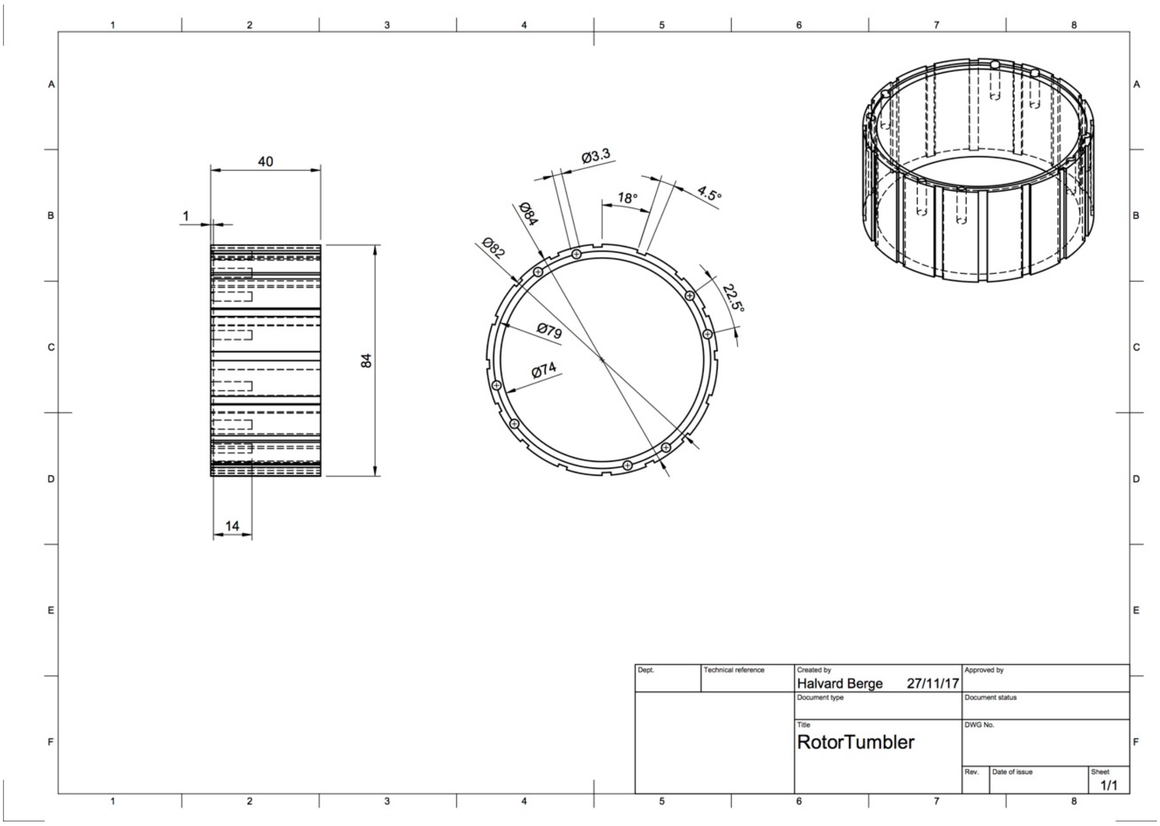
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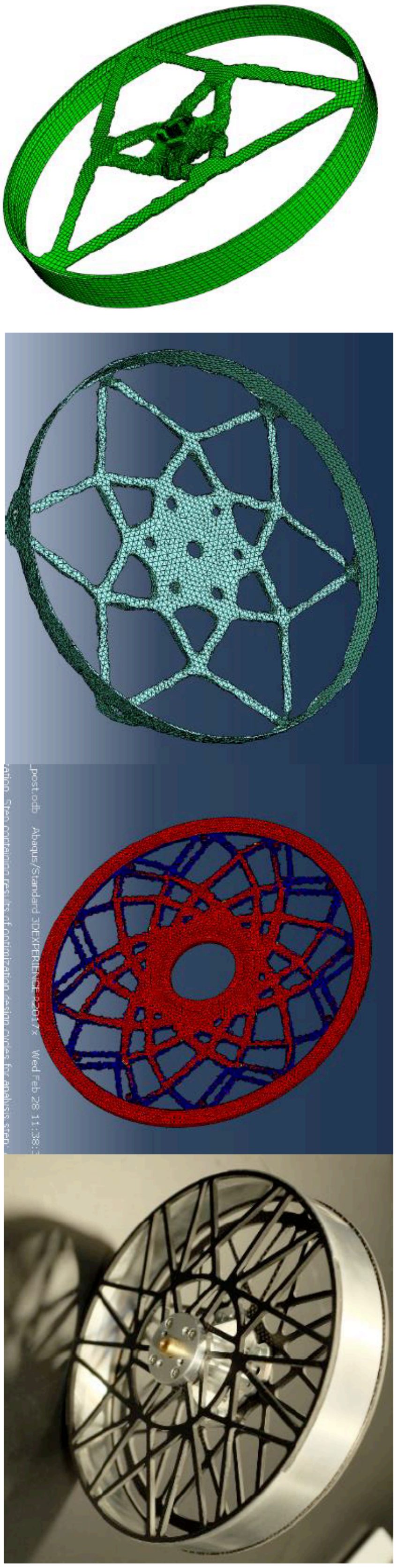


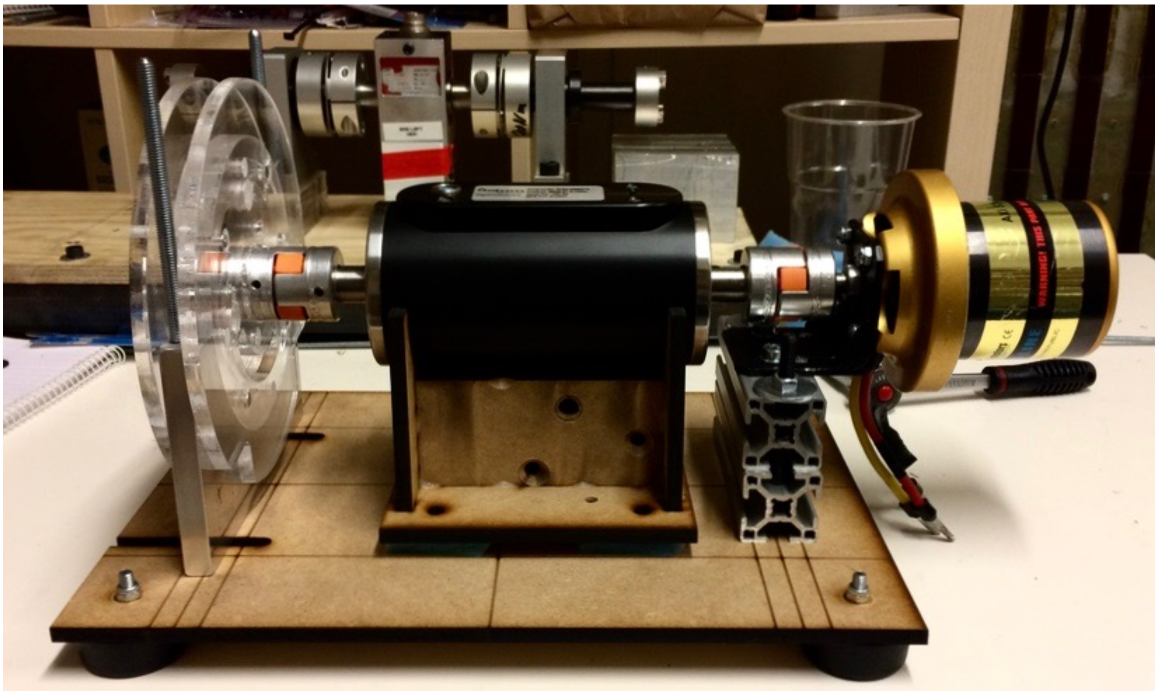
Drone Motor Design

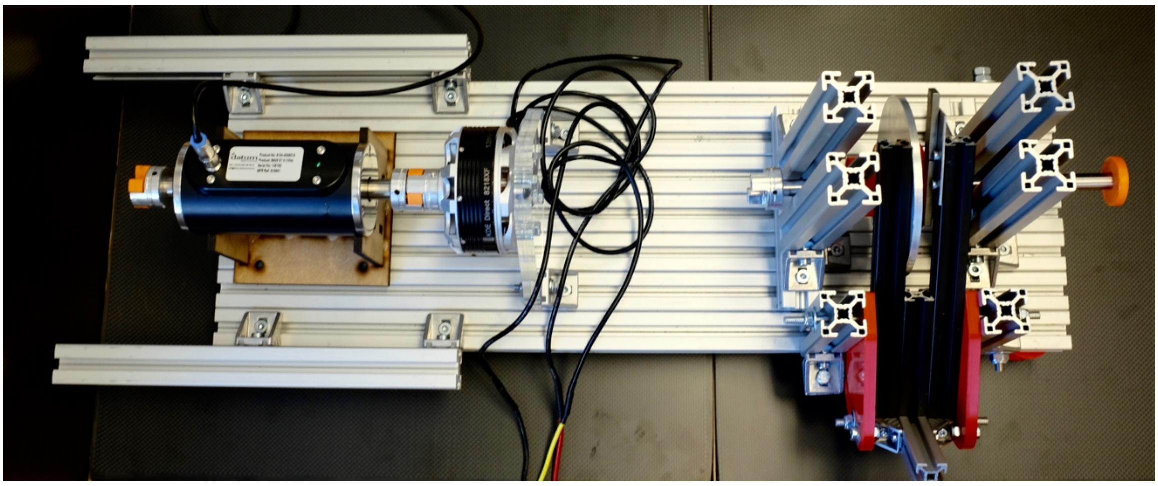
Topology optimization was conducted during the development of the drone motor. Some was used, some was not, and some is under production now.

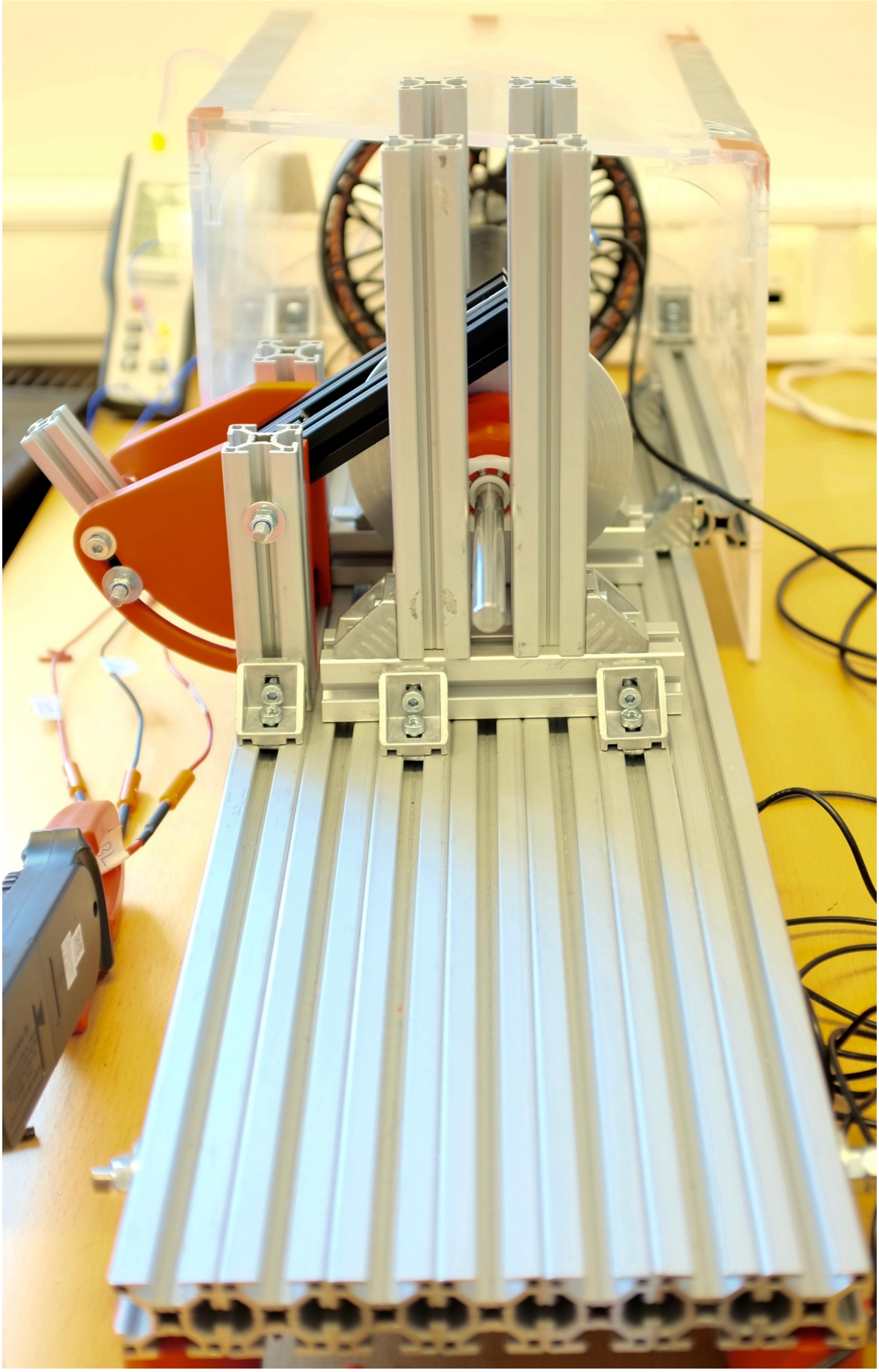
APPENDIX B: Test Equipment

Test Benches

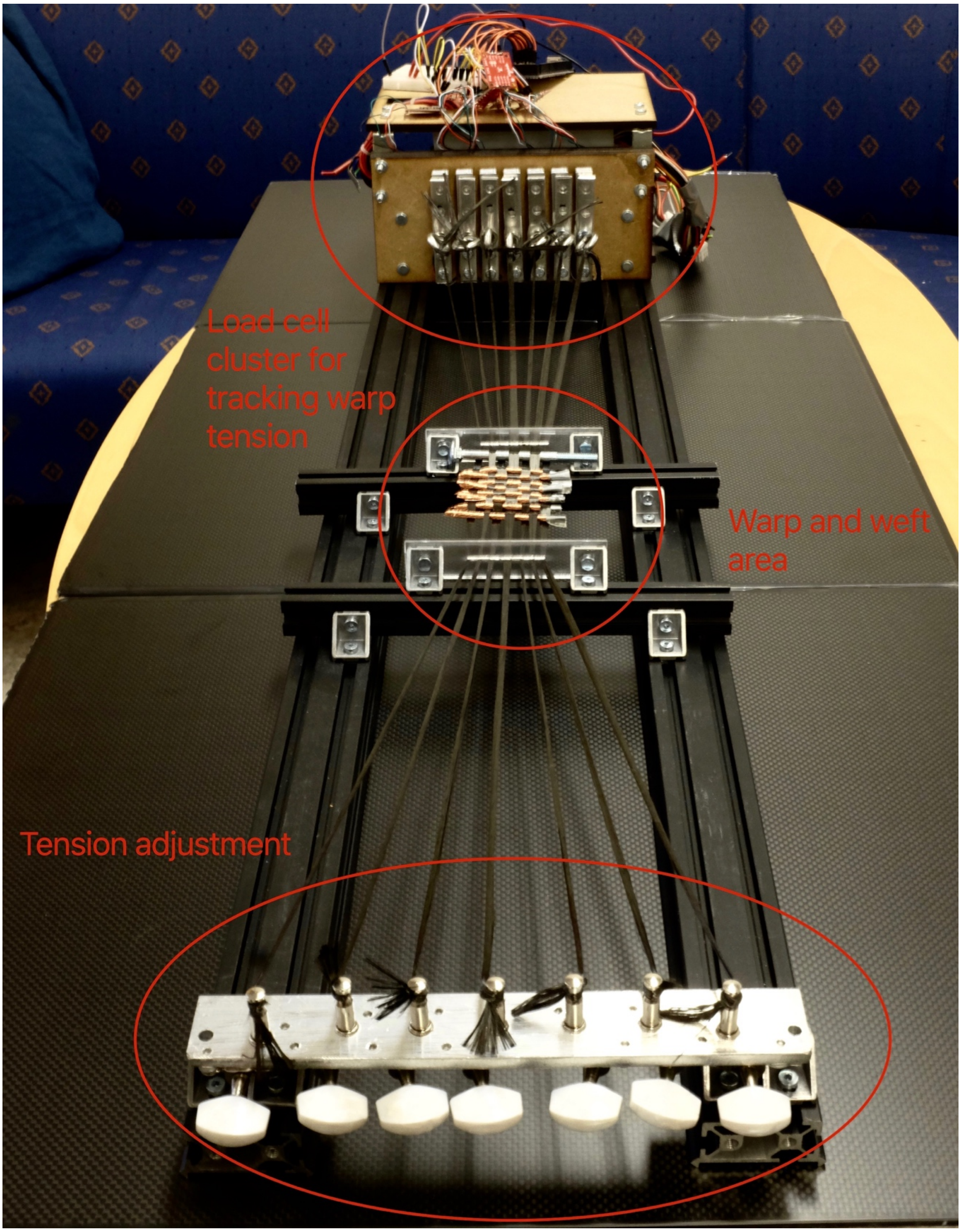
For testing stators and motors, test benches have been built. These are equipped with torque meter, prime mover motor, and eventually an eddy current break.







Tension Testing and logging



APPENDIX C: Patents

The patent of Martin Gudem

Electromagnetic composite material (emcm)

Abstract

A composite drive unit includes a composite material including conductive fibers 14 as an integrated part of the composite material. The conductive fibers 14 can be organized in different patterns, and each of the conductive fibers is terminated to an electrical conductor. A material for a composite drive unit includes a plurality of conductive fibers 14 arranged in a predetermined pattern 30. The plurality of conductive fibers 14 are embedded in a matrix material 12. The plurality of the conductive fibers 14 is connectable to a source of electricity to generate a magnetic field 18 for operating the composite drive unit.

Description

ELECTROMAGNETIC COMPOSITE MATERIAL (EMCM)

CROSS-REFERENCE TO RELATED APPLIC ATION

[0001] This application claims priority to U.S. Provisional Application No.

61/380,573, filed on September 7, 2010, the entire contents of which are hereby incorporated by reference.

BACKGROUND OF THE INVENTION

1. Field of the invention:

[0002] The present invention is related to electromagnetic composite materials

(EMCM). In particular, the present invention is related to electromagnetic composite materials (EMCM) that can be used as part of a composite drive unit.

SUMMARY OF THE INVENTION

[0003] The present invention is directed to a composite drive unit, comprising: a composite material including conductive fibers as an integrated part of the composite material, wherein the conductive fibers can be organized in different patterns, and wherein each of the conductive fibers is terminated to an electrical conductor.

[0004] According to an embodiment of the present invention, the composite drive unit further comprises a stator; and a moving part, wherein said stator and/or said moving part includes said conductive fibers embedded in a matrix material, said conductive fibers being connected to a source of electricity to generate a magnetic field.

[0005] According to an embodiment of the present invention, the composite drive unit is constructed as an electric motor.

[0006] According to an embodiment of the present invention, the composite drive unit further comprises a coil, which is an integral structural component, wherein the coil functions as reinforcement fiber in a composite material, and wherein the fibers may be ferromagnetic or ferrimagnetic. [0007] According to an embodiment of the present invention, the ferromagnetic or ferrimagnetic fibers may also be integrated in the material, so as to guide the magnetic flux, and may also be used as electromagnetic conductors.

[0008] According to an embodiment of the present invention, the composite drive unit is constructed as an electromagnetic generator.

[0009] According to an embodiment of the present invention, the composite drive unit is constructed as a wheel motor, windmill or tidewater generator, a high-speed motor or generator, or a transformer.

[0010] The present invention is also directed to a material for a composite drive unit, comprising: a plurality of conductive fibers arranged in a predetermined pattern, said plurality of conductive fibers being embedded in a matrix material, wherein said plurality of the conductive fibers are connectable to a source of electricity to generate a magnetic field for operating the composite drive unit.

[0011] The present invention is also directed to a method of making a composite material for a composite drive unit, comprising the steps of: arranging a plurality of conductive fibers in a predetermined pattern; embedding said plurality of conductive fibers in a matrix material to make a composite material; and etching edges of the composite material, wherein said plurality of conductive fibers are connectable to a source of electricity to generate a magnetic field for operating the composite drive unit.

[0012] According to an embodiment of the present invention, the method of making a material for a composite drive unit further comprises the steps of: combining the plurality of conductive fibers with structural fibers; and winding the plurality of conductive fibers and the structural fibers on a mandrel, wherein said step of embedding the plurality of conductive fibers in a matrix material includes adding the matrix material during the winding process.

[0013] According to an embodiment of the present invention, the method of making a material for a composite drive unit further comprises the steps of: weaving the plurality of conductive fibers into plies with structural fibers; and assembling the plies, wherein said step of embedding the plurality of conductive fibers in a matrix material includes adding the matrix material during the weaving and assembling steps.

[0014] According to an embodiment of the present invention, the method of making a material for a composite drive unit further comprises the steps of: providing a base having a chamfered surface, a plurality of pins and a central peg; and winding structural fibers around the pins and the central peg, wherein the structural fibers are maintained in close contact with the base. [0015] The present invention is also directed to a method of making a composite material for a composite drive unit further comprises the steps of: inserting pins into a foam base covered with a non-stick material; winding a plurality of conductive fibers in predetermined patterns using the pins to hold the plurality of conductive fibers in place; and embedding said plurality of conductive fibers in a matrix material to make a composite material, wherein said plurality of conductive fibers are connectable to a source of electricity to generate a magnetic field for operating the composite drive unit.

[0016] According to an embodiment of the present invention, the method of making a composite material for a composite drive unit further comprises the steps of: covering the embedded conductive fibers with a sheet of non-stick material; pressing a foam block onto the non-stick material, so that the pins protrude through a top of the non-stick material and into the foam block, resulting in compression on the embedded conductive fibers; curing the embedded conductive fibers while under compression; and removing the foam-blocks, nonstick materials, and pins to form the composite material.

[0017] The EMCM (Electromagnetic Composite Material) according to the present invention uses conductive fibers as an integrated part of a long-fiber composite. The conductive fibers can be organized in different patterns, and each conductive fiber is terminated to an electrical conductor, so as to make the EMCM exhibit electromagnetic properties. The material has the potential of offering increased design flexibility and improved performance in electromagnetic devices, such as motors, generators, resonators, solenoids, etc.

[0018] Motors and generators using the EMCM can be designed with basis in existing coreless machinery. Coreless machines exclude the use of ferromagnetic cores as a means of directing the magnetic flux. Benefits associated with this technology include more lightweight design solutions. Furthermore, enclosing the conductive fibers inside a nonmagnetic structure will reduce or eliminate unintended buckling of rotor and/or stator components, which can be experienced in axial flux permanent magnets (AFPM) and similar structures. This property is particularly important for designing large-scale machines.

[0019] Ferrimagnetic and/or Ferromagnetic fibers, for example made from ferritic steel, may also be integrated in the material, so as to guide the magnetic flux. These fibers can be terminated, thereby serving as electrical conductors as well as flux-carriers.

[0020] The composite material may include structural fibers, which serve solely as reinforcement to the overall structure (e.g. glassfiber, carbon fiber, etc.). [0021] Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] The present invention will become more fully understood from the detailed description given hereinbelow and the accompanying drawings which are given by way of illustration only, and thus are not limitative of the present invention, and wherein: The invention will now be explained in more detail with reference to the appended drawings, wherein:

[0023] Figure 1 is a schematic view illustrating the composition of a long fiber composite;

[0024] Figure 2 is a schematic view illustrating conductive material integrated into a sandwich structure;

[0025] Figure 3 is a schematic view illustrating a different orientation of the structural and conductive fibers;

[0026] Figure 4 is a schematic view illustrating a magnetic field resulting from imposing an electric current in the conductive fibers;

[0027] Figure 5 is a schematic view illustrating a piece of EMCM where the conductive fibers are made from a ferrimagnetic or ferromagnetic material;

[0028] Figure 6 is a schematic view illustrating the same piece of EMCM as in Figure

5, but with an electric current running through the upper and lower layer;

[0029] Figure 7 is a photograph illustrating a manual prototype before epoxy resin is added;

[0030] Figure 8 is a photograph illustrating a manual prototype after curing;

[0031] Figure 9 is a photograph illustrating a foam base, release liner, pattern markup, and guiding pins;

[0032] Figure 10 is a photograph illustrating plies of reinforcement fibers and a winding tool;

[0033] Figure 11 is a photograph illustrating matrix material added;

[0034] Figure 12 is a photograph illustrating the part being cured under compression;

[0035] Figure 13 is a photograph illustrating the part after compression; [0036] Figure 14 is a photograph illustrating the trimmed part after removal of the release liners and guiding-pins;

[0037] Figure 15 is a photograph illustrating the center peg and chamfered sides keeping fibers close to base;

[0038] Figures 16a, 16b and 16c are schematic views illustrating an AFPM based on

EMCM technology, wherein Figure 16a illustrates the entire construction; Figure 16b illustrates the stator; and Figure 16c illustrates the rotor; and

[0039] Figure 17 is a schematic view illustrating conductive fibers arranged on a 3- phase configuration, and the resulting magnetic field.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0040] The EMCM is developed with a basis in long-fiber composites. Long-fiber composites gain their strength from structural fibers (e.g. glass or carbon fibers), held together by a matrix material (e.g. epoxy). Figure 1 illustrates the make-up of a typical long- fiber composite. In Figure 1, a plurality of structural fibers 10 is illustrated stacked up in three layers with the longitudinal axis of each fiber being oriented in the same direction. A matrix material 12 occupies the volume between the fibers. However, the fibers 10 may be oriented in layers, or plies in different directions, so as to achieve direction-specific mechanical properties.

[0041] As illustrated in Figure 2, EMCM uses conductive fibers 14 (e.g. thin wires), which are integrated into a sandwich structure. The conductive fibers 14 may consist of copper, steel, aluminum, or any other material with satisfactory electric conductivity. The conductive fiber or wire may be pre-coated with insulation (not shown), so as to prevent short-circuiting. The insulation is etched off at the contact points where the conductors are connected to an electric circuit.

[0042] As illustrated in Figure 3, the conductive fibers may be oriented in a direction different from that of the structural fibers. Furthermore, the sandwich construction may be based on conductive fibers 14 serving as structural elements, eliminating the need for separate structural fibers 10.

[0043] Figure 4 illustrates a magnetic field 18 resulting from imposing an electric current 16 in the conductive fibers 14.

[0044] Figure 5 illustrates a piece of EMCM where the conductive fibers are made from a ferrimagnetic or ferromagnetic material. Imposing an electric current 16 in one layer induces a magnetic field 18 in the perpendicular layers. [0045] Figure 6 shows the same piece of EMCM as in Figure 5, but with an electric current 16 running through the upper and lower layer. This imposes a magnetic field 18, which is carried by the center layer.

[0046] In Figures 4 to 6, the conductors are not shown. However, the arrows indicate the electric current 16 resulting from terminating the conductive fibers 14.

[0047] The EMCM can be manufactured using processes similar to those associated with the production of other long-fiber composites. However, the manufacturing process requires high precision to avoid tearing off the conductive fibers 14 and ensuring that conductors are terminated properly. Manufacturing methods include:

1. Filament winding

[0048] Conductive fibers 14 are combined with structural fibers 10 and wound onto a mandrel. Matrix material 12 is added in the winding process. The edges of the resulting component are etched, and the conductive fibers are soldered to connector points.

2. Lay-up

[0049] Conductive fibers 14 are woven into plies with structural fibers 10. Plies are assembled and matrix material 12 is added in a lay-up process. The edges of the resulting component are etched, and the conductive fibers are soldered to connector points.

3. Pin-guided winding process (see below)

[0050] Two EMCM prototypes have been developed using a process here referred to as the "pin-guided winding process." The second prototype was manufactured using a semi- automated process where the conductive fiber 14 was wound using a CNC-machine (Computer Numerical Control). The ping-guided winding process is suitable for making flat or curved parts with fiber-orientation that changes direction while staying parallel to the part surface. The process includes the following steps:

1. A foam-base is prepared with a release liner;

2. Pins are inserted for each corner of the pattern;

3. Conductive fibers 14 are wound around pins using CNC machinery;

4. Fibers are applied by hand (lay-up) or by CNC machinery (winding);

5. Steps 4 and 5 are repeated to create a sandwich construction;

6. Matrix material 12 is added;

7. Upper release liner is installed; 8. The part is put under compression (and/or vacuum) and cured;

9. Release liner and guiding pins are removed; and

10. The part is trimmed.

[0051] Figure 7 shows a prototype made using a manual pin-guided winding process before epoxy resin is added. Copper wire (conductive fibers 14) was fed through the tip of an automatic pencil 22, and glass-fibers (structural fibers 10) were wound around a foam base 24. The pins 26 served as guides for both the conductive fibers 14 and the structural glass- fiber (structural fibers 10). The workpiece is made up from several layers of copper wire and glassfiber stacked onto each other.

[0052] In Figure 7, the pins 26 are made of metal. However, it should be understood that other materials such as plastic or glass may be more suitable. For example, pins made of thermoplastic material may be molten after the part is cured, making the removal process easier.

[0053] Figure 8 shows the final part after the matrix material 12 has been added and the part has been compressed and cured. This test was conducted without covering the foam base with non-stick film, and the EMCM is consequently glued onto the foam base 24.

[0054] The final part in Figure 8 will then be trimmed, and once the portion of the conductive fibers 14 outside of the matrix material 12 is cut, the terminal ends of the conductive fibers 14 can be connected to an electrical conductor (at 27).

[0055] Figure 9 shows the foam base 24 used in a semi-automated pin-guided winding process. The foam base 24 has been covered by a release liner 28, and a pattern 30 has been sketched out using a felt pen guided by a CNC machine. Pins 26 have been placed in each corner of the pattern 30.

[0056] The conductive wire (conductive fibers 14) are wound around the pins 26 using a CNC machine, and plies of reinforcement fibers (structural fibers 10) are added. The process is repeated to create a desired sandwich-structure.

[0057] Figure 10 shows the workpiece, which is made up from multiple plies of reinforcement fibers (structural fibers 10), stacked with conductive wire (conductive fibers 14).

[0058] As shown in Figure 11, matrix material 12 is added, and the part is cured under compression (see Figure 12). In Figures 13 and 14, the final product is illustrated. Once the final product is trimmed, the terminal ends of the conductive fibers 14 extending out of the matrix material 12 can be connected to an electrical connector (at 27). [0059] Whereas the above semi-automated process used fiber mats as the structural fibers 10, the foam base 24 used in this process has also been designed to work with fiber strands as the structural fibers 10, laid out by a CNC machine. Keeping the fibers close to the base represents a challenge when using this method, since loose fibers may interfere with the routing of conductive fibers 14. Structural fibers 10 are wound around needles 34 positioned at a chamfered edge 36 below the final part surface, thereby being pulled towards the base 24. A peg 32 with a tapered surface is placed at the center for the base 24. Winding the structural fibers 10 around or partly around the peg ensures good contact between base and structural fibers 10 at the center (Figure 15).

[0060] Manufacturing processes 1 and 3 described above, (filament winding and pin- guided winding) are not likely to require removal of matrix material, since the conductive fibers 14 can be guided to a termination point outside the final part. Etching will be needed to remove any insulation material (if applied) from the conductive fibers 14. This is standard procedure when working with electromagnetic coils.

[0061] Manufacturing process 2 described above (lay-up) uses pre- woven mats consisting of conductive fibers 14 and structural fibers 10. The ends of the conductive fibers 14 in this process will either have to be separated from the reinforcement fibers before matrix material 12 is added (un-sewing the edges and separating the fiber ends will work). Alternatively, grinding and/or dissolving the matrix material 12 covering the material edges will be necessary if the ends of the conductive fibers 14 have not been separated from the rest of the part before matrix is added. Other matrix materials such as thermoplastics, may be more suitable for this process.

Example

[0062] The following example describes a 3-phase axial flux permanent magnet

(AFPM) machine based on EMCM technology. An AFPM uses a magnetic field parallel to the machine's axle 4 in creating torque. The short distance between the opposing magnetic poles of the two stators 2 eliminates the need for a ferromagnetic core for guiding the magnetic flux. The machine is made up from two stators 2 consisting of permanent magnets backed by a steel disc, which provides structural support and guides the magnetic field (see Figure 16a). The rotor 1, which is made from EMCM, is attached to the axle 4, which is held in place by two bearings 3. The pin-guided winding process described above may be suitable for manufacturing the rotor 1. [0063] The conductive fibers are wound according to the pattern illustrated in Figure

17. Imposing electric current through the conductors will result in a magnetic field, as indicated by the arrows (dot=arrow tip, cross=arrow tail). An electric controller or a mechanical system based on brushes contacting a commutator can be used in changing polarity of the three conductors, causing the magnetic field to change direction. The pattern indicated in Figure 17 is curved around a center axis, resulting in a disc-shaped rotor, as shown in Figure 16c.

[0064] One of the benefits of EMCM is that the electrical conductors represent an integrated part of the structural support. As a result, a rotor made from EMCM will be more lightweight and support higher rotational speed compared to traditional designs where separate coils of copper are held in place by a mechanical structure.

[0065] Enclosing the conductive fibers inside a non-magnetic structure will also reduce or eliminate unintended buckling of rotor and/or stator components, which can be experienced in axial flux permanent magnet (AFPM) machines and similar structures. This property is particularly important for designing large-scale turbines. Traditional, large- diameter rotors made from ferromagnetic material will be affected by the magnetic field in which the coils travel to produce electricity. The rotors must exhibit high bending stiffness, so as to avoid sticking to the permanent magnets. EMCM is expected to eliminate this problem, supporting the development of large-diameter, high-power, and lightweight axial flux generators.

[0066] Parts made from EMCM are sealed units, a quality that can make them particularly suitable for harsh operating conditions, such as corrosive environments, or underwater installations.

[0067] The EMCM-technology may offer increased design flexibility and improved performance in electromagnetic devices, such as motors, generators, resonators, solenoids, etc. Application areas that may benefit from the introduction of EMCM include:

1. Wheel motors

[0068] The concept may offer significant weight savings, thereby reducing the unsprung mass when installed in cars, scooters, etc.

2. Windmill or tidewater generators

[0069] The concept may offer significant weight savings, easing the structural requirements for such installations. 3. Motors and/or generators for harsh operating environments

[0070] Parts made from EMCM are sealed units, a quality that can make them particularly suitable for harsh operating conditions, such as corrosive environments, or underwater installations.

4. High-speed motors/generators

[0071] A rotor made from composite material may offer higher strength, and thus permit higher angular speed for motors/generators. This may be particularly relevant for large-scale generators.

5. Lightweight, low-cost, and/or flexible power transformers

[0072] An AC transformer can be made by installing two or more coil-shaped circuits on a patch of material. AC current is run through the input coil, imposing a magnetic field. The changing magnetic field induces electricity in the output coil(s).

6. Curved or flat plates

[0073] Can be used in setting up a steady or varying magnetic field, applicable for transmitting electricity wirelessly or support propulsion and/or elevation for mag-lev (magnetic levitation) designs.

[0074] The invention being thus described, it will be obvious that the same may be varied in many ways. Such variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.

Claims

What is claimed is:

1. A composite drive unit, comprising:

a composite material including conductive fibers (14) as an integrated part of the composite material,

wherein the conductive (14) can be organized in different patterns, and wherein each of the conductive fibers (14) is terminated to an electrical conductor (27).

2. The composite drive unit according to claim 1, further comprising:

a stator (2); and

a moving part (1),

wherein said stator (2) and/or said moving part (1) includes said conductive fibers (14) embedded in a matrix material (12), said conductive fibers (14) being connected to a source of electricity to generate a magnetic field (18).

3. The composite drive unit according to claim 1, wherein the composite drive unit is constructed as an electric motor.

4. The composite drive unit according to claim 1, further comprising a coil, which is an integral structural component, wherein the coil functions as reinforcement fiber in a composite material, and wherein the fibers may be ferromagnetic or ferrimagnetic.

5. The composite drive unit according to claim 4, wherein the ferromagnetic or ferrimagnetic fibers may also be integrated in the material, so as to guide the magnetic flux, and may also be used as electromagnetic conductors.

6. The composite drive unit according to claim 2 wherein the composite drive unit is constructed as an electromagnetic generator.

7. The composite drive unit according to claim 6, wherein the composite drive unit is constructed as a wheel motor, windmill or tidewater generator, a high-speed motor or generator, or a transformer.

8. A material for a composite drive unit, comprising: a plurality of conductive fibers (14) arranged in a predetermined pattern (30), said plurality of conductive fibers (14) being embedded in a matrix material (12),

wherein said plurality of the conductive fibers (14) are connectable to a source of electricity to generate a magnetic field for operating the composite drive unit.

9. A method of making a composite material for a composite drive unit, comprising the steps of:

arranging a plurality of conductive fibers (14) in a predetermined pattern (30);

embedding said plurality of conductive fibers (14) in a matrix material (12) to make a composite material; and

etching edges of the composite material,

wherein said plurality of conductive fibers (14) are connectable to a source of electricity to generate a magnetic field for operating the composite drive unit.

10. The method of making a material for a composite drive unit according to claim 9, further comprising the steps of:

combining the plurality of conductive fibers (14) with structural fibers (10); and winding the plurality of conductive fibers (14) and the structural fibers (10) on a mandrel,

wherein said step of embedding the plurality of conductive fibers (14) in a matrix material (12) includes adding the matrix material (12) during the winding process.

11. The method of making a material for a composite drive unit according to claim 9, further comprising the steps of:

weaving the plurality of conductive fibers (14) into plies with structural fibers (10); and

assembling the plies,

wherein said step of embedding the plurality of conductive fibers (14) in a matrix material (12) includes adding the matrix material (12) during the weaving and assembling steps.

12. The method of making a material for a composite drive unit according to claim 9, further comprising the steps of: providing a base (24) having a chamfered surface (36), a plurality of pins (26, 34) and a central peg (32); and

winding structural fibers (10) around the pins (26, 34) and the central peg (32), wherein the structural fibers (10) are maintained in close contact with the base (24).

13. A method of making a composite material for a composite drive unit, comprising the steps of:

inserting pins (26) into a foam base (24) covered with a non-stick material (28);

winding a plurality of conductive fibers (14) in predetermined patterns (30) using the pins (26) to hold the plurality of conductive fibers (14) in place; and

embedding said plurality of conductive fibers (14) in a matrix material (12) to make a composite material,

wherein said plurality of conductive fibers (14) are connectable to a source of electricity to generate a magnetic field (18) for operating the composite drive unit.

14. The method of making a composite material for a composite drive unit according to claim 12, further comprising the steps of:

covering the embedded conductive fibers (14) with a sheet of non-stick material (28); pressing a foam block (24) onto the non-stick material (28), so that the pins (26) protrude through a top of the non-stick material (28) and into the foam block (24), resulting in compression on the embedded conductive fibers (14);

curing the embedded conductive fibers (14) while under compression; and

removing the foam-blocks (24), non-stick materials (28), and pins (26) to form the composite material.

The patent pending of Alva Motor Solutions in current version

**********************SENSITIVE INFORMATION**********************

Not to be shared or published before the three valid year standard agreement contract with NTNU is outdated.

Application number:

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Reference: U3875

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Title: Method for production of stator or rotor component for electrical machine and stator or rotor component for electrical machine

Method for production of stator or rotor component for electrical machine and stator or rotor component for electrical machine

The present invention is related to production of stator or rotor component for electrical machine according to the preamble of claim 1.

The present invention is also related to a stator or rotor component for electrical machine according to the preamble of claim 11.

Background

As electrical motors are becoming more abundant in different application it has lately been an increasing focus on developing high performance electric motors, generator or other electrical machine in more cost-efficient manner.

In US2014333169 A1 is described a design for a method of winding an electric motor, generator or other electrical machine using multiple strands of wire preformed into a wave shape with a plurality of legs connected by shaped end turns. This results in efficient packing and improved machine performance in terms of both efficiency and power density without the need for flux concentrators. The conductors or windings may be preformed so as to be a self supporting structure, aiding assembly and eliminating the need for an iron core.

From US20120080970 A1 is known a high voltage and high temperature winding insulation for electrical submersible pump motors. It is described a litz wire including, in one embodiment, a plurality of twisted strands, wherein one or more of the strands includes a composite magnet wire. The composite magnet wire includes a metal wire having a nanocoating on its outer surface. The nanocoating includes an electrical insulating polyimide matrix and a plurality of alumina nano particles dispersed homegenueoslytherein. The alumina nano particles have a phenyl siloxane surface coating. Motors and ESP assemblies utilizing the litz wire are also disclosed.

In US2003001441 A1 is described a stator construction for high performance rotating machines. A rotating machine is provided which includes a stator having a number of field winding slots; a number of field windings disposed in each of the field winding slots, at least two of the field windings have: an outer jacket; and a number of conductive wires disposed within and enclosed by the outer jacket such that longitudinal passages are defined between the conductive wires; and circulation means for circulating a coolant into and from the rotating machine through the longitudinal passages. Preferably, the rotating machine further includes a housing which has a cavity for acceptance of the stator therein. The housing and stator define first and second plenums at first and second ends of the stator. The coolant enters the rotating machine into the first plenum and exits the rotating machine from the second plenum.

From EP1633032 A1 is known an electrical machine with coils which are interconnected to form one or more windings. The coils are made up of at least two sub-coils, connected in series, the sub-coil closest to the airgap having strands in each turn which have a smaller cross sectional area than the strands in the turns in other sub-coils. This arrangement reduces the high-frequency loss in the windings while minimizing any penalty associated with introducing stranding to the coil.

A solution which improves the above mentioned solution is known from WO201203299 A2 where it is described a composite drive unit including a composite material comprising conductive fibers as an integrated part of the composite material. The conductive fibers can be organized in different patterns, and each of the conductive fibers is terminated to an electrical conductor. A material for a composite drive unit includes a plurality of conductive fibers arranged in a predetermined pattern. The plurality of conductive fibers are embedded in a matrix material, and the conductive fibers are connectable to a source of electricity to generate a magnetic field for operating the composite drive unit.

In WO2013169945 A1 is described a rotating electromechanical apparatus including a cylindrical ironless stator coil comprising a plurality of wires, a magnetic rotor arranged with the stator coil, wherein the magnetic field flux associated with the rotor interacts with the stator coil wires by electromagnetic induction, a cylindrical bobbin arranged to support the wires, a strand woven on at least the outer circumference of the wire-wrapped cylindrical bobbin, and a curable potting material potting the wires, bobbin and strand to provide an ironless composite stator coil when cured.

The prior art solutions fail to disclose scalable and flexible production methods for ironless/slotless electrical machines of any design or size, but will be limited to specific electrical machines.

Further, a disadvantage of prior art solutions is among others that they fail to disclose a method for production of and stator or rotor component for electrical machine which can be customized for different areas of use.

It is further a disadvantage of prior art solutions is that they fail to disclose a method for production of and stator or rotor component which is easy to adapt according to requirements.

Prior art further fails to disclose to provide a method for production of and stator or rotor component enabling opportunities for altering the design and/or properties of the stator or rotor component, and thus the electrical machine, in a simple manner.

Lightweight is crucial in emerging markets like drones, automotive, aerospace, etc., which will increase the need for methods for production of and rotor or stator of slotless/ironless designs for electrical machines.

There is further a need for a method for production of and stator or rotor component which enables production of ironless or slotless electrical machines.

For ironless stator or rotors there is further a need for providing stator or rotor with increased mechanical stability to meet requirements.

Today, automatic winding equipment is very expensive and customized for a low number of products. There is accordingly a need for a method for production of and stator or rotor components that will cut production steps and costs.

Accordingly, there exists no generalized method in the present market for production of stator or rotor with any winding configuration.

Object

The main object of the present invention is to provide a method for production of stator or rotor component for electrical machine and stator or rotor component for electrical machine partly or entirely solving the above mentioned drawbacks/lacks of prior art.

It is further an object of the present invention to provide a method for production of and stator or rotor component for electrical machine enabling opportunities for altering the design in a simple matter.

An object of the present invention is to provide a method for production of and stator or rotor component for electrical machine with electromagnetic, mechanical and/or thermal properties.

It is an object of the present invention to provide a method for production of and stator or rotor component for electrical machine based on weaving, twinning or winding of fiber warps with non-conductive surface and electrical conductor fiber wefts.

An object of the present invention is to provide a method for production of and stator or rotor for electrical machine formed by an electromagnetic mat that can be rolled up or folded to form a stator or rotor component, which can be used in rotary or linear electric machines.

It is an object of the present invention to provide a method for production of and stator or rotor component for electrical machine formed by an electromagnetic mat that can be molded with a curable liquid potting material, as epoxy/resin, to ensure higher mechanical strength, improved heat transfer, etc. for the stator or rotor component.

An object of the present invention is to provide a method for production of and stator or rotor component for electrical machine that can be used as stator or rotor components in a wide range of applications.

An object of the present invention is to provide a method for production of and stator or rotor component for electrical machine which in a simple manner can be tailored as regards design and properties the electrical machine.

It is an object of the present invention to provide a method for production of and stator or rotor component for electrical machine which results in lower production costs, both for mass production and low volume products.

It is an object of the present invention to provide a method for production of and stator or rotor component for electrical machine enabling new electrical machine design possibilities through novel combinations of materials and winding designs.

It is further an object of the present invention to provide a method for production of and stator or rotor component for electrical machine which results in simplified winding of larger electrical machines.

It is an object of the present invention to provide a method for production of and stator or rotor component for electrical machine which simplify production of large electric machines.

An object of the present invention is to provide a method for production of and iron-cored, ironless or slotless stator or rotor for electrical machines.

It is an object of the present invention to provide a method for production of and ironless or slotless stator or rotor components for electrical machine with increased thermal properties

It is an object of the present invention to provide a method for production of and very thin iron-cored, ironless or slotless stator or rotor components for electrical machine.

Further objects of the present invention will appear from the following description, claims and attached drawings.

The invention

A method for production of a stator or rotor component for an electrical machine according to the present invention is disclosed in claim 1. Preferable features of the method are described in the dependent claims.

A stator or rotor for electrical machine according to the present invention is disclosed in claim 11. Preferable features of the electrical motor are described in the dependent claims.

The present invention provides a novel production method for stator or rotor components with electromagnetic, mechanical and/or thermal properties.

By electromagnetic properties is understood herein properties as conductive, insulating, magnetic, etc.

According to a method for production of rotor or stator component of an electric machine according to the present invention the method comprises an initial step of weaving, twinning or winding an electromagnetic mat consisting of at least two fiber warps with non-conductive surface in longitudinal direction of the electromagnetic mat and at least one winding formed by:

at least one continuous electrical conductor fiber weft extending mainly in transversal direction of the electromagnetic mat, or

cut electrical conductor fiber wefts extending in mainly transversal direction of the electromagnetic mat and connected at end windings to create at least one continuous conductor fiber weft,

wherein the at least one continuous electrical conductor fiber weft is aligned in a winding pattern so as to create a moving electromagnetic field when induced with an alternating current or constant electromagnetic field when induced with direct current.

Fiber warps with non-conductive surface can according to the present invention be formed by a conductive core with an insulating layer or be formed by a non-conductive material or several non-conductive materials.

The term transversal direction is not limited to perpendicular direction, but also covers that the fiber wefts extend with a direction deviating from the perpendicular direction.

By fiber is understood herein any material or materials that can be formed to a long thread.

According to one embodiment of the method according to the present invention the method further comprises weaving, twinning or winding alternating non-conductive fiber wefts and/or fiber wefts with mechanical, electromagnetic and/or thermal properties and cut or continuous electrical conductor fiber wefts in transversal direction of the electromagnetic mat. By this the mechanical, electromagnetic and/or thermal properties of the electromagnetic mat and thus stator or rotor component can be altered to exhibit desired properties.

According to one embodiment of the present invention the method comprises an intermediate step of impregnation of the electromagnetic mat with a curable liquid potting material, as epoxy or resin. This step can be performed at different stages of the production process as is explained in the example description.

In the embodiment with the use of cut electrical conductor fiber wefts the method comprises an intermediate step of connecting end windings of the cut electrical conductor fiber wefts, so to create continuous electrical conductor fiber wefts for the purpose of creating different winding pattern designs. Also this step can be performed at different stages of the production process as is explained in the example description.

In a further embodiment of the present invention the method comprises an intermediate step of rolling the electromagnetic mat in one or multiple layers on a base or object, or folding the electromagnetic mat in one or multiple layers to form a desired geometrical shape for the rotor or stator component.

In a further embodiment of the method according to the present invention the method comprises weaving, twinning or winding the electromagnetic mat with at least two windings formed by electrical conductor fiber wefts. Accordingly, a stator or rotor component according to the present invention can be formed by at least two windings appropriately connected in serial/parallel to a desired winding pattern, hereunder also three or more windings.

According to a further embodiment of the method according to the present invention the method comprises weaving, twinning or winding the electromagnetic mat with fiber warps with non-conductive surface of different lengths so as to form a circular, S-shaped, 8-shaped, helical electromagnetic mat or other desired shapes.

In a further embodiment of the method according to the present invention the method comprises weaving, twinning or winding the electromagnetic mat with both fiber warps with non-conductive surface and fiber warps with mechanical, electromagnetic and/or thermal properties. By this an electromagnetic mat with varied properties can be achieved.

According to a further embodiment of the method according to the present invention the method comprises weaving, twinning or winding the electromagnetic mat with fiber warps with non-conductive surface, fiber warps with mechanical, electromagnetic and/or thermal properties, electrical conductor fiber wefts, non-conductive fiber wefts and/or fiber wefts with mechanical, electromagnetic and/or thermal properties extending in at least one dimension, two dimensions or three dimensions.

In a further embodiment of the method according to the present invention the method comprises arranging objects, such as magnets or pipes, in the electronic mat. E.g. water pipes can be arranged for improved cooling properties.

According to a further embodiment of the method according to the present invention the method comprises a final step of forming the electromagnetic mat to a shape of a rotor or stator component and molding/encapsulating the formed electromagnetic mat with a curable liquid potting material, as epoxy/resin.

A rotor or stator component of an electric machine according to the present invention is formed by a woven, twinned or winded electromagnetic mat consisting of at least two fiber warps with non-conductive surface extending in longitudinal direction of the electromagnetic mat and at least one winding formed by.

at least one continuous electrical conductor fiber weft extending in mainly transversal direction of the electromagnetic mat, or

cut electrical conductor fiber wefts extending in mainly transversal direction of the electromagnetic mat and connected at end windings to create at least one continuous conductor fiber weft, wherein the at least one continuous electrical conductor fiber weft is aligned in a winding pattern creating a moving electromagnetic field when induced with an alternating current or constant electromagnetic field when induced with direct current. Accordingly, by connecting the at least one winding to an AC or DC power source a moving or constant, respectively, electromagnetic field can be created. Further, when brushes are used, DC current can be applied to create an AC current.

By the above described is achieved an iron-cored, slotless or ironless stator or rotor component.

In a further embodiment of the rotor or stator component according to the present invention the electromagnetic mat is woven, twinned or winded with alternating non-conductive fiber wefts and/or fiber wefts with mechanical, electromagnetic and thermal properties and cut or continuous electrical conductor wefts in transversal direction of the electromagnetic mat. In this way the stator or rotor component can be added properties, hereunder also providing the stator or rotor component with iron teeth, back iron or similar.

According to one embodiment of the rotor or stator component according to the present invention the electromagnetic mat is impregnated with a curable liquid potting material, as epoxy or resin. This can be performed at different stages in the production process as will be described in the following example description.

According to one embodiment of the rotor or stator component according to the present invention the electromagnetic mat comprises both fiber warps with non-conductive surface and fiber warps with mechanical, electromagnetic and/or thermal properties. By this one can add e.g. enhanced thermal properties to the stator or rotor component.

In one embodiment of the rotor or stator component according to the present invention the electromagnetic mat is rolled or folded in one or multiple layers to form a desired geometry for the rotor or stator component.

According to one embodiment of the present invention of the rotor or stator component the electromagnetic mat is formed to a shape of a rotor or stator component and molded/encapsulated in a curable liquid potting material, as epoxy or resin. In this way the shape will be maintained as well as strengthened.

In a further embodiment of the rotor or stator component according to the present invention the electromagnetic mat comprises at least two, at least three or more, windings, formed by connected cut electrical conductor fiber wefts or continuous electrical conductor fiber wefts.

According to a further embodiment of the rotor or stator component according to the present invention the fiber warps with non-conductive surface exhibit different length so as to form a circular, S-shaped, 8-shaped, helical or otherwise shaped electromagnetic mat.

In a further embodiment of the stator or rotor component according to the present invention, the electronic mat is provided with objects, such as magnets or pipes. E.g. water pipes can be arranged for improved cooling properties.

Further preferable features and advantageous details of the present invention will appear from the following example description, claims and attached drawings.

Example

The present invention will below be described in further detail with references to the attached drawings, where:

Fig. 1 is a principle drawing of weaving of a mat according to prior art,

Fig. 2 is a principle drawing of electromagnetic mat for a stator or rotor component according to the present invention,

Fig. 3a-c are principle drawings of further embodiments of the electromagnetic mat according to the present invention,

Fig. 4a-b are principle drawings of EM-design patterns according to the present invention,

Fig. 5 is a principle drawing of a rolled-up electromagnetic mat according to the present invention,

Fig. 6a-c are principle drawings visualizing one of the embodiments of the production method according to the present invention,

Fig. 7a-d are principle drawings of an electromagnetic mat according to one embodiment of the present invention and connection of cut electrical conductor fiber wefts,

Fig. 8 is a principle drawing of windings formed by continuous electrical conductor fiber wefts,

Fig. 9 is a principle drawing of a further embodiment of the present invention, with fiber wefts with mechanical, electromagnetic and/or thermal properties,

Fig. 10-11 are principle drawings of an electromagnetic mat according to the present invention with multiple layers,

Fig. 12 shown principle drawings of an electromagnetic mat according to the present invention in different dimension,

Fig. 13-14a-b are principle drawings of weaving of a shaped electromagnetic mat,

Fig. 15 is a principle drawing of production of stator or rotor components for four machines at the same time,

Fig. 16a-c are principle drawing of production of an electromagnetic mat by means of twinning,

Fig. 17 is a principle drawing of the use of an electromagnetic mat according to the present invention for twin motors, and

Fig. 18 is a principle drawing of an application of the twin motor in Figure 17.

Reference is now made to Figure 1 which is a principle drawing of weaving of a mat according to prior art. A woven mat is formed by fibers extending in longitudinal direction of the mat (X-fibers) called warps, and fibers extending in transversal direction of the mat (Y-fibers) called wefts. There exists different types of weaving which can be utilized in the present invention, hereunder, twill, satin, Dutch, etc.

The present invention is based on using this technique for production of stator or rotor components of rotary or lineary electrical machines by production of an electromagnetic mat 10.

In a first embodiment of the present invention there is provided a 2D electromagnetic mat with fiber warps with non-conductive surface extending in longitudinal direction of the electromagnetic mat and at least one winding formed by at least one continuous electrical conductor fiber wefts extending mainly in transversal direction of the electromagnetic mat or cut electrical conductor fiber wefts extending in mainly transversal direction of the electromagnetic mat and connected at end windings to create at least one continuous conductor fiber weft, wherein the at least one continuous electric conductor fiber weft or cut electrical conductor fiber weft is formed by electrical conductors.

According to the present invention the at least one continuous electrical conductor fiber weft is aligned in a winding pattern creating a moving electromagnetic field when induced with an alternating current or constant electromagnetic field when induced with direct current from a power supply source.

The winding pattern formed by the electrical conductor fiber weft pattern can according to the present invention be adapted/modified according to different applications requiring different motor designs.

For rotating motors the electromagnetic mat 10 can according to one embodiment of the present invention be rolled up on a geometrically shaped object (base), typically a mainly cylindrical shape, formed and casted/molded with a curable liquid potting material, as resin or epoxy. The stator or rotor component can be removed from the object or base and is ready to be assembled with the other electric motor components.

As will be described in further detail below the electromagnetic mat can also comprise fiber warps with mechanical, electromagnetic and/or thermal properties.

According to the present invention the fiber warps with non-conductive surface or fiber warps with mechanical, electromagnetic and/or thermal properties are fibers or threads with mechanical, electromagnetic and/or thermal properties, e.g. fiberglass, Kevlar, carbon fiber, or similar, and can be in any form (flat, circular, other) and size (diameter, length/width). Accordingly, the fiber warps non-conductive surface or fiber warps with mechanical, electromagnetic and/or thermal properties can be formed by materials suitable for forming a single- or multidimensional grid, hereunder be formed by either a single fiber or thread type, or a mix of different fibers or threads. The number of warps with non-conductive surface in the electromagnetic mat will be at least two.

The fiber warps with non-conductive surface (and possible fiber warps with mechanical, electromagnetic and/or thermal properties) will, according to the present invention, keep electrical conductor fiber wefts in place in the electromagnetic mat by acting as a supporting grid. As will be described below the electromagnetic mat can also comprise fiber wefts with mechanical, electromagnetic and/or thermal properties which will be supported in the same manner as the electrical conductor fiber wefts.

All fiber warps and wefts in the electromagnetic mat will contribute to mechanical support, as well as thermal and/or electromagnetic properties.

The electrical conductor fiber wefts are according to the present invention e.g. made of copper, aluminum, or other conductive materials, as threads or fibers.

In the embodiment where cut electrical conductor fiber wefts are used to form the at least one winding, the cut electrical conductor fiber wefts will after they are arranged to the electromagnetic mat exhibit ends outside of the electromagnetic mat's width, i.e. outside the grid formed by the warps with non-conductive surface and possibly warps with mechanical, electromagnetic and/or thermal properties, where they can be connected by desired connectors to form continuous electrical conductor fiber warps as described above.

According to the present invention the electrical conductor fiber wefts can have any geometrical form (flat/circular/other) and size (diameter/length/width) and will be based on the desired design of the stator or rotor component, or general requirements of the winding of the electrical machine.

Reference is now made to Figure 2 which is a principle drawing of electromagnetic mat 10 for a stator or rotor component according to the present invention, where the electromagnetic mat 10 is formed by fiber warps 20 with non-conductive surface and windings formed by electrical conductor fiber wefts 30. In a) shows eight un-connected cut electrical conductor fiber wefts 30 inserted into the grid formed by fiber warps 20 with non-conductive surface. The following figures, b) to e), shows different ways/combinations of connecting these cut electrical conductor fiber wefts 30 so to create different winding pattern (EM-fields): b) shows 2-phase, concentrated winding, c) shows 3-phase, wave winding, d) shows 2-phase, distributed winding, e) shows 2-phase, wave winding, 2 electrical conductors fiber wefts 30 per phase.

The EM-design is e.g. given by the inner and outer diameter of the stator or rotor component for rotary machines, and length and thickness for linear machines. This information can, according to the present invention, be used for calculating the total length of the electromagnetic mat 10, and the number of layers in total. As circumference increase, each new layer will be slightly longer than the layer within. For each new "layer length" of the electromagnetic mat 10 the electrical conductor fiber wefts 30 can thus be separated more so that they fall onto their correct position (independent of diameter, the angle of slots will be constant).

Reference is now made to Figures 3a-c which are principle drawings of forming of a stator or rotor component according to the present invention. According to the present invention the electromagnetic mat 10 can be pulled linearly and cut, or rolled up on an object or base, typically mainly cylindrical, for rotary electrical machines. For linear electrical machines the electromagnetic mat 10 will typically be folded.

In Figure 3a it is shown a principle drawing showing first a grid of fiber warps 20 with non-conductive surface and electrical conductor fiber wefts 30, wherein it between the electrical conductor fiber wefts 30, seen in longitudinal direction of the electromagnetic mat 10, are arranged non-conductive fiber wefts 40, wherein the non-conductive fiber wefts 40 can be arranged to provide insulation or other mechanical or thermal properties. As will be described below there can also be arranged fiber wefts with electromagnetic properties. In the shown embodiment the windings are formed by cut electrical conductor fiber wefts 30 that are connected outside of the grid (arrows) formed by the fiber warps 20 with non-conductive surface, non-conductive fiber wefts 40 and cut electrical conductor fiber wefts 30. Below is shown the resulting EM-field - alternating north and south poles - when current is applied in the direction of the arrows.

In Figure 3b it is shown a principle drawing showing first a 2D-pattern of conductors. Initially, all electrical conductor fiber wefts 30 are the same. Letters A, B, C indicates which cut electrical conductor fiber wefts 30 that are to be connected together to form Phase A, Phase B and Phase C. Below is shown how the electromagnetic mat 10 can be rolled up on a cylindrical object or base 50.

In Figure 3c is shown a principle drawing showing folding of the electromagnetic mat 10, which can be basis of linear motor components.

Reference is now made to Figures 4a-b showing principle drawings of winding patterns (EM-design) for 1-phase motor and 2-phase motor, respectively, in the form of a 2D-representation. By applying current EM-fields will be induced.

In the production method according to the present invention the winding pattern is e.g. in the form of a barcode pattern that can be changed easily. E.g. by using cut electrical conductor fiber wefts 30 the desired winding pattern (number of wires per slots, number of phases, etc.) can be arranged by connecting the ending windings of the cut electrical conductor fiber wefts 30 after they are arranged in the electromagnetic mat 10. Accordingly, this allows production of a similar electromagnetic mat 10 for different electrical machines as the winding can be arranged at the end.

In the case of continuous electrical conductor wefts 30, the winding pattern (electromagnetic design (number of wires per slots, number of phases, etc.)) will have to be decided during the winding process. This winding pattern (electromagnetic design) can be modified just by modifying how the continuous electrical conductor fiber wefts 30 are inserted.

Thus, by the present invention, regardless if continuous electrical conductor fiber wefts 30 or cut electrical conductor fiber wefts 30 are used, all designs can be created.

As it can be seen in Figures 4a-b and Figure 2, all cut electrical conductor fiber wefts 30 extend mainly in transversal direction in the active area, and makes up a winding pattern. This pattern is different for different types of electric machines, but as regards the production process all cut electrical conductor fiber wefts 30 are the same until connected to other cut electrical conductor fiber wefts 30. Thus, changing the winding pattern (EM-design) (the machine specifications) only affects how the cut electrical conductor wefts 30 are connected.

In the present invention the diameter of the stator or rotor component can easily be changed by changing the geometry of the mainly cylindrical base or object 50 the electromagnetic mat 10 is rolled up on.

Reference is now made to Figure 5 showing a principle drawing of a rolled-up electromagnetic mat 10 according to the present invention. According to the present invention the thickness of a stator or rotor component can easily be changed by rolling/folding more of the electromagnetic mat 10 on top of the other layers. Accordingly, the longer the electromagnetic mat 10, the thicker the component is.

Further, according to the present invention, by adding or removing fiber warps 20 with non-conductive surface (and/or non-conductive fiber wefts 40 and/or electrical conductor fiber wefts 30) the mechanical strength of the stator or rotor component can be altered. This can also be affected by the tension in the fiber warps/wefts, as well as impregnation material and/or molding material chosen. Further, by adding or removing the same also other properties can be altered, such as thermal properties.

A production method for a component according to the present invention will include an initial step of weaving, twinning or winding of electromagnetic mat 10. The method will preferably also comprise a final step of molding. The production method will further preferably comprise intermediate steps for forming through roll-up, folding or other, and impregnation. For the use of cut electrical conductor fiber wefts 30, the method also comprises an intermediate step of connection of end windings thereof. The sequence of intermediate steps can be altered, such that the intermediate steps can be performed in any order, depending on the application or desires, i.e. can be performed in the following orders:

- connection of end windings (only when using cut electrical conductor fiber wefts), roll-up or folding and impregnation,
- connection of end windings (only when using cut electrical conductor fiber wefts), impregnation and roll-up or folding,
- roll-up or folding, connection of end windings (only when using cut electrical conductor fiber wefts) and impregnation,
- roll-up or folding, impregnation and connection of end windings (only when using cut electrical conductor fiber wefts),
- impregnation, roll-up or folding and connection of end windings (only when using cut electrical conductor fiber wefts),
- impregnation, connection of end windings (only when using cut electrical conductor fiber wefts) and roll-up or folding.

Reference is now made to Figure 6a-c which are principle drawings visualizing one of the embodiments of the production method as described above, with continuous electrical conductor fiber wefts 30. In the figures is shown a solution with three phases A, B and C. It should be mentioned that even though only one electronical conductor fiber weft 30 is shown per phase, also several electrical conductor fiber wefts 30 can be used for each phase/winding.

In Figure 6a is shown a principle drawing of the initial step of weaving the continuous electrical conductor fiber wefts 30 into an electromagnetic mat 10 formed by fiber warps 20 with non-conductive surface, where the pattern is customized, based on the motor design.

In Figure 6b is shown a principle drawing of an intermediate step of rolling the electromagnetic mat 10 formed by fiber warps 20 with non-conductive surface and continuous electrical conductor fiber wefts 30 up on a cylindrical base or object 50.

In Figure 6c is shown a principle drawing of the stator or rotor component according to the present invention, i.e. electromagnetic mat 10 after the final step of molding, where the object or base 50 is removed, and the stator or rotor component is ready for integration in an electrical machine and connection of the windings to a power supply source and control system.

In an alternative embodiment according to the present invention the cylindrical object or base 50 is not removed, but is a part of the final stator or rotor component. The properties of the base or object 50 can be of mechanical, electromagnetic, thermal, conductive or other nature.

The intermediate step of impregnation will typically be performed with a curable liquid potting material, as epoxy, resin or similar, which can be applied before or after the roll-up or folding, or the warps 20 and/or wefts 30, 40, 70 can be pre-impregnated.

Reference is now made to Figures 7a-d showing principle drawings of connection of electrical cut conductor fiber wefts 30 of the electromagnetic mat 10.

The figures show the electromagnetic mat 10 formed with cut electrical conductor fiber wefts 30 through the winding process. After the electromagnetic mat 10 is created, each cut electrical conductor fiber weft 30 is to be connected to its respective partner(s).

In Figure 7a is shown a principle drawing of an electromagnetic mat 10 with cut electrical conductor fiber wefts 30. The length in this example corresponds to two layers. Each cut electrical conductor fiber weft 30 is to be connected to the neighboring cut electrical conductor fiber weft 30 of same phase. In the shown example the winding pattern is wave winding. In Figure 7b is shown a principle drawing of the electromagnetic mat 10 in Figure 7a rolled up on a cylindrical base or object 50 seen from above. Arrows show how the cut electrical conductor fiber wefts 30 are connected, where thick arrow for front side, dotted arrow for back side.

According to the present invention the cut electrical conductor fiber wefts 30 can be connected before or after the rotor or stator component is formed.

In Figures 7c and 7d is shown an example of how cut electrical conductor fiber wefts 30 can be connected. Using cut electrical conductor fiber wefts 30 will simplify the production method. In that case, connections between respective cut electrical conductor fiber wefts 30 will have to be performed.

In Figure 7c is first shown a connection strip 60, formed by a conductive material 61 enclosed by insulating (non-conductive) material 62 at three of the sides thereof which can be used for connection of cut electrical conductor fiber wefts 30. Below is shown how the end windings/cut electrical conductor fiber wefts 30 of the electromagnetic mat 10 is connected to different connection strips 60, where each phase A, B, and C, is connected to separate connection strips 60.

In Figure 7d is shown an example of how each connection strip 60 can be inserted during the production process, where cut electrical conductor fiber wefts 30 are inserted in the same way as in the electromagnetic mat 10.

Reference is now made to Figure 8 showing a principle drawing of continuous electrical conductor wefts 30. Accordingly, an alternative embodiment of cut electrical conductor fiber wefts 30 is continuous electrical conductor fiber wefts 30, where instead of cutting the electrical conductor wefts 30 for each time it is passed over the grid of the warps 20 with non-conductive surface, and possibly warps with other properties, in the electromagnetic mat 10, the electrical conductor fiber wefts 30 are continuous. In Figure 8 is shown an example of 3-phases, with three continuous electrical conductor fiber wefts 30 per phase, where only the continuous electrical conductor fiber wefts 30 are shown. The continuous electrical conductor fiber wefts 30 can be arranged as last in - first out-principle or first in - first out-principle.

Here one can e.g. utilize multi-shuttle weaving, where each shuttle is in control of one or more continuous electrical conductor fiber wefts 30.

Accordingly, by the present invention it is provided a multidimensional grid with multiple properties.

Reference is now made to Figure 9 which shows a principle drawing of a further embodiment of the present invention, where there are arranged fiber wefts 70 with mechanical, electromagnetic and/or thermal properties, e.g. ferromagnetic, arranged between the electrical conductor fiber wefts 30 creating a slotted (iron-cored) stator or rotor component. The density and variations of these fiber wefts 70 can be modified so they create unique electromechanical or mechanical (or other) properties. In the shown example the pattern alternates between electrical conductor fiber wefts 30 and fiber wefts 70 with mechanical, electromagnetic and/or thermal properties. When the electromagnetic mat 10 is rolled up, the fiber wefts 70 with mechanical, electromagnetic and/or thermal properties, e.g. formed by iron fibers, form iron slots. This will mimic the properties of iron-cored electrical machines with iron teeth. For this setup, back-iron is not needed. The density of fiber wefts 70 with mechanical, electromagnetic and/or thermal properties can be chosen so to create a lightweight stator or rotor component with good mechanical, electromagnetic and/or thermal properties.

In a further embodiment of the present invention the electromagnetic mat 10 also comprises, in addition to warps 20 with non-conductive surface, warps exhibiting mechanical, electromagnetic and/or thermal properties, so to guide the magnetic flux, or work as a heat sink. For a combination of fiber warps and fiber wefts with mechanical, electromagnetic and/or thermal properties, e.g. back iron could be created by applying layers of these mechanical, electromagnetic and/or thermal properties on top of, under, or between layers.

In yet a further embodiment according to the present invention Z-fibers can be introduced, i.e. fibers extending in mainly vertical direction of the electromagnetic mat 10. By introducing Z-fibers, both electromagnetic and mechanical properties can be altered. Z-fibers could be added for support by e.g. stitching the layers of the electromagnetic mat 10 together. Z-fibers could also have e.g. flux carrying properties. In this way, iron slots can be created as described above, but with the fiber in the radial direction.

In an alternative embodiment, instead of using Z-fibers directly in the production, electromagnetic mats 10 can be arranged/folded on top of each other and stitched together with fibers in Z-direction.

Reference is now made to Figure 10 showing a principle drawing of an electromagnetic mat 10 according to the present invention with multiple layers. One of the major benefits of the production method is the flexible way of adding material in the thickness direction, simply by rolling up/adding more layers of the electromagnetic mat 10.

As the circumference increases with each new layer of the electromagnetic mat 10, the length of each layer also increases. That means that the pattern also should be more spread out, or distributed. If each layer of the electromagnetic mat 10 is designed to be the same length then the slots for each new layer of the electromagnetic mat 10 will be placed slightly "off-set". For several layers, the effect would be as shown in Figure 11.

According to the present invention electrical conductor fiber wefts 30 are inserted and arranged in a pattern which can be used to form a stator or rotor component, e.g. for electromagnetic purposes. The direction of the electrical conductor fiber wefts 30, relative to each other, can be in several dimensions, thus providing such as 2-dimensional or 3-dimensional winding. Reference is here made to Figure 12 which is a principle drawing of examples of different winding patterns which can be achieved.

In Figure 12 X-direction is in the direction of the fiber warps 20, while Y-direction is the direction perpendicular to X and the direction of the fiber wefts 30, in the same plane, and Z-direction is in a direction perpendicular to both X and Y. In the example a) the electrical conductor fiber wefts 30 extend in parallel and only in the "normal" Y-direction inside the "active area". In the shown example b) the electrical conductor fiber wefts 30 extend in parallel, in YX-direction. The electrical conductor fiber wefts 30 form a constant angle with the fiber warps 20 non-conductive surface inside the "active area". In the example c) the electrical conductor fiber wefts 30 move in parallel in YX and XY direction. The electrical conductor fiber wefts 30 form a constant angle with the fiber warps 20 with non-conductive surface, but change direction for each "turn". This pattern can be described as a tilted or zig-zag pattern. In the example d) the fiber warps 20 with non-conductive surface are formed in two (or more) layers, creating a 3D-grid. The electrical conductor fiber wefts 30 extends in YX-, XY- and Z-direction, thus in all directions simultaneously. The electrical conductor fiber wefts 30 do not need to be aligned, meaning some electrical conductor fiber wefts 30 could extend in ZY-direction, some in XY-direction and some in XYZ-direction, simultaneously. Accordingly, forming a 3D winding.

If the electrical conductor fiber wefts 30 are arranged in other dimensional directions than Y-direction, the forming of the stator or rotor component might have to be performed differently. E.g. the electromagnetic mat 10 can be plied onto something, instead of rolled up or folded. In an alternative embodiment the 3D-winding would take place on, around, or through a previously made stator or rotor component, e.g. a cube or rectangle with holes.

Reference is now made to Figure 13 which is a principle drawing of an electromagnetic mat 10 with bended/curved shape which is a further embodiment according to the present invention. By utilizing a variation of the embodiments of the present invention, an electromagnetic mat 10 could be woven, twinned or winded as for the prior embodiments, but where it exhibits a bended/curved shape. This can be achieved by that the fiber warps 20 with non-conductive surface exhibit different lengths. This can e.g. be solved by allowing different pull-up speeds for different fiber warps 20 with non-conductive surface. The result will be a bended/curved electromagnetic mat 10, as shown in Figure 13. In Figure 13 it is shown electrical conductor fiber wefts 30 inserted into a bent/curved grid formed by warps 20 with non-conductive surface. In the shown example the bend/curve is constant, and represent a circle with a constant inner and outer diameter. The electrical conductor fiber wefts 30 will be arranged in radial direction, and the grid is formed by warps 20 with non-conductive surface in tangential direction. Also this embodiment can make use of wefts 40, 70 as well as warps with mechanical, electromagnetic and/or thermal properties as described above.

By changing/altering the rate of bending (curvature) the resulting electromagnetic mat 10 can be shaped as for example a circle, an "S" or the number "8".

One application for this electromagnetic mat 10 with bended/curved shape is electrical axial-flux machines. Electrical axial-flux machines have their magnetic flux in the axial direction. This can, according to the present invention, be achieved by providing a bended/curved electromagnetic mat 10 to create the form of a helix. By collapsing the helix a desired disc-shaped single- or multi-layered electromagnetic mat 10 is created, as shown in Figure 14, where a) shows a helix-shaped electromagnetic mat 10, and b) shows the collapsed helix-shaped electromagnetic mat 10 forming a disc-shaped multi-layered stator or rotor component.

Accordingly, also this embodiment benefits from the advantages of the prior described embodiments, including the design of the pattern of the electrical conductor fiber wefts 30, geometry, connection of the electrical conductor fiber wefts 30, and the use of cut or continuous electrical conductor fiber wefts 30.

Also this embodiment will have flexibility in that distance between outermost non-conductive warps 20, in combination with the "bending angle" (curvature), determines inner and outer diameter of stator or rotor component. Further, thickness of each layer, and number of layers of the electromagnetic mat 10 can be used to decides thickness of the stator or rotor component.

Also this embodiment can make use of the above described warps or wefts with other properties, i.e. the use of fiber warps or fiber wefts with mechanical, electromagnetic and/or thermal properties. For example could iron fiber wefts and/or fiber warps be used to create iron teeth or back-iron, for increased magnetic flux.

Similar to the above embodiments also this embodiment can make use of the intermediate step of impregnation and molding to form the final stator or rotor component.

Reference is now made to Figure 15 showing a principle drawing of production of stator or rotor components for four machines at the same time, wherein dotted lines show where they can be cut after the electromagnetic mat 10 is formed. For a set of equal stator or rotor components, the pattern of fiber warps and wefts will be identical. By increasing the width of the electromagnetic mat 10 formed by the fiber warps 20 with non-conductive surface (and possibly fiber warps with mechanical, electromagnetic and/or thermal properties) is increased e.g. by a factor of 4 (plus necessary buffer), as well as the lengths of each electrical conductor fiber weft 30, non-conductive fiber wefts 40 and/or fiber wefts 70 with mechanical, electromagnetic and/or thermal properties inserted into the grid is increased by a factor of e.g. 4 and enable the basis of 4 identical products. After the winding is performed, the stator or rotor component can in a simple manner be cut in the longitudinal direction of the electromagnetic mat 10. This can be scaled up to as many products as wanted.

Reference is now made to Figures 16a-c which are principle drawings of an alternative embodiment according to the present invention suitable for continuous electrical conductor fiber wefts 30. In the alternative embodiment the pattern of the electrical conductor fiber wefts 30 is provided by means of twinning. In this embodiment at least two warps 20 with non-conductive surface (and possibly fiber warps with mechanical, electromagnetic and/or thermal properties) form a grid that is stretched out between a cylindrical object or base 50 and a feeder assembly 80. A twinning assembly 90 is positioned around the grid formed by the fiber warps 20 non-conductive surface, which is arranged to rotate around the grid. The twinning assembly 90 is arranged to lay out continuous electrical conductor fiber wefts 30 in a desired pattern around the grid. Similar to the embodiments above the mechanical, electromagnetic and/or thermal properties can be altered. E.g. can all continuous electrical conductor fiber wefts 30 from all phases A, B, C (e.g. 3) be winded at the same time, e.g. by that they are arranged in a thin, flat, tape-format, as shown in Figure 16b. In this embodiment the continuous electrical conductor fiber wefts 30 are arranged to the grid formed by the fiber warps 20 with non-conductive surface (and possibly fiber warps with mechanical, electromagnetic and/or thermal properties) at the same time as the electromagnetic mat 10 is rolled-up on the cylindrical object or base 50. In an alternative embodiment the resulting electromagnetic mat 10 is folded. This results in a zig-zag, or tilted, pattern, as shown in Figure 16c. Benefits of this design is that end-windings and harmonics can be reduced, which will result in lower weight and higher efficiency.

Also this embodiment can make use of the intermediate step of impregnation and final step of molding. This embodiment can also be adapted for the use of cut electrical conductor fiber wefts 30, but this will require attachment of the cut electrical conductor fiber wefts 30 to the grid of fiber warps 20 with non-conductive surface (and possibly fiber warps with mechanical, electromagnetic and/or thermal properties) e.g. by the tape, by impregnation or some other suitable means.

This embodiment also benefits from the advantages of the prior described embodiments, including the design of the pattern of the electrical conductor fiber wefts, geometry, connection of the electrical conductor fiber wefts, and the use of cut or continuous electrical conductor fiber wefts.

As for the other embodiments fiber warps and/or fiber wefts with mechanical, electromagnetic and/or thermal properties can be utilized. For example could iron fiber wefts 70 be used to create tilted iron teeth. Iron fiber wefts 70 could also be used to create back iron (in the case where the first, or last, part of the electromagnetic mat 10 is pure iron).

In a further embodiment according to the present invention the electromagnetic mat 10 can further be provided with other objects, such as magnets or pipes. E.g. can the electromagnetic mat 10 be provided with water pipes for improved cooling properties.

The above described embodiments can be combined and modified to form other embodiments which are within the scope of the claims.

Modifications

The present invention is also applicable for twin motors. By creating an electronical conductor fiber weft 30 pattern for the given stator or rotor component (total) length and then reversing (or repeating) the pattern, a double - or twin - motor can be created. Applying current to the phases will produce the same - or mirrored - rotation in both motors. Such a solution is shown in Figure 17, where one electromagnetic mat 10 is used for two different components.

In a further modification, the present invention is applied on ring motors attached over one or more rotors attached to a rod 100 with threads. By applying a varying EM-field, the rotors will start rotating and move vertically up or down. Such a solution is shown in Figure 18 where two vertical rods 100 with threads have rotors 102 (with inner gangs and outer magnets 103) attached. When rotating they will move vertically. Over them, ring stators are arranged (e.g. the twin motor in Figure 17).

In a further modification, the method further comprises weaving, twinning or winding with non-conductive wefts and/or wefts with other mechanical, electromagnetic and/or thermal properties and warps with electromagnetic, mechanical and/or thermal properties and/or warps with conductive properties. For instance, a mat without conductive fibers but with electromagnetic, mechanical and/or thermal properties could be created and used as part of a rotor or stator component to enhance properties. For instance, mats of mentioned properties could be plied or formed by rolling or folding on rotor or stator components, either on top, under, or between layers with conductive properties. For instance, mats of mentioned properties could have flux carrying properties and be applied to the outer or inner surface of a rotor or stator component to function in the production process presented or in a separate step outside mentioned production process.

Claims

1. Method for production of rotor or stator component of an electric machine, wherein the method comprises an initial step of

- weaving, twinning or winding an electromagnetic mat (10) consisting of at least two fiber warps (20) with non-conductive surface in longitudinal direction of the electromagnetic mat (10) and at least one winding formed by:

at least one continuous electrical conductor fiber weft (30) extending mainly in transversal direction of the electromagnetic mat (10), or

cut electrical conductor fiber wefts (30) extending in mainly transversal direction of the electromagnetic mat (10) and connected at end windings to create at least one continuous conductor fiber weft (30),

wherein the at least one continuous electrical conductor fiber weft (30) is aligned in a winding pattern so as to create a moving electromagnetic field when induced with an alternating current or constant electromagnetic field when induced with direct current.

2. Method according to claim 1, wherein the method further comprises weaving, twinning or winding alternating non-conductive fiber wefts (40) and/or fiber wefts (70) with mechanical, electromagnetic and/or thermal properties and cut or continuous electrical conductor fiber wefts (30) in mainly transversal direction of the electromagnetic mat (10).

3. Method according to claim 1, wherein the method comprises an intermediate step of impregnation of the electromagnetic mat (10) with a curable liquid potting material, as epoxy or resin.

4. Method according to claim 1, wherein the method comprises an intermediate step of connecting end windings of the cut electrical conductor wefts (30).

5. Method according to claim 1, wherein the method comprises an intermediate step of rolling or plying the electromagnetic mat (10) in one or multiple layers on a base or object (50), or folding the electromagnetic mat (10) in one or multiple layers to form a desired geometrical shape for the rotor or stator component.

6. Method according to any one of the preceding claims, wherein the method comprises weaving, twinning or winding the electromagnetic mat (10) with at least two windings formed by cut or continuous electrical conductor fiber wefts (30).

7. Method according to claim 1, wherein the method comprises weaving, twinning or winding the electromagnetic mat (10) with fiber warps (20) with non-conductive surface of different length so as to form a circular, S-shaped, 8-shaped, helical or otherwise shaped electromagnetic mat (10).

8. Method according claim 1, wherein the method comprises weaving, twinning or winding the electromagnetic mat (10) with both fiber warps (20) with non-conductive surface and fiber warps with mechanical, electromagnetic and/or thermal properties.

9. Method according to any one of the preceding claims, wherein the method comprises weaving, twinning or winding the electromagnetic mat (10) with fiber warps (20) with non-conductive surface, fiber warps with mechanical, electromagnetic and/or thermal properties, electrical conductor fiber wefts (30), non-conductive fiber wefts (40) and/or fiber wefts (70) with mechanical, electromagnetic and/or thermal properties extending in at least one dimension, two dimensions or three dimensions.

10. Method according to any one of the proceeding claims, wherein the method comprises a final step of molding/encapsulating the electromagnetic mat (10) in a curable liquid potting material, as epoxy or resin, to form a stator or rotor component.

11. Rotor or stator component of an electric machine, wherein the rotor or stator component is formed by a woven, twinned or winded electromagnetic mat (10) consisting of at least two fiber warps (20) with non-conductive surface extending in longitudinal direction of the electromagnetic mat (10) and at least one winding formed by:

at least one continuous electrical conductor fiber weft (30) extending in mainly transversal direction of the electromagnetic mat (10), or

cut electrical conductor fiber wefts (30) extending in mainly transversal direction of the electromagnetic mat (10) and connected at end windings to create at least one continuous conductor fiber weft (30),

wherein the at least one continuous electrical conductor weft (30) is aligned in a winding pattern creating a moving electromagnetic field when induced with an alternating current or constant electromagnetic field when induced with direct current.

12. Rotor or stator component according to claim 11, wherein the electromagnetic mat (10) is woven, twinned or winded with alternating non-conductive fiber wefts (40) and/or fiber wefts (70) with mechanical, electromagnetic and/or thermal properties and cut or continuous electrical conductor fiber wefts (30) in mainly transversal direction of the electromagnetic mat (10).

13. Rotor or stator component according to claim 11, wherein the electromagnetic mat (10) is impregnated with a curable liquid potting material, as epoxy or resin.

14. Rotor or stator component according to claim 11, wherein the electromagnetic mat (10) comprises both fiber warps (20) non-magnetic surface and fiber warps with mechanical, electromagnetic and/or thermal properties.

15. Rotor or stator component according to claim 11, wherein the electromagnetic mat (30) is rolled or folded in one or multiple layers to form a desired geometry for the rotor or stator component.

16. Rotor or stator component according to any one of the claims 11-15, wherein the electromagnetic mat (10) is the molded/encapsulated in a curable liquid potting material, as epoxy or resin, to form a stator or rotor component.

17. Rotor or stator component according to any one of the claims 11-16, wherein the electromagnetic mat (10) comprises at least two windings formed by cut or continuous electrical conductor fiber wefts (30).

18. Rotor or stator component according to any one of the claims 11-17, wherein warps (20) with non-conductive surface exhibit different length so as to form a circular, S-shaped, 8-shaped, helical or otherwise shaped electromagnetic mat (10).

Abstract

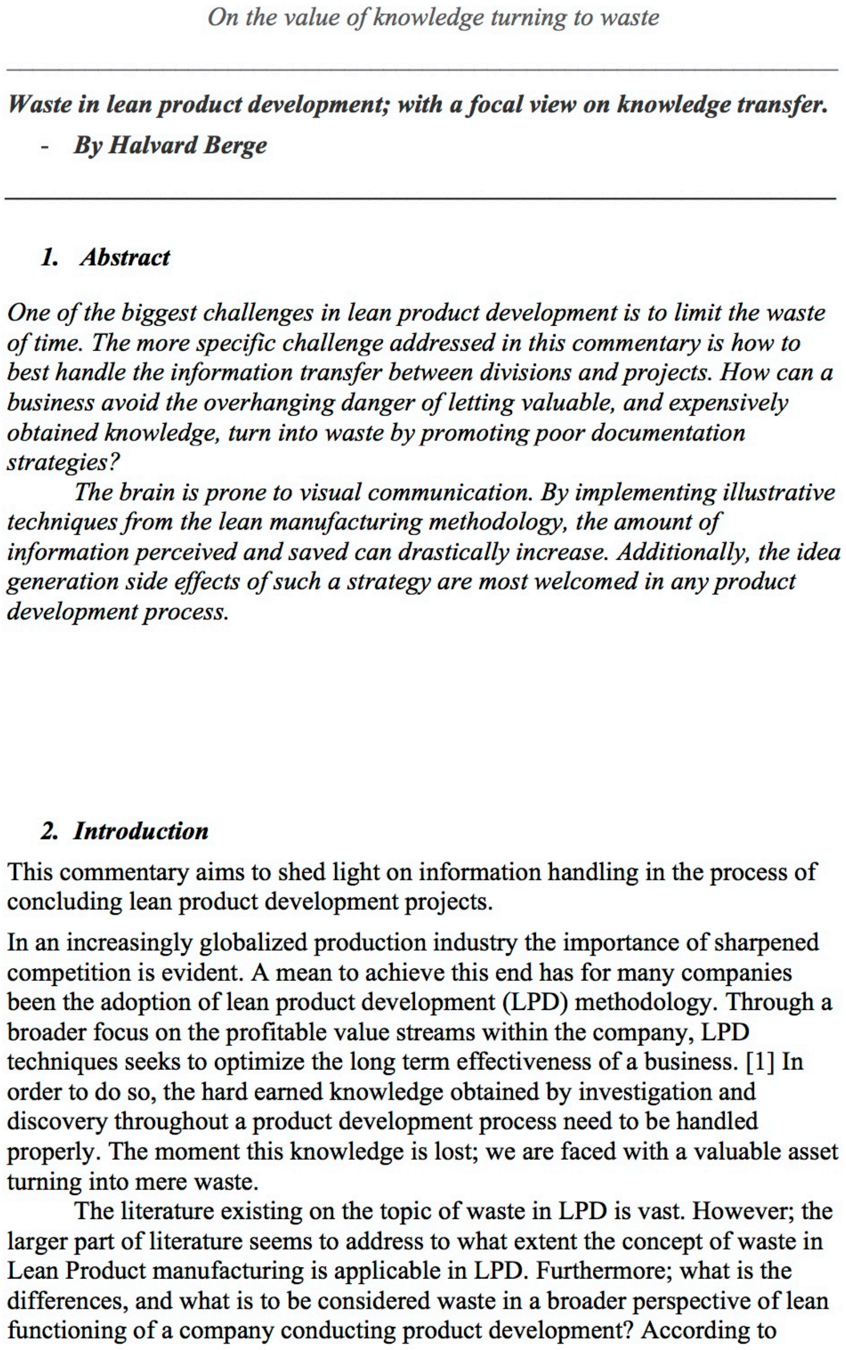
Method for production of and rotor or stator component of an electric machine, comprising

- weaving, twinning or winding an electromagnetic mat (10) consisting of at least two fiber warps (20) with non-conductive surface in longitudinal direction of the electromagnetic mat (10) and at least one winding formed by:
- at least one continuous electrical conductor fiber weft (30) extending mainly in transversal direction of the electromagnetic mat (10), or
- cut electrical conductor fiber wefts (30) extending in mainly transversal direction of the electromagnetic mat (10) and connected at end windings to create at least one continuous conductor fiber weft (30),

wherein the at least one continuous electrical conductor fiber weft (30) is aligned in a winding pattern so as to create a moving electromagnetic field when induced with an alternating current or constant electromagnetic field when induced with direct current.

Fig. 6c.

APPENDIX D: On the value of knowledge turning to waste



Waste in lean product development; with a focal view on knowledge transfer.

- ***By Halvard Berge***

1. Abstract

One of the biggest challenges in lean product development is to limit the waste of time. The more specific challenge addressed in this commentary is how to best handle the information transfer between divisions and projects. How can a business avoid the overhanging danger of letting valuable, and expensively obtained knowledge, turn into waste by promoting poor documentation strategies?

The brain is prone to visual communication. By implementing illustrative techniques from the lean manufacturing methodology, the amount of information perceived and saved can drastically increase. Additionally, the idea generation side effects of such a strategy are most welcomed in any product development process.

2. Introduction

This commentary aims to shed light on information handling in the process of concluding lean product development projects.

In an increasingly globalized production industry the importance of sharpened competition is evident. A mean to achieve this end has for many companies been the adoption of lean product development (LPD) methodology. Through a broader focus on the profitable value streams within the company, LPD techniques seeks to optimize the long term effectiveness of a business. [1] In order to do so, the hard earned knowledge obtained by investigation and discovery throughout a product development process need to be handled properly. The moment this knowledge is lost; we are faced with a valuable asset turning into mere waste.

The literature existing on the topic of waste in LPD is vast. However; the larger part of literature seems to address to what extent the concept of waste in Lean Product manufacturing is applicable in LPD. Furthermore; what is the differences, and what is to be considered waste in a broader perspective of lean functioning of a company conducting product development? According to

Browning and Worth [2] the structural influence of LPD goes far beyond the mere elimination of waste; its goal is to maximize the value added to customers, shareholders, employees, society and suppliers. If information is lost in between projects and product launches, the respective team starting a new endeavour can to a lesser extent apply, work and build on previous experiences. Thus such a transformation from value to waste as the result of poor documentation influences not only the need for catching up knowledge-wise; but also prolongs waiting time for anticipating customers and suppliers. Slower movement within a business also affects the profitability; and thereby also shareholders and ultimately society.

3. Literature review/background

In order to thoroughly investigate the research on the knowledge transfer between teams and projects, one must look to both value- and waste concerned papers. Moreover, the value of well kept knowledge and the waste of lost information.

The Lean Product Development activities within a company is centered around a "quality house"; that is, the very core of the company brand. Having the values and governing principles, including its applied methods and standardized way of working, as long as it is not hindering the lean adaptations introduced by LPD-thinking. [3] Gremyr and Fouquet (2012) emphasize the importance of sharing information batch-wise throughout the product development way of working. By doing this, one will distribute knowledge to co-workers and suppliers, but also decrease the probability of missing pieces of information being the root cause for delay in any part of a project. Diminishing waiting time is one of the most important aspects of implemented LPD. Because of concurrent engineering technique, the development depends heavily upon real-time information sharing, due to many parts if the work is carried out simultaneously. If the value of knowledge obtained is shared smoothly, one avoids the loss of turning parts of this knowledge into waste. By causing halts in the work, the need for rediscovery and double work occur as a result of waiting. The similarities between information flow in concurrent engineering and in the transition between projects are arguably very much the same.

The potential in several popular sharing strategies today are to a large degree left unmapped. Several types of platforms like Slack, Notion, Google Drive, Dropbox and OneNote are designed for effortless sharing, widely used by startups. It will be interesting to investigate weather this still will be a trend when startups grow to larger businesses.

No matter how the information is transported, the principles of perception and knowledge sharing is to be considered timeless. With this in mind, the relevance of properly conveying knowledge is all-time present.

According to a line of studies [4], the brain has the capability to process images much better than text. In lean manufacturing this has been a frequent technique for conveying knowledge. Therefor the benefits of using illustrations rather than text are evident: Quicker realizations of concepts, thorough understanding of details, effective base for discussion, quick transferability from mental image to physical function.

Another important point to make is that low resolution visual illustrations save time in terms of documentation. From the knowledge deliverer´s point of view, this is a source of added value, and avoided time waste.

According to Parry and Turner[4], a growing challenge to the product development realm today is information overload. Even though an overly detailed level of a concept not always is needed to be conveyed, managers and engineers are often faced with large amounts of information captured through heavy documentation in the form of text, manuals and technical drawings. With a rather long processing time needed to internalize the knowledge, one can argue that even though information in its purest form is considered value in lean product development, it can quickly turn into waste if conveyed in a poor and inefficient manner.

A more visual approach to knowledge transfer shows, according to Lindlöf, Söderberg and Persson (2013) [5], a more precise and quicker perception on the receiver's behalf. Studies done on visualization of information in project-based work indicates that ”visual representation disrupts the tactic-codified dichotomy" [4]. An important point to make with regard to potential use of visualization tools in LPD, is that these tools are good for more than mere transfer of knowledge. Lindlöf, Söderberg and Persson (2013) [4] suggest that this way of communicating actually sparks idea generation. By using concept illustrations, the receiver easily can modify and discuss the respective information. Low thresholds for documenting yields low thresholds for modifying.

Gratifying techniques for visualization of knowledge

When loaning terms and experiences from lean manufacturing, one can take advantage of several principles. Two common strategies are the use of visual boards, Value Stream Mapping and dense A3-reports. The respective techniques are considered to be highly effective in knowledge-intensive industries [5]. Better quality of comprehensions, including upped understanding of both conveyer and receiver, adds value to the lean product development process.

Moreover, the value is already there in terms of information, but the handling and manner one eternalize it within the company or division is crucial.

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This is arguably the make- or brake point in the transaction from one project run to the other. If the information is lost, the value of knowledge is, at least partially, turned into waste. This value loss will in this respect, post development, make the work done less lean.

4. Result and conclusion

Typically, one of the biggest challenges in LPD-implementations is to limit the waste of time. The more specific challenge addressed in this commentary is how to best handle the information transfer between divisions and projects. Engineers and managers are faced with what is referred to as overwhelming amounts of text-based information. How does a business avoid the overhanging danger of letting valuable, and expensively obtained knowledge, turn into waste by promoting poor documentation strategies?

As stated, the halt of a larger projects often stems from missing pieces of information needed to precede. A trend in our nature is to collect and complete larger batches of instructions before we share it. By deliberately working towards upping the frequency of information sharing, smaller, but more frequent batches of info delivered can resolve productivity halts quicker.

The brain is prone to visual communication. By implementing illustrative techniques from the lean manufacturing methodology, the amount of information perceived and saved can drastically increase. Additionally, the idea generation side effects of such a strategy are most welcomed in any product development process.

The concept of lean product development is largely concerned with minimizing waste, and in that respect share overlapping principles with lean manufacturing. However, the waste sources in LPD are much subtler. But when dealing with time waste on a macro perspective all investigations, experiments and analysis done twice should be avoided. Even though documentation work is saved when left out from a particular project, the overall line of projects will suffer from the missing bits and pieces leaving knowledge to be rediscovered.

References:

1. Kumar, Sharma, and Agarwal 2015Kumar, R., M. Sharma, and A. Agarwal. 2015. “An Experimental Investigation of Lean Management in Aviation: Avoiding Unforced Errors for Better Supply Chain.” *Journal of Manufacturing Technology Management* 26 (2): 231–260.[Crossref], [Web of Science ®], [Google Scholar];
   Slack 1999Slack, R. 1999. *The Lean Value Principle in Military Aerospace Product Development*. Cambridge: Lean Aerospace Initiative Massachusetts Institute of Technology.

2. 2000 Browning, T., and F. Worth. 2000. “Value-based Product Development: Refocusing Lean.” *Engineering Management Journal* 168–172.

3. Ida Gremyr, Jean-Baptiste Fouquet, (2012) "Design for Six Sigma and lean product development", International Journal of Lean Six Sigma, Vol. 3 Issue: 1, pp.45-58.

4. Ludvig Lindlöf , Björn Söderberg & Magnus Persson (2013) Practices supporting knowledge transfer – an analysis of lean product development, International Journal of Computer Integrated Manufacturing, 26:12, 1128-1135, DOI: 10.1080/0951192X.2011.651160.

5. Kotnour 2000, Stovel and Bontis 2002, Schindler and Eppler 2003). Second, the PPR is usually conducted by the project manager (Busby 1999, Kotnour 2000, Williams 2008). Third, it is presented in a large, inaccessible document (Von Zedtwitz 2002, Schindler and Eppler 2003, Parry and Turner 2006). Fourth, there is a lack of purposeful input, which decreases its use (Bresnen et al. 2003.

6. G. C. Parry & C. E. Turner (2006) Application of lean visual process management tools, Production Planning & Control, 17:1, 77-86, DOI: 10.1080/09537280500414991.

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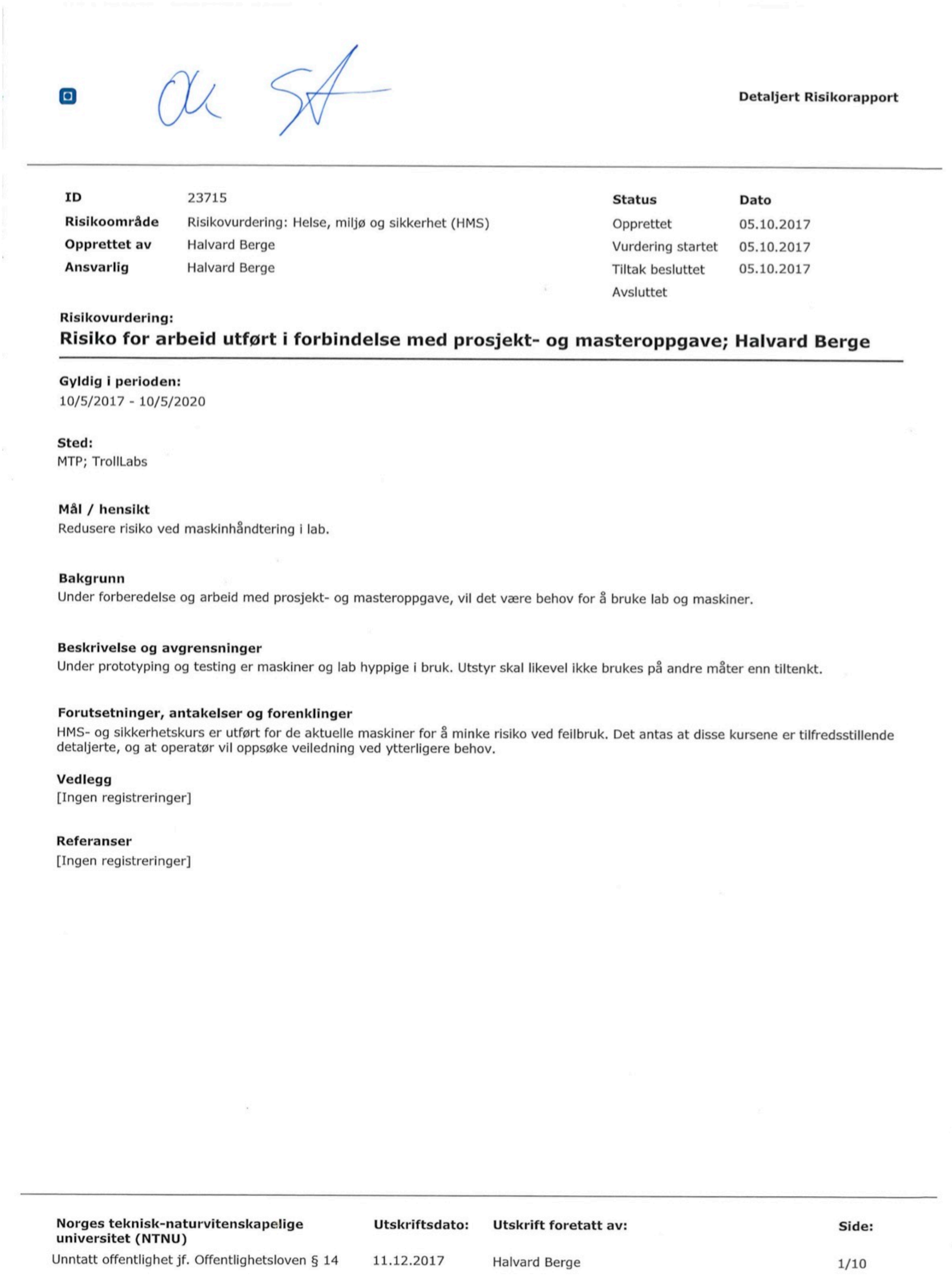
APPENDIX E: Risk Assessment



Detaljert Risikorapport

ID	23715	**Status**	**Dato**
Risikoområde	Risikovurdering: Helse, miljø og sikkerhet (HMS)	Opprettet	05.10.2017
Opprettet av	Halvard Berge	Vurdering startet	05.10.2017
Ansvarlig	Halvard Berge	Tiltak besluttet	05.10.2017
		Avsluttet	

Risikovurdering:

Risiko for arbeid utført i forbindelse med prosjekt- og masteroppgave; Halvard Berge

Gyldig i perioden:
10/5/2017 - 10/5/2020

Sted:
MTP; TrollLabs

Mål / hensikt
Redusere risiko ved maskinhåndtering i lab.

Bakgrunn
Under forberedelse og arbeid med prosjekt- og masteroppgave, vil det være behov for å bruke lab og maskiner.

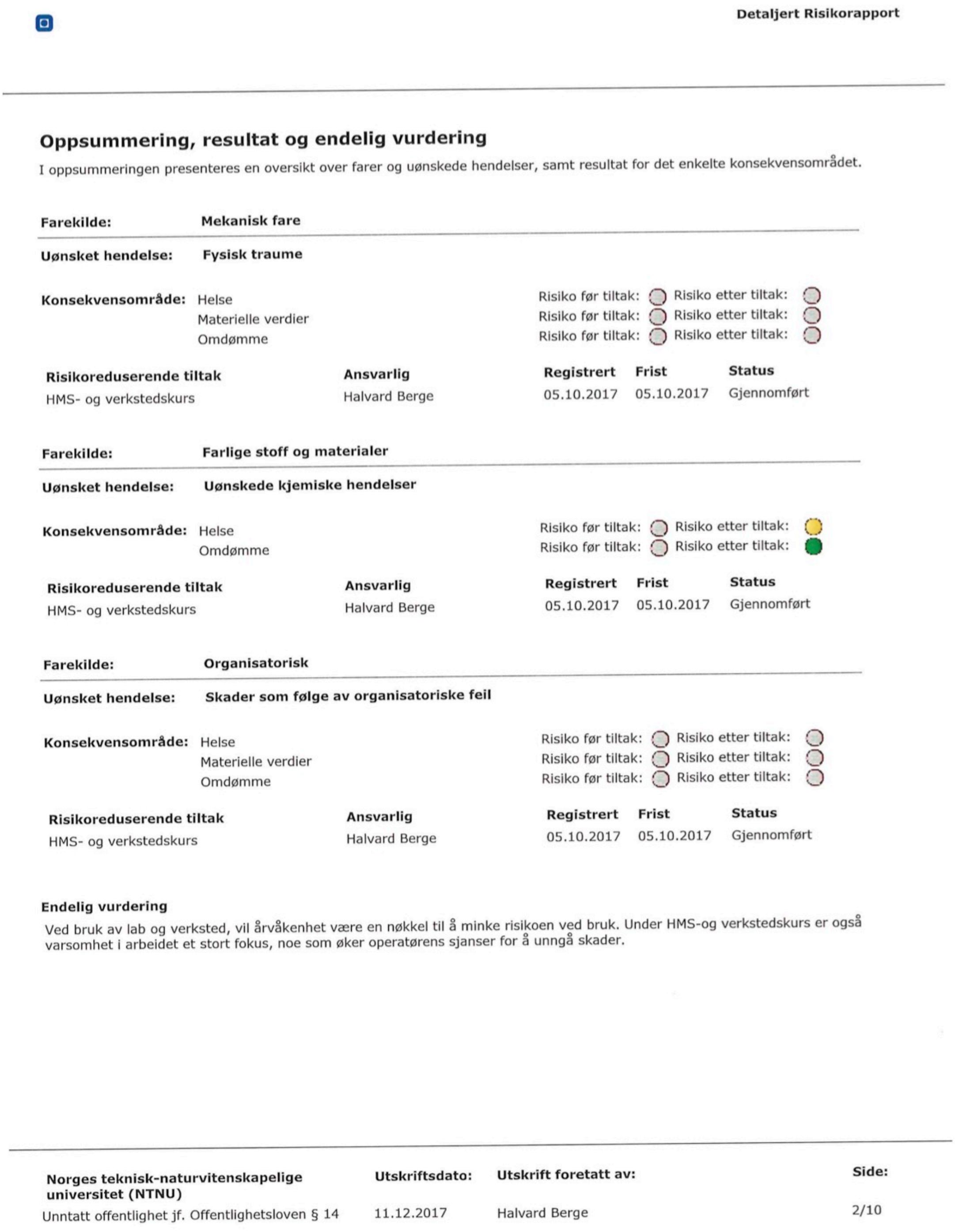
Beskrivelse og avgrensninger
Under prototyping og testing er maskiner og lab hyppige i bruk. Utstyr skal likevel ikke brukes på andre måter enn tiltenkt.

Forutsetninger, antakelser og forenklinger
HMS- og sikkerhetskurs er utført for de aktuelle maskiner for å minke risiko ved feilbruk. Det antas at disse kursene er tilfredsstillende detaljerte, og at operatør vil oppsøke veiledning ved ytterligere behov.

Vedlegg
[Ingen registreringer]

Referanser
[Ingen registreringer]

Norges teknisk-naturvitenskapelige universitet (NTNU)	**Utskriftsdato:**	**Utskrift foretatt av:**	**Side:**
Unntatt offentlighet jf. Offentlighetsloven § 14	11.12.2017	Halvard Berge	1/10



Oppsummering, resultat og endelig vurdering

I oppsummeringen presenteres en oversikt over farer og uønskede hendelser, samt resultat for det enkelte konsekvensområdet.

Farekilde: **Mekanisk fare**

Uønsket hendelse: **Fysisk traume**

Konsekvensområde:	Helse	Risiko før tiltak: ○	Risiko etter tiltak: ○
	Materielle verdier	Risiko før tiltak: ○	Risiko etter tiltak: ○
	Omdømme	Risiko før tiltak: ○	Risiko etter tiltak: ○

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
HMS- og verkstedskurs	Halvard Berge	05.10.2017	05.10.2017	Gjennomført

Farekilde: **Farlige stoff og materialer**

Uønsket hendelse: **Uønskede kjemiske hendelser**

Konsekvensområde:	Helse	Risiko før tiltak: ○	Risiko etter tiltak: 🟡
	Omdømme	Risiko før tiltak: ○	Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
HMS- og verkstedskurs	Halvard Berge	05.10.2017	05.10.2017	Gjennomført

Farekilde: **Organisatorisk**

Uønsket hendelse: **Skader som følge av organisatoriske feil**

Konsekvensområde:	Helse	Risiko før tiltak: ○	Risiko etter tiltak: ○
	Materielle verdier	Risiko før tiltak: ○	Risiko etter tiltak: ○
	Omdømme	Risiko før tiltak: ○	Risiko etter tiltak: ○

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
HMS- og verkstedskurs	Halvard Berge	05.10.2017	05.10.2017	Gjennomført

Endelig vurdering

Ved bruk av lab og verksted, vil årvåkenhet være en nøkkel til å minke risikoen ved bruk. Under HMS-og verkstedskurs er også varsomhet i arbeidet et stort fokus, noe som øker operatørens sjanser for å unngå skader.

Involverte enheter og personer

En risikovurdering kan gjelde for en, eller flere enheter i organisasjonen. Denne oversikten presenterer involverte enheter og personell for gjeldende risikovurdering.

Enhet /-er risikovurderingen omfatter

- Institutt for maskinteknikk og produksjon

Deltakere

[Ingen registreringer]

Lesere

[Ingen registreringer]

Andre involverte/interessenter

[Ingen registreringer]

Følgende akseptkriterier er besluttet for risikoområdet Risikovurdering: Helse, miljø og sikkerhet (HMS):

Helse

Materielle verdier

Omdømme

Ytre miljø

Oversikt over eksisterende, relevante tiltak som er hensyntatt i risikovurderingen

I tabellen under presenteres eksisterende tiltak som er hensyntatt ved vurdering av sannsynlighet og konsekvens for aktuelle uønskede hendelser.

Farekilde	Uønsket hendelse	Tiltak hensyntatt ved vurdering
Mekanisk fare	Fysisk traume	
Farlige stoff og materialer	Uønskede kjemiske hendelser	
Organisatorisk	Skader som følge av organisatoriske feil	

Eksisterende og relevante tiltak med beskrivelse:

HMS- og verkstedskurs
Gjennomført HMS- og verkstedskurs

Risikoanalyse med vurdering av sannsynlighet og konsekvens

I denne delen av rapporten presenteres detaljer dokumentasjon av de farer, uønskede hendelser og årsaker som er vurdert. Innledningsvis oppsummeres farer med tilhørende uønskede hendelser som er tatt med i vurderingen.

Følgende farer og uønskede hendelser er vurdert i denne risikovurderingen:

- **Mekanisk fare**
    - Fysisk traume
- **Farlige stoff og materialer**
    - Uønskede kjemiske hendelser
- **Organisatorisk**
    - Skader som følge av organisatoriske feil

Detaljert oversikt over farekilder og uønskede hendelser:

Farekilde: Mekanisk fare

- Akselerasjon eller retardasjon, bevegelsesenergi
- Skarpe kanter
- Fallende last
- Oppspent energi (for eksempel fjærer)
- Høyt trykk
- Vakuum
- Bevegelige deler
- Roterende enheter

Uønsket hendelse: Fysisk traume

- Miste lemmer
- Sette seg fast
- Få materialer over seg
- Skli i oljesøl o.l

Sannsynlighet for hendelsen (felles for alle konsekvensområder): **(0)**

Kommentar:
[Ingen registreringer]

Konsekvensområde: Helse

Vurdert konsekvens: **()**

Kommentar: [Ingen registreringer]

Risiko:

Konsekvensområde: Materielle verdier

Vurdert konsekvens: **()**

Kommentar: [Ingen registreringer]

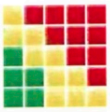
Risiko:

Konsekvensområde: Omdømme

Vurdert konsekvens: **()**

Kommentar: [Ingen registreringer]

Risiko:



Farekilde: Farlige stoff og materialer

- Brennbare
- Giftige
- Skadelige (asbest, cyanider)

Uønsket hendelse: Uønskede kjemiske hendelser

- Inhalasjon av toksiske stoffer
- Etsende kontakt
- Peroral intoks

Sannsynlighet for hendelsen (felles for alle konsekvensområder): **(0)**

Kommentar:

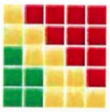
[Ingen registreringer]

Konsekvensområde: Helse

Vurdert konsekvens: **()**

Kommentar: [Ingen registreringer]

Risiko:

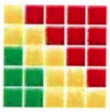


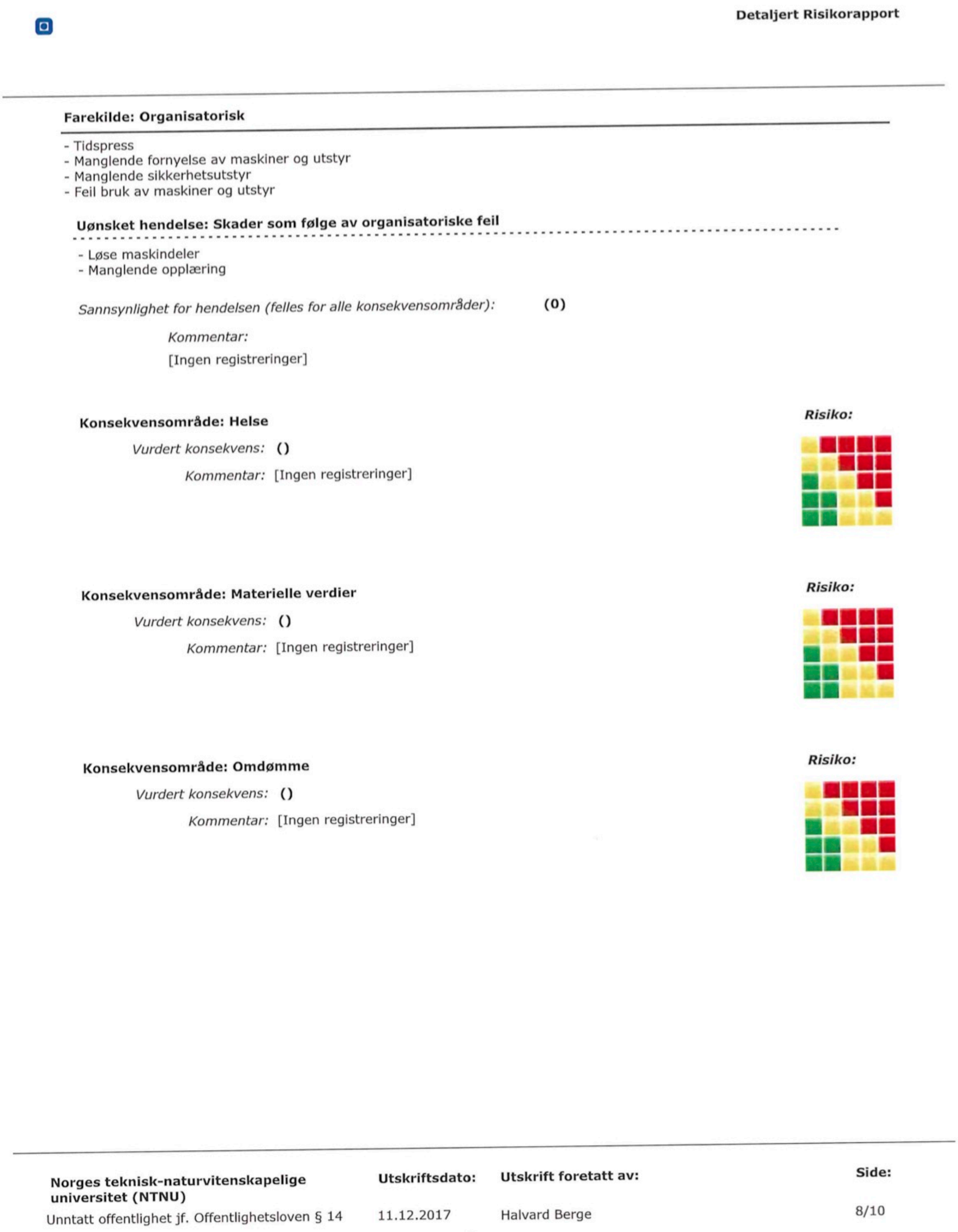
Konsekvensområde: Omdømme

Vurdert konsekvens: **()**

Kommentar: [Ingen registreringer]

Risiko:





Farekilde: Organisatorisk

- Tidspress
- Manglende fornyelse av maskiner og utstyr
- Manglende sikkerhetsutstyr
- Feil bruk av maskiner og utstyr

Uønsket hendelse: Skader som følge av organisatoriske feil

- Løse maskindeler
- Manglende opplæring

Sannsynlighet for hendelsen (felles for alle konsekvensområder): **(0)**

Kommentar:
[Ingen registreringer]

Konsekvensområde: Helse

Vurdert konsekvens: **()**

Kommentar: [Ingen registreringer]

Risiko:

Konsekvensområde: Materielle verdier

Vurdert konsekvens: **()**

Kommentar: [Ingen registreringer]

Risiko:

Konsekvensområde: Omdømme

Vurdert konsekvens: **()**

Kommentar: [Ingen registreringer]

Risiko:

Oversikt over besluttede risikoreduserende tiltak:

Under presenteres en oversikt over risikoreduserende tiltak som skal bidra til å reduseres sannsynlighet og/eller konsekvens for uønskede hendelser.

- HMS- og verkstedskurs

Detaljert oversikt over besluttede risikoreduserende tiltak med beskrivelse:

HMS- og verkstedskurs

Gjennomført HMS- og verkstedskurs ved Realiseringslabben

Tiltak besluttet av:	Halvard Berge
Ansvarlig for gjennomføring:	Halvard Berge
Frist for gjennomføring:	10/5/2017

Detaljert oversikt over vurdert risiko for hver farekilde/uønsket hendelse før og etter besluttede tiltak

Farekilde: **Farlige stoff og materialer**

Uønsket hendelse: **Uønskede kjemiske hendelser**

Sannsynlighetsvurderinger (felles for alle konsekvensområder):

Opprinnelig sannsynlighet: (0)

Begrunnelse:

Sannsynlighet etter tiltak: Lite sannsynlig (2)

Begrunnelse: Mengden stoffer er svært begrenset, noe som fører til stor bevissthet rundt bruk

Konsekvensvurderinger:

Konsekvensområde: **Helse**

Risiko:

Opprinnelig konsekvens: ()

Begrunnelse:

Konsekvens etter tiltak: Stor (3)

Begrunnelse: Kjemisk kontakt kan ha store konsekvenser for hud, og ved inhalering

Konsekvensområde: **Omdømme**

Risiko:

Opprinnelig konsekvens: ()

Begrunnelse:

Konsekvens etter tiltak: Liten (1)

Begrunnelse: Liten konsekvens.