Master Thesis

Construction and design of an electro-spinning production unit

Björn Svensson

Division of Machine Design • Department of Design Sciences
Faculty of Engineering LTH • Lund University • 2015

LUND UNIVERSITY

Cellevate

Construction and design of an electro-spinning production unit

Björn Svensson

Division of Machine Design • Department of Design Sciences

Faculty of Engineering LTH • Lund University • 2015

Division of Machine Design, Department of Design Sciences
Faculty of Engineering LTH, Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

Preface

It has been quite a bumpy ride finishing this thesis. I would like to thank the people closest to me, for all the support and help. To my loving Emelie who keep pushing me forward through the rough. To mom and dad for their support.

Lund, December 2015

Björn Svensson

Abstract

This master's thesis presents the design and construction of a centrifugal electrospinning nano-fiber production unit. The design is realized to as great extent as the limits of the thesis allows. The thesis presents the stages of product design from both Ullrich & Eppinger methodology as well as others, from concept generation to materials selection and finally manufacturing and assembling and redesign according to the NASA Design by prototyping methodology.

The concept is presented in detail, regarding components, material selection as well as a detailed brief on the building process.

It also evaluates these processes and discusses any improvements to different machine components, the project layout and the methodology used.

Keywords:

Electro spinning, Product design, Ullrich & Eppinger, Nano-fiber production, Construction and design

Sammanfattning

Detta examensarbete i teknisk design har gått ut på att konstruera och bygga en miniatyr av en befintlig produktions enhet för nanofibertillverkning, med förbättringar och omkonstruktion av befintliga delar.

Initialt har elektrospinning och tillverkning av nanofibrer kartlagts och undersökts med hjälp av literaturstudier och samtal med handledare på Cellevate AB.

Som bas för genomförandet av detta har ett urval av metoder använts, däribland de som presenteras i Ullrich och Eppingers (U&E) bok ”Produktutveckling, konstruktion och design”, NASAs ” Designing by prototype” samt de metoder som presenterats i delar av kursutbudet på programmet Maskinteknik med Teknisk Design på LTH av Per Liljeqvist, föreläsare och kursansvarig i flertalet av designkurserna som ges.

Genom analys av den befintliga produktionsenheten, samt intervjuer med anställda och ägare på Cellevate AB, som också äger enheten, har en bas av information byggts upp. Denna har sedan legat till grund för en funktionsanalys som sedan mynnat ut i olika konceptförslag som utvärderats tillsammans med Cellevate AB samt handledare och genom U&E matrismetoder för poängsättning av koncept.

Dessa konceptförslag har sedan realiserats i så hög utsträckning som möjligt inom tidsramarna för examensarbetet.

Delar av det vinnande konceptförslaget utreds i skrivande stund gällande patentmöjligheter.

I stora drag består konceptet av ett ramverk tillverkat av aluminiumprofiler, i vilket själva elektrospinningmaskinen återfinns. Denna består i sin tur av ett antal modulära enheter som kollektor samt roterande utslungningsenhet/disk, samt drift för dessa.

Driften är till stor utsträckning automatiserad och datorstyrd och tanken med konceptet är att apparaten enkelt skall kunna kontrolleras med tillhörande programvara via t.ex en dator eller tablet-enhet.

Detta koncept har sedan vidareutvecklats och förslag gällande konstruktion och materialval har genomförts. Färdiga standardenheter, t.ex. extuderade aluminiumprofiler, stegmotorer, drivremmar och tandade remhjul, har i så stor utsträckning använts för att minimera kostnader.

Stor del av tiden har lagts på realisation av konceptet, där har många av de tänkta lösningarna fått omvärderas och ändras vilket också är en stor del av NASA metoden.

Resultatet har via designförslagen som lagts fram, bestått i en sammanställd befintlig produktionsenhet, med ett antal kvarvarande nyckelmoment gällande sammanställning innan denna kan tas i drift. De delar som är fungerande i skrivande stund är, ramverk i aluminium, motordrift, kollektor samt den roterande emittor/utslungningsenheten.

Detta diskuteras och förslag till lämpliga ändringar och omkonstruktioner har sammanställts. Dessa förslag innefattar bland annat utvärderingar av materialval, omstrukturering av design och konstruktionsmetod samt hur ett bättre upplägg för ett liknande projekt skulle kunna se ut.

Table of Contents

1 Introduction

Nano-fiber production and application in general and at Cellevate AB explained.

1.1 Nano-fiber production by electro-spinning, in general

Electro-spinning is one of the most common methods of producing polymer nano-fibers. The more common set up is by letting a polymer solute pass through a syringe needle, while being exposed to a high voltage induced electric field. The high electric force from the field produces a Taylor cone at the tip of the syringe needle, from which fibers are then drawn to the collector of the spinning unit [1]-[3].

The outcome of the process and the quality of the fibers are determined by several factors such as the type of polymer and solvent and their mixing ratio, the applied voltage and the distance from emitter (syringe) to collector; ergo the electrostatic field strength [1]-[3].

Every polymer coupled with a suitable solvent have a specific optimal work set up [1], [2]. In general the voltage and distance are interchangeable as to the fact that a larger voltage potential gives leeway for a larger distance between emitter and collector and vice versa [1]-[3]. However, to obtain good fiber quality, the distance must be large enough for the solvent to evaporate entirely, before reaching the collector. It must also not evaporate too quickly, leaving hardened polymer to build up and interfere with the spinning process [2].

1.2 Cellevate AB

Cellevate AB was founded in 2014 with the mission to provide life science businesses with “more realistic in vitro models, for more relevant data and research”. This is achieved by manufacturing nanofiber environments by using a patented electro spinning process [1], [4].

1.3 Nano-fiber production at Cellevate AB

At Cellevate AB, the current production unit (PU) uses a slightly different method from that mentioned above, a centrifugal electro spinning process. This uses the centrifugal force to distribute a very thin layer of polymer and solvent over a reverse funnel shaped spinning disc, from which several Taylor cones are formed, thus allowing the spinning process to be very rapid and allows for very large quantities of fibers to be produced in a short period of time [1], [2]. The reversed funnel spinning disc will be referred to as the spinner reversed funnel or spinner funnel in this thesis.

1.4 The original PU

An overview of the original PU is shown in **Figure 1.1**. Some of the parts and components are circled. Circle *A* highlights the substrate paper rolls. These consist of a mounting system which accommodates the actual paper roll by inserting two cone shaped parts with flanges that grip the paper roll on the inside. The substrate paper is then fed under and over two additional rolls and then attached in the same manner on the opposite side of the PU. The relaxed substrate paper is also visible, and by following the paper, the drive side of the substrate paper is possible to locate.

The following circle *B*, highlights the spinner system. Three pipes with spinner reversed funnels are attached to a white nylon or acetal base. The polymer solution is fed by a hose through the pipes and on to the spinner funnels. The pipes and the reversed funnels are made from aluminum and are welded together. The pipes and reversed funnels spin together during the fiber production process and are driven by an electrical motor using simple plain rubber belts and pulleys. A closer view of the drive and the reversed funnel shape are found in **Figure 1.2** and **Figure 1.3** respectively.

In circle *C* the electrical controls for the different motors are highlighted. These consist of the pump drive, the substrate paper roll drive and the spinner drive, as well as the on-off control of the high voltage power supplies.

Circle *D* highlights the collector grid which is attached to the roof of the PU by PVC rods.

Not apparently shown in **Figure 1.1**, are the high voltage supplies, which are made by Gamma High Voltage and supply ±50 kV, giving a total potential of 100 kV. The two power supplies are placed on the spinner mounting table, also not shown, and immediately above the collector grid. They also connect to the spinner and collector grid respectively.

The spinner mounting table is adjustable by hand from inside the PU and obviously requires a total power down in order to adjust.

In the bottom part of the PU, a pumping mechanism along with a reservoir, holding the polymer solution, feeds the polymer solution on to the spinner funnels via a tube system. These are fed by hand through the entire length of the aluminum pipe and funnel and is done before every spinning session.

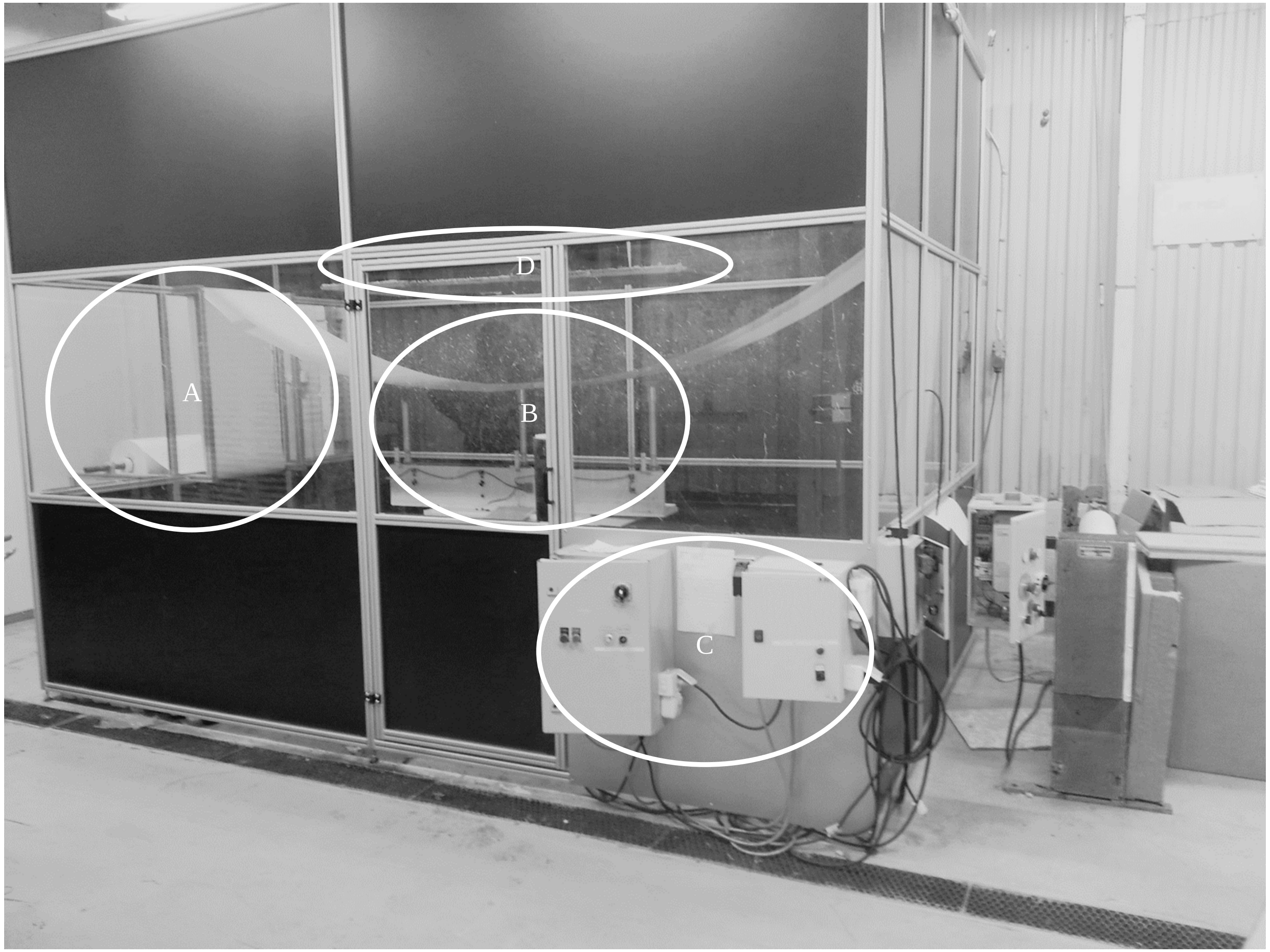

Figure 1.1 An overview of the original PU. The entire enclosure is displayed. Further key features are circled. A: The substrate paper roll system, B: The spinner system with the three spinners, C: Controls for motors and pumps, D: The collector grid

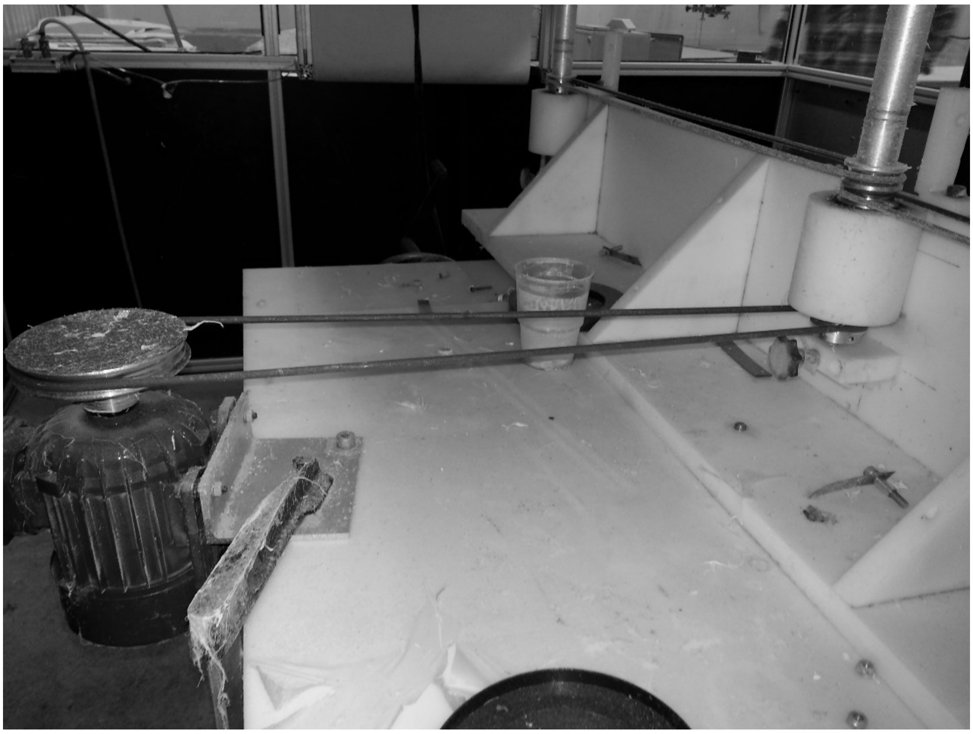

Figure 1.2 A close-up of the driver system for the spinners

Figure 1.3 A close-up view of the spinner reversed funnel, covered with polymer residue

1.5 Application and markets

Nanofibers are currently used in a variety of markets. The more prominent are the filter industries and the life science industries [1], [2]. As mentioned Cellevate AB focus primarily on the life science markets [1], [4].

Other markets are currently being surveyed by Cellevate AB, where other applications of nano-fibers might be used [1].

2 Aims

The aims of the project described as a design brief.

The aims of this project are to design, construct and build a standalone, table-top centrifugal electrospinning device. It should be able to perform as both a platform for scientific studies and research, as well as performing as a low volume nanofiber production unit for industrial purposes.

Moreover the device should be compatible with regular laptop computer devices for easy controlling, and extraction of laboratory data.

The device should be ergonomic, cost effective and small enough to fit on a regular laboratory bench. The parts must be resistant to any type of solvent used in the spinning process.

The device should contain as few custom elements and/or parts as possible to preferably keep costs low and facilitate the assembly process.

The design and build should be finished within the given time and budget.

3 Method

The method used for this project is based on the product development methodology described by Ullrich and Eppinger in "Product Design and Development", albeit modified, as well as the NASA "Production by Prototype" methodology, also modified. These two are mixed with the methodology presented during design courses at LTH.

3.1 The Ullrich and Eppinger product development methodology

In the generic design methodology presented in Product Design and Development, there are several stages or phases that combine to make an entire development chain, from concept to finished product and mass production [5].

The stages or phases are as follows [5].

- Product planning phase
- Conceptual development
- Product system development
- Product detail design
- Prototyping, testing and redesign
- Production start and early manufacturing

For this thesis, the conceptual development phase to the prototyping-phase are relevant and will be briefly explained below.

3.2 Conceptual development phase

The conceptual development phase consists of several different parts. The first part is defining and finding costumer need [5]. This can be done by a variety of different methods, e.g. interviews, surveys, observations. This is then followed by specifying objectives and functions for the product, based on the data from the previous step [5].

The product specification is followed by three other steps, concept generation, concept screening and finally concept scoring. During the concept generation step, a vast amount of different conceptual solutions are suggested. The screening process then follows, discarding the more outrageous or weak concepts. This is followed by the concept scoring step which is a way to quantify and evaluate the generated concepts against each other. The scoring is conducted by using a matrix, where the concepts are benchmarked. As basis for the scoring either one of the concepts or an existing product, competitive or non competitive, is used. This can be iterated any number of times. When a satisfactory concept has been generated the next phase can be initiated [5].

3.3 Product system development

During the product system development, the highest scoring concept is then fine-tuned, and propositions for product layout and further design is done. Technical solutions to obtain concept functionality are investigated and proposed. This is then followed by the product detail design phase [5].

3.4 Product detail design

During this phase, the components of the now rather refined concept/product are designed in detail. Materials for the components are evaluated and set as well as tolerances. Drawings and documentation of the product are/is made [5].

3.5 NASA Designing by prototype

The NASA design by prototype methodology is dedicated to product development and design of low quantity production and/or one off-builds, specially developed for aerospace applications [6].

It gives the designer or constructing engineer valuable tools to realize and evaluate product design which are made using CAD-software and digital prototyping. Extensive use of CAD might lead to difficulties in manufacturing and by utilizing physical prototyping along with the CAD, work arounds any of these difficulties can be made, thus lowering manufacturing costs and reengineering [6].

3.6 Per Liljeqvist design methodology

Per Liljeqvist is a lecturer at the department of industrial design at LTH. He has been course administrator and lecturer in several of the design courses in the mechanical engineering with industrial design program. His design philosophies are explained and presented below.

3.6.1 Idea generation and manipulation

Good design needs to spring from ideas though not all ideas propose good designs. From one hundred ideas, maybe one is a good place to start when designing. To obtain a number of new ideas, techniques can be used to divert from thinking in the same patterns thus eliminating repeating ideas or mind patterns. A method presented by Per Liljeqvist in the course “Design Methodology” at LTH, is to start out with a timer set to 1 minute. A random word is then announced or generated, and the timer is started. During the single minute, six different product ideas based on the random word is to be drawn up/presented. This is then carried on until enough ideas are obtained. The product ideas are then refined and evaluated [7].

3.6.2 Design as a learning experience or process

The design process by Per Lijekvist method is considered to be a learning experience. The product evolves as the designer evolves in the project. In order to construct a design project, observations of people are made in order to isolate a need. The need is then made into a design brief, stating what product is to be made [7].

The design brief is then analyzed using a function analysis which takes the main usage objectives of the product, or functions, and gives the designer only desired objectives or functions to work with, thus decoupling from the product stated in the brief. This allows for better creativity as the functions not necessarily needs to be obtained by designing the product in the brief [7].

3.6.3 Design by prototyping

This is somewhat related to the NASA method, but the intent is to realize a product or function solution in a quick and easy way to evolve in the design project faster. It is even possible to obtain good design solutions from experimenting with shapes and prototypes as a starting point, with no brief or previous function analysis. It is a tool such as sketching or idea generation [7].

Per encourages students to make between 40-50 prototypes, where one or maybe two might possess any value for further refining. This can be repeated until satisfactory results are achieved [7].

4 Finding customer needs

To find the customer needs of this project, close collaboration with the customer (Cellevate AB) as well as several interviews with the staff was held. Evaluation of the existing PU was also conducted.

4.1 Interviews

As advised both in U&E and by Per Liljeqvist, several interviews were held during the project, to obtain the wishes and wanted features of the new PU [5], [7]. The subjects of these interviews were the staff at Cellevate AB, mainly the supervisors of this project, Maximilian Ottosson and Albin Jakobsson. Both of them are working as R&D engineers at Cellevate AB, as well as machine operators.

4.2 Function analysis

To break down the true objectives of the PU, a function analysis was made as by the Per Liljeqvist method [7]. This was based upon studying the existing PU and the additional features wanted by Cellevate AB obtained through interviews [7]. The function analysis in its whole is displayed below in **Table 4.1**.

Table 4.1 Function analysis containing a verb followed by a noun and/or adjective to form a function or need. MF stands for "Main Function", W for "Wanted" and N stands for "Needed".

Verb	*Adjective or/and noun*	*Grade*
Produce	Nano fibers	**MF**
Fit trough	Door	W
Allow	Easy access	W
Allow	Easy maintenance	N
Allow	Automatic adjustments	N
Have	Voltage overcapacity	W
Have	Height adjustment overcapacity	W
Be	Modular	N
Be	Portable	W
Allow	Voltage potential difference (Collector, emitter and frame)	W

4.3 Revision during build process

Revising interviews were held continuously during the build process which resulted in adding and subtracting various features, such as extended modularity which was added and humidity measurement which was also added but later subtracted due to time issues [1], [5] and [7].

5 Concept generation, -scoring, -screening and conceptual design

Due to the nature of this project, the concept generation process was done in a fashion that allowed for a quick realization of the conceptual design. This means concept scoring and concept screening were to a large extent taken out of the concept generation phase but used to evaluate the power supply as this would be a very large part of the budget, and needed more consideration.

The U&E method was largely used in this part of the process as well as the Per Liljeqvist method when suitable and overlapping the U&E method such as in the generation process [5], [7].

5.1 Concept generation

Based on the collected material from the interviews and analysis of the FA, a concept was generated in brainstorming sessions with the employees at Cellevate AB [5], [7]. This concept consists not only of the PU, but describes an entire production system, where various modules can be paired up to customize a production system for a variety of applications. This is illustrated below in **Figure 5.1**.

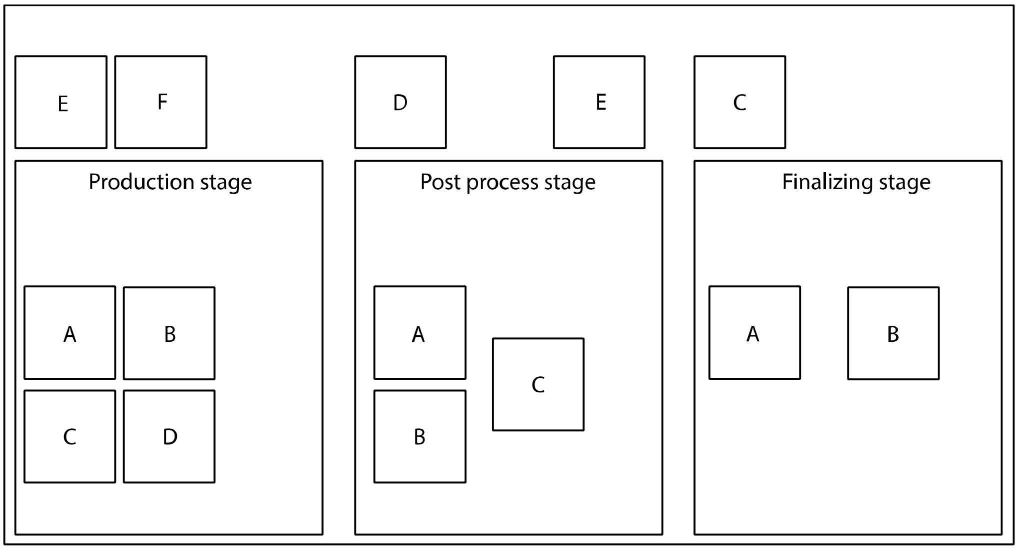

Figure 5.1 The production system concept visualized in a block scheme.

As displayed above, the production system involves several different stages or modules, where the PU designed for this thesis is the first module, displayed as production stage. The following module contains post production processing, e.g. quality control using SEM, cell cultivation or similar. This is followed by a finalizing module, where cutting, packaging and similar tasks occur.

The various lettered square blocks represent different modules that can be added, subtracted or substituted for other corresponding blocks, e.g. The block containing the letter A could be said to represent a specific spinner funnel shape, and can be substituted for the block containing the letter E or F.

This entire system solution can be offered to the customer and is then installed, supplied and maintained by the producer and offers both solutions for industrial production applications as well as applications for scientific research.

The entire production system was of course outside the limits of this thesis which is focused around design and realization of the PU. The PU is the key element of the larger production system concept. The entire production system concept is still relevant to the presentation of this thesis as it, as well as the PU, are parts in current undergoing patent application enquiries. Part of the budget for this thesis project was withdrawn to be used for the patent application.

The PU designed in this thesis is the key component, and is itself very customizable. To obtain as much flexibility as possible, all parts that are known to- or may be of significance to the outcome of the fiber quality/structure, are modular. Such parts are the collector, the spinner funnel, the voltage and the slurry flow.

Other parameters that were suggested but not taken into consideration due to time constraints, are humidity and solvent saturation in the surrounding environment. The design therefore aimed to make any retrofitting of equipment to read these parameters, as easy as possible.

Any moving parts of the PU should be controllable using a single computer interface as opposed to having to adjust some parameters manually or turning every part on or off individually as the only option.

5.2 Conceptual design

5.2.1 Housing/enclosure

Using block schemes and sketching, a quick version of the PU was drawn up [5], [7]. It was suggested that pre-fabricated aluminum extrusions would be a good choice for any housing of the PU components.

5.2.2 Controls and power supplies

As it was considered beneficial to keep any controls and expensive equipment, such as the control of the motors and the power supplies for the high voltage outside of the actual PU, a rackmount to hold these placed in the proximity of the PU was suggested. It was also suggested that the possibility to obtain at least as large potential difference as that of the existing PU would be beneficial [1].

5.2.3 Table and spinner

To minimize unwanted coating of the enclosure or any equipment located inside the PU, a rise- and lower-able table covering almost the entire horizontal surface of the PU would hold the spinner and the spinner motor. This would minimize any unwanted coating of the moving parts, pumps and other components such as syringes and motors [1].

Another good reason to have the table as large as possible, was to ensure any metal parts, such as ball screws or as the revision of the height adjusting mechanism, the motorized carjacks, to place as far away from the spinner as possible to avoid any risk of short circuits.

The spinner should be equipped with an upgraded drive system. It was suggested using a toothed pulley with a corresponding belt in order to avoid any slipping, which was a problem in the original PU [1].

An overview of the intended design of the total spinner and table assembly is shown below in **Figure 5.2**. To allow adjustment for the belt tention, a small slot was cut in which the spinner motor was able to slide and fasten as correct belt tension was achieved.

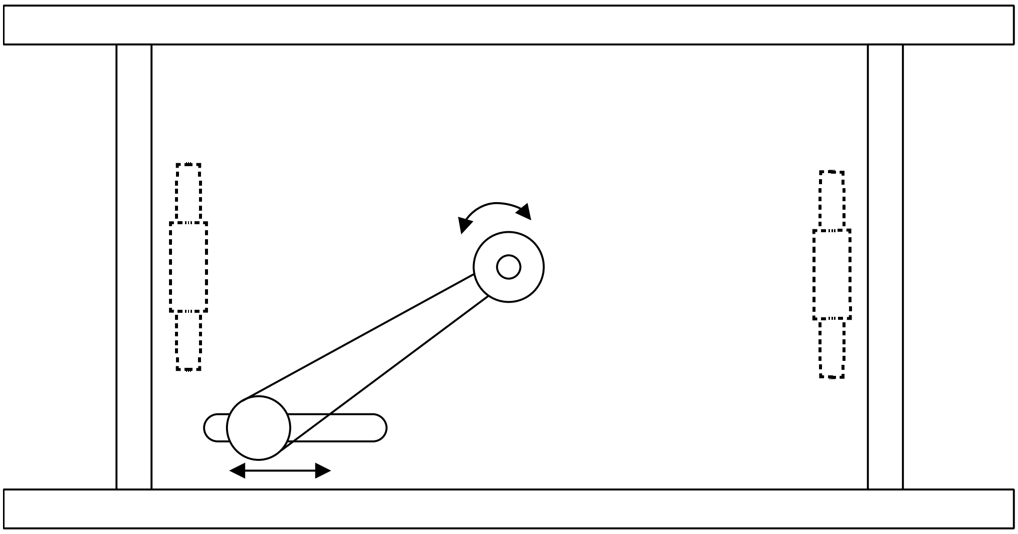

Figure 5.2 A top view of the total table and spinner assembly, showing the carjacks mounting under the table, the spinner drive by pulley and belt and the aluminum frame.

It should also be modular and designed to allow different shapes of the funnel [1]. It would preferably also be easy to disassemble in order to allow cleaning and ease of use [1]. The conceptual design suggested a cylindrical body with a threaded part of the exterior surface to mount different spinner funnels, and attachment of a pulley in the lower part of the body to minimize strains and deformations which might interfere with the belt drive. The cylindrical body together with the attached spinner funnel would be suspended with bearings on a smaller cylindrical tube which would provide the base.

The spinner concept is illustrated in **Figure 5.3**.

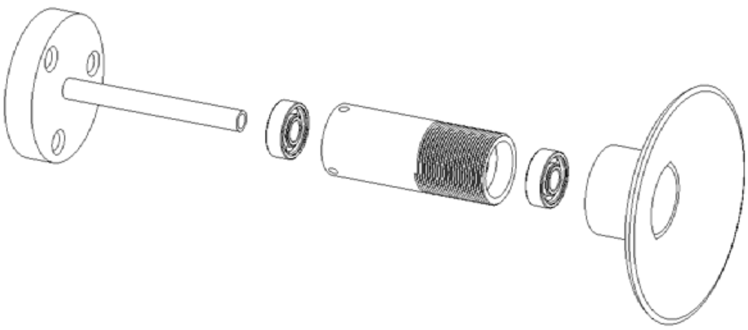

Figure 5.3 An exploded view of the entire spinner assembly, featuring the spinner funnel, ball bearings, main body and mounting axis.

5.2.4 Collector

The collector should also be modular and take a variety of different collector plate shapes[1]. The concept design suggested a mounting structure which provided a sufficient distance from the metal parts of the enclosure to avoid short circuits, to which the different collector plates could be easily mounted.

5.2.5 Pumps and substrate paper rollers

The pumping mechanism was preferred to be continuous and to mount inside the PU if possible, it was suggested to use an existing syringe-pump system, modified to allow the pump reservoir (syringe) to be supported and used without being attached to the actual pump housing. Being attached to the pump housing might cause short circuits if a polymer solution with notable electrical conductivity, such as formic acid, was to be used[1].

To ensure proper use of the syringe pump system, a syringe support equivalent of the one on the actual syringe pump was designed, along with a piston extension.

The substrate paper rolls were designed to attach to the aluminum frame of the enclosure. Two arms on each side of the PU would hold one roll each, from which the paper could be rolled back and forth.

For the roll-up roll was designed as a pipe with sealed sides. The pipe was to be slotted in order for the substrate paper to pull through and be rolled up to fasten before operation of the PU.

The arms were done in two different types, one for holding the stepper motor, and one for holding the non-drive side of the roll attachments. The non-drive side arms were then each modified to accommodate the two different types pf mounts.

These are displayed below in **Figure 5.4**

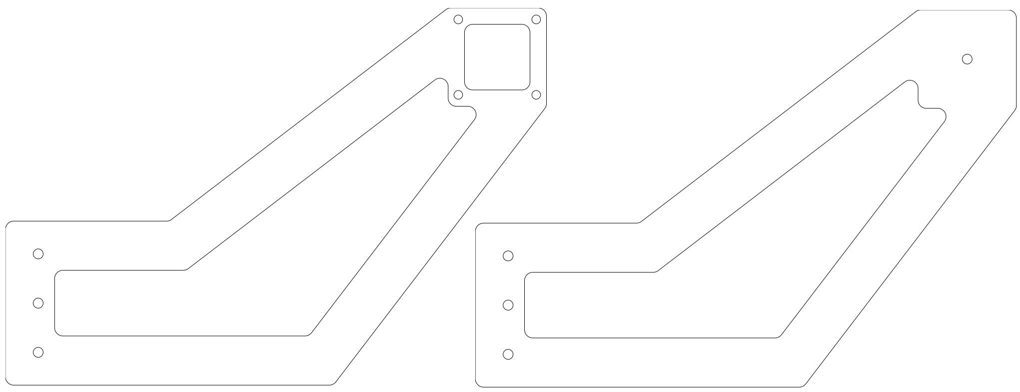

Figure 5.4 The roller mounting arms in view. To the left the design for the drive side is displayed and to the right, the non-drive side is displayed

The arms would then hold the rolls between them and allow for a motor do be attached to each of the rolls. For the substrate paper side, the paper roll would attach between two cones as displayed below in **Figure 5.5**.

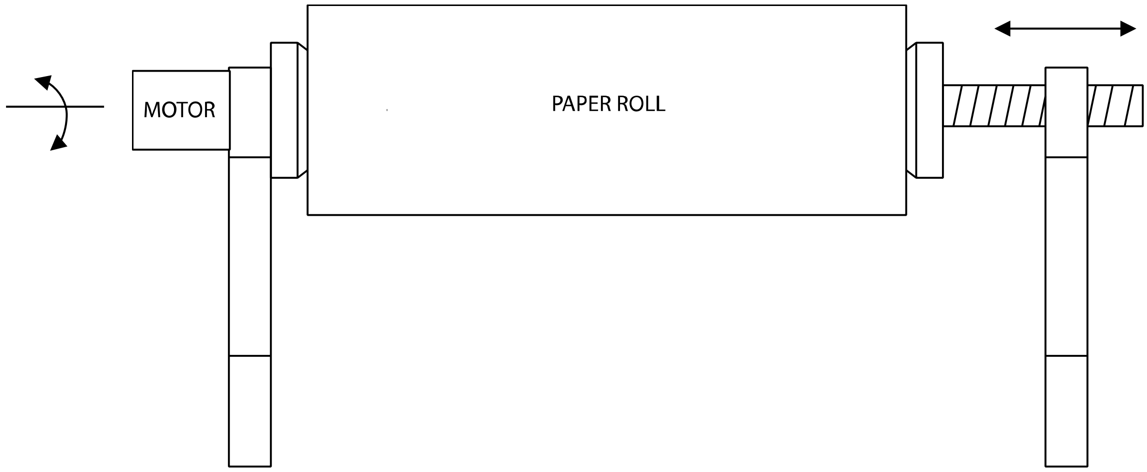

Figure 5.5 A display of the paper roll attached between the roller arms, and fastended by a cone on each side.

As displayed the motor drive attaches to the arm and the roll and on the opposite side a screw-type axis allows for adjustments in roll size and tension.

5.3 Concept screening and scoring

As there was only one basic concept, the dedicated concept screening phase was not very extensive. Time constraints would only allow for a quick realization of the concept.

As ordering of parts were about to commence, the basic concept was divided into new different concepts based on what power supplies for the high voltage that was going to be used.

At first, the basic PU concept with the option of only a single power supply was scored against the basic PU concept using two power supplies. The use of two power supplies would allow for the same potential difference between collector and emitter but keeping the enclosure at a different potential than the two.

As per the U&E method, a scoring matrix was used [5].

The scoring is shown below in **Table 5.1** in which A represents the solution using two power supplies, and B represents the concept using one power supply. For reference, the original PU is used, which as mentioned in the introduction, uses two 100 kV power supplies.

Table 5.1 Scoring between two concepts, regarding abilities in voltage potential.

	Concept		
Feature	Orig. PU (REf	A	B
Possible potential difference from collector and emitter to ground	3	3	2
Sum	**3**	**3**	**2**
Continue	No	Yes	No

As the concept using two power supplies was considered to be the best solution, it was taken into further consideration. The concept was now divided into three possible conceptual solutions based partly on power supply manufacturer as well as voltage capacity.

Three different power supplies gave three different concepts, one using two FUG power supplies allowing for a potential difference of 130 kV in total, the second using two FUG power supplies allowing for a potential difference of 70 kV in total, and the third based on a Gamma High Voltage power supply, allowing for a potential difference of 100 kV.

The two power supplies from FUG allowed each power supply to be placed outside the PU with a dielectric cable running to the emitter and collector. Both concepts using a combination of two power supplies resulted in a higher cost. The FUG power supplies could also be computer controlled to an additional added cost.

The Gamma High Voltage power supply was lower priced but had to be placed inside the PU. It was however controllable with a supplied remote controller at added cost but without possibility to control by computer.

The three concepts were scored against each other based on how well they fulfilled the intended design in the basic concept, evaluation features as voltage overcapacity, controllability and finally cost.

The scoring is shown below in **Table 5.2**.

Table 5.2 The table shows scoring in the second stage of concept generation, considering the choices in power supplies. X represents the FUG ±65 (130) kV option, Y represents the FUG ±35 (70) kV option and Z represents the GHV ±50 (100) kV option.

		Concept			
Feature	*Factor*	Orig. PU	X	Y	Z
Possible voltage potential	*0,2*	3	4	2	3
Cost	*0,4*	3	1	4	4
Controllability	*0,4*	2	4	4	2
Sum	***1***	**2,6**	**2,8**	**3,6**	**3**
Continue		No	No	Yes	No

For the second scoring, a multiplying factor is used to rank the importance of the different features [5]. Cost and controllability was considered more important than the possible voltage potential, and this shows in the “factor” column in **Table 5.2**. Again, the original PU has been used as a reference. The reference is supposed to score 3 on all features, but as the original PU has no remote control on the power supplies, it is considered to score 2 in that specific feature [5].

6 Materials selection

In order to determine what would be the ideal material for use, each part of the PU was treated separately. Factors that was used, was machinability, price, electrical conductivity, strength, chemical resistance and availability. For evaluation and guidance, materials charts were used to get an overview of how the different materials compare.

6.1 Materials charts and usage

In order to make materials selection easy and give an overview of different materials and their properties compared to each other, materials charts can be used. These often plot certain important properties against each other, such as Young's-modulus, strength, density, electrical conductivity and cost.

For this thesis, the charts shown below in **Figure 6.1-Figure 6.4** were uses as a guide to select materials, as well as specific data for many of the materials that was taken into consideration. The charts are an outtake from the interactive materials charts found on the Cambridge University physics department website and have been modified to show properties for both metals and polymer in one chart, where possible [8].

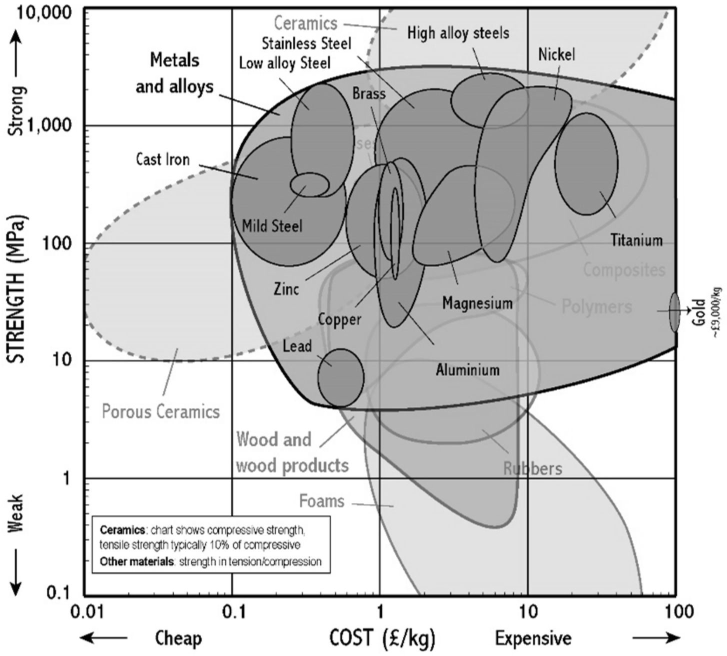

Figure 6.1 Materials chart plotting strength vs. cost for metals [9]

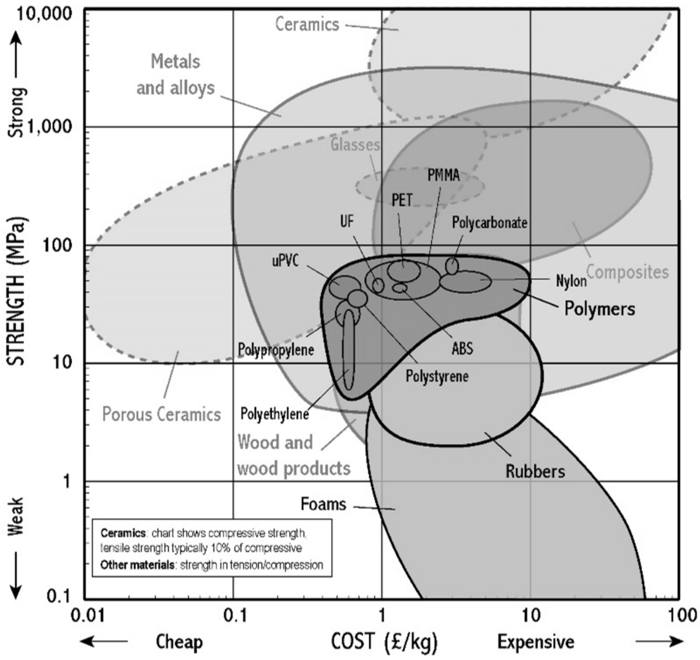

Figure 6.2 Materials chart plotting strength vs. cost for polymers [9]

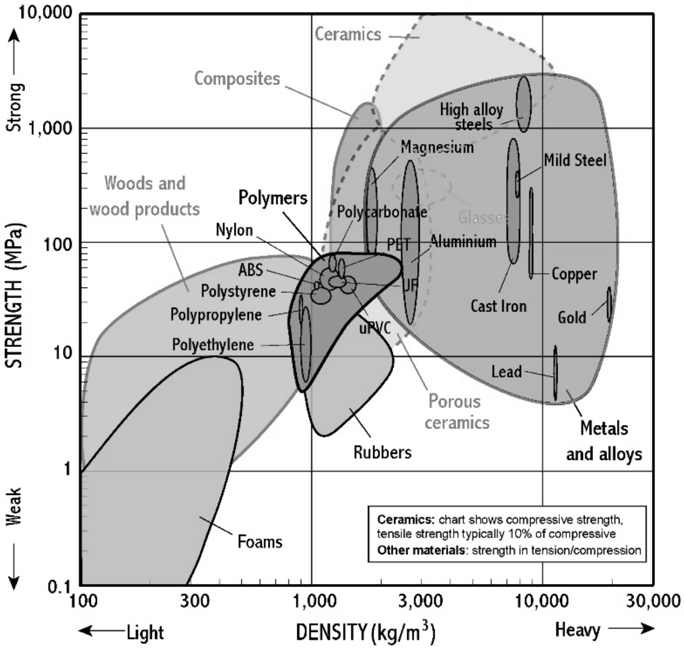

Figure 6.4 Materials chart plotting strength vs. density for both metals and polymers [10]

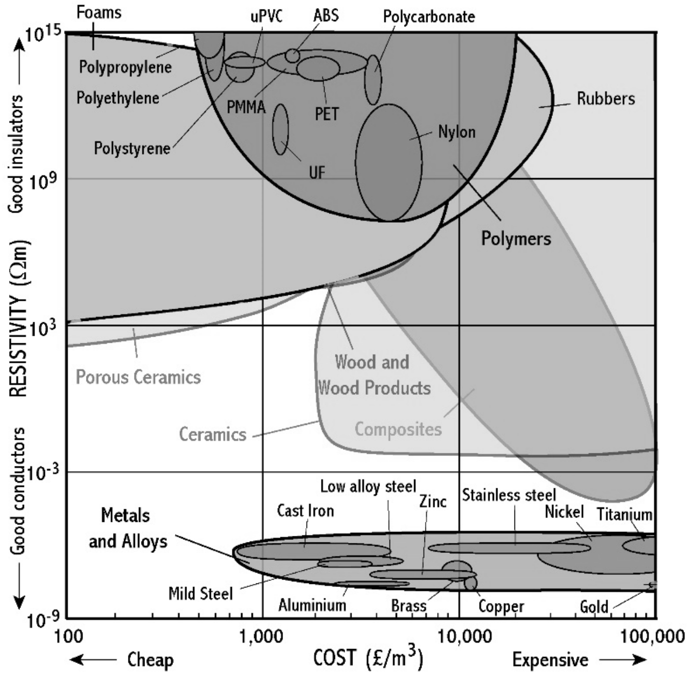

Figure 6.3 Materials chart plotting resistivity vs. cost for both polymers and metals [11]

6.2 Frame

The desired properties of the cage material were as follows:

- Low price
- Good/sufficient strength
- Good electrical conductivity
- Low density

Taking these parameters in consideration, aluminum was selected, as it fulfills every desired property as well as being offered as extrusions, both ideal for attaching any other parts, and easy to cut [12]. Other options might have been steel, or construction plastics like PVC or acetal, but these lack in some aspects [13], [14] and [15]. Steel was considered much too heavy, being three times heavier than aluminum [12], [13]. As seen in **Figure 6.4**, the plastics like PVC and acetal is not as strong as the metals and display very low electrical conductivity and would possibly allow for static electricity charges to build up [14], [15].

6.3 Table and side panels

For the table and side panels, de desired properties were:

- Good strength
- Transparent
- Good chemical resistance
- Low density
- Good machinability

The materials taken into consideration were glass, polycarbonate and acrylic.

Glass has very high chemical resistance, but is week when subject to tensile stresses. It also has higher density than the other choices, and is hard to machine, it was therefore ruled out early on [16].

Polycarbonate has got several features that would fit the design, such as impact resistance and transparency, and is often used in casing or housing due to the strength and ductile properties[17]. It does however loose many of these properties when used in solvent rich environments, especially when subjected to acetone, one of the more common solvents used in the electrospinning process at Cellevate AB [1], [17] and [18]. It is also only available at higher cost than Acrylic [17]. Taking this into consideration polycarbonate was ruled out as well.

Acrylic is equivalent to polycarbonate in many of the desired aspects, but is brittle and not as strong [19]. It does also deteriorate when exposed to Acetone and other solvents, but it is both less expensive compared to polycarbonate and is also proven to suffice in the original PU [1], [20].

6.4 Collector

The collector is divided into two different parts, the collector plate and the collector suspension. These have vastly different property demands, mainly the suspension needs to be an isolator, while the plate needs to be highly conductive [1].

For the collector plate the wanted properties were

- good electrical conductivity
- good strength
- preferably low density

For the suspension/fastener, the wanted properties were instead

- Good electrical isolation properties, even for high voltages
- Good strength
- Low price

For the conducting plate, aluminum was chosen as it was properly suited [12]. Punched sheets were used, to ensure that there was enough collector material to get even cover, but also obtain sufficiently low friction against the substrate paper.

For the fastener structure PVC was originally selected, but as parts of the budget was used for funding patent enquiries, thus reducing the budget for additional material purchases, some spare acrylic was used to economize the construction [14], [19].

6.5 Spinner

The spinner has several parts but they all display the same needs in terms of material properties. The wanted properties were

- Good electrical conductivity
- Good machinability,
- Preferably low density
- Easy accessible

Aluminum became the choice for all parts except the ball bearings which were pre-fabricated in steel. Although aluminum was used for all parts, it might have been better to manufacture one or more parts in steel, especially the parts interacting, such as the spinner funnel and body, to avoid any of the threaded surfaces to weld together if not used with caution [12].

7 The build process

This section intends to give an overview of the building process

7.1 Building the PU

7.1.1 Material ordering and sourcing

As the CAD-model was completed enough to get the build process started, material for the frame and the drive (stepper motors, control card etc.) of the PU was ordered. As these arrived, the building commenced. Later, other components were ordered, such as the power supplies and the encasing for the motor control cards and belts and pulleys, followed by acrylic sheets for the enclosure panels.

Some minor problems with ordering occurred which mainly consisted of time consumption due to delivery handling. For the first two deliveries, these were held in storage at the storage facilities at IKDC and no notifications were sent in order to pick these up. This was however sorted out and once the issue was noticed it did not recur.

7.1.2 Spinner manufacturing and assembly

7.1.2.1 Spinner main body

The spinner main body was turned from a piece of aluminum rod to an outer dimension of 24 mm. An 8 mm diameter hole runs through the entire length of the body, and at each end a cut out is placed which shall hold the ball bearings. The lower ball bearing cut out is drilled to accommodate screws which locks the ball bearing in place. The upper part of the body is threaded with a 24x1 mm fine thread to fit a spinner funnel with the corresponding thread.

7.1.2.2 The spinner funnel

The spinner funnel designed for this thesis is CNC-turned to shape from solid aluminum rod. The center is drilled out to a diameter of 23 mm and from there threaded to 24x1 mm fine thread. The maximum diameter of the funnel is approximately 80 mm. The shape allows for the centrifugal forces to spread a polymer solution to the outer edge of the funnel where a slight flange keeps the solution from being plunged over the entire PU.

Other shapes of the funnel are possible to evaluate.

7.1.2.3 Ball bearings

The ball bearings are purchased from a local car part supplier and are in this case used to comply with the existing PU. As they are replaced before any electro spinning session, they were chosen to be readily available and low cost. The use of a more permanent solution such as capsuled bearings was briefly discussed, but not investigated. The bearings measure 19mm outer diameter, and 7 mm center hole diameter.

7.1.2.4 Pulleys

The pulleys are, along with the ball bearings, a standard component ordered from a local supplier, and is made from aluminum. The only modifications made are a center hole of 24 mm and 3 holes on the small flange to fit screws to attach to the main body.

7.1.2.5 Mounting axis/tube

The mounting axis is turned from a solid piece of aluminum rod. It consists of two diameters, the base of approximately 80 mm and the axis/tube which has a diameter of 7 mm. It has a center hole of 5 mm leaving a wall thickness on the tube section of 1 mm. This proved very hard to manufacture from one piece.

A revision of this is suggested where the axis and base could be made from two separate parts that are attached, each with its specific diameter, rather than a single piece.

The choice of manufacturing the axis from a single work piece was to ensure sufficient straightness and tolerances as is should hold the spinner body.

7.1.3 Collector and collector mount

The initial design of the collector was based on perforated aluminum sheet, attached to a frame of PVC extrusions. This would be mounted on extensions from the enclosure, made by the same type of PVC extrusions. As the project moved into assembly and manufacture of the collector the reduced budget forced a redesign of the collector. The solution was to use left overs and spare material.

Below, the intended design, as well as the redesign will be presented.

7.1.3.1 PVC frame

The frame would consist of a horizontal square shape formed by 40x40 mm PVC square extrusions. These would be glued together. The ends over which the substrate paper would go were initially designed to have small rolls attached to avoid any tear or ripping. As time and budget would not allow these to be made, a simplification was made which was to give a radius to the edges. This would give slightly more friction, but would avoid any tearing.

The frame would then have vertical rods made from the same PVC square extrusions, these would be fastened by screws to the horizontal frame and attach with screws to the enclosure. This would allow for a quick change of collector material and shape.

7.1.3.2 The collector plate

The collector plate designed for this project consisted of pre punched aluminum sheet metal which was bended to shape. This would be attached by screws to the horizontal part of the frame. The punched holes in the sheet would allow for less friction while applying high voltage during spinning, compared to using a completely solid sheet.

7.1.3.3 Redesign and final construction

Since the reduced budget would not allow a purchase of the intended PVC rods, manufacturing of the PVC parts was impossible. The solution was to instead make the vertical rods out of some spare acrylic sheet which was heat bended and drilled to attach to the enclosure and accommodate the frame.

As for the collector plate, the reuse of two pieces of spare aluminum extrusions for the sides of the enclosure was utilized, as these possessed a radius equivalent of that intended for the PVC rods. There was however not enough spare material to make an entire frame, and the final build relied on the elasticity of the acrylic and the strength of the aluminum sheet to keep the collector form bowing.

An illustration of the final outcome is displayed below.

7.1.4 Frame assembly

The frame was constructed using aluminum extrusions. These proved to be very easy to put together and the fact that they were delivered cut to length saved a lot of time during the assembly. As the frame was coming together, it was noted that it needed some heightening in order to have enough space between the frame and the collector. To attach the square 40x40 extrusion cross bars, center attachment screws were used. To fit these, each of the cross bars were drilled using a drill press to accommodate the locking mechanism. During the drilling there was some problems with vibrations that might have caused misalignment of the holes, but all holes lined up straight enough to not have any difficulties during assembly.

7.1.5 Assembly of control card rackmount enclosure, and motor drive

The control unit for the drive of the PU was based on a rackmount metal box in which the different controllers and boards were mounted, as well as the power supply for the spinner- and stepper motors. The front was routed to hold a USB connection and an ON/OFF and off switch with pilot light combined. An additional On/Off switch was added to the side of the rack enclosure as an added safety.

The motors was together with the frame one of the first things that was ordered. A set with USB controller card/drivers, power supply, appropriate software and four stepper motors was purchased from Ali Express. The motors were rated 3A and suitable for DIY CNC-routers. The control card was plug and play and with the power supply connected, the motors were quickly being controlled using the provided remote control.

The spinner needed a motor as well, and the choice fell upon a CNC router spindle. This was modified to hold a pulley to be able to drive the spinner from a safe distance.

The motor driver and control card were said to be able to connect, to control features as on/off, and direction of rotation, using the control card and software.

7.1.6 Carjack modification and table drive

The drive for the table was as mentioned earlier done by using two standard automotive scissor type carjacks. These were modified by adding a bracket to hold the motors. The motor holder part of bracket was waterjet cut from 10 mm aluminum sheet metal. The two arms that attach to the jack was waterjet cut from 5 mm aluminum and then routed at the ends to mount to a slot in the motor holder. This was then pressed together. The jack was then drilled in the center of the screw anchor point using a drill press followed by threading the hole. The bracket was then mounted to these holes using screws.

The motor was given a shaft extension to be able to drive the screw. A cylinder shaped piece of aluminum was drilled to fit the shaft. This was then drilled perpendicular to the shaft hole to fit two more screws, one to lock it to the motor shaft, and one to attach it to the jack screw U shaped turning hub.

7.1.7 Table

The size of the table was determined to be as large as possible, but still able to fit the laser cuter at IKDC. The table was cut to dimensional size using circular saw. It was then laser cut to hold both the spinner motor and the spinner shaft/base as well as allowing any tube to be led trough the spinner shaft. The table top was finally mounted in a frame of aluminum extrusions which were joined by the same type of center attachment screws as the frame.

7.1.8 Roller attachment arms, roller mount and roll-up roller

7.1.8.1 Roller attachment arms

The roller attachment arms were cut by water jet from 10 mm aluminum sheet metal. They then had the holes drilled to size as the cut from the water jet deviates, slightly but noticeable; when cutting thicker sheets of metal.

As mentioned, the side where the cardboard tube holding the substrate paper would be attached, needed to be able to adjust to different sizes of rolls. The non-drive side was for this purpose drilled out and threaded to M20.

The non-drive side for the roll-up roll only needed to provide a good bushing surface and was drilled to 20 mm and not threaded.

7.1.8.2 Roller mount

The roller mount was made of aluminum and PVC. Two cone shaped pieces of PVC was manufactured by turning, one with a small flange to attach to the stepper motor.

The flange was drilled to be able to mount to the motor shaft, and equipped with a locking screw to hold it in place on the shaft.

The other cone was drilled out to take two ball bearings of 19 mm outer diameter.

A shaft of aluminum was also manufactured. A section of the shaft was sized to fit two ball bearings with inner diameter of 7 mm. Another section was threaded to fit the M20 thread of the attachment arm. A flange at the end of the shaft was made to make adjustments easier.

One issue that occurred during the manufacturing of the different pieces, was the limited access to the lathes, which increased the total manufacturing time.

7.1.8.3 Roll-up roller

The roll-up roller was made from three pieces of PVC. First a pipe of 40 mm diameter and 6 mm wall thickness was turned at the ends in order to have a flat surface. Then two flanged cap ends were turned to fit the pipe ends. These were made from solid PVC rod 50 mm in diameter. One was drilled to attach to the stepper motor shaft, and the other was given a flange to sit in the corresponding hole in the attachment arm. The ends were then glued to the ends of the pipe.

The entire roll-up roll was then milled, adding a slot 610 mm in length through the entire pipe on either side to make mounting and securing of the substrate paper onto the roll possible.

7.1.9 Acrylic panels

The acrylic panels for the sides, top and bottom were all cut to size using a circular saw. The panels that mounted to one or more of the corner fittings of the aluminum frame were then cut to fit in the corners using a band saw. This was rather time consuming as the large acrylic pieces needed additional support while cutting the corner parts. This was solved by involving two or more people, providing manual support by holding the panels during the process. A large part of the time taken to cut all the pieces was waiting and trying to schedule time for Maximilian and Albin to assist.

7.1.10 Pump-system

The pumps chosen for the project were made by WPI (World Precision Instruments) which are a well-known manufacturer of syringe type pumps. The particular pump system selected and sourced uses two syringe pumps with automated control pumping in a push-pull setup, which allows for continuous pumping action using the corresponding tube and valve-system. The pumps had to be isolated from the high voltage, especially since the possibility of short circuits will occur if any conductive solvents are used for the polymer slurry. To do this, mounts for the syringes were 3D-printed using PLA and an extension piston was designed to drive the syringe using the WPI syringe pumps.

8 Results

This chapter shows the finalization of the PU this far and provides a short description of the parts and component systems.

8.1 The PU at the end of this project

The results are displayed below as figures, highlighting and explaining the finished parts of the PU. At this point in time, there are still work to be done in order to get the PU fully functional but the results of the work done during this thesis will be covered in this section. Further work has been done to the PU after this thesis was finished, and some of the figures might display som slight changes as to what has been presented.

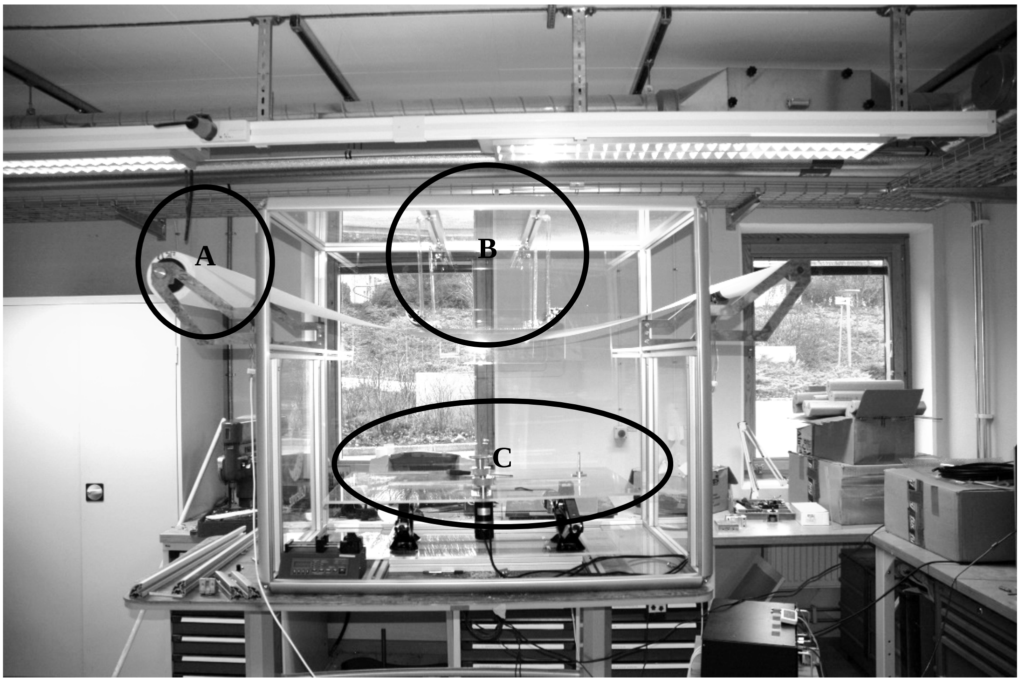

Figure 8.1 An overview of the PU in its state at completion of this thesis work

Above, **Figure 8.1** shows the entire PU. The different parts are circled. Circle A highlights the substrate paper end of the PU with the drive side and stepper motors facing away from the viewer. The paper can be rolled back and forth, by driving either the highlighted area or the roll on the corresponding side of the PU, allowing the paper to slide across the collector plate. Circle B highlights the collector and its acrylic suspension. Circle C highlights the table and the carjacks, slightly modified in comparison to what this thesis proposed (e.g. no aluminum frame). Also visible but not highlighted, the roll-up roller (far right side), and one syringe pump (lower left corner).

Figure 8.2 A closer view of the substrate paper rolls, displaying the motor, paper roll, attachment cones and fastening screw arrangement.

As shown above in **Figure 8.2**, the substrate paper roll is held in place by the suspension system involving the aluminum arms, the PVC cones and the aluminum shaft/screw that make adjustments possible. Also visible is the stepper motor, connected by cord to the control card.

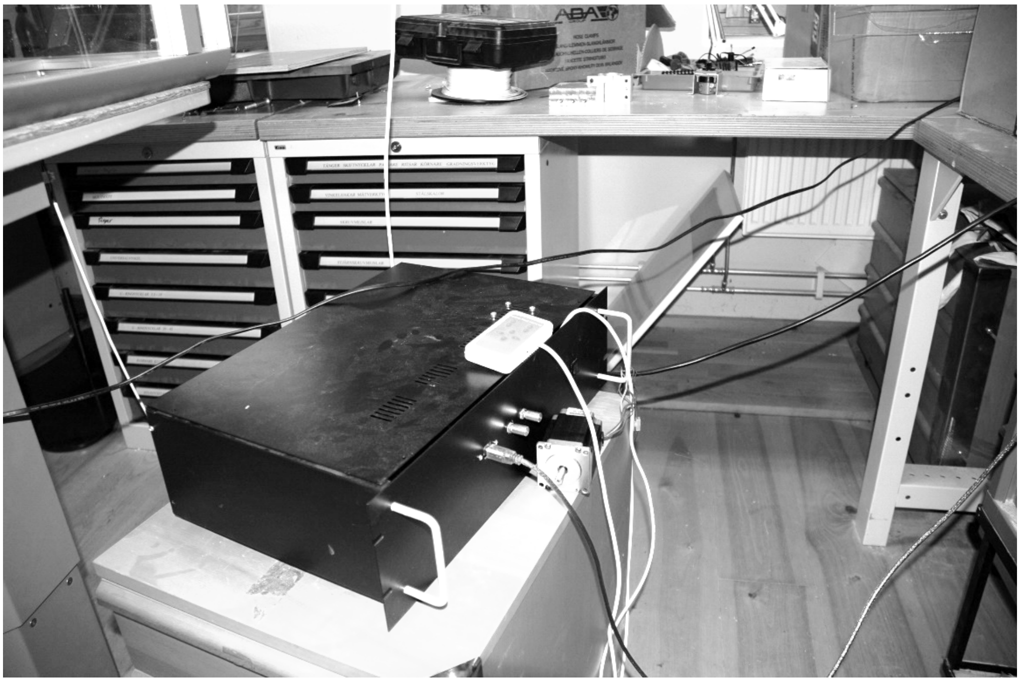

Figure 8.3 An outside view of the rackmount enclosure for the control card etc.

Figure 8.3 shows the control card enclosure, visible is the USB connection. On the back, the cords for the stepper motor and spindle motor are accommodated and feed through the back plate of the enclosure.

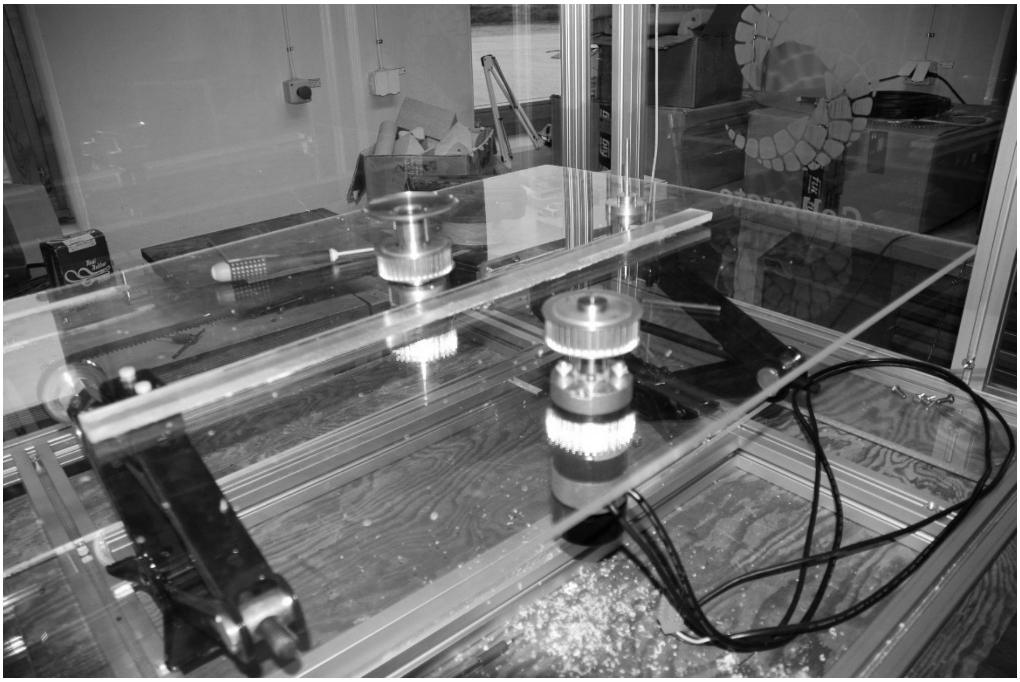

Figure 8.4 This figure shows the spindle motor and spinner assembly, only missing the driving belt.

The last figure, **Figure 8.4** shows the spinner assembly and drive, still not connected with the belt.

9 Discussion

This section will discuss design and build process and provide propositions for changes, redesign and solutions that might have provided a better end result.

9.1 Discussion of the design process

9.1.1 Method analysis and discussion

The method used for this project has been largely based on the U&E methods presented above. This has been mixed with various methods from design courses at LTH, which have much less definition compared to the U&E, as well as the Design by Prototyping process from NASA.

Over all there are several benefits from using various bits from all these methods, as they fit very well in during different stages in the process. There are of course also some drawbacks, as they pull in slightly different directions.

One obvious drawback was exclude the U&E planning phase, which was done as this was contradicted by Per Liljeqvist's method. The philosophy that no planning or schedule is needed, since it will be revised and failed to keep, was in hindsight probably a reason that elongated some stages of the project. It would have been better to follow the U&E method closer in the beginning of the project.

Other aspects of Per Liljeqvist's methods are very powerful and achieve great results, both in this thesis project as well as other project where this has been used, such as the function analysis. It is a very good tool to visualize the functions of a product and focuses the designer on solving these functions as opposed to design exactly what a design brief or project description states.

Regarding the NASA method, it proved very powerful during the assembly and manufacturing phases of the project, and with an extended budget and better access to workshop tools (lathes, routers etc.), allowing for a larger amount of iteration and better prototyping, this would have been even more powerful and I would highly advice towards using this method.

9.1.2 Project goals discussion

There was some apparent issues with the project goals for this thesis. It was originally going to accommodate two masters-students, and no revision or narrowing was done to accommodate only one. This is one of the major reasons for the project not being finished on the planned schedule. It is possible that the original setup, accommodating two masters-students, might not even have been enough to cope with and finish such a vast project as this turned out to be.

In retrospect, it might have been better to limit this thesis to only design a concept for the PU and not take on any building or assembling. This might have produced a more detailed result, and possibly even better solutions to many of the components of the PU.

To present only a concept was also suggested by Olaf Diegel in June as the intended presentation date was close ahead, but was turned down due to time investment in the building process. This was in hindsight probably an unwise decision.

For any similar projects, it is highly recommended that a thesis producing a concept is done, followed by another thesis, focusing on the manufacturing and building of said concept.

9.2 Discussion of the build process and final PU

9.2.1 The frame

The frame was very straight forward, and provided no problems except for having to do some adjustment to the height of the cage. The expediting at AluCon, was fast and helpful, and the option to have every piece of extrusion precut to length saved some time. It would probably be no problem to have extrusion cut at the University workshops, but it would be time consuming, and to little or no cost saving. In order to have them precut, everything has to be drawn up using CAD-software, but this is easy as the extrusion profiles, as well as the connectors are available for download, making any length, width or height adjustments easy to do.

9.2.2 The height adjustment mechanism

On the original PU, the height adjustment had to be made by hand, by raising or lowering a table. On the wish list from Cellevate AB was that the new PU would have this feature motorized and software controllable.

The height adjustment mechanism was constructed using two very cut-price carjacks. The first intention was to use two ball screws, but in an effort to get a sufficient mechanism to very low cost, the decision fell on using the jacks instead. The jacks however, needed some modification in order to work properly.

As the jacks are in rising- or lowering motion, the screw bearing house is moving along, both up/down and in/out. To keep the motor driving the screw, a bracket was designed to hold the motor and attach to the jack.

To get motion of both the jacks, there were the options to connect the two by pulley and belt, or by using two separate stepper motors, since there was one of these “left over”. I decided to go with using two motors, making one of them a slave to the other in the controller software.

A few problems appeared while building and testing the mechanism.

The jacks were obviously not intended for such a precision drive as provided by a stepper motor, and the bearing housing for the screw was very wobbly. This made the entire bracket along with the motor move about and wobble.

The first prototype for the bracket was made in acrylic, which was very weak and could not handle the forces from the wobbling motors without very large elastic deformations and strains.

The redesign, and final working prototype, was as mentioned constructed using aluminum of overall thicker sheets than the acrylic. This improved the drive, but the bracket and the motor was still moving up and down as the bearing housing was rotating.

The use of two motors is not the best solution, but as the project was coming to an end and was long overdue, the bracket was much easier to duplicate, and was considered less time consuming than to heavily modify the cut-cost jacks in order to obtain the one motor drive.

In hindsight, opting for a ball-screw arrangement would definitely provide a substantial upgrade to the PU and this is highly recommended to be further investigated. It needs however to be shielded from any fiber residue, as this will interfere with proper function. This might be done using a soft cover or some kind of telescopic cover arrangement.

9.2.3 Motors, drivers and control card

As mentioned the motors and the driver/control card was purchased from Ali-Express as a kit. As testing commenced, a few problems occurred. First, the controller software was installed and all seemed fine. Then there was some issues with installing the proper hardware drivers.

The installation readme and installation guide was optimized for Windows XP and with the newer Windows OPs there were some features that needed to be turned off in order to install the control card drivers properly. As the read me and installation guide was not updated to current operation system standards, and was an obvious child of google translate I gave up deciphering the read me files.

The solution to the problem was found on an internet website called Planet-CNC, whose webmaster was also the origin of the provided software. After some browsing on the Planet-CNC website, I found that the purchased control card was listed as an unlicensed copy of some control cards available for purchase, supposedly designed by the Planet-CNC webmaster/DIY CNC-enthusiast.

Furthermore there were problems getting the control of rotational direction of the spindle motor to work. This was found to be an outcome of the control card output and motor driver not sharing the same ground, and a potential difference of about 2 volts was present.

As this was discovered, a discussion was had about the possibilities of purchasing a Planet-CNC control card which was about the same price as the one bought from Ali Express. This might have helped solve this problem but it is not certain. It would also have added the cost of four motor drivers for the stepper motors.

The equivalent of these were already incorporated into the Ali Express control card.

Another benefit from going with the Planet-CNC control card, was it would probably be better equipped to communicate with the provided software. It was however decided the Ali Express control card would suffice, especially since Cellevate AB were investigating the possibility to have their own controller software developed.

Over all, the Ali Express kit was sufficient for this project, especially since the company would develop their own software solution. For a router project I would have gone with the slightly more expensive Planet-CNC controller card, as the software was quite easy to use Ad to this, the additional features of those cards, such as PWM outputs, will come in handy if a high level of automation is desired. There is also a forum on the Planet-CNC website which contained very good information regarding the software and hardware.

For further investigation, the development of a dedicated software could be programmed to adopt the use of an Arduino or similar multiple I/O card, to give access to PWM control for better automation.

9.2.4 Spinner

As mentioned the spinners in the original PU consisted of three spinner funnels. These were each attached to a piece of pipe about 300 mm long. They were then driven by a toothless belt and a large DC or AC motor. These rotated around an inner pipe and was supported by bearings in the ends. The polymer solution was fed on to the funnels by a tube which had to be fed through the inner pipe.

There were several problems with this, such as feeding the tube through the pipe, and maintenance and cleaning, all of which were expressed by Cellevate AB staff. Also, the belt often slid providing no motion on the spinners. The long pipes were using unnecessary amounts of space and since the spinner funnels were attached to the pipe, there was very little possibility to test and optimize funnel design and shape.

These issues are addressed in the design suggested in this thesis. The modularity of the spinner is far superior to the original PU, as is the belt drive which now utilizes a toothed pulley and corresponding belt.

If any improvements were to be suggested, one might be that the main tube might be machined in steel, to keep the electrical conductivity at sufficient level while ensuring that the threads for the spinner funnel attachment does not wear or friction weld together.

9.2.5 Substrate paper rollers

The substrate paper is delivered rolled up on a cardboard tube. The design solution involves this tube to be mounted on two cones as mentioned.

To overcome the apparent issue of the substrate roll, and roll-up roll having two different diameters and also changing diameter while operating, one motor for each of the two rollers were used. This allows the rolls to pull in the desired direction, while the other acts as a break, to ensure the back and forth motion of the substrate paper as well as not rolling of any substrate uncontrollably into the PU.

The side that takes the paper roll had to be able to fasten and loosen the roll while providing enough friction for the motor to drive the roll.

There were some issues with the design of the substrate paper cones that became apparent when manufacturing and testing. Unfortunately, the length of the shaft, as well as the size of the cones were not optimized and would benefit from a redesign.

They currently allow for screw adjustment to obtain enough friction to drive the rolls, but it is quite hard to change out the rolls when needed, due to the cone size and shaft length. They could easily be improved by shortening the length of the cones as a lot of excess was given in order to accommodate a wider spread of roller cardboard tube diameters, and if the same supplier is used for the paper rolls, these could be optimized to take only the size of roll they provide.

Regarding the roll-up roll, the slot proved to be a bit unnecessary, as the structural integrity of the pipe was lost and the benefit from the slot was not that great. A better solution might have been to use double sided tape to fasten the substrate paper as suggested by prof. Olaf Diegel, or even to only make one single slot, and not have it go through to the other side of the pipe.

The arms were drilled out on the non-drive side to fit the end cap of the pipe. The aluminum of the arm and the PVC provide a sufficient bushing and support for the roll-up roll.

There are some more possible improvements that can be made to optimize the performance of the roller-system. Additional rolls on either side of the PU could provide better tension and control of the motion of the substrate paper. These would have to be supported with bearings to ensure as little added friction as possible. This might also help with aligning the paper when rolling back and forth. In addition to more rolls, guides could be installed on either roll to ensure proper roll-up alignment.

9.2.6 Acrylic panels

At this time, since the project was not able to finish within the limits of this thesis, there are still some parts to be cut, including the front panel and the hatch to access the inside of the PU. These are rough cut, but need to be either water jet cut or milled to allow access inside the PU. The hatch doors can be manufactured using the laser cutter to have good surface finish on the edges. These will then be fitted with hinges to allow opening and closing, as well as a power switch to ensure for safety precautions in order to avoid the PU being operated while the hatch doors are open.

Regarding materials, acrylic might not be very resistant to heavy solvents like acetone, but it has proven to be sufficient in the original PU. If a larger budget is added, and there are certain applications for this PU in which there might be exposed to damaging forces such as, pieces of spinner material, it might be of interest to investigate re-fabrication of the side panels, using polycarbonate instead.

9.2.7 Power supplies and pumps

These were components that were very budget consuming. The benefits from these are however in large correspondent to the added cost, and it would be better to find ways to add to the now entirely consumed budget rather than sacrificing any performance of these parts.

The FUG power supplies are very well built and will probably never be the weak point of this PU, neither are the WPI syringe pumps.

Further studies should be done, in constructing and programming a software compatible with these units as well as, previously mentioned, the motor drive.

9.3 Proposals and recommendations for further studies

There are several interesting possibilities for further continuing of this thesis. There might be reason to investigate how to realize a small series production of the PU and its attributes mentioned in the production system concept. There are also evaluating and mapping of what other production stages might be of interest for different applications, such as sterilizing, packaging and/or SEM- quality control to name a few.

There might be some applications for 3D-printing nanofiber shapes, or even coating pre-existing shapes of other materials to grow prosthetics. This might be done by modifying the PU to have a movable collector and emitter.

There are also interesting ground to be explored in directing the fibers, by currents or laminar gas flows, to create continuous directional fibers. This might even spawn investigations regarding spinning of ceramic fibers e.g. glass or carbon and infusing these with resins to create nanofiber composites.

10 References

[1] Jakobsson, A. & Ottosson, M., R&D/Production Engineers, Cellevate AB, Personal conversations and interviews Feb 2015- Sept. 2015

[2] Kongstad, P. (2011). Optimizing a centrifugal electrospinning process of nanofibers for filter applications. Masters Thesis. Division of Polymer & Materials Chemistry, Faculty of Engineering, LTH, Lund University, Lund

[3] Ramakrishna, S., Fujihara, K., Teo, W., Lim, T. & Ma, Z. (2005). An introduction to electrospinning and nanofibers. World Scientific Publishing Co. Ptc. Ltd, Singapore

[4] Cellevate AB website (Electronic), http://cellevate.com/, 2015-11-22

[5] Ulrich, K. & Eppinger, S. (2014) *(2012)*. Produktutveckling, Konstruktion och design *(Product design and development)*. Studentliteratur AB, Lund, SE *(McGraw-Hill Education, New York, USA)*

[6] Mulenburg, G. & Gundo, D. (2004). Design by Prototyping: Examples from the National Aeronautics and Space Administrations. National Aeronautics and Space Administration, Ames Research Center, CA, USA. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040081092.pdf, 2015-11-21

[7] Liljeqvist, Per, lecturer at Division of Industrial Design, Lund University, Lectures 2011-2014, various courses

[8] Material Selection and processing (Electronic), Cambridge University, http://www-materials.eng.cam.ac.uk/mpsite/default.html, 2015-11-21

[9] Strength vs. cost materials diagram (Electronic), Cambridge University, http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/strength-cost/NS6Chart.html, 2015-11-22

[10] Strength vs. density materials diagram (Electronic), Cambridge University, http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/strength-density/NS6Chart.html, 2015-11-22

[11] Resistivity vs. cost materials diagram (Electronic), Cambridge University, http://www-

materials.eng.cam.ac.uk/mpsite/interactive_charts/resistivity-cost/NS6Chart.html, 2015-11-22

[12] Aluminium alloys information site (Electronic), Cambridge University, http://www-materials.eng.cam.ac.uk/mpsite/materialsdb/default.html#Aluminium_alloys, 2015-11-22

[13] Alloy steels information site (Electronic), Cambridge University, http://www-materials.eng.cam.ac.uk/mpsite/materialsdb/default.html#Alloy_steels, 2015-11-22

[14] PVC information site (electronic), Cambridge University, http://www-materials.eng.cam.ac.uk/mpsite/materialsdb/default.html#uPVC, 2015-11-22

[15] POM/Acetal product information site (Electronic), Nordic Plastics Group, http://www.npgroup.se/vara-plaster/pom-acetalplast/, 2015-11-22

[16] Glass properties information site (Electronic), Saint-Gobain, http://www.saint-gobain-sekurit.com/glossary/glass-properties, 2015-11-22

[17] Polycarbonate information site (Electronic), Cambridge University, http://www-materials.eng.cam.ac.uk/mpsite/materialsdb/default.html#Polycarbonate, 2015-11-22

[18] Polycarbonate chemical resistance chart (Electronic), Palram Technical support department, http://ilgbcatalog.org/wp-content/uploads/2015/02/PC-chemical-resistance.pdf Sdf, 2015-11-22

[19] PMMA/Acrylic information site (Electronic), Cambridge University, http://www-materials.eng.cam.ac.uk/mpsite/materialsdb/default.html#PMMA, 2015-11-22

[20] PMMA/Acrylic chemical resistance chart (Electronic), ePlastics, http://www.eplastics.com/Plastic/Plastics_Library/Chemical-Resistance-of-Plexiglass-Acrylic, 2015-11-22

[21] Information regarding aluminum extrusions, Alucon AB, http://www.alucon.se/, 2015-11-22